ABSTRACT

Title of Dissertation:	MENTAL WORKLOAD ASSESSMENT DURING UPPER LIMB PROSTHETIC TRAINING AND TASK PERFORMANCE
	Peter Christopher Gaskins, Doctor of Philosophy, 2023
Dissertation directed by:	Associate Professor, Dr. Rodolphe Gentili, Department of Kinesiology

Mental workload, defined as the recruitment and allocation of cortical resources in response to task demands, is an integral underlying mechanism of cognitive-motor learning and performance. Although widely examined in individuals without motor impairment, the study of mental workload in a clinical context of motor rehabilitation is limited. In particular, it is not well understood how the cortical processes underlying mental workload adapt over time as individuals learn to operate upper-limb prosthetic devices. In this work, mental workload assessment using electroencephalography (EEG) along with other ancillary measurement tools were employed to examine the recruitment of cognitive-motor processes as individuals learned to operate either a body-powered (BP) or myoelectric (MYO) bypass prosthesis during a ten session upper limb prosthetic training program. The first two studies examined changes in mental workload and cognitive-motor performance as prosthesis users executed tasks requiring transport of objects with the same or different shape/size during a prosthetic training program. Then, these newly trained prosthesis users engaged in activities which manipulated contextual demands to examine how real-world scenarios affect mental workload and cognitive-motor performance. Finally, a preliminary validation of a novel mental workload self-report measure aimed to

address the paucity of mental workload measurement tools in upper-limb rehabilitation was implemented. Although these four studies offer a rich and complex pattern of results, the main findings suggested that i) while both prosthetic groups experienced similar levels of cognitive-motor performance by the end of training, the BP group exhibited more refined cortical dynamics and better cognitive-motor efficiency when compared to the MYO group, thus indicating a more advanced progression of learning; ii) contextual demands degrade mental workload and cognitive-motor performance similarly in both prosthetic groups and; iv) the preliminary assessment of reliability and validity of the novel mental workload self-report measure shows promise for capturing changes in mental workload during cognitive-motor performance in a rehabilitation context. Although more research is warranted to confirm and extend the findings of this work to clinical upper-limb prosthesis users, this work has the potential to inform the cognitive-motor processes in this population and inform prescriptive decisions for patient device selection, prosthetic device design and rehabilitation program development.

MENTAL WORKLOAD ASSESSMENT DURING UPPER LIMB PROSTHETIC TRAINING AND TASK PERFORMANCE

by

Peter Christopher Gaskins

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2023

Advisory Committee:
Professor Rodolphe Gentili, Chair
Professor Matthew Roesch, Dean's Representative
Professor Bradley Hatfield
Professor Donald Bolger
Professor Xin He
Dr. Kimberly Kontson

Dedication

To my grandparents, who labored tirelessly as sharecroppers, home keepers, and blue-collar workers in rural South Carolina to provide the opportunity for my parents to become first generation college graduates. To my parents, for always supporting my academic and professional endeavors and challenging me to push the boundaries of my expectations. To my wife Tiffany, for your unwavering support and patience during this challenging but rewarding PhD process. Lastly, to my sweet little girl Nyla, I promise you will enjoy the fruits of my labor and professional growth that this PhD experience has afforded me. I love you all.

Table of Contents

Chapter 1: General Introduction

Mental Workload Assessment During Motor Performance

Mental workload assessment is critical to understanding the underlying cortical mechanisms of cognitive-motor learning and performance. Mental workload can be defined as the recruitment and allocation of mental resources in response to task demands (Kantowitz, 1998; Wickens, 2008). In the context of motor performance, cognitive (e.g., attentional, working memory) and sensorimotor processes are the primary mental sources of interests to examine. When task demands are low, fewer mental resources are recruited to complete goal-directed actions, mental workload is low, kinematics are enhanced, and cognitive-motor performance is elevated. In this state, individuals are able to allocate mental resources efficiently to necessary cortical regions to elicit effective responses to task demands. An increase in task demands can result in additional mental resources being recruited leading to an elevation of mental workload and a degradation or maintenance of cognitive-motor performance. Furthermore, strategies are continuously updated, an increased reliance on feedback mechanisms persists and resource allocation becomes inefficient and computationally expensive. Mental workload can be conceptualized by the Cognitive Load Theory (CLT). This framework suggests that there are three components: intrinsic, extraneous, and germane load (Sweller, 2010; Sweller et al., 2011; Whelan, 2007). For this work, intrinsic load refers to the level of the complexity of the prosthetic device operational information that needs to be acquired to complete goal-directed activities. Extrinsic load refers to the cognitive load that can be modulated by instructional concepts such as prosthetic training program design, types of practice that facilitate learning (e.g., blocked, or random practice), skill transfer and knowledge of performance and knowledge of results feedback. Germane load, which in our work is representative of the underlying cortical resources of cognitive-motor performance, reflects the deployment of resources that are deployed to mitigate the intrinsic load. Through practice, we develop structured sets of cognitive processes called schemas that allow us to process information more efficiently thus reducing our germane cognitive load and approach automaticity (Sweller, 1988, 2010; Van Merriënboer & Sweller, 2005). The process of achieving automaticity is a goal of training and is also encapsulated in the Fitts and Posner's Three-Stage Model (Fitts & Posner, 1967). In the initial cognitive stage of this model, learning is primarily focused on understanding the task demands and deploying frontally mediated resources to modulate performance. Usually, errors are common in this stage and performance variability is high. During the associative stage, learners continue to practice the skill, gradual refinement of cognitive-motor resources ensues and less errors are noted. In the final stage of motor learning, motor performance is accurate, consistent, requires little cognitive effort and automaticity is achieved. Such automaticity can also be considered as the result of an encoding of internal models which enables individuals to transition mainly from a feedback to a feedforward control modality (Desmurget & Grafton, 2000; Gentili et al., 2011; Shuggi et al., 2019) Empirically, past work has informed how humans recruit and allocate mental resources during motor performance by employing electroencephalography (EEG) to examine cognitive-motor processing(Alan Gevins et al., 1997; Hatfield et al., 2004; Jaquess et al., 2017). Specifically, the spectral indices low-alpha (8-10Hz), high-alpha (11-13Hz) and theta (4-7Hz) have been shown to index various aspects of cognitive-motor processing while beta (14-35 Hz) has been shown to index sensorimotor processing (Gentili et al., 2014, 2015; Neuper & Pfurtscheller, 2001; Pfurtscheller et al., 1996; Shaw et al., 2018; van Ede et al., 2015). There is evidence that suggests that theta (particularly frontal theta) reflects working memory engagement, attention, and error monitoring processes. Increased theta (an increase in spectral power is also referred to as synchrony) represents an increased engagement in these cognitive processes(Kao et al., 2013; S. W. H. Wong et al., 2014). A decrease in low-alpha power (a decrease in spectral power is also referred to as desynchrony) reflects an elevation of general arousal while a decrease in high-alpha power reflects increased recruitment of task specific attentional resources (Gentili et al., 2011, 2014, 2018; Jaquess et al., 2017; Klimesch, 2012). A decrease in beta power has been shown to reflect an elevation of sensorimotor processing (Espenhahn et al., 2019; van Ede & Maris, 2013; Zaepffel et al., 2013). A smaller body of work has examined how the recruitment and allocation of mental resources changes over time as individuals engage in practice and learn a new skill (Jaquess et al., 2018; Margraf et al., 2023; Shuggi et al., 2018, 2019). Low and high-alpha has been evidenced to increase as individuals engage in practice and refine their motor skills, which reflects an attenuation of general arousal and relevant cognitive-motor processing, respectively. While theta has been shown to be higher in tasks with more difficulty, in the context of practice theta has been evidenced to increase as individuals practice a skill, as this has been thought to reflect more effective attentional control and enhanced ability to identify and correct errors as well as encoding novel internal models of perturbation (Gentili et al., 2011; Alan Gevins et al., 1997; Jaquess et al., 2018).

While this empirical corpus has been foundational, this prior effort has examined mental workload and motor performance in healthy individuals who did not have any cognitive-motor deficiency without considering a clinical context. In rehabilitation, more healthcare professionals are training individuals with motor impairments to use human-machine interfaces such as robotics and prosthetics to augment or replace upper limb function (Butkus et al., 2014; Gull et al., 2020; Pasquina et al., 2015). Although external augmentations to the upper limb have been evidenced to cause cortical changes (Kieliba et al., 2021; Langer et al., 2012) little is known on the how the cortical dynamics underlying mental workload and the motor performance are modulated when individuals i) learn to operate prosthetic devices and ii) once trained, operate these devices under various cognitive-motor demands. Theoretically, these prosthetic devices can be considered as human-machine interfaces which provide novel and unusual sensorimotor mappings that individuals have to learn thus enabling the study of human motor learning. The sensorimotor mappings between the arm and cortex that derived from prior motor experience are disrupted to some degree and prosthesis users must undergo a reorganization of cortical resources to learn to use these devices and truly embody the human-machine interface as an integral and seamless part of the body schema (Casadio et al., 2012). Therefore, addressing the cognitive-motor processes underlying prosthesis performance and learning questions are important not only from a clinical perspective but also from a theoretical standpoint to inform the human cognitive-motor processes. In particular, it is not well understood how the cortical dynamics are affected by i) the intrinsic cognitive load of the device and the motor task(e.g. pick up a cup, button a shirt); ii) the extrinsic cognitive load of the training instructions and iii) multiple practice sessions across several weeks. From an applied perspective, this work could inform training strategies and practice duration for when individuals use prostheses as well as provide evidence on how device design affects mental workload in a context of both motor learning and performance. Thus, the assessment of body-powered (BP) and myoelectric (MYO) prosthesis performance could be an informative model to inform the cognitive-motor processes underlying prosthesis operation as well as inform if these different prosthetic designs are using different sensorimotor mappings that affect motor performance and recruit cognitive-motor resource differently.

Body-Powered vs. Myoelectric Prostheses

The control mechanisms of the BP and MYO prostheses are quite different; however, prior research has not clearly distinguished if these devices facilitate motor performance and engage the cognitive-motor resources differently, thus leading to different levels of mental workload. The BP device commonly uses a voluntary opening or closing hook terminal device with manual wrist adjustment capability. The terminal device is operated via a control harness with a cable pulley system that is controlled via prosthetic side shoulder flexion or extension, bilateral, sound side or prosthetic side scapular protraction or retraction. The proximal muscles such as the shoulder and muscles surrounding the scapulae are designed for more gross motor movements; however, the user must adapt their pre-existing motor plans to utilize these muscles to control grasp and manipulation functions of the terminal device. MYO devices that use a direct control mechanism receive electrical signals from an agonist and antagonist muscle proximal to the amputation to open and close the terminal device. Typically, a co-contraction of these two muscles will change the wrist position of the terminal device. The terminal device of the myoelectric prosthesis is a mechanical replica of the hand; thus the degrees of freedom are somewhat comparable to an anatomical hand.

When comparing BP and MYO devices, the grip strength of a myoelectric device supersedes the strength of a voluntary opening body-powered device and with less effort due to the sensitivity of the EMG sensor (Uellendahl, 2017). Also, it has been reported that myoelectric devices typically weigh more than body-powered devices (Uellendahl, 2017) which may cause additional exertion from the proximal arm and trunk muscles. In an effort to make MYO devices closed loop systems, some devices deploy haptic feedback to the powered hand when an object is firmly grasped to compensate for the proprioceptive limitations of the device (Brown et al., 2015; K. Kim et al., 2010). BP devices have been appreciated for their proprioceptive feedback through the cable-pulley system that generates tension changes detected through the back and arm of the user to open or close the terminal device (Carey et al., 2015; Uellendahl, 2017). These tension changes may help prosthesis users perceive the degree of terminal device opening, thus reducing the need for a visual confirmation of the position of the terminal device aperture. Furthermore, it has been reported that the hook terminal device doesn't significantly impact the field of vision that an object of interest is in, thus possibly allowing for foveal vision on the object of interest, instead of on the terminal device (T. W. Williams, 2011). This is in contrast to MYO devices which have been shown to rely more on visual feedback in the absence of proprioceptive feedback therefore potentially detracting from time to visual fixate on the object of interest in preparation for grasping thus leading to slower movement times (J. V.V. Parr et al., 2019; J. V. V Parr et al., 2018). When learning to use these devices, it has been reported that more training may be required for myoelectric users (Bouwsema et al., 2008; Carey et al., 2015). Some work suggests body-powered devices may be more versatile as they could be used for light or heavy work while the myoelectric device may be preferred for lighter work with the manipulation of small objects (Uellendahl, 2017). While some work has shown that BP users have faster movement times when compared to MYO users, it is not known if different sensorimotor mappings and cognitive-motor resource deployment explain the performance differences between these groups (Bouwsema et al., 2008; Resnik et al., 2022).

While these constructs are important to examine, the upper limb amputation population is relatively small when compared to other forms of disability, thus posing significant participant recruitment challenges (T. W. Williams, 2011). Most amputations are lower limb amputations that are due to complications arising from vascular disease while upper limb amputations are more commonly due to traumatic events. Upper limp amputees with major limb loss (excluding finger amputations) represent only 8% of all amputees (Ziegler-Graham et al., 2008). Despite this small population, when compared to lower limb prosthesis users, this group experiences more significant disability (Tennent et al., 2014).

However, the number of individuals living with limb loss is expected to double by 2050. Regarding upper limb amputations specifically in the United States, conflicts in the Middle East have led to an increase in the overall prevalence of upper limb amputations. In response to this, advancements in prosthetic research and technology have been made to improve prosthetic rehabilitation (Naufel et al., 2020; Pasquina et al., 2015). However, there is still significant variability in the amount of training upper limb prosthesis users receive, residual limb integrity, levels of prosthetic experience, types of devices used (Resnik et al., 2019). Due to these variations and the small population size of upper limb amputees, alternative models to examine mental workload in this population must be explored.

The Bypass Prosthesis Model

One approach to these recruitment challenges is to examine individuals without limb loss while using a bypass prosthesis (Figure 1). A bypass prosthesis is a device that allows individuals without limb loss operate to simulate the cognitive-motor demands that an actual prosthesis user experiences (A. W. Wilson et al., 2017). This device limits sensation and upper limb degrees of freedom, thus posing novel sensorimotor challenges for the user that is similar to a prosthesis used by an individual living with an upper limb amputation (Casadio et al., 2012; H. E. Williams et al., 2021). This device has been used in past research to inform prosthesis use in individuals living with upper limb amputations (Bloomer et al., 2018, 2020; Bloomer & Kontson, 2020; Haverkate et al., 2016). Although commonly used in prosthetic research, the bypass approach may not be able to exactly replicate the cortical reorganization caused after upper limb amputation in clinical prosthesis users (Chen et al., 2013). However, several arguments support that this bypass technique can to some extent inform how clinical prosthesis users learn to operate their devices. First, bypass users and clinical prosthesis users have shown similar kinematic patterns (Bloomer et al., 2018; Carey et al., 2008; H. E. Williams et al., 2021); thus, supporting the use of the bypass study design. The similarity of kinematic patterns between bypass prosthesis users and prosthesis users with an amputation may suggest that the afferent information traveling to the cortical regions may bear some similarity between these two groups; however, this has not been thoroughly examined. Second, similarly to clinical prosthesis users, the bypass device may provide individuals with a similar challenge by offering the need to acquire skills via practice, an internal model of the novel and unusual sensorimotor mappings to control the prosthetic device (Casadio et al., 2012; Lum et al., 2014).

Fig. 1. i-limb® Ultra Myoelectric Bypass Prosthesis with Biosim smartphone application(top picture). Body-powered bypass prosthesis with voluntary opening Hosmer 5X hook (bottom picture).

While research has indicated that the bypass model may be a comparable model to examine the cognitive-motor processes in individuals with upper limb loss, most work using able-bodied individuals or amputees is centered on task performance, but few studies have examined prosthetic training. It is not clear if prosthetic training programs are similar in training content and are regularly implemented to facilitate learning. For example, for military amputee veterans, 33% reported never receiving training for their current prosthesis and of the veterans who did receive training, 28% report having less than 3 sessions while approximately 15% report having more than 30 training sessions (Resnik et al., 2019). There has been attempts to develop standardized bypass prosthetic training programs to inform programs for amputees (Bloomer et al., 2018; Bouwsema et al., 2008, 2014; Huinink et al., 2016); however, these training programs vary widely in length from as few as two training sessions (Bouwsema et al., 2008) to as many as ten training sessions (Bloomer et al., 2018). The inconsistency in training length makes it challenging to understand how the cognitive-motor processes adapt to task demands over time. To the author's knowledge, no work has examined differences in the underlying neural resources associated with mental workload as individuals learned to either a BP or MYO prostheses over multiple training sessions.

Line of Research Synopsis

To model the clinical population of upper limb prosthesis users, we trained 20 individuals with intact upper limbs to use either a BP or MYO bypass prosthesis across 10 practice sessions using a standardized bypass prosthetic training protocol (Bloomer et al., 2018). Our approach was to examine mental workload and motor performance during prosthetic training with a combined examination including behavioral performance (task outcome and movement measurements), surveys and cortical dynamics to inform the cognitive-motor processes that influence performance. First, motor performance will be captured using the standardized and validated performance outcome measures, the Box and Blocks Test (BBT) and the Southampton Hand Assessment Procedure (SHAP). In addition, we will further inform task performance by examining the underlying movement characteristics associated with motor performance by using kinematic analysis. The relationship between mental workload and motor performance will be examined by assessing perceived mental workload via the NASA-TLX as well as employing spectral EEG analyses to identify how theta, beta, and low and high-alpha change as a function of practice and task difficulty. This approach will be employed across multiple practice sessions and during a retention session at least a week after training has been completed.

Study 1, entitled "Mental Workload and Dexterity Performance", examines how dexterity (BBT) and mental workload change in individuals learning to use a bypass BP or MYO prosthesis throughout the training program.

Study 2, entitled “Mental Workload and Prehensile Performance,” determines if there are difference in prehensile performance(SHAP) and mental workload between BP and MYO users as they learn to manipulate objects of different shape and sizes that require various types of grips.

Study 3 , entitled “Mental Workload and Performance Under Varying Contextual Demands”, captures the newly trained bypass prosthesis users at least one week after completion of their training program as they completed four real-world activities in more ecological valid scenarios when compared to Study 1 and 2. To manipulate the real-world demands of the activities, prosthesis users completed these activities under a non-contextual condition, which provided basic instructions to complete the activity and a contextual condition in which prosthesis suers were instructed to complete the activity within the context of a real world scenario, thus creating contextual demands that were designed to elevate working memory, sequencing, and organizational demands. We compared the results of the prosthesis users to a control group who used their intact, dominant upper limb to complete the activities.

Study 4, entitled “Preliminary Validation of a Self-Report Mental Workload Measure”, addresses the paucity of mental workload assessment in upper limb prosthesis research, by introducing the Prosthesis-Orthosis Load Index (POLI) questionnaire. Internal consistency of the measure was used to establish reliability and validity was established by assessing the POLI’s relationship with the well-established mental workload questionnaire, the National Aeronautics Space Administration Task Load Index (NASA-TLX) as well as other measures of cognitive-motor performance.

Finally, this line of research will conclude with a General Conclusion, which will serve as a cohesive summary of general findings of each study that will aid the reader in formulating comprehensive insights that can be derived from this empirical corpus.

References

Bloomer, C., & Kontson, K. L. (2020). Comparison of DEKA Arm and Body-Powered Upper Limb Prosthesis Joint Kinematics. *Archives of Rehabilitation Research and Clinical Translation*, *2*(3), 100057. https://doi.org/10.1016/j.arrct.2020.100057

Bloomer, C., Wang, S., & Kontson, K. (2020). Kinematic analysis of motor learning in upper limb body-powered bypass prosthesis training. *PLoS ONE*, *15*(1), 1–16. https://doi.org/10.1371/journal.pone.0226563

Bloomer, C., Wang, S., & Kontson, K. L. (2018). Creating a standardized , quantitative training protocol for upper limb bypass prostheses. *Physical Medicine and Rehabilitation Research*.

Bouwsema, H., Van Der Sluis, C. K., & Bongers, R. M. (2008). *The Role of Order of Practice in Learning to Handle an Upper-Limb Prosthesis*. https://doi.org/10.1016/j.apmr.2007.12.046

Bouwsema, H., Van Der Sluis, C. K., & Bongers, R. M. (2014). Changes in performance over time while learning to use a myoelectric prosthesis. In *Journal of NeuroEngineering and Rehabilitation* (Vol. 11). https://doi.org/10.1186/1743-0003-11-16

Brown, J. D., Paek, A., Syed, M., O'Malley, M. K., Shewokis, P. A., Contreras-Vidal, J. L., Davis, A. J., & Gillespie, R. B. (2015). An exploration of grip force regulation with a low-impedance myoelectric prosthesis featuring referred haptic feedback. *Journal of NeuroEngineering and Rehabilitation*, *12*(1), 1–17. https://doi.org/10.1186/s12984-015-0098-1

Butkus, J., Dennison, C., Orr, A., & Laurent, M. St. (2014). Occupational Therapy with the Military Upper Extremity Amputee: Advances and Research Implications. *Current Physical Medicine and Rehabilitation Reports*, *2*(4), 255–262. https://doi.org/10.1007/s40141-014-0065-y

Carey, S. L., Jason Highsmith, M., Maitland, M. E., & Dubey, R. V. (2008). Compensatory movements of transradial prosthesis users during common tasks. *Clinical Biomechanics*, *23*(9), 1128–1135. https://doi.org/10.1016/j.clinbiomech.2008.05.008

Carey, S. L., Lura, D. J., & Highsmith, M. J. (2015). *Differences in myoelectric and body-powered upper-limb prostheses: Systematic literature review*. *52*(3), 247–262.

https://doi.org/10.1682/JRRD.2014.08.0192

Casadio, M., Ranganathan, R., & Mussa-Ivaldi, F. A. (2012). The body-machine interface: A new perspective on an old theme. *Journal of Motor Behavior*, *44*(6), 419–433. https://doi.org/10.1080/00222895.2012.700968

Chen, A., Yao, J., Kuiken, T., & Dewald, J. P. A. (2013). Cortical motor activity and reorganization following upper-limb amputation and subsequent targeted reinnervation. *NeuroImage: Clinical*, *3*, 498–506. https://doi.org/10.1016/j.nicl.2013.10.001

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences*, *4*(11), 423–431. https://doi.org/10.1016/S1364-6613(00)01537-0

Espenhahn, S., van Wijk, B. C. M., Rossiter, H. E., de Berker, A. O., Redman, N. D., Rondina, J., Diedrichsen, J., & Ward, N. S. (2019). Cortical beta oscillations are associated with motor performance following visuomotor learning. *NeuroImage*, *195*(April), 340–353. https://doi.org/10.1016/j.neuroimage.2019.03.079

Fitts, P. M., & Posner, M. I. (1967). Human performance. In *Human performance*. Brooks/Cole.

Gentili, R. J., Bradberry, T. J., Oh, H., Costanzo, M. E., Kerick, S. E., Contreras-Vidal, J. L., & Hatfield, B. D. (2015). Evolution of cerebral cortico-cortical communication during visuomotor adaptation to a cognitive-motor executive challenge. *Biological Psychology*, *105*, 51–65. https://doi.org/10.1016/j.biopsycho.2014.12.003

Gentili, R. J., Bradberry, T. J., Oh, H., Hatfield, B. D., & Contreras Vidal, J. L. (2011). Cerebral cortical dynamics during visuomotor transformation: Adaptation to a cognitive-motor executive challenge. *Psychophysiology*, *48*(6), 813–824. https://doi.org/10.1111/j.1469-8986.2010.01143.x

Gentili, R. J., Jaquess, K. J., Shuggi, I. M., Shaw, E. P., Oh, H., Lo, L. C., Tan, Y. Y., Domingues, C. A., Blanco, J. A., Rietschel, J. C., Miller, M. W., & Hatfield, B. D. (2018). Combined assessment of attentional reserve and cognitive-motor effort under various levels of challenge with a dry EEG system. *Psychophysiology*, *55*(6), 1–17. https://doi.org/10.1111/psyp.13059

Gentili, R. J., Rietschel, J. C., Jaquess, K. J., Lo, L. C., Prevost, M., Miller, M. W., Mohler, J. M., Oh, H., Tan, Y. Y. ing, & Hatfield, B. D. (2014). Brain biomarkers based assessment of cognitive workload in pilots under various task demands. *Conference Proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference*, *2014*, 5860–5863. https://doi.org/10.1109/EMBC.2014.6944961

Gevins, A., Smith, M. E., McEvoy, L., & Yu, D. (1997). High-resolution EEG mapping of cortical activation related to working memory: Effects of task difficulty, type of processing, and practice. *Cerebral Cortex*, *7*(4), 374–385. https://doi.org/10.1093/cercor/7.4.374

Gull, M. A., Bai, S., & Bak, T. (2020). A review on design of upper limb exoskeletons. *Robotics*, *9*(1), 1–35. https://doi.org/10.3390/robotics9010016

Hatfield, B. D., Haufler, A. J., Hung, T.-M., & Spalding, T. W. (2004). Electroencephalographic Studies of Skilled Psychomotor Performance. *Journal of Clinical Neurophysiology*, *21*(3).

Haverkate, L., Smit, G., & Plettenburg, Di. H. (2016). Assessment of body-powered upper limb prostheses by able-bodied subjects, using the Box and Blocks Test and the Nine-Hole Peg Test. *Prosthetics and Orthotics International*, *40*(1), 109–116. https://doi.org/10.1177/0309364614554030

Huinink, L. H. B., Bouwsema, H., Plettenburg, D. H., Van Der Sluis, C. K., & Bongers, R. M. (2016). *Learning to use a body-powered prosthesis: changes in functionality and kinematics*. https://doi.org/10.1186/s12984-016-0197-7

Jaquess, K. J., Gentili, R. J., Lo, L. C., Oh, H., Zhang, J., Rietschel, J. C., Miller, M. W., Tan, Y. Y., & Hatfield, B. D. (2017). Empirical evidence for the relationship between cognitive workload and attentional reserve. *International Journal of Psychophysiology*, *121*(February), 46–55. https://doi.org/10.1016/j.ijpsycho.2017.09.007

Jaquess, K. J., Lo, L. C., Oh, H., Lu, C., Ginsberg, A., Tan, Y. Y., Lohse, K. R., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Changes in Mental Workload and Motor Performance Throughout

Multiple Practice Sessions Under Various Levels of Task Difficulty. *Neuroscience*, *393*, 305–318. https://doi.org/10.1016/j.neuroscience.2018.09.019

Kantowitz, B. H. (1998). Attention and Mental Workload. *Proceedings of the IEA 2000/HFES 2000 Congress*, 456–459.

Kao, S. C., Huang, C. J., & Hung, T. M. (2013). Frontal midline theta is a specific indicator of optimal attentional engagement during skilled putting performance. *Journal of Sport and Exercise Psychology*, *35*(5), 470–478. https://doi.org/10.1123/jsep.35.5.470

Kieliba, P., Clode, D., Maimon-Mor, R. O., & Makin, T. R. (2021). Robotic hand augmentation drives changes in neural body representation. *Science Robotics*, *6*(54), 1–14. https://doi.org/10.1126/scirobotics.abd7935

Kim, K., Colgate, J. E., Santos-Munné, J. J., Makhlin, A., & Peshkin, M. A. (2010). On the design of miniature haptic devices for upper extremity prosthetics. *IEEE/ASME Transactions on Mechatronics*, *15*(1), 27–39. https://doi.org/10.1109/TMECH.2009.2013944

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences*, *16*(12), 606–617. https://doi.org/10.1016/j.tics.2012.10.007

Langer, N., Hänggi, J., Müller, N. A., Simmen, H. P., & Jäncke, L. (2012). Effects of limb immobilization on brain plasticity. *Neurology*, *78*(3), 182 LP – 188. https://doi.org/10.1212/WNL.0b013e31823fcd9c

Lum, P. S., Black, I., Holley, R. J., Barth, J., & Dromerick, A. W. (2014). Internal models of upper limb prosthesis users when grasping and lifting a fragile object with their prosthetic limb. *Experimental Brain Research*, *232*(12), 3785–3795. https://doi.org/10.1007/s00221-014-4071-1

Margraf, L., Krause, D., & Weigelt, M. (2023). Frontal theta reveals further information about neural valence-dependent processing of augmented feedback in extensive motor practice—A secondary analysis. *European Journal of Neuroscience*, *57*(8), 1297–1316. https://doi.org/10.1111/ejn.15951

Naufel, S., Knaack, G. L., Miranda, R., Best, T. K., Fitzpatrick, K., Emondi, A. A., Van Gieson, E., & McClure-Begley, T. (2020). DARPA investment in peripheral nerve interfaces for prosthetics, prescriptions, and plasticity. *Journal of Neuroscience Methods*, *332*(November 2019), 108539. https://doi.org/10.1016/j.jneumeth.2019.108539

Neuper, C., & Pfurtscheller, G. (2001). Event-related dynamics of cortical rhythms: Frequency-specific features and functional correlates. *International Journal of Psychophysiology*, *43*(1), 41–58. https://doi.org/10.1016/S0167-8760(01)00178-7

Parr, J. V. V., Vine, S. J., Wilson, M. R., Harrison, N. R., & Wood, G. (2019). Visual attention, EEG alpha power and T7-Fz connectivity are implicated in prosthetic hand control and can be optimized through gaze training. *Journal of NeuroEngineering and Rehabilitation*, *16*(1), 1–20. https://doi.org/10.1186/s12984-019-0524-x

Parr, J. V. V, Vine, S. J., Harrison, N. R., & Wood, G. (2018). Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand. *Journal of Motor Behavior*, *50*(4), 416–425. http://10.0.4.56/00222895.2017.1363703

Pasquina, P. F., Perry, B. N., Miller, M. E., Ling, G. S. F., & Tsao, J. W. (2015). Recent Advances in Bioelectric Protheses. *Neurology Clinical Practice*, 164–170.

Pfurtscheller, G., Stancák, A., & Neuper, C. (1996). Event-related synchronization (ERS) in the alpha band - An electrophysiological correlate of cortical idling: A review. *International Journal of Psychophysiology*, *24*(1–2), 39–46. https://doi.org/10.1016/S0167-8760(96)00066-9

Resnik, L., Borgia, M., Cancio, J., Heckman, J., Highsmith, J., Levy, C., Phillips, S., & Webster, J. (2022). Dexterity, activity performance, disability, quality of life, and independence in upper limb Veteran prosthesis users: a normative study. *Disability and Rehabilitation*, *44*(11), 2470–2481. https://doi.org/10.1080/09638288.2020.1829106

Resnik, L., Ekerholm, S., Borgia, M., & Clark, M. A. (2019). A national study of Veterans with major upper limb amputation: Survey methods, participants, and summary findings. *PLoS ONE*, *14*(3), 1–24. https://doi.org/10.1371/journal.pone.0213578

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological Psychology*. https://doi.org/10.1016/j.biopsycho.2018.01.009

Shuggi, I. M., Oh, H., Wu, H., Ayoub, M. J., Moreno, A., Shaw, E. P., Shewokis, P. A., & Gentili, R. J. (2019). Motor Performance, Mental Workload and Self-Efficacy Dynamics during Learning of Reaching Movements throughout Multiple Practice Sessions. *Neuroscience*, *423*, 232–248. https://doi.org/10.1016/j.neuroscience.2019.07.001

Shuggi, I. M., Shewokis, P. A., Herrmann, J. W., & Gentili, R. J. (2018). Changes in motor performance and mental workload during practice of reaching movements: a team dynamics perspective. *Experimental Brain Research*. https://doi.org/10.1007/s00221-017-5136-8

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1016/0364-0213(88)90023-7

Sweller, J. (2010). Element interactivity and intrinsic, extraneous, and germane cognitive load. *Educational Psychology Review*, *22*(2), 123–138. https://doi.org/10.1007/s10648-010-9128-5

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive Load Theory*. https://doi.org/10.1007/978-1-4419-8126-4

Tennent, D. J., Wenke, J. C., Rivera, J. C., & Krueger, C. A. (2014). Characterisation and outcomes of upper extremity amputations §. *Injury*, *45*(6), 965–969. https://doi.org/10.1016/j.injury.2014.02.009

Uellendahl, J. (2017). Myoelectric versus Body-Powered Upper-Limb Prostheses: A Clinical Perspective. *JPO Journal of Prosthetics and Orthotics*, *29*(4S), P25–P29. https://doi.org/10.1097/jpo.0000000000000151

van Ede, F., & Maris, E. (2013). Somatosensory demands modulate muscular beta oscillations, independent of motor demands. *Journal of Neuroscience*, *33*(26), 10849–10857. https://doi.org/10.1523/JNEUROSCI.5629-12.2013

van Ede, F., Winner, T., & Maris, E. (2015). Touch automatically upregulates motor readiness in humans. *Journal of Neurophysiology*, *114*(6), 3121–3130. https://doi.org/10.1152/jn.00504.2015

Van Merriënboer, J. J. G., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. In *Educational Psychology Review* (Vol. 17, Issue 2). https://doi.org/10.1007/s10648-005-3951-0

Whelan, R. R. (2007). Neuroimaging of cognitive load in instructional multimedia. *Educational Research Review*, *2*(1), 1–12. https://doi.org/10.1016/j.edurev.2006.11.001

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394.

Williams, H. E., Chapman, C. S., Pilarski, P. M., Vette, A. H., & Hebert, J. S. (2021). Myoelectric prosthesis users and non-disabled individuals wearing a simulated prosthesis exhibit similar compensatory movement strategies. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 1–15. https://doi.org/10.1186/s12984-021-00855-x

Williams, T. W. (2011). Progress on stabilizing and controlling powered upper-limb prostheses. *Journal of Rehabilitation Research and Development*, *48*(6), ix–xix. http://www.ncbi.nlm.nih.gov/pubmed/21938646

Wilson, A. W., Blustein, D. H., & Sensinger, J. W. (2017). A third arm - Design of a bypass prosthesis enabling incorporation. *IEEE International Conference on Rehabilitation Robotics*, 1381–1386. https://doi.org/10.1109/ICORR.2017.8009441

Wong, S. W. H., Chan, R. H. M., & Mak, J. N. (2014). Spectral modulation of frontal EEG during motor skill acquisition: A mobile EEG study. *International Journal of Psychophysiology*, *91*(1), 16–21. https://doi.org/10.1016/j.ijpsycho.2013.09.004

Zaepffel, M., Trachel, R., Kilavik, B. E., & Brochier, T. (2013). Modulations of EEG Beta Power during Planning and Execution of Grasping Movements. *PLoS ONE*, *8*(3). https://doi.org/10.1371/journal.pone.0060060

Ziegler-Graham, K., MacKenzie, E. J., Ephraim, P. L., Travison, T. G., & Brookmeyer, R. (2008). Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050. *Archives of Physical Medicine and Rehabilitation*, *89*(3), 422–429. https://doi.org/10.1016/j.apmr.2007.11.005

Chapter 2: Mental Workload and Dexterity Performance During Training

Abstract

Despite the technological advancement of upper limb prostheses, it is unclear how the design of these devices (e.g., body-powered hook or myoelectric hand) affect the underlying cognitive-motor processes of mental workload that facilitate the acquisition of dexterity skill over time. Therefore, in this first study, 20 individuals with intact upper limbs were trained to use a body-powered bypass prosthesis (BP) or myoelectric bypass prosthesis (MYO). The Box and Block Test (BBT) was employed to assess manual dexterity at the 2nd (initial training session), 5th, 8^{th,} and 11th (final training) and retention sessions. Motor performance (number of blocks transported in one minute), movement smoothness (normalized jerk), perceived mental workload (National Aeronautics Space Administration Task Load Index questionnaire [NASA-TLX]), and spectral electroencephalography indices of cognitive-motor and sensorimotor processing(theta [4-7Hz], low-alpha [8-10Hz], high- alpha [11-13Hz] and beta [14-35Hz]) were examined. Both groups indicated an improvement in manual dexterity and an increase in movement smoothness as a result of training. While both groups experienced a similar decrease in perceived mental workload(NASA-TLX) as a result of training, the spectral analysis revealed differences in cortical dynamics underlying mental workload between the two groups. Specifically, throughout training, the MYO group experienced attenuated beta as well as low and high-alpha power when compared to the BP users. These differences in cognitive-motor processing persisted into the retention session. These findings may suggest that the MYO users experienced greater arousal and recruitment of cognitive-motor and sensorimotor resources to obtain a similar BBT performance to that of the BP users. This suggests that the MYO users exhibited lower cognitive-motor efficiency when compared to the BP users. To our knowledge, this work is the first to distinguish differences in cognitive-motor efficiency between different types of prostheses by capturing divergences in the recruitment of cognitive-motor resources underlying mental workload between BP and MYO users during prosthetic training.

Introduction

Dexterity is a critical skill that humans need to manipulate objects during participation in meaningful activities; however, research that examines the underlying cognitive-motor processes that facilitate the acquisition of this skill is sparse (Espenhahn et al., 2019; Krauth et al., 2019). In particular, the cognitive-motor processes underlying mental workload, which can be considered as the amount of cortical resources recruited to meet tasks demands to complete a goal-directed action can inform cognitive-motor performance (Gentili et al., 2014, 2018; Rietschel et al., 2014; Shaw et al., 2018; Shuggi et al., 2019; Wickens, 2008). Dexterity is particularly disrupted when individuals with upper limb loss perform upper extremity movement using a prosthesis (Resnik et al., 2022). In a rehabilitative context, it is important to understand the recruitment of cognitive-motor (e.g., attentional, working memory) and sensorimotor resources underlying mental workload during completion of a dexterous task.

However, it is not well understood if the control systems of a prosthetic device (e.g., body-powered vs. myoelectric) imposing different sensorimotor maps between the human user and the device differently affect the underlying cognitive-motor resources that drive dexterity acquisition. This is critical information as various technology advancements in the field are shifting prosthesis design to more technological advanced systems such as myoelectric (MYO) prostheses (Pasquina et al., 2015). In a study examining the effects of the order of practice tasks on performance, individuals with intact upper limbs who used a BP simulator performed tasks faster during retention and transfer sessions than those using a MYO simulator (Bouwsema et al., 2008). A subsequent systematic review suggested that despite various design differences between BP and MYO devices, there is no clear performance advantage for either device (Carey et al., 2015). This finding was further supported by a survey administered to over 800 veterans who currently use or formerly used an upper limb prosthesis (Resnik et al., 2019). While both of these works were informative, a limitation of these efforts is that the findings were primarily based on subjective reports. As a follow-up to this limitation, Resnik and colleagues assessed dexterity in 127 upper limb prosthesis users by utilizing the Jebsen-Taylor Hand Function Test (JHFT), Nine Hole Peg (NHP) Test, the Box and Block Test (BBT) and the Southampton Hand Assessment Procedure (SHAP)

(Resnik et al., 2022). Out of the four different performance outcome measures used in this study, only the NHP detected better dexterity between unilateral upper limb prosthesis users, such that BP users had better dexterity performance when compared to MYO users. While research that suggests differences in dexterity performance between BP and MYO devices is significantly limited (Bouwsema et al., 2008; Resnik et al., 2022), the elucidation of the underlying cognitive-motor resources of mental workload during dexterous tasks may contribute a cortical basis for refining the hypotheses for why these performance differences occurred. In addition, none of this work comparing both types of prosthetic performance were conducted in conjunction with examination of mental workload in a training context.

The National Aeronautics and Space Program Task Load Index (NASA-TLX) is considered as the standard for subjective mental workload assessment(Hart & Staveland, 1988). The NASA-TLX has been shown to reliably index changes in mental workload (Akizuki & Ohashi, 2015; J. Y. Kim & Ji, 2013; Shuggi et al., 2018) and is often used in conjunction with electroencephalography (EEG) to provide a comprehensive mental workload assessment (Fallahi et al., 2016; Gentili et al., 2014; Jaquess et al., 2017; Rietschel et al., 2014; Shaw et al., 2018). In EEG spectral analysis, an attenuation of low-alpha (8-10Hz) has been evidenced to represent general arousal while evidence suggests an attenuation in high-alpha(11-13Hz) reflects an increased recruitment of the relevant, task specific attentional resources(Gentili et al., 2014; Shaw et al., 2018). An elevation in theta (particularly frontal theta) has been thought to reflect attention, working memory and error monitoring. The power in these bandwidths is typically used to assess recruitment of cognitive-motor resources. Given the different control systems and reports of different proprioceptive and tactile feedback elicited by BP and MYO devices (Carey et al., 2015; T. W. Williams, 2011), the incorporation of beta (14-35 Hz) into mental workload assessment could enhance our understanding of the cognitive-motor and sensorimotor processes underlying motor performance (Babiloni et al., 2008; Espenhahn et al., 2019; Nelson et al., 2017). While some evidence suggests beta is related to motor learning processes (Espenhahn et al., 2019; Meissner et al., 2018), recent work suggests beta indexes differences in task difficulty (van der Cruijsen et al., 2021).

To our knowledge, no work has systematically compared mental workload between BP and MYO users during a training program. There is a small body of work that has examined EEG indices of mental workload in prosthesis users; however, this work has been mostly limited to lower limb prosthesis users (Pruziner et al., 2019; Shaw et al., 2019) or upper limb MYO users (Deeny et al., 2014; J. Parr et al., 2020; Johnny V.V. Parr et al., 2020) that may inform the present study. For example, when assessing mental workload between two types of myoelectric prostheses (direct and pattern recognition control), the researchers observed that the direct control group experienced a greater depletion of attentional resources when compared to the pattern recognition control group (Deeny et al., 2014). Parr and colleagues provided evidence that MYO users over the course of three practice sessions, experienced greater cognitive effort as indexed by an attenuation in alpha power to complete upper limb motor tasks when compared to using an intact, anatomical hand (J. V.V. Parr et al., 2019). The authors also demonstrated that visual training to facilitate gaze on the object to be grasped instead of the prosthetic hand was associated with visual attention improvements and reduction in cognitive control. In addition, another prior investigation revealed that alpha attenuation indexed higher levels of mental effort when relying on visual feedback when compared to auditory feedback while no differences were detected for beta (Gonzalez et al., 2012). When employing spectral indices of alpha and theta to assess differences in task difficulty in lower limb prosthesis users, attenuated alpha and elevated theta were associated with completion of more difficult tasks (Pruziner et al., 2019).

To examine mental workload during multiple practice sessions in BP and MYO users, we trained 20 individuals with intact limbs to learn to use either a BP or MYO bypass prosthesis during a standardized 10-session training program that was adopted from an established bypass prosthetic training program (Bloomer et al., 2018). The BBT (performance outcome measure), normalized jerk(movement smoothness), NASA-TLX (perceived mental workload), low-alpha, high-alpha, theta, and beta were assessed at various timepoints to assess changes in these metrics as a function of training. We assessed these metrics again during the retention session to determine if there were permanent changes in dexterity and mental workload as a marker of learning. The goal of this study was to first determine if dexterity and mental workload changed as prosthesis users advanced through training and secondly if there were differences in dexterity and mental workload between the BP and MYO prosthesis users. We predicted that by the retention session, prosthesis users would demonstrate improved dexterity, increased movement smoothness and an attenuated mental workload when compared to the initial training session. When assessing differences between BP and MYO users, we predicted that the BP group would exhibit better performance, more enhanced movement smoothness and an attenuated mental workload compared to the MYO users. This information could better inform the attentional and sensorimotor processes associated with changes in motor performance as an individual learns to use a prosthesis. This work may inform strategies to reduce a lack of device intuitiveness, usability problems and device rejection that has been reported by upper limb prosthesis users (Biddiss & Chau, 2007; Resnik et al., 2019).

Methods

Participants

To participate in the study, participants were required to be right hand dominant (confirmed by the Edinburg Handedness Survey), have normal or corrected-to-normal vision, not have an upper limb injury, have no neurological disorders that would negatively influence movement and not be on psychotropic medication. A convenience sample of 28 participants volunteered to participate in the study, five participants were excluded from the study due to not meeting all inclusion criteria and three participants either signed up for the study or started the study but dropped out due to personal reasons. Thus, a final total sample of 20 right-handed participants (10 males, 10 females) with intact upper limbs between the ages of 19 and 58 (mean = 25.85, SD = 8.35) completed the 10-session bypass prosthetic training program. Participants were randomly split into the BP (4 males, 6 females, mean age = 23.5, SD = 3.77) or MYO (5 males, 5 females, mean age = 28.5, SD = 10.83) groups. All participants were current or former University of Maryland, College Park students or faculty. The sample size was determined based upon a prior upper limb prosthetic training study (J. V.V. Parr et al., 2019). During training, three MYO participants experienced a MYO device malfunction in which the index finger of the device remained in the open position during one or more assessment sessions. To determine if the malfunction had a significant effect on study results, a linear mixed effect model was employed for MYO users to see if the covariate, device malfunction, significantly affected motor performance, kinematic or perception of task demands. This covariate of device malfunction was insignificant for BBT motor performance, movement smoothness or perception of task demands for each dimension of the NASA-TLX. Therefore, the data for these MYO participants who experienced this malfunction were preserved in this study.

All participants provide their informed consent prior to participating in the study. The Institutional Review Board at the University of Maryland-College Park approved this study.

Bypass Prosthesis Donning and Operational Check

The BP bypass prosthesis used in this study was designed by Arm Dynamics (Dallas, TX) utilized a voluntary opening Hosmer 5X hook terminal device, with manual wrist rotation, figure eight harness and a 12 cm distal offset. While standing, the BP users donned the prosthesis harness on the right, dominant arm and the forearm was secured in the arm socket with straps with assistance from the experimenter. While seated, the participants demonstrated voluntary opening of the terminal device via a cable pulley system by using shoulder flexion and scapular protraction with three techniques. The bypass side technique only used the right side of the body, the sound side technique used the left side of the body and the bi-scapular technique used both scapulae to open the terminal device. Opening of the terminal device was demonstrated at a 50% and 100% aperture. The BP users also demonstrated unlocking of the wrist, manual rotation of the wrist to achieve the desired hook direction and a locking of the wrist to secure the hook positioning. The BP users pre-selected the orientation of their prosthetic hook prior to beginning each task during training and assessment.

The MYO terminal device used in this study was the i-limb Ultra® created by Össur (Foothill Ranch, CA). The myoelectric terminal device was mounted to a forearm brace adapter provided by Next Step Bionics with a perpendicular handlebar with a medial offset of 15° from the participant’s forearm. This device featured individualized motorized digits, compliant grip capability, direct control system using two electromyography sensors, manual thumb, and wrist rotation functionality. This prosthesis was used with a companion I-phone application (Biosim™) via Bluetooth connection. Biosim™ features a real-time EMG graph to assess muscle contraction quality and 12 automated ‘quick’ grips. While the MYO users were seated, their ventral and dorsal aspect of the right forearm was cleaned using an alcohol swab prior to placing the flexor sensor on the muscle belly of the flexor carpi radialis superficialis and the extensor sensor on the muscle belly of the extensor carpi radialis. The electrodes were secured with skin tape to reduce electrode movement during the experiment. This was done to remove skin debris that may interfere with the skin/electrode connection and the electromyograph (EMG) signal. Once the prosthesis was on, participants completed repetitive hand opening and closing for approximately 5-10 seconds while viewing the EMG signal in real time to assess for contraction quality and for existence of interfering co-contraction of the flexor and extensor muscles. Knowledge of performance feedback was provided as needed until optimal muscle contractions with minimal or undetected co-contraction was detected and no significant latency was noted between the contraction and the subsequent MYO hand movement. The MYO users then selected 11 grips one at a time (Figure 1) using the Biosim™ application. They performed isometric wrist flexion to flex the digits/hand followed by isometric wrist extension to open the digits/ hand based upon the pre-selected digit operation of each grip. The thumb park quick grip was not used for the study due to usability concerns since this grip only allowed for a 1.5 second time window for the thumb to be operated via the user’s input signal before returning to an open hand position. The 12th and final grip used for the MYO users was the composite grip (full fist closure) which was accessed via a double tap on any grip icon on the app. The MYO participants used the left hand to demonstrate manual rotation of the terminal device wrist and thumb opposition. If signal latency issues were detected at any time during the session, the study was paused, electrode signal quality was immediately re-inspected and position adjustments of the electrode were made as needed. The MYO users pre-selected their grip and wrist and thumb position prior to beginning each task during training and assessment.

Prosthetic Training Program

The bypass prosthetic training program was adopted from an established training protocol (Bloomer et al., 2018) with an adjustment of the frequency of performance outcome measure administration from every training session to every 3rd training session. Participants typically completed 2-3 sessions each week. This was done to more closely approximate of the frequency of practice sessions and administration of performance outcome measures typically observed in an outpatient rehabilitation setting (El Hayek et al., 2023). An experienced occupational therapist administered the prosthetic training to ensure the training was standardized and training techniques that were utilized were similar to an actual rehabilitation program (Butkus et al., 2014; Resnik et al., 2019). Participants first completed an orientation session (S1) in which the informed consent was reviewed, the prosthetic group was assigned, EEG cap size was determined, prosthesis harness fitting (BP group only) and scheduling of the first training sessions were completed. All sessions in the program were completed while seated. Customized table heights for each participant were selected so that the participants forearm/arm angle was at a 90-degree angle when resting their prosthesis and left hand on the table with feet flat on the floor.

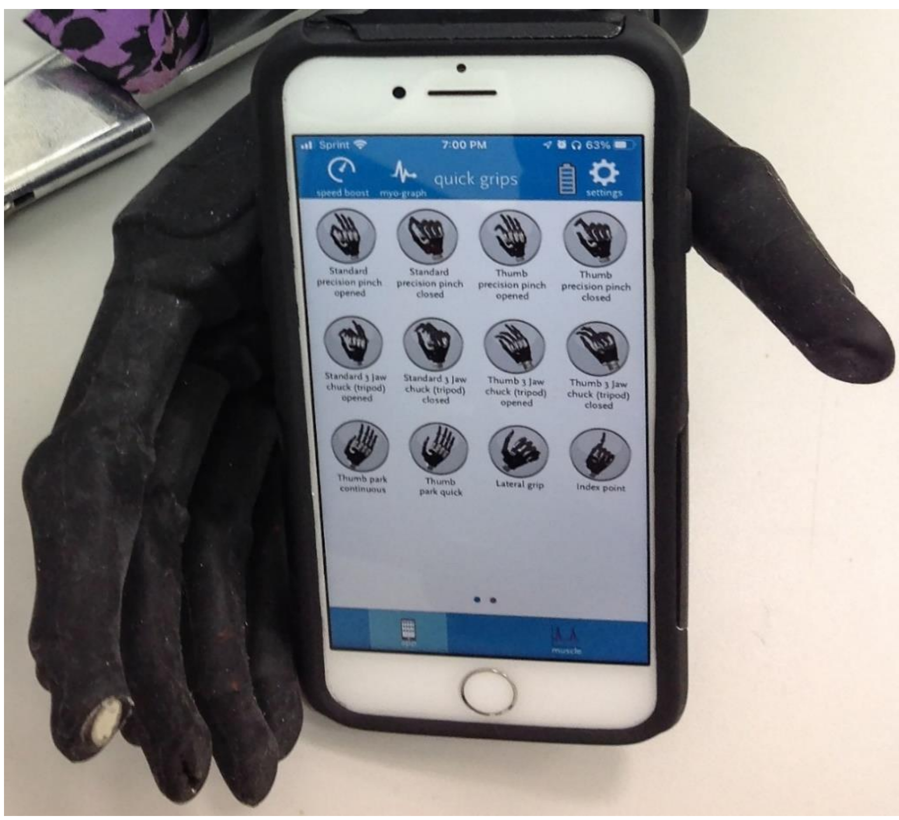


Fig. 1. Biosim™ smartphone application with 12 available grips. Top row(left to right): standard precision pinch opened, standard precision pinch closed, thumb precision grip opened, thumb precision grip closed. Middle row (left

to right): standard 3- jaw chuck (tripod) opened, standard 3- jaw chuck (tripod) closed, thumb 3-jaw chuck (tripod) opened, thumb 3-jaw chuck (tripod) closed, Bottom row (left to right): thumb park continuous, thumb park quick(not used), lateral grip, index point. Not pictured: composite grip. This grip was acquired by double-tapping any grip icon.

Training Only Sessions

Sessions S3,S4,S6,S7,S9 and S10 were training only sessions. Sessions at the beginning of the training program typically lasted 50 minutes while sessions later in the program lasted around 30 minutes due to the participants advancing more quickly through the object manipulation portion of the training and completing all tasks of the ADL training before the 20 minute time allotment elapsed. Before the start of training, participants donned their prosthetic devices and device set-up was completed.

Object Manipulation

Prosthesis users demonstrated three types of object manipulation strategies (direct grasping, indirect grasping, and fixation) to manipulate a variety of objects. The prosthesis users employed a direct grasp (grasp items directly from surface) and indirect grasp (pick up item from table using intact hand, then use prosthetic hand to grasp item from intact hand) to transport a wood cube, metal can and foam ball. For fixation, both groups used their prosthesis to stabilize a zipper, sweater, and ruler while the intact hand opened and closed the zipper, unbuttoned the sweater buttons, and drew a straight line using the ruler, respectively.

Free Training

Free training permitted five minutes of unstructured time for the participants to use their prosthesis while seated to manipulate a variety of objects (plates, pens, bottles; etc.) using the object manipulation strategies just learned.

ADL Training

Participants then completed 10 activity of daily living (ADL) and instrumental activities of daily living (iADLs) from the validated Activities Measure for Upper Limb Amputees (Resnik, Adams, Otr, et al., 2013) in a 20-minute time window. Knowledge of performance and results feedback were delivered as needed via verbal and physical demonstration mediums throughout training. For more details of the training protocol, please refer to the Study 1 Protocol in the Appendix.

Training and Assessment Sessions

The participants completed training and assessment segments during the initial training session (S2), sessions 5 (S5) and 8 (S8) and the final training session (S11). Prosthesis users donned their prostheses before EEG and Inertial Measurement Unit (IMU) set-up and completed the prosthesis operational check after EEG and IMU set-up. The participants then completed the BBT. Please see the Data Acquisition section for the EEG, IMU, BBT and NASA-TLX data capture. Including EEG and kinematic set-up and breakdown, sessions on average took approximately 3.5 hours.

Retention Session

The median days spent in the training program (S2-S11) was 33 days for the BP users and 38 days for the MYO users. At least one week after the completion of training, participants completed the retention session. No training was completed during this session. EEG and IMU set-up were completed first. Prosthesis users donned their prostheses before EEG and Inertial Measurement Unit (IMU) set-up and completed the prosthesis operational check after EEG and IMU set-up. The participants then completed the BBT. Please see the Data Acquisition section for the EEG, IMU, BBT and NASA-TLX data acquisition process. Including EEG and kinematic set-up and breakdown, sessions on average took approximately 2.5 hours. The average number of days between the final training session and retention session for the BP and MYO users were 12.4 and 14.7 days, respectively.

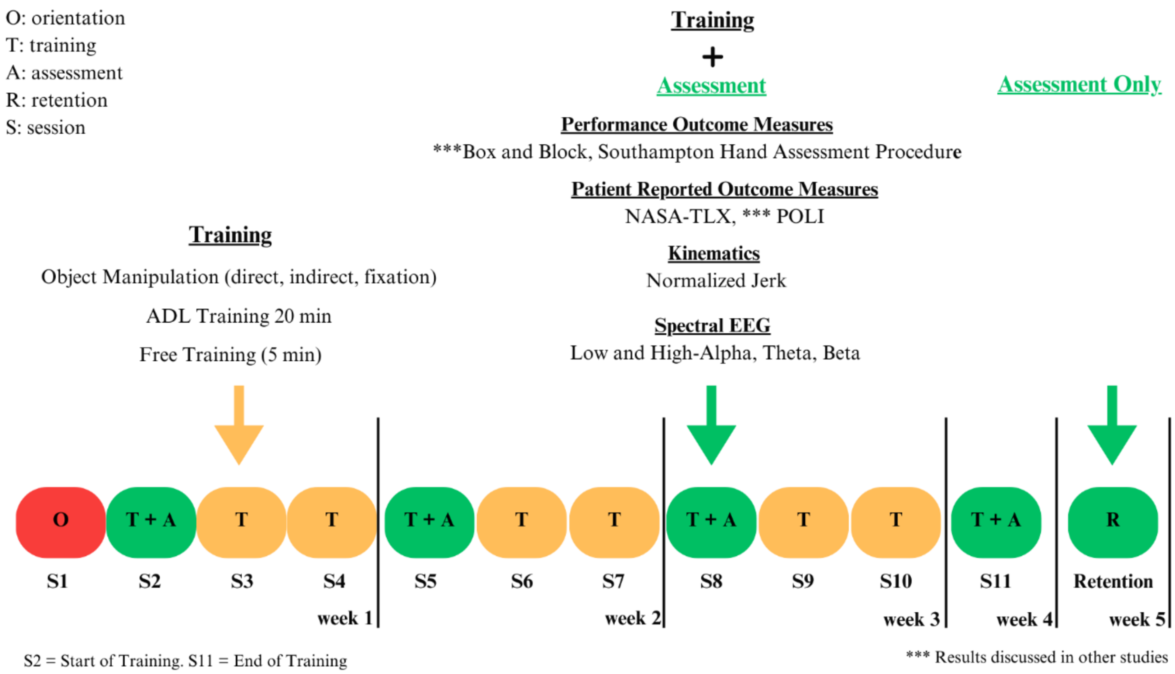


Fig. 2. Training Program. S2 denotes the start of the training program and S11 denotes the end of the training program. The retention session was completed at least one week after the final training session. *** indicates results that are not of primary interest in this study and are reported in other studies.

Experimental Set-Up

A pre-fitted EEG cap was donned on the participant's head and secured using chin and chest straps to reduce unwanted movement artifacts. Electrode lines were gathered and felt material secured the electrode lines in a ponytail using a simple rope knot. The lines were then clipped to the participant's the participant's back. Line bundles that were not included in the ponytail were taped to the participant's back. Gel was applied to each electrode until an impedance below 10 kΩ was achieved. EEG was recorded from 64 active electrode sites (10-20 system) at a 1000 Hz sampling rate using the Brain Vision EEG system (Brain Products GmbH, Germany). The EEG data was online referenced to the left earlobe and offline re-referenced using activity from the right earlobe. and a common ground was employed at the AFz site on the scalp. The horizontal electro-oculographic channel (HEOG) and vertical electro-oculographic channel (VEOG) was recorded by one electrode on the right outer canthus of the eye and one electrode on the superior orbital ridge of the right eye, respectively.

EEG

EEG data was processed using the EEGlab package of Matlab®(The Mathworks Inc., USA) using custom code. Bad channels were identified and interpolated. Data was band-pass filtered with a low cut-off of 0.1 Hz and a high cut-off of 60 Hz with a 48 dB rolloff. Next, independent component analysis (ICA) was employed to remove ocular, muscle, and line noise artifacts. Data was resampled to 500Hz for synchronization with inertial measurement units (IMUs). Using a custom Matlab® script, data was epoched into early (-2 to -1 seconds) and late planning (-1 to 0 seconds) before movement onset. Movement onset was epoched from 0 seconds to the end of the trial which was marked by a manual end of movement execution trigger from the IMU system. Spectral power was calculated across 1-Hz bins and summed across theta (4-7Hz) low-alpha (8-10Hz), high-alpha (11-13 Hz) and beta (14-35 Hz) frequency bandwidths.

IMU

An inertial movement unit (IMU; Xsens™) was placed on the center of the participant's forehead, the right mid- humerus and distal end of the bypass prosthesis to measure kinematic changes of the head, arm, and wrist, respectively at a sampling rate of 100Hz. Data was bandpass filtered with a low cut-off of 0.01 Hz and a high cut-off of 20 Hz with an 80 dB rolloff. Data was up sampled to 500 Hz to synchronize with the EEG data. Normalized jerk was computed from the acceleration data using a custom Matlab® script. Due to the focus of this work to examine differences in upper limb movement smoothness, normalized jerk for the wrist and arm was computed to determine the rate of change in movement acceleration as an index of movement smoothness (Balasubramanian et al., 2015).

BBT and NASA-TLX

After EEG and IMU set-up, training was completed as outlined in the Training Only sessions section. For the BBT, participants were required to individually transport as many 2.5cm^3 blocks as possible across a 15.2 cm partition (Desrosiers et al., 1994). The BBT instructions were explained to the participant and the experimenter provided a physical demonstration of a proper block transfer sequence.

Participants were allowed to transport 3 blocks prior to their first BBT trial per the BBT instructions. The experimenter then explained the EEG and kinematic data capture sequence. Participants were instructed to remain still with their head facing forward and their left forearm and prosthesis resting on the border of the BBT box. The experimenter verbally confirmed that the participant was ready to begin the data capture. Four seconds prior to the start of each trial, the experimenter asked the question, “Ready?” EEG and IMU recording were started manually. After four seconds elapsed, an audible beep sounded from the computer speaker, and the participant began the trial. A manual trigger was created at the start of the trial in the EEG and IMU recordings. After one minute elapsed, the experimenter stated the word, “Stop.” A manual trigger was created at the end of the trial to mark the end of movement execution in the EEG and IMU recordings. If a block was in transport when the trial was stopped, it was not included in the summation of the total number of blocks transported for the trial. After a two-minute rest break, the second trial was completed. No feedback was provided between or after trials. Scoring was based on the number of blocks transported in one minute. The average number of blocks was computed using scores from both trials for each Training and Assessment session.

In addition to the BBT, performance outcome measure, the Southampton Hand Assessment Procedure (SHAP) was also completed. Both measures were completed in a counterbalanced order. The SHAP is beyond the scope of the current study and will be discussed in Chapter 3.

After the completion of the 2nd BBT trial, participants completed the NASA-TLX and Prosthesis-Orthosis Load Index (POLI) paper surveys in a counterbalanced order using their non-prosthetic hand to circle tick marks that corresponded with their average perceived workload levels across both trials of the BBT. The POLI is beyond the scope of this study and will be discussed in Chapter 5.

Including EEG and kinematic set-up and breakdown, sessions on average took approximately 3 hours.

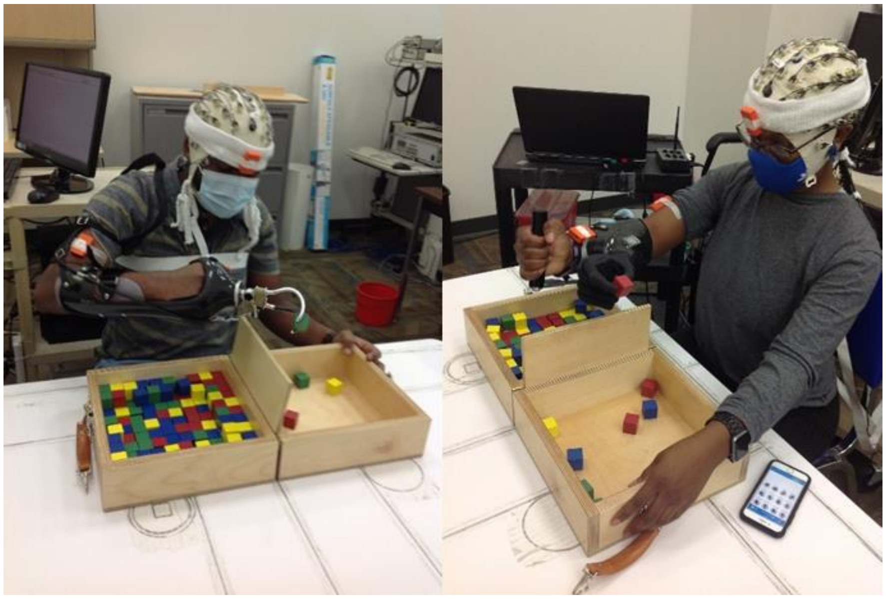


Fig. 3. Images of a BP user(left) and a MYO user(right) completing the BBT.

Statistical Analysis

Linear mixed effect modeling was conducted for all measures due to the model's ability to model random effects, its robustness against missing data and model flexibility (Yu et al., 2022). This approach was implemented due to the presence of data dependence as a result of the within subject design study design as well as the length of the training which resulted in minor loss of data due to infrequent device malfunctions/ experimental technical issues. Random effects were applied to the Participant variable for all models. All data was subjected to a visual inspection to assess model assumptions. The EEG and kinematic data were natural log-transformed to reduce positive skewness. Outlier removal was conducted based on Cook's distance for each model dataset to reduce the outlier influence on the model performance (Cook, 1977). Linear mixed effects models are reported with a Type III ANOVA output to communicate the results in a more concise manner and to explain complex interactions that occurred during the study. Satterthwaite's method was used to approximate degrees of freedom. Partial eta squared effect sizes are reported for all statistically significant main effects and interactions. Partial eta squared effect sizes were categorized as small ($\eta p^2 = 0.01$), medium ($\eta p^2 = 0.06$, large ($\eta p^2 = 0.14$). Post-hoc analyses with a Tukey HSD correction were performed for all statistically significant main effects and interactions with a p-value threshold of $p < 0.05$. Cohen's d effect sizes are reported for all significant post-hoc comparisons. Cohen's d effect sizes were categorized as small ($d = 0.2$), medium ($d = 0.5$) and large ($d= 0.8$). All statistical analyses were performed using R Studio (RStudio Team, 2023).

To increase clarity in reporting, only relevant effects to answer our hypothesis were considered. Namely, only the Prosthesis and Session main effects or interactions including Prosthesis and/or Session variables are reported for all measures since these are the variables that were manipulated in the experiment. While data was captured for all Training and Assessment sessions, to grasp the overall effect of the training program, Session main effects and interactions between the initial session and final training session or the initial session and the retention session or within each session for all measures are reported. Data points are displayed with standard error bars to visualize variance.

The linear mixed effects model for dexterity performance, the BBT scores were subjected to a 2 (Prosthesis (BP, MYO) x 3 (Session (S2, S11, Retention)) design.

The linear mixed effects model for wrist and arm normalized jerk data were subjected to a 2 (Prosthesis (BP, MYO) x 3 (Session (S2, S11, Retention)) design.

For each dimension of the NASA-TLX, a linear mixed effects model was subjected to a 2 (Prosthesis (BP, MYO) x 3 (Session (S2, S11, Retention)) design.

For each spectral bandwidth of interest(theta, beta and low and high-alpha), a linear mixed effects model was subjected to a 2 (Prosthesis (BP, MYO)) x 3 (Session (S2, S11, Retention)) x 2 (Hemisphere(Left, Right)) x 5 (Region(Frontal, Central, Parietal, Occipital, Temporal)) design. P-values are reported with a $p < 0.05$ threshold to determine statistical significance.

Results

Performance

A main effect was revealed for Session ($F(2,36) = 42.312$, $p < 0.001$, $\eta p^2 = 0.702$). The post-hoc analysis revealed that when compared to the initial training session, prosthesis users transported more blocks in during the final training session ($p < 0.001$, d = 1.624) and the retention session ($p < 0.001$, d = 1.703).

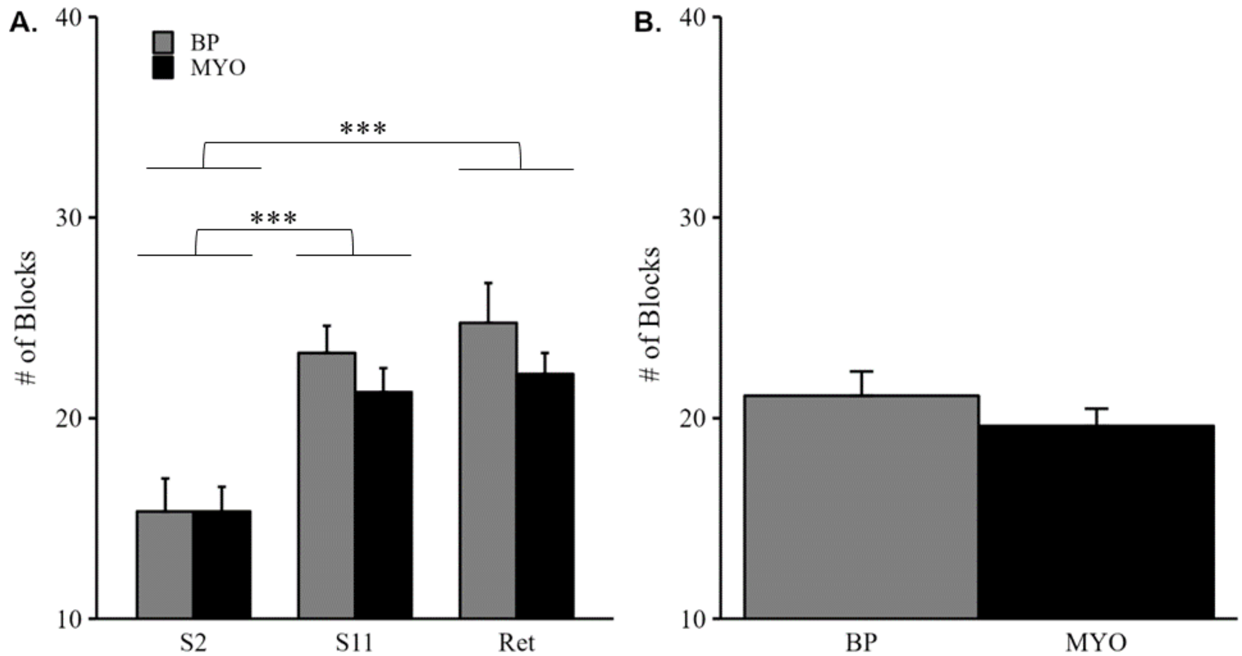


Fig. 4. A. BBT performance across sessions. **B.** BBT performance per prosthetic group . S2-Initial training session. S11- Final training session. Ret- Retention session. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Kinematics

Wrist Normalized Jerk

A main effect was revealed for Prosthesis ($F(1, 49) = 55.063$, $p < 0.001$, $\eta p^2 = 0.529$) such that the MYO users produced less movement smoothness when compared to the BP users.

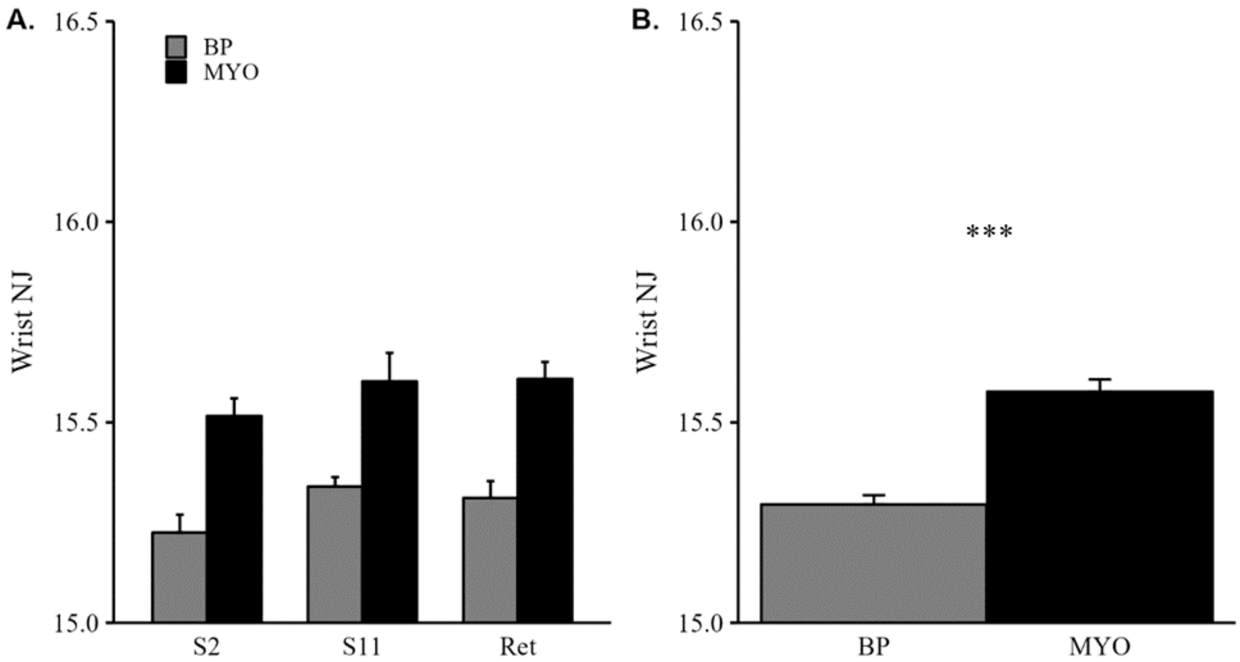


Fig.5. A. Wrist normalized jerk across sessions. **B.** Wrist normalized jerk per prosthetic group . S2-Initial training session. S11- Final training session. Ret- Retention session. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Arm Normalized Jerk

A main effect was revealed for Prosthesis ($F(1, 18) = 36.221$, $p < 0.001$, $\eta p^2 = 0.66$) such that the MYO users had less movement smoothness when compared to the BP users. A main effect was revealed for Session ($F(2, 32) = 3.757$, $p = 0.034$, $\eta p^2 = 0.674$). The post-hoc analysis revealed that the MYO users produced less movement smoothness when compared to the BP users during the initial ($p < 0.001$, 0. 1.875) and final training session ($p < 0.001$, 2.385) as well as the retention session ($p = 0.013$, 1.470). In comparison to the initial session, the MYO users generated jerkier arm movement in the final training session ($p = 0.049$, $d = 0.717$). These changes were not observed for the BP users.

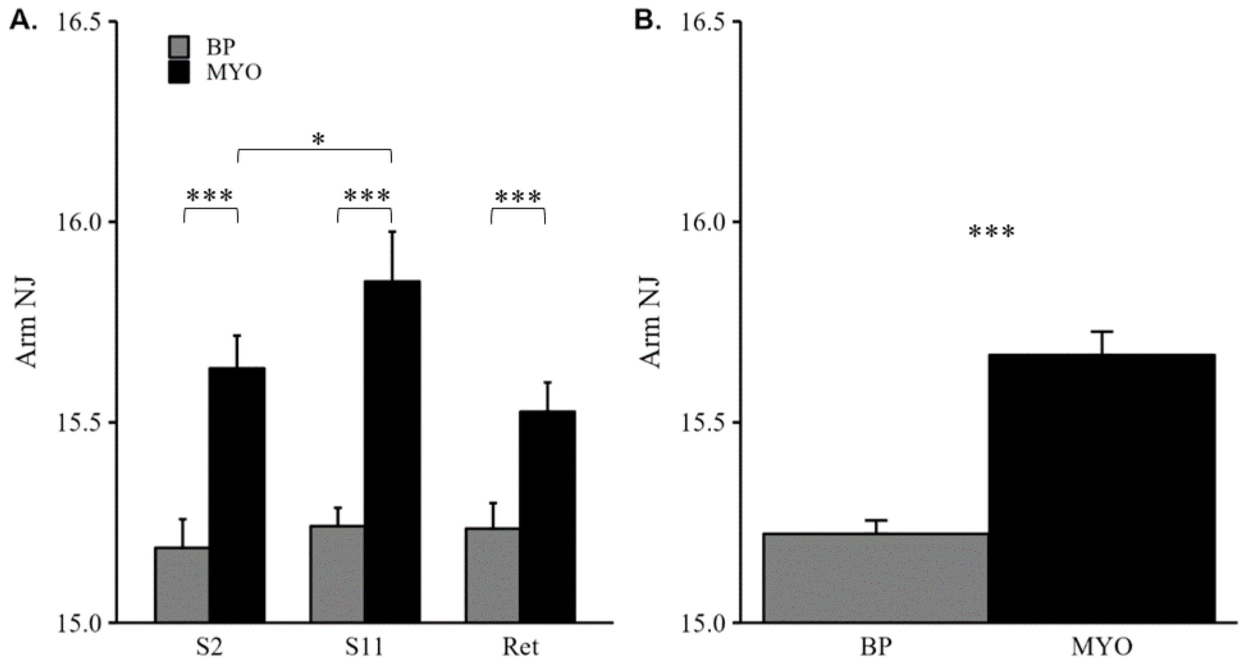


Fig.6. A. Arm normalized jerk across sessions. **B.** Arm normalized jerk per prosthetic group . S2-Initial training session. S11- Final training session. Ret- Retention session. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. * p < 0.05, ** p < 0.01, *** p < 0.001.

NASA-TLX

Mental Demand

A main effect was revealed for Session ($F(2, 32) = 21.363$, $p < 0.001$, $\eta p^2 = 0.570$). The post-hoc analysis revealed that when compared to the initial training session, prosthesis users experienced a reduction in perceived mental demand during the final training session ($p < 0.001$, $d = 1.654$) and the retention session ($p < 0.001$, $d = 1.504$).

Physical Demand

A main effect was revealed for Session ($F(2,33) = 16.209$, $p < 0.001$, $\eta p^2 = 0.384$). The post-hoc analysis revealed that after the initial training session, prosthesis users experienced a reduction in perceived physical demand during the final training session ($p < 0.001$, $d = 1.211$) and the retention session ($p < 0.001$, $d = 1.244$).

Temporal Demand

A main effect was revealed for Session ($F(2,32) = 11.392$, $p < 0.001$, $\eta p^2 = 0.416$). The post-hoc analysis revealed that when compared to the initial training session, prosthesis users experienced an attenuation in perceived temporal demand during the final training session ($p < 0.001$, $d = 1.045$) and the retention session ($p < 0.001$, $d = 1.079$).

Effort

A main effect was revealed for Session ($F(2,34) = 11.263$, $p < 0.001$, $\eta p^2 = 0.399$). The post-hoc analysis revealed that after the initial training session, prosthesis users experienced a reduction in perceived effort during the final training session ($p = 0.004$, $d = 0.948$) and the retention session ($p < 0.001$, $d = 1.283$).

Performance

A main effect was revealed for Session ($F(2, 33) = 30.02$, $p < 0.001$, $\eta p^2 = 0.469$). The post-hoc analysis revealed that after the initial training session, prosthesis users experienced an attenuation in perceived performance demand during the final training session ($p < 0.001$, $d = 1.408$) and the retention session ($p < 0.001$, $d = 1.539$).

Frustration

A main effect was revealed for Session ($F(2,31) = 17.130$, $p < 0.001$, $\eta p^2 = 0.526$). Post-hoc analyses revealed that after the initial training session, prosthesis users experienced an attenuation in perceived frustration during the final training session ($p < 0.001$, $d = 1.023$) and the retention session ($p < 0.001$, $d = 1.490$).

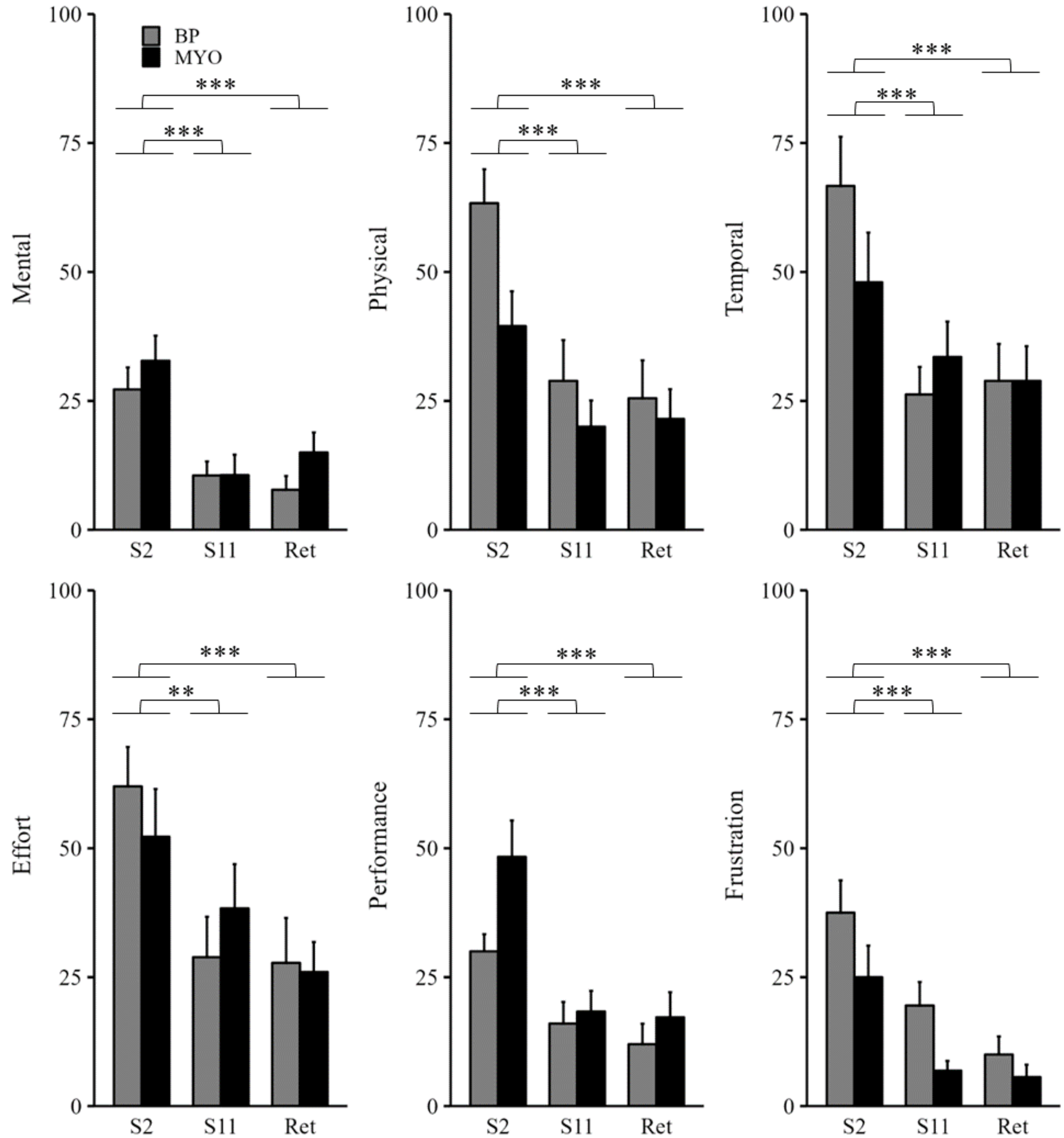


Fig. 7. NASA-TLX dimensions across sessions. S2-Initial training session. S11- Final training session. Ret-Retention session. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Spectral EEG

Theta

No significant differences in theta power were noted when the initial session was compared to the final training session or when the initial session was compared to the retention sessions.

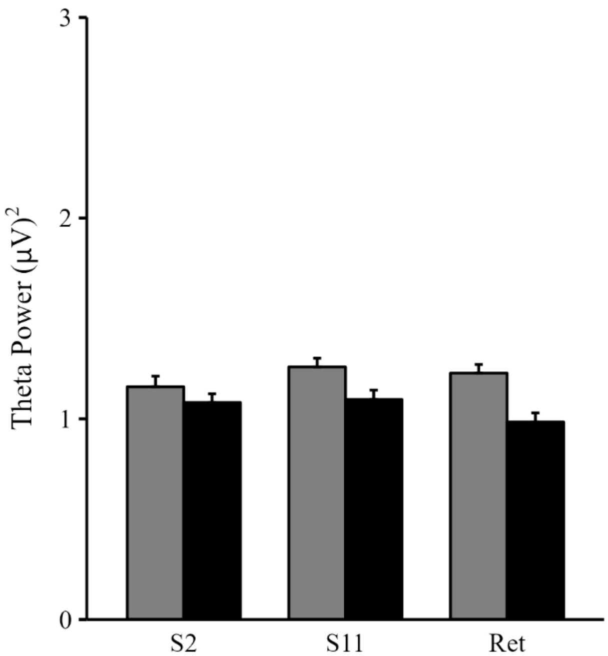


Fig. 8. Theta power across sessions. S2- Initial training session. S11- Final training session. Ret- Retention session. BP- Body-powered prosthesis. MYO - Myoelectric prosthesis. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Low-Alpha

A significant Prosthesis x Session interaction was revealed ($F(2, 479) = 5.163$, $p = 0.006$, $\eta p^2 = 0.021$). The post-hoc analysis revealed that the MYO users experienced attenuated low-alpha power during the final training session ($p = 0.041$, $d = 0.552$) and the retention($p = 0.039$, $d = 0.551$) session when compared to the BP users. The BP users experienced an elevation of low-alpha power during the final training session when compared to the initial training session ($p = 0.009$, $d = 0.238$); however, this effect was not maintained during the retention session.

A significant Prosthesis x Region interaction ($F(4, 479) = 5.765$, $p < 0.001$, $\eta p^2 = 0.046$). The post-hoc analysis revealed that the MYO users experienced attenuated low-alpha power in the occipital ($p = 0.005$, $d = 0.897$) and temporal($p = 0.036$, $d = 0.856$) when compared to the BP users.

A significant Prosthesis x Hemisphere interaction ($F(1, 479) = 5.087$, $p = 0.025$, $\eta p^2 = 0.011$). The post-hoc analysis revealed that the MYO users experienced attenuated low-alpha power in the left hemisphere ($p = 0.038$, $d = 0.479$) when compared to the BP users.

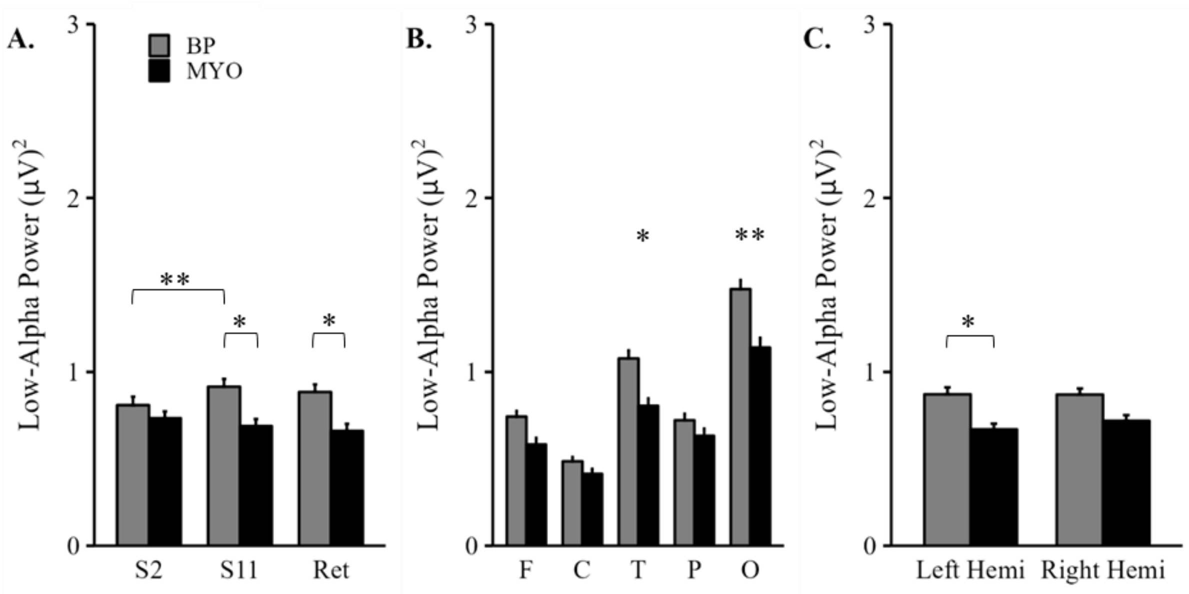


Fig. 9. A. Low-alpha power across sessions. **B.** Low-alpha power in each cortical region. C. Low-alpha power in the right and left hemisphere. S2-Initial training session. S11- Final training session. Ret- Retention session. BP-Body-powered prosthesis. MYO-Myoelectric prosthesis. F-Frontal, C-Central, T-Temporal, P-Parietal, O-Occipital. Left Hemi- Left Hemisphere. Right Hemi- Right Hemisphere. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

High-Alpha

A main effect was revealed for Prosthesis ($F(1, 18) = 16.996$, $p = 0.001$, $\eta p^2 = 0.487$) such that the MYO users had attenuated high-alpha power when compared to the BP users. The Prosthesis main effect was superseded by a Prosthesis x Session interaction ($F(2, 474) = 5.627$, 0.004, $\eta p^2 = 0.023$). The post-hoc analysis revealed that the MYO users experienced lower high-alpha power during the initial training session ($p = 0.021$, $d = 0.193$), final training session ($p < 0.001$, $d = 0.671$) and retention session ($p < 0.001$, $d = 0.735$) when compared to the BP users. The post-hoc analysis also revealed that when in comparison to the initial session, the BP users experienced an elevation of high-alpha during the final training session ($p = 0.048$, $d = 0.291$); however, this change in high-alpha did not persist into the retention session. In contrast, the MYO users experienced an attenuation in high-alpha power during the retention session when compared to the initial session ($p = 0.020$, $d = 0.298$).

The Prosthesis main effect was also superseded by a Prosthesis x Region interaction ($F(4, 474) = 17.956$, $p < 0.001$, $\eta p^2 = 0.132$). The post-hoc analysis revealed that the MYO users experienced reduced high-alpha power in the occipital ($p < 0.001$, $d = 1.635$), temporal ($p = 0.001$, $d = 0.896$), frontal ($p = 0.005$, $d = 1.063$), and parietal($p = 0.048$, $d = 0.544$) regions when compared to the BP users.

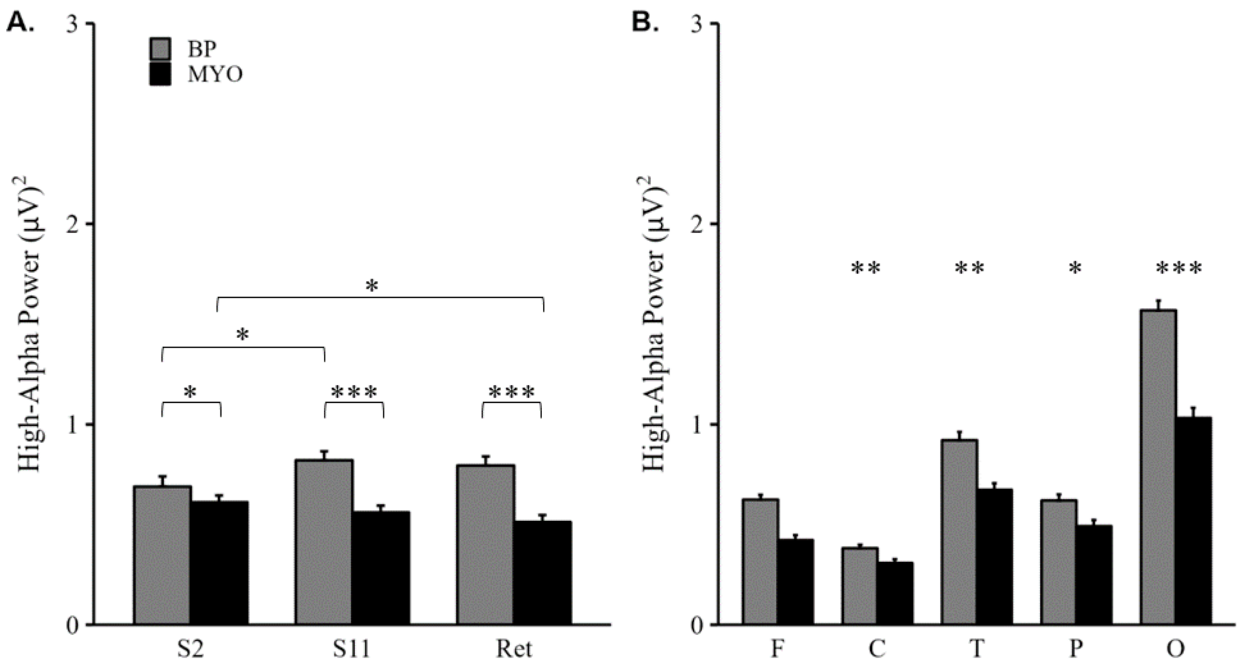


Fig. 10. A. High-alpha power across sessions. **B.** High-alpha power in each cortical region. BP- Body-powered prosthesis. MYO - Myoelectric prosthesis. S2-Initial training session. S11- Final training session. Ret- Retention session. F-Frontal, C-Central, T-Temporal, P-Parietal, O-Occipital. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Beta

A main effect was revealed for Prosthesis ($F(1, 18) = 9.109$, $p = 0.007$, $\eta p^2 = 0.336$).

The Prosthesis main effects were superseded by a significant Prosthesis x Session interaction ($F(2, 473) = 10.893$, $p < 0.001$, $\eta p^2 = 0.044$). Post-hoc analyses revealed that the MYO users produced lower levels of beta power during the final training session ($p = 0.002$, d, $= 0.507$) and the retention (p <

0.001 d, = 0.662) session when compared to the BP users. The BP users experienced an elevation of beta power in the final ($p = 0.001$, $d = 0.331$) and retention ($p = 0.003$, $d = 0.335$) sessions when compared to the initial session. In contrast, the MYO users experienced an attenuation of beta power in the retention session when compared to the initial session ($p = 0.011$, $d = 0.270$).

The Prosthesis main effects were also superseded by a significant Prosthesis x Region interaction ($F(4, 473) = 14.404$, $p < 0.001$, $\eta p^2 = 0.108$). Post-hoc analyses revealed that the MYO users experienced lower beta power in the occipital ($p < 0.001$, $d = 1.414$), temporal ($p = 0.048$, $d = 0.48$) and frontal ($p = 0.033$, $d = 0.705$) regions when compared to the BP users.

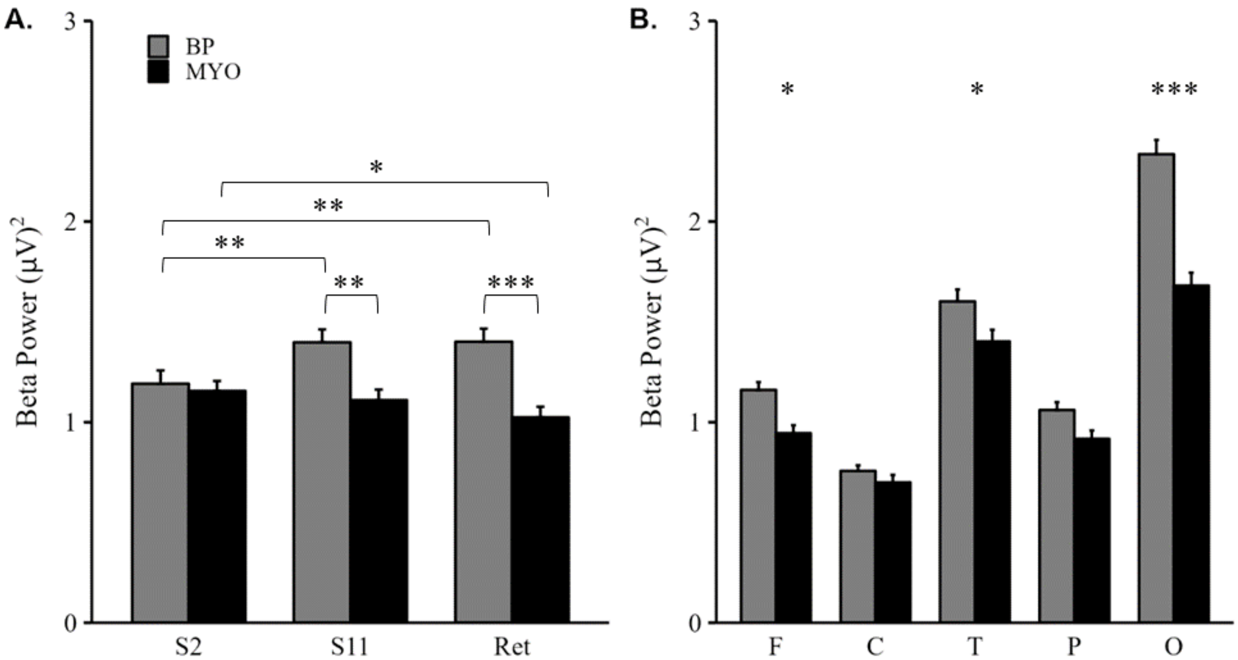


Fig. 11. A. Beta power across sessions. **B.** Beta power in each cortical region. BP- Body-powered prosthesis. MYO - Myoelectric prosthesis. S2- Initial training session. S11- Final training session. Ret- Retention session. F-Frontal, C-Central, T-Temporal, P-Parietal, O-Occipital. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Discussion

The study successfully provided empirical evidence to achieve the study goals to 1) elucidate the cortical dynamics of mental workload in response to a prosthetic training program and 2) determine if the prosthesis type (BP or MYO) influenced dexterity performance, motor learning, and mental workload.

As predicted, dexterity performance improved for both groups as a result of training(Fig.4A). These improvements persisted during the retention session, which suggests permanent learning adaptations for grasp and release skills occurred. This finding is in alignment with past work examining characteristics of motor learning in prosthesis users (Bloomer et al., 2018; Bouwsema et al., 2008). While the prosthesis users were able to transport more blocks by the end of the session, movement smoothness did not improve as a result of training (Fig.5,6) despite reductions in perceived effort and physical demand by both prosthetic groups (Fig.7). Past work has suggested that improvements in movement smoothness is a marker of motor learning (Balasubramanian et al., 2015; Bloomer et al., 2020; Shuggi et al., 2018), improved sensorimotor control (Franklin & Wolpert, 2011) and a reduction in effort (Harris & Wolpert, 1998; J. D. Wong et al., 2021). There are two possibilities that may explain why no changes in movement smoothness occurred in the present study. When examining the steps to complete a single block transport during the BBT, participants typically unseated a block from its adjacent position to other blocks before a grasp attempt. The unseating of a block created additional space for the terminal device to grasp the block without grasping interference by inadvertently hitting surrounding blocks. Next, the block was grasped, transported over the partition, and released on the other side of the box (Fig. 4). When examining these steps, it is likely that most movement variance at the wrist and arm were generated during the first step. Both groups used these quick and random movements (depending upon the location of the block) as a strategy to quickly position the block in an optimal location for grasping. A possible explanation for the unchanged movement smoothness may be that prosthesis users found this strategy to be helpful and continued to deploy this method throughout training. Since the movements of this strategy varied greatly per block, a decrease in movement variance may have reflected lower and less wrist and arm strokes to unseat a block from surrounding blocks on all sides, thus, increasing physical demand and block transport time. A secondary explanation for the unchanged movement smoothness, is that prosthesis users were still exploring various movement strategies. As a result, an optimal movement strategy was not employed and used consistently enough to undergo refinement and a subsequent improvement in movement smoothness. For the MYO users, an increase in arm movement variability occurred at the end of training; however, this kinematic change did not persist during the retention session which may imply that a movement strategy was not solidified. While both explanations are plausible, the first explanation may better explain our results. The quick and variable movements to unseat blocks from their original position were used consistently throughout training and may have been an intentional strategy that allowed for faster block transport, reductions in perceived mental workload.

This position appears to be supported by the spectral EEG evidence. Specifically, an attenuation of beta accompanied a stable level of movement smoothness in the BP group, which may reflect less sensorimotor processing as the BP users consistently engaged this strategy to grasp and transport the blocks (Fig.11A). In contrast, MYO users engaged more sensorimotor processes to achieve a similar motor performance to that of the BP users (Fig.11). While evidence suggests similar perceptions of physical demand and effort between both groups (Fig.7), the MYO users produced significantly more arm movement jerkiness by the end of training. However, this production of more jerky and variable movements did not persist during the retention session (Fig.6). This may indicate that the engagement of more sensorimotor processes as a result of training in the MYO users may provide a cortical basis for their inconsistent biomechanical approach to transport the blocks (Fig.11).

Similarly, MYO users also experienced an attenuation of high-alpha power as a result of training (Fig.9A). This may suggest that the in addition to increased engagement in sensorimotor processes throughout training, MYO users deployed more task-relevant cognitive-motor resources throughout training which may reflect ongoing cortical adaptations as the MYO users were still stabilizing their biomechanical approach for block transport. Unlike the BP users who experienced a general reduction in cognitive-motor resources as a progression towards cognitive-motor efficiency, the MYO users engaged more cognitive-motor processes as a result of training. Fitts & Posner's Stages of Motor Learning may provide a theoretical basis for these findings (Fitts & Posner, 1967). The pattern of cortical activation exhibited by the MYO group may suggest that they were still in the cognitive stage of motor skill learning which is marked by inconsistent movements (Fig. 6) and significant cognitive-motor processing (Fig.8) (Fitts & Posner, 1967). Cortical evidence from the BP users may suggest that they progressed from the cognitive stage of motor learning to the associative stage of motor skill learning where less cognitive effort was (Fig.9A). Evidence of this may be the BP group's permanent reduction in sensorimotor processing(elevation of beta power) during the retention session which is evidence of enhanced sensorimotor efficiency and subsequent motor learning (Fig.11).

Reductions in general arousal and task relevant cognitive-motor processing during the final session were also produced by the BP users which suggests a decrease in top-down cortical processes and emergence of cognitive-motor efficiency (Fig.9A). This cortical evidence may characterize the associative stage of learning. However, these changes in cognitive-motor processes were not permanent, as they were not maintained during the retention session which reflects inconsistency of cognitive-motor refinements that characterize the associative stage of motor learning (Fig.11A). Collectively, these findings may suggest that both prosthetic groups require more prosthetic training to exhibit permanent improvements in cognitive-motor efficiency during dexterous tasks; however, the BP users may require less training, since spectral evidence suggested the presence of sensorimotor refinement and the emergence of cognitive-motor efficiency that was not observed in the MYO group. This cortical evidence suggests the BP users engage a different pattern of cortical activation that reflects the emergence of motor learning while MYO users produced greater cortical activation in response to task demands. These distinct neurophysiological patterns between prosthetic groups supports clinical reports that BP users require less training time than MYO prosthesis users (Huang et al., 2001; Uellendahl, 2017).

While performance was similar between both groups, BP users exhibited significantly more movement smoothness when compared to the MYO users during the BBT. The BP users produced greater high-alpha power over the parietal and central regions, which may reflect less engagement of sensorimotor resources when compared to the MYO users. Additionally, BP users produced enhanced beta power over the frontal region when compared to the MYO users, which may reflect less engagement in the executive processes related to sensorimotor control (Tan et al., 2016; Tatti et al., 2021). The MYO users also deployed more visual resources than the BP users during the BBT as represented by greater cortical activation in the occipital region (low and high-alpha power and beta power). These findings align with past research that suggest that prosthesis users utilize more visual attention resources when compared to the normative population due to lack of end effector functionality (H. E. Williams et al., 2019). Furthermore, it has been reported that that the use of a myoelectric prosthesis requires significant visual attention and has been cited as a usability concern (Carey et al., 2015; J. Parr et al., 2020; J. V. V Parr et al., 2018; Uellendahl, 2017). Additionally, greater activation of the temporal region(greater beta, low and high-alpha desynchrony) was revealed for the MYO users when compared to the BP users (Fig.7B,8B,10B). The temporal region, particularly the left temporal region may reflect verbal processing which has been thought to reflect a reliance on declarative knowledge and conscious motor control (Hatfield et al., 2004b; J. V.V. Parr et al., 2019; Johnny V.V. Parr et al., 2020). The stronger activation over the temporal region for the MYO users may suggest they employed more online, conscious motor control to transport the blocks when compared to the BP users.

Surprisingly, the present study did not reveal significant findings for theta power (Fig.9). Past motor learning research has been varied with some work reporting increases in theta power as a result of training (Jaquess et al., 2018; Perfetti et al., 2011) while other work shows the inverse relationship (Kao et al., 2013). In the present study, the lack of permanent changes in movement smoothness was accompanied by stabilized theta power throughout training, which may reflect consistent engagement of working memory, error monitoring and attentional processing. Since the BBT measures dexterity and does not manipulate working memory demands, it is thought that the stabilized theta power in this study may more likely reflected the sustained attention that was required to actively attend to each block transport during the trial (Kao et al., 2013; Kardos et al., 2014). Due to the block unseating technique that was used throughout the BBT, there may have been less prioritization of movement accuracy and subsequently less of a performance for committing poorly planned movements. Additionally, the goal of the BBT was to assess how quickly an individual could transport an object, thus speed was likely prioritized over accuracy. This lack of prioritization of movement accuracy might be explained by the speed-accuracy tradeoff which may suggest prioritization of speed, facilitating movement patterns that transported the blocks faster with less regard for accuracy thus leading to faster movements with less accuracy (Fernani et al., 2017; Heitz, 2014; Heitz & Schall, 2012). It is possible that for dexterous tasks in which movement speed is prioritized and the consequence for poorer movement accuracy is minimal, theta power may not be modulated as strongly due to the participant's decreased reliance on error monitoring. Therefore, theta power may not be the be sensitive to changes in mental workload during motor performance in which movement accuracy is not a primary aim.

Conclusions, Limitations, and Future Directions

In conclusion, these findings show that the incorporation of spectral EEG reveals divergent skill acquisition cognitive-motor processes between prosthetic groups despite similar performance and perceptions of mental workload. Evidence suggests that the BP users engaged in a more advanced, associative stage of motor learning by producing permanent sensorimotor efficiency enhancements and exhibiting signs of the emergence of cognitive-motor efficiency while MYO users increasingly employed more executive control throughout training, which may reflect a more cognitive state of motor learning for the MYO users. Furthermore, MYO users demonstrated greater movement jerkiness that was accompanied by a greater activation of cognitive-motor and sensorimotor processes when compared to the BP users. Compared to the MYO group, the BP users had a better encoding albeit not fully completing of the human-device sensorimotor mapping into their internal models, thus enabling them to execute the task with less reliance on feedback control and resulting in more efficient cognitive-motor performance.

While this study is informative, there are several limitations. First, we assessed mental workload in individuals without amputation, thus we were unable to exactly model peripheral neuromuscular and sensory impairment experienced by clinical prosthesis users that may further challenge prosthetic training. As a result, our findings may not be sufficiently generalized as a representative of the relationship between mental workload and motor performance in clinical upper limb prosthesis users. To address this limitation, a future direction of this work is to examine mental workload during motor performance in clinical prothesis users. Secondly, our study utilized continuous EEG monitoring to capture performance throughout the entire BBT trial. Due to the interest in capturing training scenarios that were ecologically valid and resembled clinical rehabilitation sessions, our EEG measurement during motor performance also included variable events such as brief prosthesis repositioning, verbal grunts or moans due to task difficulty(participants were instructed to not talk during recording) and minor changes in sensor connectivity quality with the MYO device. On the latter event, it is important to note that, when possible, trials were repeated if sensor issues arose during a task. However, to represent experiences that prosthesis users encounter with device use, the capturing of these device design challenges such as minor sensor quality changes (Alix Chadwell et al., 2016a; Rackerby et al., 2022; Resnik et al., 2019) may capture the variability of prosthesis use and should be modeled in research. Another limitation of this work was that only local regional activity was examined without accounting for inter-regional information exchange. Thus, another future direction of this work could examine corticocortical communication during prosthetic training to better elucidate how different cortical regions communicate in response to task demand and training.

Lastly, the length of the training session may not have been long enough to cause permanent changes in cognitive-motor efficiency. However, this limitation brings forth the importance of the evaluation of training length for prosthesis users. While prior work has exhibited performance improvement plateaus in less than 10 sessions, it is likely that cortical dynamics are undergoing refinement and cognitive-motor efficiency has not been obtained (Bloomer et al., 2018). Furthermore, nearly 40% of United States military veterans receive 10 sessions or less of prosthetic training (Resnik et al., 2019). In another study that surveyed individuals living with upper limb amputations in Austria, roughly 50% of participants reported receiving more than 16 hours of prosthetic training (Salminger et al., 2022). Future efforts for this study could focus on motor learning over a longer period to examine corresponding cortical changes underlying mental workload. Despite these limitations, this work interpreted in the context of current prosthetic rehabilitation practices suggests that the integration of mental workload assessment in traditional performance assessment approaches may better inform performance outcomes, improve device usability, training duration and program design.

References

Akizuki, K., & Ohashi, Y. (2015). Measurement of functional task difficulty during motor learning: What level of difficulty corresponds to the optimal challenge point? *Human Movement Science*, *43*, 107–117. https://doi.org/10.1016/j.humov.2015.07.007

Babiloni, C., Del Percio, C., Iacoboni, M., Infarinato, F., Lizio, R., Marzano, N., Crespi, G., Dassù, F., Pirritano, M., Gallamini, M., & Eusebi, F. (2008). Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. *Journal of Physiology*, *586*(1), 131–139. https://doi.org/10.1113/jphysiol.2007.141630

Balasubramanian, S., Melendez-Calderon, A., Roby-Brami, A., & Burdet, E. (2015). On the analysis of movement smoothness. *Journal of NeuroEngineering and Rehabilitation*, *12*(1), 1–11. https://doi.org/10.1186/s12984-015-0090-9

Biddiss, E., & Chau, T. (2007). Upper limb prosthesis use and abandonment: A survey of the last 25 years. *Prosthetics and Orthotics International*, *31*(3), 236–257. https://doi.org/10.1080/03093640600994581

Bloomer, C., Wang, S., & Kontson, K. (2020). Kinematic analysis of motor learning in upper limb body-powered bypass prosthesis training. *PLoS ONE*, *15*(1), 1–16. https://doi.org/10.1371/journal.pone.0226563

Bloomer, C., Wang, S., & Kontson, K. L. (2018). Creating a standardized , quantitative training protocol for upper limb bypass prostheses. *Physical Medicine and Rehabilitation Research*.

Bouwsema, H., Van Der Sluis, C. K., & Bongers, R. M. (2008). *The Role of Order of Practice in Learning to Handle an Upper-Limb Prosthesis*. https://doi.org/10.1016/j.apmr.2007.12.046

Butkus, J., Dennison, C., Orr, A., & Laurent, M. St. (2014). Occupational Therapy with the Military Upper Extremity Amputee: Advances and Research Implications. *Current Physical Medicine and Rehabilitation Reports*, *2*(4), 255–262. https://doi.org/10.1007/s40141-014-0065-y

Carey, S. L., Lura, D. J., & Highsmith, M. J. (2015). *Differences in myoelectric and body-powered upper-*

limb prostheses: Systematic literature review. *52*(3), 247–262. https://doi.org/10.1682/JRRD.2014.08.0192

Chadwell, A., Kenney, L., Thies, S., Galpin, A., & Head, J. (2016). The reality of myoelectric prostheses: Understanding what makes these devices difficult for some users to control. *Frontiers in Neurorobotics*, *10*(AUG), 1–21. https://doi.org/10.3389/fnbot.2016.00007

Cook, R. D. (1977). Detection of Influential Observation in Linear Regression. *Technometrics*, *19*(1), 15–18. https://doi.org/10.2307/1268249

Deeny, S., Chicoine, C., Hargrove, L., Parrish, T., & Jayaraman, A. (2014). A Simple ERP Method for Quantitative Analysis of Cognitive Workload in Myoelectric Prosthesis Control and Human-Machine Interaction. *PLoS ONE*, *9*(11), e112091. https://doi.org/10.1371/JOURNAL.PONE.0112091

Desrosiers, J., Bravo, G., Hébert, R., Dutil, É., & Mercier, L. (1994). Validation of the Box and Block Test as a measure of dexterity of elderly people: Reliability, validity, and norms studies. *Archives of Physical Medicine and Rehabilitation*, *75*(7), 751–755. https://doi.org/10.5555/uri:pii:0003999394901309

El Hayek, M., Lobo Jofili Lopes, J. L. M., Lelaurin, J. H., Gregory, M. E., Abi Nehme, A. M., McCall-Junkin, P., Au, K. L. K., Okun, M. S., & Salloum, R. G. (2023). Type, Timing, Frequency, and Durability of Outcome of Physical Therapy for Parkinson Disease: A Systematic Review and Meta-Analysis. *JAMA Network Open*, *6*(7), E2324860. https://doi.org/10.1001/jamanetworkopen.2023.24860

Espenhahn, S., van Wijk, B. C. M., Rossiter, H. E., de Berker, A. O., Redman, N. D., Rondina, J., Diedrichsen, J., & Ward, N. S. (2019). Cortical beta oscillations are associated with motor performance following visuomotor learning. *NeuroImage*, *195*(April), 340–353. https://doi.org/10.1016/j.neuroimage.2019.03.079

Fallahi, M., Motamedzade, M., Heidarimoghadam, R., Soltanian, A. R., & Miyake, S. (2016). Assessment of operators' mental workload using physiological andsubjective measures in cement, city traffic and power plant controlcenters. *Health Promotion Perspectives*, *6*(2), 96–103. https://doi.org/10.15171/hpp.2016.17

Fernani, D. C. G. L., Prado, M. T. A., da Silva, T. D., Massetti, T., de Abreu, L. C., Magalhães, F. H., Dawes, H., & de Mello Monteiro, C. B. (2017). Evaluation of speed-accuracy trade-off in a computer task in individuals with cerebral palsy: A cross-sectional study. *BMC Neurology*, *17*(1), 1–9. https://doi.org/10.1186/s12883-017-0920-4

Fitts, P. M., & Posner, M. I. (1967). Human performance. In *Human performance*. Brooks/Cole.

Franklin, D. W., & Wolpert, D. M. (2011). Computational mechanisms of sensorimotor control. *Neuron*, *72*(3), 425–442. https://doi.org/10.1016/j.neuron.2011.10.006

Gentili, R. J., Jaquess, K. J., Shuggi, I. M., Shaw, E. P., Oh, H., Lo, L. C., Tan, Y. Y., Domingues, C. A., Blanco, J. A., Rietschel, J. C., Miller, M. W., & Hatfield, B. D. (2018). Combined assessment of attentional reserve and cognitive-motor effort under various levels of challenge with a dry EEG system. *Psychophysiology*, *55*(6), 1–17. https://doi.org/10.1111/psyp.13059

Gentili, R. J., Rietschel, J. C., Jaquess, K. J., Lo, L. C., Prevost, M., Miller, M. W., Mohler, J. M., Oh, H., Tan, Y. Y. ing, & Hatfield, B. D. (2014). Brain biomarkers based assessment of cognitive workload in pilots under various task demands. *Conference Proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference*, *2014*, 5860–5863. https://doi.org/10.1109/EMBC.2014.6944961

Gonzalez, J., Soma, H., Sekine, M., & Yu, W. (2012). Psycho-physiological assessment of a prosthetic hand sensory feedback system based on an auditory display: A preliminary study. *Journal of NeuroEngineering and Rehabilitation*, *9*(1), 1–14. https://doi.org/10.1186/1743-0003-9-33

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. *Nature*, *394*(6695), 780–784. https://doi.org/10.1038/29528

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*, *52*, 139–183.

https://doi.org/10.1016/S0166-4115(08)62386-9

Hatfield, B. D., Haufler, A. J., Hung, T.-M., & Spalding, T. W. (2004). Electroencephalographic Studies of Skilled Psychomotor Performance. *Journal of Clinical Neurophysiology*, *21*(3).

Heitz, R. P. (2014). The speed-accuracy tradeoff: History, physiology, methodology, and behavior. *Frontiers in Neuroscience*, *8*(8 JUN), 1–19. https://doi.org/10.3389/fnins.2014.00150

Heitz, R. P., & Schall, J. D. (2012). Neural Mechanisms of Speed-Accuracy Tradeoff. *Neuron*, *76*(3), 616–628. https://doi.org/10.1016/j.neuron.2012.08.030

Huang, M. E., Levy, C. E., & Webster, J. B. (2001). Acquired limb deficiencies. 3. Prosthetic components, prescriptions, and indications. *Archives of Physical Medicine and Rehabilitation*, *82*(3B), 0s17-0s24. https://doi.org/10.1053/apmr.2001.22226

Jaquess, K. J., Gentili, R. J., Lo, L. C., Oh, H., Zhang, J., Rietschel, J. C., Miller, M. W., Tan, Y. Y., & Hatfield, B. D. (2017). Empirical evidence for the relationship between cognitive workload and attentional reserve. *International Journal of Psychophysiology*, *121*(February), 46–55. https://doi.org/10.1016/j.ijpsycho.2017.09.007

Jaquess, K. J., Lo, L. C., Oh, H., Lu, C., Ginsberg, A., Tan, Y. Y., Lohse, K. R., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Changes in Mental Workload and Motor Performance Throughout Multiple Practice Sessions Under Various Levels of Task Difficulty. *Neuroscience*, *393*, 305–318. https://doi.org/10.1016/j.neuroscience.2018.09.019

Kao, S. C., Huang, C. J., & Hung, T. M. (2013). Frontal midline theta is a specific indicator of optimal attentional engagement during skilled putting performance. *Journal of Sport and Exercise Psychology*, *35*(5), 470–478. https://doi.org/10.1123/jsep.35.5.470

Kardos, Z., Tóth, B., Boha, R., File, B., & Molnár, M. (2014). Age-related changes of frontal-midline theta is predictive of efficient memory maintenance. *Neuroscience*, *273*, 152–162. https://doi.org/10.1016/j.neuroscience.2014.04.071

Kim, J. Y., & Ji, Y. G. (2013). *A Comparison of Subjective Mental Workload Measures in Driving Contexts*. *32*(2), 167–177.

Krauth, R., Schwertner, J., Vogt, S., Lindquist, S., Sailer, M., Sickert, A., Lamprecht, J., Perdikis, S., Corbet, T., Del Millán, J. R., Hinrichs, H., Heinze, H. J., & Sweeney-Reed, C. M. (2019). Cortico-muscular coherence is reduced acutely post-stroke and increases bilaterally during motor recovery: A pilot study. *Frontiers in Neurology*, *10*(FEB). https://doi.org/10.3389/fneur.2019.00126

Lawson, D. H., Lee, S., Zhao, F., Tarhini, A. A., Margolin, K. A., Ernstoff, M. S., Atkins, M. B., Cohen, G. I., Whiteside, T. L., Butterfield, L. H., Kirkwood, J. M., MA Gillentine, LN Berry, RP Goin-Kochel, MA Ali, J Ge, D Guffey, JA Rosenfeld, V Hannig, P Bader, M Proud, M Shinawi, BH Graham1, A Lin, SR Lalani, J Reynolds, M Chen, T Grebe, CG Minard, P Stankiewicz, AL Beaudet, and C., Schaaf, Van Willigen, W. W., Bloemendal, M., Gerritsen, W. R., Schreibelt, G., de Vries, I. J. M., Bol, K. F., … 口田圭吾. (2016). This is to certify that. *Journal of Clinical Oncology*, *1*(1), 97680. https://doi.org/10.1016/j.jconrel.2012.07.004.Enhanced

Meissner, S. N., Krause, V., Südmeyer, M., Hartmann, C. J., & Pollok, B. (2018). The significance of brain oscillations in motor sequence learning: Insights from Parkinson's disease. *NeuroImage: Clinical*, *20*(August), 448–457. https://doi.org/10.1016/j.nicl.2018.08.009

Nelson, A. B., Moisello, C., Lin, J., Panday, P., Ricci, S., Canessa, A., Di Rocco, A., Quartarone, A., Frazzitta, G., Isaias, I. U., Tononi, G., Cirelli, C., & Ghilardi, M. F. (2017). Beta oscillatory changes and retention of motor skills during practice in healthy subjects and in patients with Parkinson's disease. *Frontiers in Human Neuroscience*, *11*(March), 1–12. https://doi.org/10.3389/fnhum.2017.00104

Parr, J. V.V., Vine, S. J., Wilson, M. R., Harrison, N. R., & Wood, G. (2019). Visual attention, EEG alpha power and T7-Fz connectivity are implicated in prosthetic hand control and can be optimized through gaze training. *Journal of NeuroEngineering and Rehabilitation*, *16*(1), 1–20. https://doi.org/10.1186/s12984-019-0524-x

Parr, J., Vic, J., & Parr, V. (2020). *Evaluating and alleviating the cognitive burden associated with myoelectric prosthetic hand control Evaluating and alleviating the cognitive burden associated with* *myoelectric prosthetic hand control A thesis submitted in partial fulfilment of the require*. *January*. https://doi.org/10.13140/RG.2.2.26474.47048

Parr, Johnny V.V., Gallicchio, G., Harrison, N. R., Johnen, A. K., & Wood, G. (2020). All talk? Challenging the use of left-temporal EEG alpha oscillations as valid measures of verbal processing and conscious motor control. *Biological Psychology*, *155*(May), 107943. https://doi.org/10.1016/j.biopsycho.2020.107943

Parr, J. V. V, Vine, S. J., Harrison, N. R., & Wood, G. (2018). Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand. *Journal of Motor Behavior*, *50*(4), 416–425. http://10.0.4.56/00222895.2017.1363703

Pasquina, P. F., Perry, B. N., Miller, M. E., Ling, G. S. F., & Tsao, J. W. (2015). Recent Advances in Bioelectric Protheses. *Neurology Clinical Practice*, 164–170.

Perfetti, B., Moisello, C., Landsness, E. C., Kvint, S., Lanzafame, S., Onofrj, M., Di Rocco, A., Tononi, G., & Ghilardi, M. F. (2011). Modulation of Gamma and Theta Spectral Amplitude and Phase Synchronization Is Associated with the Development of Visuo-Motor Learning. *Journal of Neuroscience*, *31*(41), 14810–14819. https://doi.org/10.1523/JNEUROSCI.1319-11.2011

Pruziner, A. L., Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Miller, M. W., Wolf, E. J., Hatfield, B. D., Dearth, C. L., & Gentili, R. J. (2019). Biomechanical and neurocognitive performance outcomes of walking with transtibial limb loss while challenged by a concurrent task. *Experimental Brain Research*, *237*(2), 477–491. https://doi.org/10.1007/s00221-018-5419-8

Rackerby, R., Lukosch, S., & Munro, D. (2022). Understanding and Measuring the Cognitive Load of Amputees for Rehabilitation and Prosthesis Development. *Archives of Rehabilitation Research and Clinical Translation*, *4*(3), 100216. https://doi.org/10.1016/j.arrct.2022.100216

Resnik, L., Adams, L., Otr, L., Borgia, M., Delikat, J., Otr, L., Disla, R., Ebner, C., Walters, L. S., & Otr, L. (2013). Development and Evaluation of the Activities Measure for Upper Limb Amputees. *Archives of Physical Medicine and Rehabilitation*, *94*(3), 488-494.e4. https://doi.org/10.1016/j.apmr.2012.10.004

Resnik, L., Borgia, M., Cancio, J., Heckman, J., Highsmith, J., Levy, C., Phillips, S., & Webster, J. (2022). Dexterity, activity performance, disability, quality of life, and independence in upper limb Veteran prosthesis users: a normative study. *Disability and Rehabilitation*, *44*(11), 2470–2481. https://doi.org/10.1080/09638288.2020.1829106

Resnik, L., Ekerholm, S., Borgia, M., & Clark, M. A. (2019). A national study of Veterans with major upper limb amputation: Survey methods, participants, and summary findings. *PLoS ONE*, *14*(3), 1–24. https://doi.org/10.1371/journal.pone.0213578

Rietschel, J. C., McDonald, C. G., Goodman, R. N., Miller, M. W., Jones-Lush, L. M., Wittenberg, G. F., & Hatfield, B. D. (2014). Psychophysiological support of increasing attentional reserve during the development of a motor skill. *Biological Psychology*, *103*, 349–356. https://doi.org/10.1016/j.biopsycho.2014.10.008

Salminger, S., Stino, H., Pichler, L. H., Gstoettner, C., Sturma, A., Mayer, J. A., Szivak, M., & Aszmann, O. C. (2022). Current rates of prosthetic usage in upper-limb amputees–have innovations had an impact on device acceptance? *Disability and Rehabilitation*, *44*(14), 3708–3713. https://doi.org/10.1080/09638288.2020.1866684

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological Psychology*. https://doi.org/10.1016/j.biopsycho.2018.01.009

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Wolf, E. J., Dearth, C. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2019). *A Comparison of Mental Workload in Individuals with Transtibial and Transfemoral Lower Limb Loss during Dual-Task Walking under Varying Demand*. 1–13. https://doi.org/10.1017/S1355617719000602

Shuggi, I. M., Oh, H., Wu, H., Ayoub, M. J., Moreno, A., Shaw, E. P., Shewokis, P. A., & Gentili, R. J. (2019). Motor Performance, Mental Workload and Self-Efficacy Dynamics during Learning of Reaching Movements throughout Multiple Practice Sessions. *Neuroscience*, *423*, 232–248.

https://doi.org/10.1016/j.neuroscience.2019.07.001

Shuggi, I. M., Shewokis, P. A., Herrmann, J. W., & Gentili, R. J. (2018). Changes in motor performance and mental workload during practice of reaching movements: a team dynamics perspective. *Experimental Brain Research*. https://doi.org/10.1007/s00221-017-5136-8

Tan, H., Wade, C., & Brown, P. (2016). Post-movement beta activity in sensorimotor cortex indexes confidence in the estimations from internal models. *Journal of Neuroscience*, *36*(5), 1516–1528. https://doi.org/10.1523/JNEUROSCI.3204-15.2016

Tatti, E., Ferraioli, F., Peter, J., Alalade, T., Nelson, A. B., Ricci, S., Quartarone, A., & Ghilardi, M. F. (2021). Frontal increase of beta modulation during the practice of a motor task is enhanced by visuomotor learning. *Scientific Reports*, *11*(1), 1–14. https://doi.org/10.1038/s41598-021-97004-0

Uellendahl, J. (2017). Myoelectric versus Body-Powered Upper-Limb Prostheses: A Clinical Perspective. *JPO Journal of Prosthetics and Orthotics*, *29*(4S), P25–P29. https://doi.org/10.1097/jpo.0000000000000151

van der Cruijsen, J., Manoochehri, M., Jonker, Z. D., Andrinopoulou, E. R., Frens, M. A., Ribbers, G. M., Schouten, A. C., & Selles, R. W. (2021). Theta but not beta power is positively associated with better explicit motor task learning. *NeuroImage*, *240*(July), 118373. https://doi.org/10.1016/j.neuroimage.2021.118373

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394.

Williams, H. E., Chapman, C. S., Pilarski, P. M., Vette, A. H., & Hebert, J. S. (2019). Gaze and Movement Assessment (GaMA): Inter-site validation of a visuomotor upper limb functional protocol. *PLoS ONE*, *14*(12), 1–20. https://doi.org/10.1371/journal.pone.0219333

Williams, T. W. (2011). Progress on stabilizing and controlling powered upper-limb prostheses. *Journal of Rehabilitation Research and Development*, *48*(6), ix–xix. http://www.ncbi.nlm.nih.gov/pubmed/21938646

Wong, J. D., Cluff, T., & Kuo, A. D. (2021). The energetic basis for smooth human arm movements. *ELife*, *10*, 1–17. https://doi.org/10.7554/eLife.68013

Yu, Z., Guindani, M., Grieco, S. F., Chen, L., Holmes, T. C., & Xu, X. (2022). Beyond t test and ANOVA: applications of mixed-effects models for more rigorous statistical analysis in neuroscience research. *Neuron*, *110*(1), 21–35. https://doi.org/10.1016/j.neuron.2021.10.030

Chapter 3: Mental Workload and Prehensile Performance During Training

Abstract

The ability to employ a variety of prehensile patterns to successfully grasp objects of different shapes and sizes is critical to our successful participation in everyday activities; however, the underlying cognitive-motor resources that facilitate prehensile performance are not well understood. In the context of upper limb prosthesis rehabilitation, it is critical to understand how prehensile skill acquisition is affected by multiple training sessions. Furthermore, it is also imperative to understand if different types of prostheses, such as body-powered (BP) and myoelectric (MYO) display advantages for tasks that require specific prehensile pattern. Using the same design in the first study, we employed the Southampton Hand Assessment Procedure (SHAP) to assess power vs. precision grip task performance and mental workload between BP and MYO groups during prosthetic training. Specifically, we examined the abstract lightweight object subtask of the SHAP, which contained three sub-categories of the power(spherical, cylindrical, extension) and precision (tip, lateral, and tripod) grips. The results revealed that across multiple training sessions, prosthesis users had similar improvements in prehensile performance and movement smoothness for both grip types. As a result of training, the BP users exhibited signs of an emergence of cognitive-motor efficiency as revealed by a refinement of cognitive-motor processing (elevation of high-alpha power) while the MYO users produced greater cognitive-motor processing as a result of training. Both groups exhibited increases in sensorimotor processing as a result of practice which suggests that both groups were still learning to engage the necessary sensorimotor resources to meet task demands. When examining differences between grip types, MYO users produced greater high-alpha power during the precision grip tasks when compared to the power grip tasks which may reflect an inhibitory cognitive-motor process engaged to reduce unwanted muscle co-contraction to prevent undesirable myoelectric hand movements. On the contrary, BP users deployed fewer visual resources during the power grip tasks when compared to the precision grip tasks and when compared to the MYO

users which may indicate a slight advantage in cognitive-motor efficiency for power grip tasks relative to the MYO users. This work may inform prehensile training strategies for prosthesis users.

Introduction

Utilizing a variety of prehensile patterns to grasp objects of different shapes or sizes is critical to completing everyday activities. These prehensile patterns range can be categorized broadly as power or precision grips (Feix et al., 2016; Landsmeer, 1962). A power grasp uses all fingers synergistically to form the hand around an object to apply force or to stabilize (e.g., canned food, baseball). A precision grip primarily uses the fingertips and the thumb in which movement of the fingers are individualized to allow for grasping or manipulation of smaller objects such as a coin or key. While these power and precision employ different muscle groups and movement patterns (Landsmeer, 1962; Long et al., 1970; Shim et al., 2011), the underlying cognitive-motor processes of these grips are not well understood. When examining power and precision grip movements without actually grasping objects, no significant difference in cortical activity was noted between power and precision grips (Takasawa et al., 2003) when using Positron Emission Tomography (PET). In a Functional Magnetic Resonance Imaging (fMRI), participants grasped either a cylinder that required a power grip and a smaller handle with flat surface that required a precision grip. The precision grip task was found to elicit more ipsilateral activation in the ventral premotor cortex and the cingulate motor area, while more bilateral activation was noted in the prefrontal and posterior parietal cortex when compared to the power grips (Ehrsson et al., 2000). While these findings have been informative, PET and fMRI scans capture participants while supine in a highly movement restrictive, with limited head movement that limits or prohibits visual fixation on the object to grasp, which is a critical part of grasping in a real-world environment. In a study that examined motor evoked potentials, intracortical circuits and spinal motor neurons using electromyography(EMG), researchers suggested different cortical activation patterns exist between power and precision grip types such that increased intracortical inhibition occurred during precision grip tasks (Tazoe & Perez, 2017). On the contrary, some work found an elevation in the motor evoked potential amplitude with concurrent reduction in intracortical inhibition during a precision grip task, but not during a power task (Geevasinga et al., 2014). While the examination of motor evoked potentials has revealed differences in corticospinal excitability between grip types, the findings are mixed. Secondly, motor evoked potentials are not a direct measure of cortical activity since transcranial magnetic stimulation (TMS) was used to generate an electrical current in the cortex and this current was measured downstream in the muscles of interest via electromyography (EMG).

Electroencephalography (EEG) may be able to address these measurement gaps when examining the cognitive-motor resources of power and precision grips. While EEG may have spatial resolution limitations when compared to PET and fMRI, it is a direct measure of neuronal population activity, has excellent temporal resolution and due to its portability, and allows for examination of cortical activity in more ecologic conditions (Hatfield et al., 2004). It is well established that spectral EEG bandwidths, such as beta (14-35 Hz) is modulated by movement (Beck et al., 2021; Brinkman et al., 2016; Gentili et al., 2015) and somatosensory input (van Ede et al., 2015; Van Ede et al., 2011; van Ede & Maris, 2013), however some researchers determined that beta was unable to distinguish between grip type (Zaepffel et al., 2013). While beta is frequently employed to assess changes in sensorimotor activity when completing motor tasks; the underlying cognitive-motor processes involved in grasping are less examined. Low-alpha (8-10 Hz), high-alpha (11-13 Hz) as markers of general arousal and task-specific cognitive-motor resources respectively, may inform mental workload underlying motor performance (Gentili et al., 2011, 2014; Rietschel et al., 2012; Shaw et al., 2018). When individuals grasped an object using power and precision grips, higher power was observed in the high-alpha and lower beta (13-18Hz) bands over the ipsilateral centro-parietal region (Iñaki Iturrate et al., 2018) during precision grip tasks. Past work has teased out potential separate roles for alpha and beta by suggesting alpha is related to the suppression of task irrelevant processes while beta band reflects the engagement of neural resources involved in the processing of movement parameters (Brinkman et al., 2014, 2016). Theta (4-7Hz) has not been examined significantly in the prehensile literature; however, elevations in theta has been positively associated with task demand difficulty (Gentili et al., 2018; Shaw et al., 2018) and practice (Alan Gevins et al., 1997; Jaquess et al., 2018; van der Cruijsen et al., 2021) and has been thought to reflect working memory, error monitoring and attentional processes. In the context of adaptive motor performance and human device interaction, these spectral measures could be employed to collectively index mental workload associated during acquisition of prehensile skills using an upper limb prosthesis.

These EEG results have been extended to the examination of mental workload during motor performance in lower limb (Pruziner et al., 2019; Shaw et al., 2019) and upper limb prosthesis users (Deeny et al., 2014; Gonzalez et al., 2012; J. V.V. Parr et al., 2019). While informative, it remains unclear if cognitive-motor resources are recruited and allocated differently in response to power and precision task demands when using an upper limb prosthesis. If similar cortical dynamics are observed in prosthesis use when compared to using an intact hand, it may suggest that muscle activation or force requirements may not fully explain the differences in cortical dynamics observed between power and precision grips in past studies (Ehrsson et al., 2000; Takasawa et al., 2003; Tazoe & Perez, 2017).

From an applied perspective, the determination of the required cognitive-motor resources necessary to acquire power and precision grip skills over time could inform rehabilitation training strategies. Furthermore, when examining grip performance between prosthetic types, distinguishing mental workload differences in prosthetic control types could reveal advantages for using a specific device for a grip task. While some work has suggested body-powered (BP) prostheses using a hook terminal device as being more versatile to handle light or heavy work, myoelectric (MYO) devices with an anthropomorphic hand has been thought to possess the capability to grasp larger objects by employing a composite grip while still having the fine motor ability to grasp smaller objects due to the ability to form precision prehensile patterns (Carey et al., 2015). BP devices are reported to be more durable while MYO devices have reports of unpredictable prosthesis control behavior stemming from issues such as signal acquisition and latencies in device response times (A. Chadwell et al., 2021; Alix Chadwell et al., 2016a). Additionally, MYO devices are reported to require more visual fixation on the hand during motor performance when compared to an intact hand and exhibit more frequent gaze switching between the terminal device and object of interest during object transport (J. Parr, 2018; J. V.V. Parr et al., 2019). While more visual fixation on the terminal device has also been observed in BP users when compared to the intact hand, this gaze switching strategy was not observed in BP users (Boser, 2019). Despite these differences between BP and MYO devices, as far as we know, there is contrasting evidence regarding advantages in motor performance between the prosthetic devices (Bouwsema et al., 2008; Carey et al., 2015a; Resnik et al., 2019, 2022) and no previous work has systematically examined mental workload differences between these prosthetic types when engaging in power and precision grip tasks.

Therefore this study was conducted to 1) determine the underlying cognitive-motor resources of mental workload in precision and power grip acquisition in upper limb prosthesis users during a 10-session training program, and 2) determine if there are differences in mental workload between BP and MYO users when completing power and precision grip tasks. 20 individuals with intact upper limbs participated in a 10-session training program to learn to use either a BP or MYO bypass prosthesis. Mental workload was examined at four timepoints during the training program and again during a retention session when transporting power and precision grip objects in the abstract light subtask of the validated Southampton Hand Assessment Procedure (SHAP) (Light et al., 2002). The time to complete each object transport was measured during these timepoints. Additionally, to capture the underlying kinematics associated with prehensile performance, inertial measurement units at the wrist, arm and head captured movement acceleration changes during these timepoints. Normalized jerk as a measurement of movement smoothness has been inversely related to motor performance (Balasubramanian et al., 2015; Bloomer et al., 2020; H. Yan et al., 2000; Shuggi et al., 2017). To capture perceived mental workload, the National Aeronautics and Space Administration Task Load Index (NASA-TLX) was administered (Hart & Staveland, 1988). The NASA-TLX has been well established as a mental workload subjective measure (Gentili et al., 2018; Gonzalez et al., 2012; Shaw et al., 2018; Shuggi et al., 2019). EEG was recorded to capture the neural correlates of mental workload (Gentili et al., 2011, 2018; A Gevins & Smith, 2003; Jaquess et al., 2017; Pruziner et al., 2019).

As a result of training, prosthesis users were predicted to experience similar improvements in power and precision grip performance (less time to transport objects) and in movement smoothness while experiencing reductions in perceived mental workload, reductions in cognitive-motor and sensorimotor (elevation of low and high-alpha power and beta power, respectively) and lastly, greater working memory and error-monitoring effectiveness (elevation of theta power). When compared to the precision grip tasks, prosthesis users were hypothesized to exhibit better performance (less time to transport objects), more movement smoothness, less perceived mental workload, less cognitive-motor and sensorimotor processing (greater low and high-alpha power and beta power, respectively) and less working memory and error-monitoring processing (lower theta power) when completing power grip tasks. MYO users were predicted to exhibit similar performance between grip types, while experiencing less movement smoothness, greater perceived mental workload, greater cognitive-motor and sensorimotor processing (attenuated low and high-alpha power and beta power, respectively) and more working memory and error-monitoring processing (higher theta) during precision grips when compared to power grips.

Methods

Like the first study, this study was also conducted as a part of the prosthetic training program therefore the information in the Methods section replicates most of the Methods section in the first study.

Participants

To participate in the study, participants were required to be right hand dominant (confirmed by the Edinburg Handedness Survey), have normal or corrected-to-normal vision, not have an upper limb injury, have no neurological disorders that would negatively influence movement and not be on psychotropic medication. A convenience sample of 28 participants volunteered to participate in the study, five participants were excluded from the study due to not meeting all inclusion criteria and three participants either signed up for the study or started the study but dropped out due to personal reasons. Thus, a final total sample of 20 right-handed participants (10 males, 10 females) with intact upper limbs between the ages of 19 and 58(mean = 25.85, SD = 8.35) completed the 10-session bypass prosthetic training program. Participants were randomly split into the BP (4 males, 6 females, mean age = 23.5, SD = 3.77) or MYO(5 males, 5 females, mean age = 28.5, SD = 10.83) groups. All participants were current or former University of Maryland, College Park students or faculty. The sample size was determined based upon a prior upper limb prosthetic training study (J. V.V. Parr et al., 2019). During training, three

MYO participants experienced a MYO device malfunction in which the index finger of the device remained in the open position during one or more assessment sessions. To determine if the malfunction had a significant effect on performance and perceived task demand, a linear mixed effect model was employed for MYO users to see if the covariate, device malfunction, significantly affected motor performance, kinematic or perception of demands using the NASA-TLX. This malfunction did not have an effect on SHAP motor performance or movement smoothness; however, the malfunction did increase the perceived physical demand ($p = 0.006$) of the MYO group during completion of the SHAP assessment. Upon further analysis, it was determined that one MYO user who experienced this malfunction for three assessment sessions was adversely affected, therefore this participant's data was removed from the dataset. Upon removal of the participant's results, device malfunction was found to not significantly impact perceived physical demand ($p = 0.446$) for the MYO users.

All participants provide their informed consent prior to participating in the study. The Institutional Review Board at the University of Maryland-College Park approved this study.

Bypass Prosthesis Donning and Operational Check

The BP bypass prosthesis used in this study was designed by Arm Dynamics (Dallas, TX) utilized a voluntary opening Hosmer 5X hook terminal device, with manual wrist rotation, figure eight harness and a 12 cm distal offset. While standing, the BP users donned the prosthesis harness on the right, dominant arm and the forearm was secured in the arm socket with straps with assistance from the experimenter. While seated, the participants demonstrated voluntary opening of the terminal device via a cable pulley system by using shoulder flexion and scapular protraction with three techniques. The bypass side technique only used the right side of the body, the sound side technique used the left side of the body and the bi-scapular technique used both scapulae to open the terminal device. Opening of the terminal device was demonstrated at a 50% and 100% aperture. The BP users also demonstrated unlocking of the wrist, manual rotation of the wrist to achieve the desired hook direction and a locking of the wrist to secure the hook positioning. The BP users pre-selected the orientation of their prosthetic hook prior to beginning each task during training and assessment.

The MYO terminal device used in this study was the i-limb Ultra® created by Össur (Foothill Ranch, CA). The myoelectric terminal device was mounted to a forearm brace adapter provided by Next Step Bionics with a perpendicular handlebar with a medial offset of 15° from the participant’s forearm. This device featured individualized motorized digits, compliant grip capability, direct control system using two electromyography sensors, manual thumb, and wrist rotation functionality. This prosthesis was used with a companion I-phone application (Biosim™) via Bluetooth connection. Biosim™ features a real-time EMG graph to assess muscle contraction quality and 12 automated ‘quick’ grips. While the MYO users were seated, their ventral and dorsal aspect of the right forearm was cleaned using an alcohol swab prior to placing the flexor sensor on the muscle belly of the flexor carpi radialis superficialis and the extensor sensor on the muscle belly of the extensor carpi radialis. The electrodes were secured with skin tape to reduce electrode movement during the experiment. This was done to remove skin debris that may interfere with the skin/electrode connection and the electromyograph (EMG) signal. Once the prosthesis was on, participants completed repetitive hand opening and closing for approximately 5-10 seconds while viewing the EMG signal in real time to assess for contraction quality and for existence of interfering co-contraction of the flexor and extensor muscles. Knowledge of performance feedback was provided as needed until optimal muscle contractions with minimal or undetected co-contraction was detected and no significant latency was noted between the contraction and the subsequent MYO hand movement. The MYO users then selected 11 grips one at a time (Figure 1) using the Biosim™ application. They performed isometric wrist flexion to flex the digits/hand followed by isometric wrist extension to open the digits/ hand based upon the pre-selected digit operation of each grip. The thumb park quick grip was not used for the study due to usability concerns since this grip only allowed for a 1.5 second time window for the thumb to be operated via the user’s input signal before returning to an open hand position. The 12th and final grip used for the MYO users was the composite grip(full fist closure) which was accessed via a double tap on any grip icon on the app. The MYO participants used the left hand to demonstrate manual rotation of the terminal device wrist and thumb opposition. If signal latency issues were detected at any time during the session, the study was paused, electrode signal quality was immediately re-inspected and position adjustments of the electrode were made as needed. The MYO users pre-selected their grip and wrist and thumb position prior to beginning each task during training and assessment.

Prosthetic Training Program

The bypass prosthetic training program was adopted from an established training protocol (Bloomer et al., 2018) with an adjustment of the frequency of performance outcome measure administration from every training session to every 3rd training session. Participants typically completed 2-3 sessions each week. This was done to more closely approximate of the frequency of practice sessions and administration of performance outcome measures typically observed in an outpatient rehabilitation setting (El Hayek et al., 2023). An experienced occupational therapist administered the prosthetic training to ensure the training was standardized and training techniques that were utilized were similar to an actual rehabilitation program (Butkus et al., 2014; Resnik et al., 2019). Participants first completed an orientation session (S1) in which the informed consent was reviewed, the prosthetic group was assigned, EEG cap size was determined, prosthesis harness fitting (BP group only) and scheduling of the first training sessions were completed. All sessions in the program were completed while seated. Customized table heights for each participant were selected so that the participants forearm/arm angle was at a 90-degree angle when resting their prosthesis and left hand on the table with feet flat on the floor.

Training Only Sessions

Sessions S3,S4,S6,S7,S9 and S10 were training only sessions. Sessions at the beginning of the training program typically lasted 50 minutes while sessions later in the program lasted around 30 minutes due to the participants advancing more quickly through the object manipulation portion of the training and completing all tasks of the ADL training before the 20 minute time allotment elapsed. Before the start of training, participants donned their prosthetic devices and device set-up was completed.

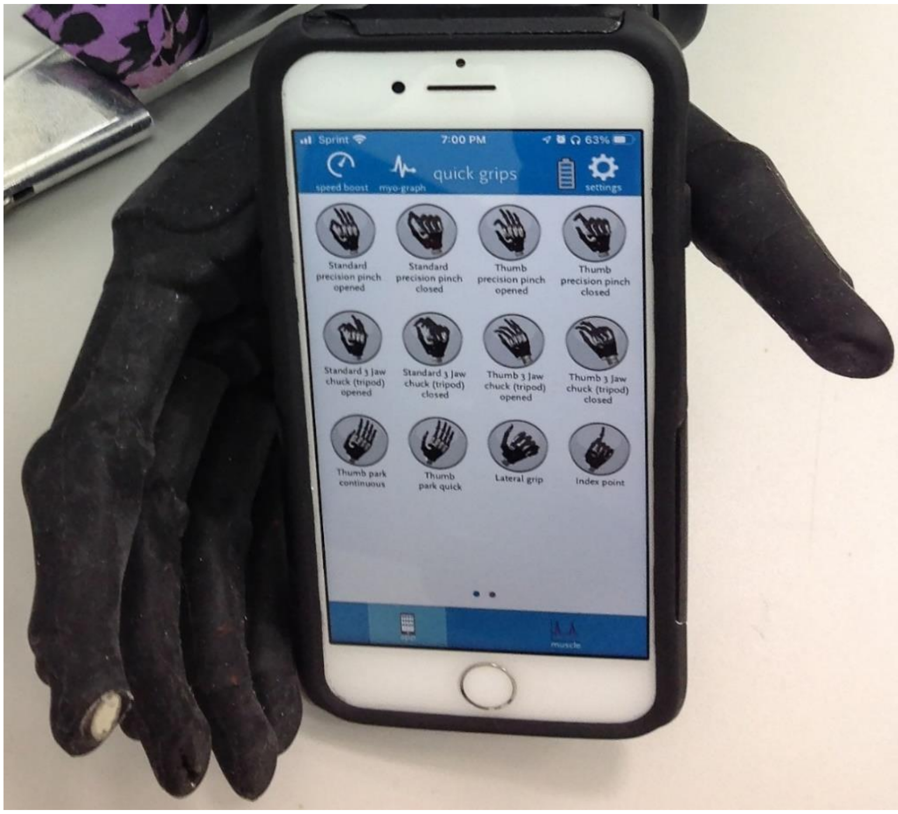


Fig. 1. Biosim™ smartphone application with 12 available grips. Top row(left to right): standard precision pinch opened, standard precision pinch closed, thumb precision grip opened, thumb precision grip closed. Middle row(left to right): standard 3- jaw chuck (tripod) opened, standard 3- jaw chuck (tripod) closed, thumb 3-jaw chuck (tripod) opened, thumb 3-jaw chuck (tripod) closed, Bottom row(left to right): thumb park continuous, thumb park quick(not used), lateral grip, index point. Not pictured: composite grip. This grip was acquired by double-tapping any grip icon.

Object Manipulation

Prosthesis users demonstrated three types of object manipulation strategies(direct grasping, indirect grasping, and fixation) to manipulate a variety of objects. The prosthesis users employed a direct grasp(grasp items directly from surface) and indirect grasp (pick up item from table using intact hand, then use prosthetic hand to grasp item from intact hand) to transport a wood cube, metal can and foam ball. For fixation, both groups used their prosthesis to stabilize a zipper, sweater, and ruler while the intact hand opened and closed the zipper, unbuttoned the sweater buttons, and drew a straight line using the ruler, respectively.

Free Training

Free training permitted five minutes of unstructured time for the participants to use their prosthesis while seated to manipulate a variety of objects(plates, pens, bottles; etc.) using the object manipulation strategies just learned.

ADL Training

Participants then completed 10 activity of daily living (ADL) and instrumental activities of daily living (iADLs) from the validated Activities Measure for Upper Limb Amputees (Resnik, Adams, Otr, et al., 2013) in a 20-minute time window. Knowledge of performance and results feedback were delivered as needed via verbal and physical demonstration mediums throughout training.

For more details of the training protocol, please refer to the Study 1 Protocol in the Appendix.

Training and Assessment Sessions

The participants completed training and assessment segments during the initial training session(S2), sessions 5(S5) and 8(S8) and the final training session(S11). Prosthesis users donned their prostheses before EEG and Inertial Measurement Unit(IMU) set-up and completed the prosthesis operational check after EEG and IMU set-up. The participants then completed the SHAP. Please see the Data Acquisition section for the EEG, IMU, SHAP, and NASA-TLX data capture. Including EEG and kinematic set-up and breakdown, sessions on average took approximately 3.5 hours.

Retention Session

The median days spent in the training program (S2-S11) was 33 days for the BP users and 38 days for the MYO users. At least one week after the completion of training, participants completed the retention session. No training was completed during this session. EEG and IMU set-up were completed first. Prosthesis users donned their prostheses before EEG and Inertial Measurement Unit (IMU) set-up and completed the prosthesis operational check after EEG and IMU set-up. The participants then completed the SHAP. Please see the Data Acquisition section for the EEG, IMU, SHAP and NASA-TLX data acquisition process. Including EEG and kinematic set-up and breakdown, sessions on average took approximately 2.5 hours. The average number of days between the final training session and retention session for the BP and MYO users were 12.4 and 14.7 days, respectively.

Fig. 2. Training Program. S2 denotes the start of the training program and S11 denotes the end of the training program. The retention session was completed at least one week after the final training session. *** indicates results that are not of primary interest in this study and are reported in other studies.

Experimental Set-Up

A pre-fitted EEG cap was donned on the participant's head and secured using chin and chest straps to reduce unwanted movement artifacts. Electrode lines were gathered and felt material secured the electrode lines in a ponytail using a simple rope knot. The lines were then clipped to the participant's the participant's back. Line bundles that were not included in the ponytail were taped to the participant's back. Gel was applied to each electrode until an impedance below 10 kΩ was achieved. EEG was recorded from 64 active electrode sites (10-20 system) at a 1000 Hz sampling rate using the Brain Vision

EEG system (Brain Products GmbH, Germany). The EEG data was online referenced to the left earlobe and offline re-referenced using activity from the right earlobe. and a common ground was employed at the AFz site on the scalp. The horizontal electro-oculographic channel (HEOG) and vertical electro-oculographic channel (VEOG) was recorded by one electrode on the right outer canthus of the eye and one electrode on the superior orbital ridge of the right eye, respectively.

EEG

EEG data was processed using the EEGlab package of Matlab®(The Mathworks Inc., USA) using custom code. Bad channels were identified and interpolated. Data was band-pass filtered with a low cut-off of 0.1 Hz and a high cut-off of 60 Hz with a 48 dB rolloff. Next, independent component analysis (ICA) was employed to remove ocular, muscle, and line noise artifacts. Data was resampled to 500Hz for synchronization with inertial measurement units (IMUs). Using a custom Matlab® script, data was epoched into early (-2 to -1 seconds) and late planning (-1 to 0 seconds) before movement onset. Movement onset was epoched from 0 seconds to the end of the trial which was marked by a manual end of movement execution trigger from the IMU system. Spectral power was calculated across 1-Hz bins and summed across theta (4-7 Hz) low-alpha (8-10 Hz), high-alpha (11-13 Hz) and beta (14-35 Hz) frequency bandwidths.

IMU

An inertial movement unit (IMU; Xsens™) was placed on the center of the participant's forehead, the right mid- humerus and distal end of the bypass prosthesis to measure kinematic changes of the head, arm, and wrist, respectively at a sampling rate of 100Hz. Data was bandpass filtered with a low cut-off of 0.01 Hz and a high cut-off of 20 Hz with an 80 dB rolloff. Data was up sampled to 500 Hz to synchronize with the EEG data. Normalized jerk was computed from the acceleration data using a custom Matlab® script. Due to the focus of this work to examine differences in upper limb movement smoothness, normalized jerk for the wrist and arm was computed to determine the rate of change in movement acceleration as an index of movement smoothness (Balasubramanian et al., 2015).

SHAP and NASA-TLX

After EEG and IMU set-up, training was completed as outlined in the Training Only Sessions section. The SHAP is a validated upper limb amputee assessment that includes two broad categories, the abstract object tasks and activities of daily living (Light et al., 2002). The abstract object tasks category required individuals to transport six objects in lightweight and heavyweight forms. The ADL category required individuals to complete 14 ADLs with primary use of the unilateral upper limb. While study participants completed the full SHAP assessment, the lightweight abstract object tasks were of primary interest to examine differences in power and precision grip performance in order to reduce confounding effects. For example, SHAP lightweight objects are more similar in weight when compared to heavyweight objects. Heavier objects have been shown to require greater grip force (Lu et al., 2015). Additionally, some ADLs in the SHAP require use of the intact hand to stabilize objects while the prosthetic limb performs transport or manipulation of objects. Bilateral tasks may elicit bi-hemispheric cortical changes, which could confound EEG results since we are primarily interested in prosthetic limb performance only (Noble et al., 2014). To examine power and precision grips, we categorized spherical, power and extension grip objects into the power grip class while tip, lateral and tripod grip objects were classified into the precision grip class based upon an established grasp taxonomy (Feix et al., 2016) (Fig.3).

Participants sat in a chair with back support with their feet flat on the floor with their intact hand and prosthetic terminal device resting on the table with their arms at a 90-degree angle. Due to the extensive time for experimental set-up and SHAP completion, participants were allowed to rest using the back support in between tasks; however, they were instructed to sit upright when completing each task. The SHAP board was positioned eight centimeters in front of the participant. Each task was explained by the experimenter, and the participants were allowed up to one minute to practice this task. No verbal feedback was provided during the practice period.

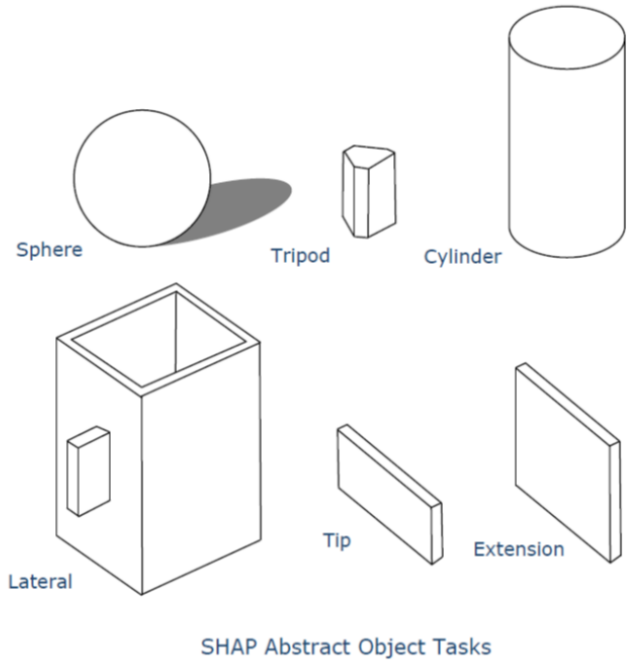


Fig. 4. Objects from the SHAP Abstract Object Tasks. Used with permission from SHAP Business Enterprise-University of Southampton.

After one minute had elapsed or the participant stated they were ready, participants were instructed to remain still with their head facing forward and their left forearm and prosthesis resting on the border of the table. The experimenter verbally confirmed again that the participant was ready to begin the data capture. Four seconds prior to the start of each trial, the experimenter asked the question, "Ready?" EEG and IMU recording were started manually. After four seconds elapsed, an audible beep sounded from the computer speaker, and the participant began the trial. A manual trigger was created at the start of the trial in the EEG and IMU recordings. Participants then used their prosthesis to start a timer located in the middle of the SHAP board by pressing a large blue button. Next, they moved the object from the rear slot to the front slot as quickly as possible, and then stopped the timer by pressing the large blue button again to stop the timer. The end of the trial was denoted by the stopping of the timer after the object transport. A manual trigger was sent by the experimenter at the end of the trial to mark the end of movement execution in the EEG and IMU recordings. Per the SHAP instructions, only one attempt was given to complete the task. If an object fell off the board, it was noted as a task failure and the time was not recorded for the task. To maintain consistency in assessment administration that is observed in a rehabilitation setting and to maintain ecological validity, the SHAP abstract power tasks were completed first (spherical, cylindrical extension and then the precision tasks(tripod, tip, lateral) were completed afterwards and were not counterbalanced. This was also done since the NASA-TLX and Prosthesis-Orthosis Load Index surveys were administered after completion of all power grip tasks and again after the precision grip tasks. This is a slight variation from the SHAP administration instructions, which directed participants to complete the abstract tasks in the following order: spherical, tripod, cylindrical, lateral, tip, extension.

In addition to the SHAP, the BBT was also completed. Both measures were completed in a counterbalanced order. The BBT is beyond the scope of the current study and was discussed in detail in Chapter 2.

After the completion of each grip category, participants completed the NASA-TLX and Prosthesis-Orthosis Load Index (POLI) paper surveys in a counterbalanced order using their non-prosthetic hand to circle tick marks that corresponded with their average perceived workload levels. The POLI is beyond the scope of this study and will be discussed in Chapter 5.

Including EEG and kinematic set-up and breakdown, sessions on average took approximately 3 hours.

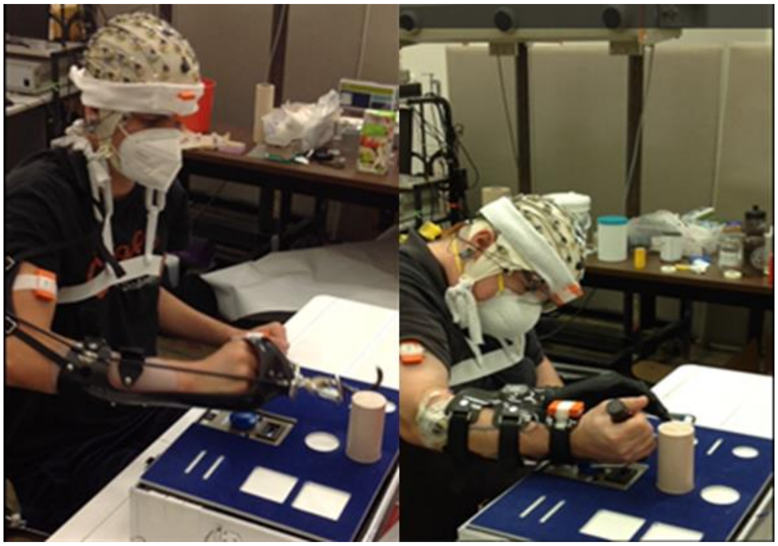


Fig. 5. Images of a BP user(left) and MYO user(right) transporting the lightweight cylinder as part of the abstract light cylindrical task of the SHAP.

Statistical Analysis

Linear mixed effect modeling was conducted for all measures due to the model's ability to model random effects, its robustness against missing data and model flexibility (Yu et al., 2022). This was imperative due to the presence of data dependence as a result of the within subject design study design as well as the length of the training which resulted in minor loss of data due to infrequent device malfunctions/ experimental technical issues. Random effects were applied to the Participant variable for all models. All data was subjected to a visual inspection to assess model assumptions. The EEG and kinematic data were natural log-transformed to reduce positive skewness. Outlier removal was conducted based on Cook's distance for each model dataset to reduce the outlier influence on the model performance (Cook, 1977). Linear mixed effects models are reported with a Type III ANOVA output to communicate the results in a more concise manner and to explain complex interactions that occurred during the study. Satterthwaite's method was used to approximate degrees of freedom. Partial eta squared effect sizes are reported for all statistically significant main effects and interactions. Partial eta squared effect sizes were categorized as small ($\eta p^2 = 0.01$), medium ($\eta p^2 = 0.06$, large ($\eta p^2 = 0.14$). Post-hoc analyses with a Tukey HSD correction were performed for all statistically significant main effects and interactions with a p-value threshold of $p < 0.05$. Cohen's d effect sizes are reported for all significant post-hoc comparisons. Cohen's d effect sizes were categorized as small ($d = 0.2$), medium ($d = 0.5$) and large ($d= 0.8$). All statistical analyses were performed using R Studio (RStudio Team, 2023).

To increase clarity in reporting, only relevant effects to answer our hypothesis were considered. Namely, only the Prosthesis and Session main effects or interactions including Prosthesis and/or Session variables are reported for all measures since these are the variables that were manipulated in the experiment. While data was captured for all Training and Assessment sessions, to grasp the overall effect of the training program, Session main effects and interactions between the initial session and final training session or the initial session and the retention session or within each session for all measures are reported. Data points are displayed with standard error bars to visualize variance.

The linear mixed effects model for prehensile performance, the SHAP scores were subjected to a 2 (Prosthesis (BP, MYO) x 2 (Grip Type(Power, Precision) x 3 (Session (S2, S11, Retention)) design.

The linear mixed effects model for wrist and arm normalized jerk data were subjected to a 2(Prosthesis (BP, MYO) x 2 (Grip Type(Power, Precision) x 3 (Session (S2, S11, Retention)) design.

For each dimension of the NASA-TLX, a linear mixed effects model was subjected to a 2 (Prosthesis (BP, MYO) x 2 (Grip Type(Power, Precision) x 3 (Session (S2, S11, Retention)) design.

For each spectral bandwidth of interest (theta, beta and low and high-alpha), a linear mixed effects model was subjected to a 2 (Prosthesis (BP, MYO)) x 2 (Grip Type(Power, Precision) x 3 (Session (S2, S11, Retention)) x 2 (Hemisphere(Left, Right)) x 5 (Region(Frontal, Central, Parietal, Occipital, Temporal)) design. P-values are reported with a $p < 0.05$ threshold to determine statistical significance.

Assessment

EEG and kinematics were measured during the assessment segment of the Training and Assessment sessions. Please see the Data Acquisition section for more details on equipment set-up. The performance outcome measures, the Box and Block Test (BBT) and the Southampton Hand Assessment Procedure (SHAP) were administered after training in the Training and Assessment sessions in a counterbalanced order. The SHAP is a validated upper limb amputee assessment that includes two sub-categories, the abstract object tasks and activities of daily living (Light et al., 2002). The abstract object tasks category requires individuals to transport six objects in lightweight and heavyweight forms. The ADL category requires individuals to complete 14 ADLs with primary use of the unilateral upper limb. While study participants completed the full SHAP assessment, the lightweight abstract object tasks were of primary interest to examine differences in power and precision grip performance in order to reduce confounding effects. For example, SHAP lightweight objects are more similar in weight when compared to heavyweight objects. Heavier objects have been shown to require greater grip force (Lu et al., 2015). Additionally, some ADL tasks require use of the intact hand to stabilize objects while the prosthetic limb performs transport or manipulation of objects. Bilateral tasks may elicit bi-hemispheric cortical changes, which could confound EEG results since we are primarily interested in prosthetic limb performance only.

To examine power and precision grips, we categorized spherical, power and extension grip objects into the power grip class while tip, lateral and tripod grip objects were classified into the precision grip class based upon an established grasp taxonomy (Feix et al., 2016) (See Figure 3). Participants sat in a chair with back support with their feet flat on the floor with their intact hand and prosthetic terminal device resting on the table with their arms at a 90-degree angle. Due to the extensive time for experimental set-up and SHAP completion, participants were allowed to rest using the back support in between tasks; however, they were instructed to sit upright when completing each task. The SHAP board was positioned eight centimeters in front of the participant. Participants were required to user their prosthesis to start a timer located in the middle of the SHAP board by pressing a large blue button, move the object from the rear slot to the front slot as quickly as possible, and then stop the timer by pressing the large blue button again to stop the timer. The end of the trial was denoted by the stopping of the timer after the object transport. Per the SHAP instructions, only one attempt was given to complete the task. If an object fell off the board, it was noted as a task failure and the time was not recorded for the task. To maintain consistency in assessment administration that is observed in a rehabilitation setting and to maintain ecological validity, the SHAP abstract power tasks were completed first (spherical, cylindrical extension and then the precision tasks (tripod, tip, lateral) were completed afterwards and were not counterbalanced. This was also done since the NASA-TLX and Prosthesis-Orthosis Load Index surveys were administered after completion of all power grip tasks and again after the precision grip tasks. This is a slight variation from the SHAP administration instructions, which directed participants to complete the abstract tasks in the following order: spherical, tripod, cylindrical, lateral, tip, extension.

The NASA-TLX and Prosthesis -Orthosis Load Index (POLI), a newly developed mental workload questionnaire for upper limb device users, were administered after the 2^{nd} BBT trial. No feedback was provided during assessment performance. Including EEG and kinematic set-up and breakdown, training + assessment sessions took approximately 3 hours.

Results

Performance

A main effect was revealed for Session ($F(2,76) = 11.466$, $p < 0.001$, $\eta p^2 = 0.231$). The post-hoc analysis revealed that prosthesis users transported the power and precision grip objects significantly faster during the final training ($p = 0.002$, $d = 0.679$) and the retention ($p < 0.001$, $d = 0.924$) sessions when compared to the initial training session.

Kinematics

Wrist Normalized Jerk

A main effect was revealed for Session ($F(2, 75) = 18.133$, $p < 0.001$, $\eta p^2 = 0.326$). The post-hoc analysis revealed that less wrist movement variability occurred after the initial session during the final training session ($p < 0.001$, $d = 0.845$) and the retention session ($p < 0.001$, $d = 1.045$).

Arm Normalized Jerk

A main effect was revealed for Session ($F(2, 71) = 7.185$, $p = 0.001$, $\eta p^2 = 0.168$). The post-hoc analysis revealed that prosthesis users experienced less arm movement variability during the final training ($p = 0.003$, $d = 0.682$) and retention ($p = 0.005$, $d = 0.683$) session when compared to the initial training session.

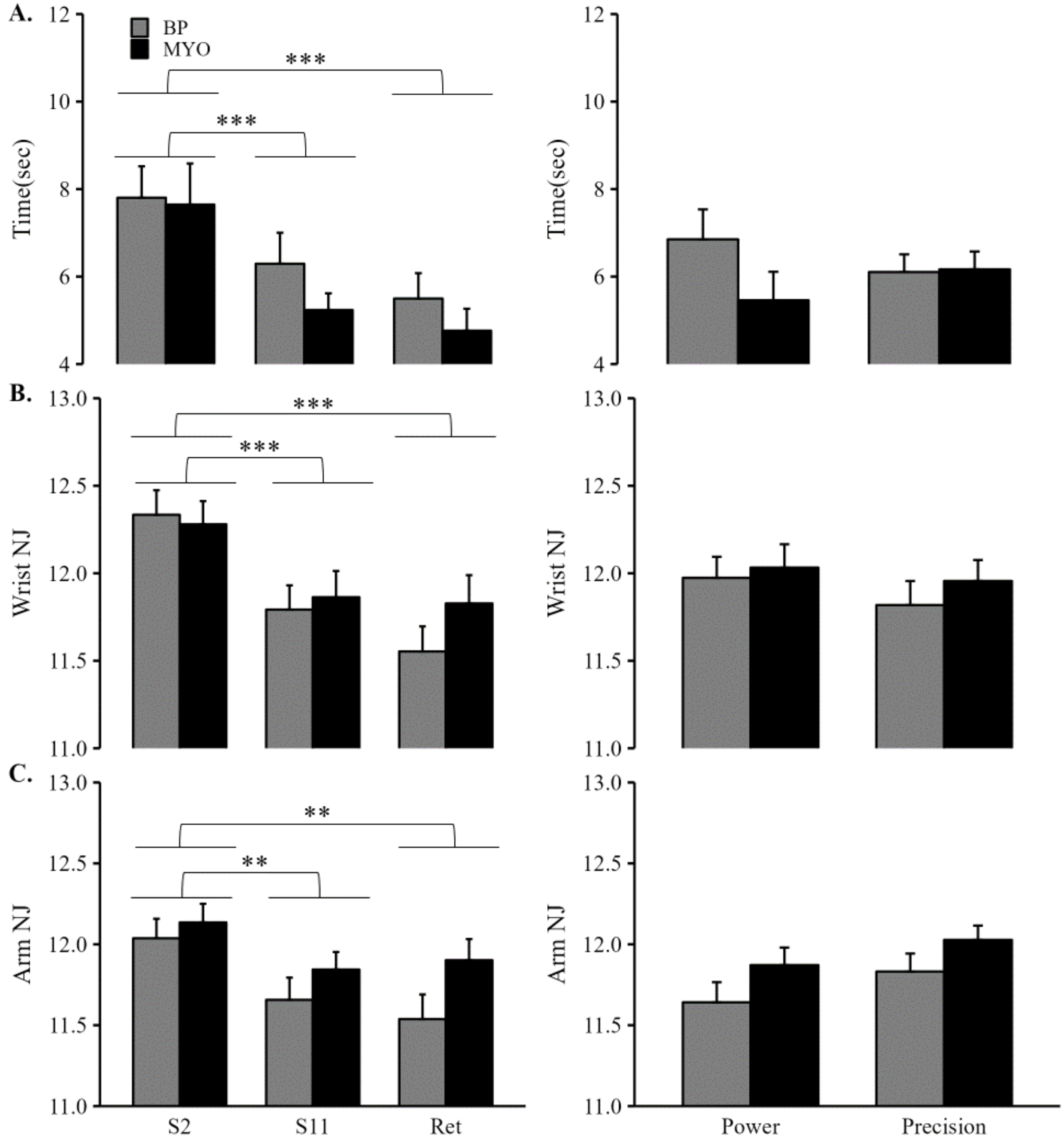


Fig. 6. **A.** SHAP performance times across sessions (left). SHAP performance times for each grip type (right). **B.** SHAP wrist normalized jerk across sessions (left). SHAP wrist normalized jerk for each grip type (right).**C.** SHAP arm normalized jerk across sessions (left). SHAP arm normalized jerk for each grip type (right). BP- Body-powered prosthesis users. MYO-Myoelectric prosthesis users. S2-Initial training session. S11- Final Training Session. Ret-Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

NASA-TLX

Mental Demand

A main effect was revealed for Session ($F(2,73) = 58.111$, $p < 0.001$, $\eta p^2 = 0.611$). The post-hoc analysis revealed that after the initial training session, prosthesis users experienced an attenuation in perceived mental demand during the final training session ($p < 0.001$, $d = 1.887$) and the retention session ($p < 0.001$, $d = 1.965$).

Physical Demand

A main effect was revealed for Session ($F(4, 72) = 113.659$, $p < 0.001$, $\eta p^2 = 0.758$). The Session main effect was superseded by a Prosthesis x Session x Grip Type interaction ($F(2, 70) = 6.716$, $p = 0.002$, $\eta p^2 = 0.160$). The post-hoc analysis revealed that during the initial session when completing the power grip tasks, the BP users perceived significantly greater physical demand when compared to the MYO users ($p < 0.001$, $d = 2.438$). During the initial session, the MYO group perceived greater physical demand when completing the precision grip tasks when compared to the power grip tasks ($p < 0.001$, $d = 1.343$). The post-hoc analysis revealed that when completing the power grip tasks, the BP group perceived less physical demand during the final training ($p < 0.001$, $d = 5.351$) and retention ($p < 0.001$, $d = 5.478$) sessions when compared to the initial training session. When completing the power grip tasks, the MYO group also perceived less physical demand during the final training ($p < 0.001$, $d = 1.315$) and retention ($p < 0.001$, $d = 1.704$) sessions when compared to the initial training session. The post-hoc analysis revealed that when completing the precision grip tasks, the BP group perceived less physical demand during the final training ($p < 0.001$, $d = 3.554$) and retention ($p < 0.001$, $d = 2.538$) sessions when compared to the initial training session. When completing the precision grip tasks, the MYO group also perceived less physical demand during the final training ($p < 0.001$, $d = 2.046$) and retention ($p < 0.001$, $d = 2.608$) sessions when compared to the initial training session.

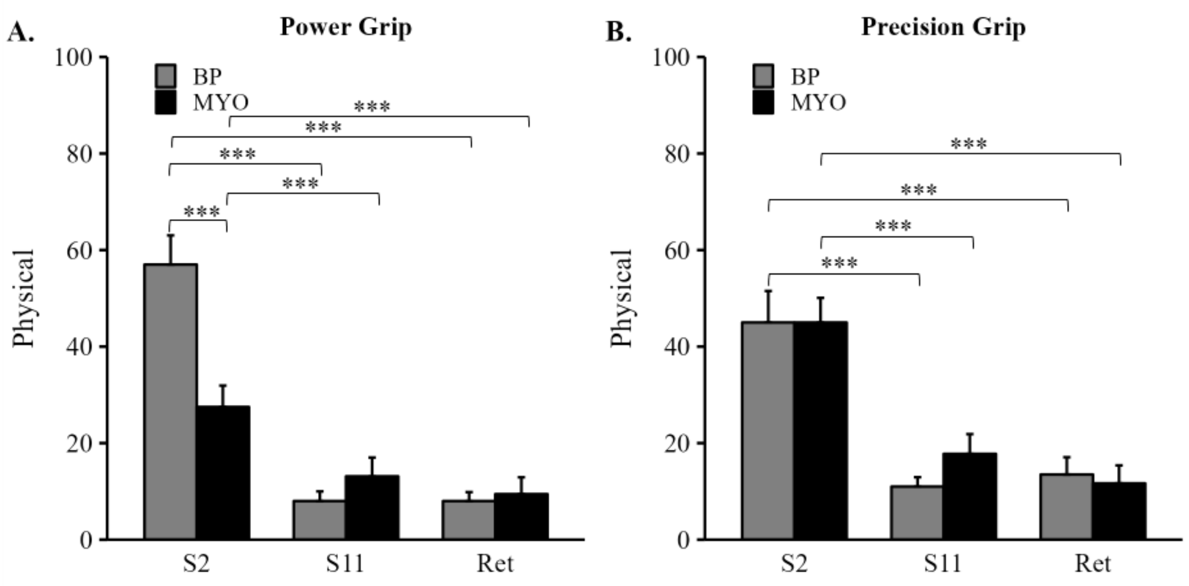


Fig. 7. **A.** NASA-TLX physical dimension scores for the power grip across sessions. **B.** NASA-TLX physical dimension scores across sessions for the precision grip. BP- Body-powered prosthesis. MYO-Myoelectric prosthesis. S2-Initial training session. S11- Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Temporal Demand

A main effect was revealed for Session ($F(4, 611) = 17.179$, $p < 0.001$, $\eta p^2 = 0.558$). The post-hoc analysis revealed that when compared to the initial training session, the prosthesis users experienced an attenuation in perceived temporal demand during the final training ($p < 0.001$, $d = 1.509$) and retention ($p < 0.001$, $d = 1.352$) sessions.

Effort

A main effect was revealed for Session ($F(2, 77) = 62.72$, $p < 0.001$, $\eta p^2 = 0.621$). The post-hoc analyses revealed that after the initial training session, prosthesis users experienced an attenuation in perceived effort during the final training session ($p < 0.001$, $d = 1.776$) and the retention session ($p < 0.001$, $d = 2.035$).

Performance

Main effects were revealed for Prosthesis ($F(1,16) = 7.8960$, p – 0.014, $\eta p^2 = 0.336$), Session ($F(2, 74) = 35.044$, $p < 0.001$, $\eta p^2 = 0.488$), and Grip Type ($F(1, 74) = 15.196$, $p < 0.001$, $\eta p^2 = 0.171$). The Prosthesis and Session main effects were superseded by a Prosthesis x Session interaction ($F(1, 74) = 4.430$, $p = 0.015$, $\eta p^2 = 0.11$). During the initial training session, the MYO users perceived poorer performance when compared to the BP users ($p < 0.001$, $d = 1.299$). When compared to the initial session, the BP users perceived better performance during the final training ($p = 0.002$, $d = 1.000$) and retention ($p = 0.001$, $d = 1.066$) sessions. When compared to the initial session, the MYO users perceived better performance during the final training ($p < 0.001$, $d = 1.819$) and retention ($p < 0.001$, $d = 1.705$) sessions. The Prosthesis and Grip Type main effects were superseded by a Prosthesis x Grip Type interaction ($F(1,74) = 6.285$, $p = 0.14$, $\eta p^2 = 0.078$). The post-hoc analysis revealed for the precision grip objects, the BP users perceived better performance when compared to the MYO users ($p < 0.001$, $d = 1.063$). Additionally, the MYO users perceived poorer performance during the precision grip tasks when compared to the power grip tasks ($p < 0.001$, $d = 0.706$).

Frustration

A main effect was revealed for Session ($F(2, 74) = 44.100$, $p < 0.001$, $\eta p^2 = 0.543$). The post-hoc analysis revealed that after the initial training session, prosthesis users experienced an attenuation in perceived frustration during the final training session ($p < 0.001$, $d = 1.541$) and the retention session ($p < 0.001$, $d = 1.746$). A main effect was revealed for Grip Type ($F(1, 74) = 8.226$, $p = 0.005$, $\eta p^2 = 0.101$). The post hoc analysis revealed that the prosthesis users perceived more frustration during the precision grip tasks when compared to the power grip tasks ($p = 0.005$, $d = 0.362$).

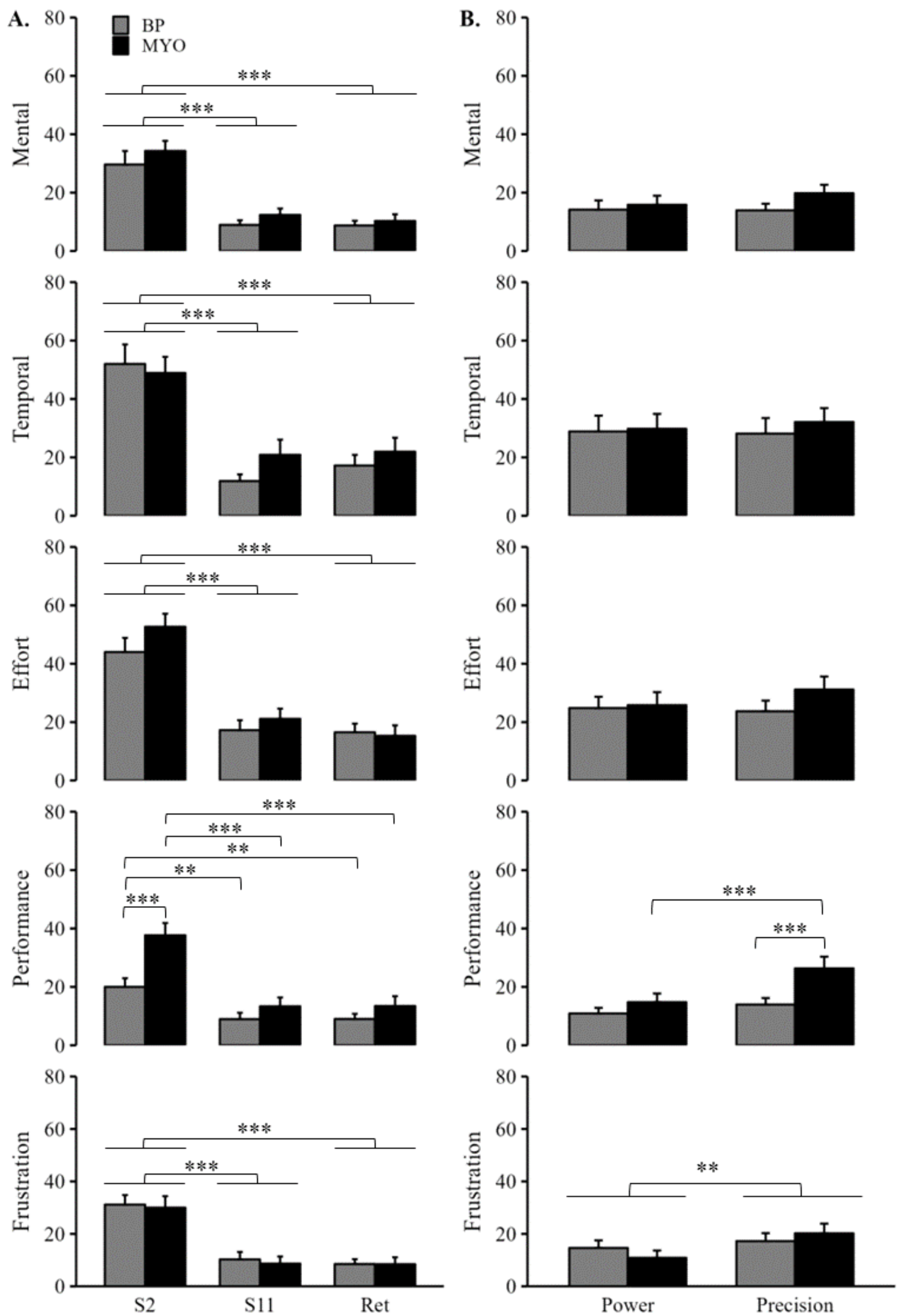

A.
B.
BP
MYO
Mental
Temporal
Effort
Performance
Frustration
S2
S11
Ret
Power
Precision
***
**

Fig. 8. A. NASA-TLX dimensions(see Fig. 6 for physical demand) across sessions. **B.** NASA-TLX dimensions (see Fig.7 for the physical demand dimension) between grip types. BP- Body-powered prosthesis users. MYO-Myoelectric prosthesis users. S2-Initial training session. S11- Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

EEG

Theta

Main effects were revealed for Session ($F(2, 887) = 4.521$, $p = 0.011$, $\eta p^2 = 0.010$) and Grip Type($F(1, 866) = 22.052$, $p < 0.001$, $\eta p^2 = 0.024$).

A Prosthesis x Session x Grip Type interaction was detected ($F(1, 866) = 3.809$, $p = 0.023$, $\eta p^2 = 0.009$). The post-hoc analysis revealed that during the retention session, BP group experienced less theta power when manipulating the power grip objects when compared to the precision grip objects ($p = 0.016$, $d = 0.246$). During the final training session, the MYO group experienced less theta power when manipulating the power grip objects when compared to the precision grip objects ($p < 0.001$, $d = 0.500$). The post-hoc analysis revealed that when competing the power grip tasks during the final training session, the BP users produced greater theta power ($p = 0.035$, $d = 0.731$) when compared to the MYO group. When compared to the initial session, the MYO users experienced lower theta power during the final training ($p < 0.001$, $d = 0.414$) and retention ($p = 0.007$, $d = 0.323$) sessions when completing the power grip tasks.

A Prosthesis x Region x Hemisphere interaction was detected ($F(4, 866) = 5.780$, $p < 0.001$, $\eta p^2 = 0.025$). The post-hoc analysis revealed that BP users produced higher theta power in the left temporal region when compared to the MYO users ($p = 0.050$, $d = 0.695$).

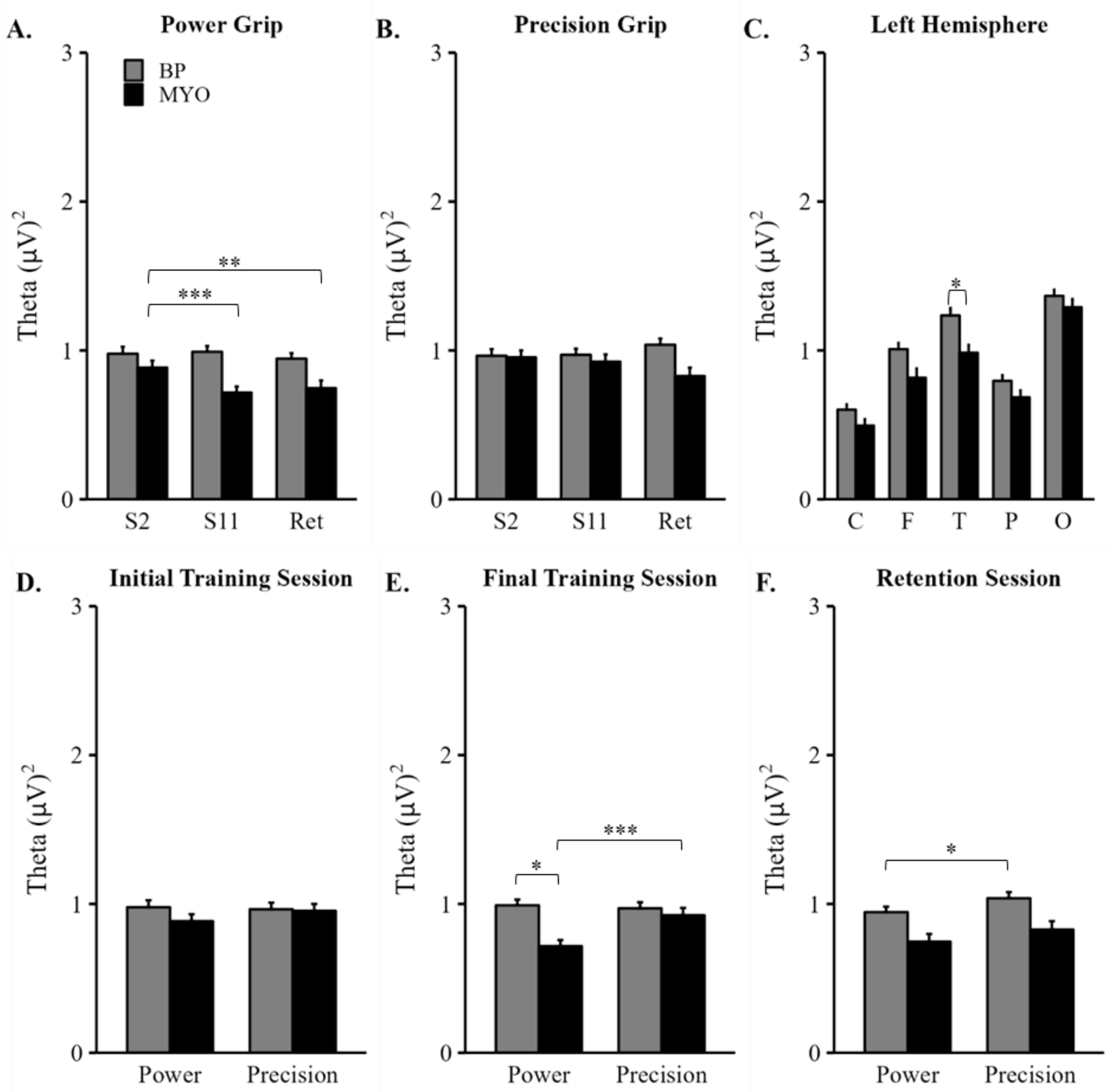


Fig. 9. A. Theta power across sessions for the power grip. **B.** Theta power across sessions for the precision grip. **C.** Theta power in the left hemisphere for all cortical regions. **D.** Theta power for each grip type for the initial session. **E.** Theta power for each grip type for the final session. **F.** Theta power for each grip type for the retention session. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. S2-Initial training session. S11- Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Low-Alpha Power

A main effect was revealed for Session ($F(1, 902) = 5.158$, $p = 0.006$, $\eta p^2 = 0.013$). The Session main effect was superseded by a Session x Region x Hemisphere x Grip Type interaction ($F(8, 901) = 2.599$, $p = 0.008$, $\eta p^2 = 0.026$). The post-hoc analysis revealed that when completing the power grip task during the final training session, the prosthesis users produced attenuated low- alpha power in the right occipital region ($p < 0.001$, $d = 1.335$) when compared to the initial session. When completing the precision grip task, the prosthesis users produced attenuated low-alpha power in the right temporal region during the final training session when compared to the initial session ($p = 0.020$, $d = 0.309$).

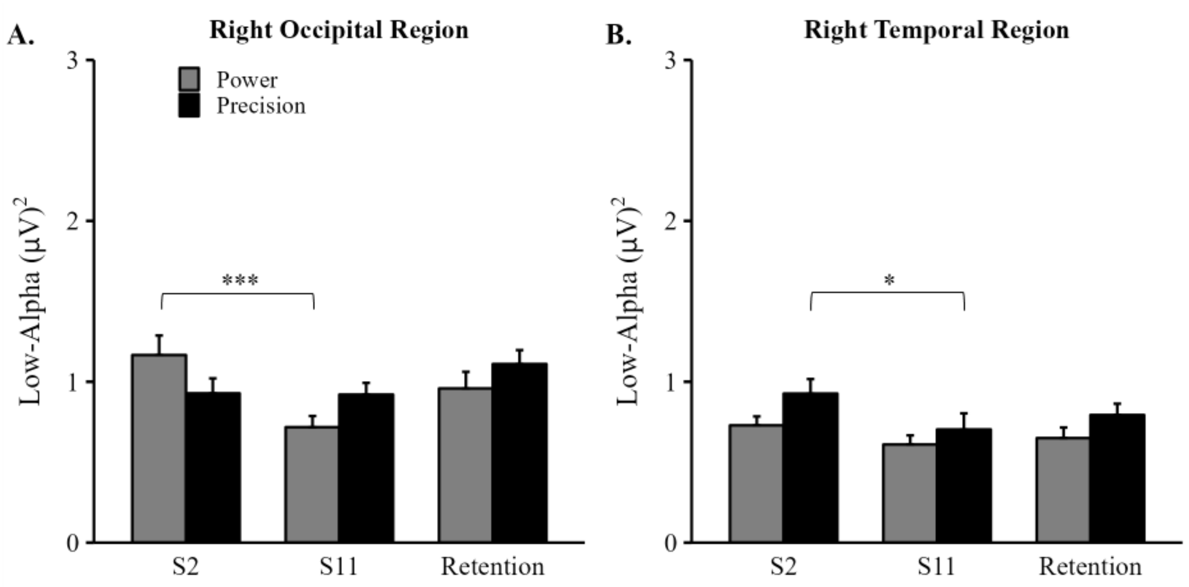


Fig. 10. A. Low-alpha power across sessions for each grip in the right occipital region. **B.** Low-alpha power across sessions for each grip in the right temporal region. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. S2-Initial training session. S11- Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Initial Training Session

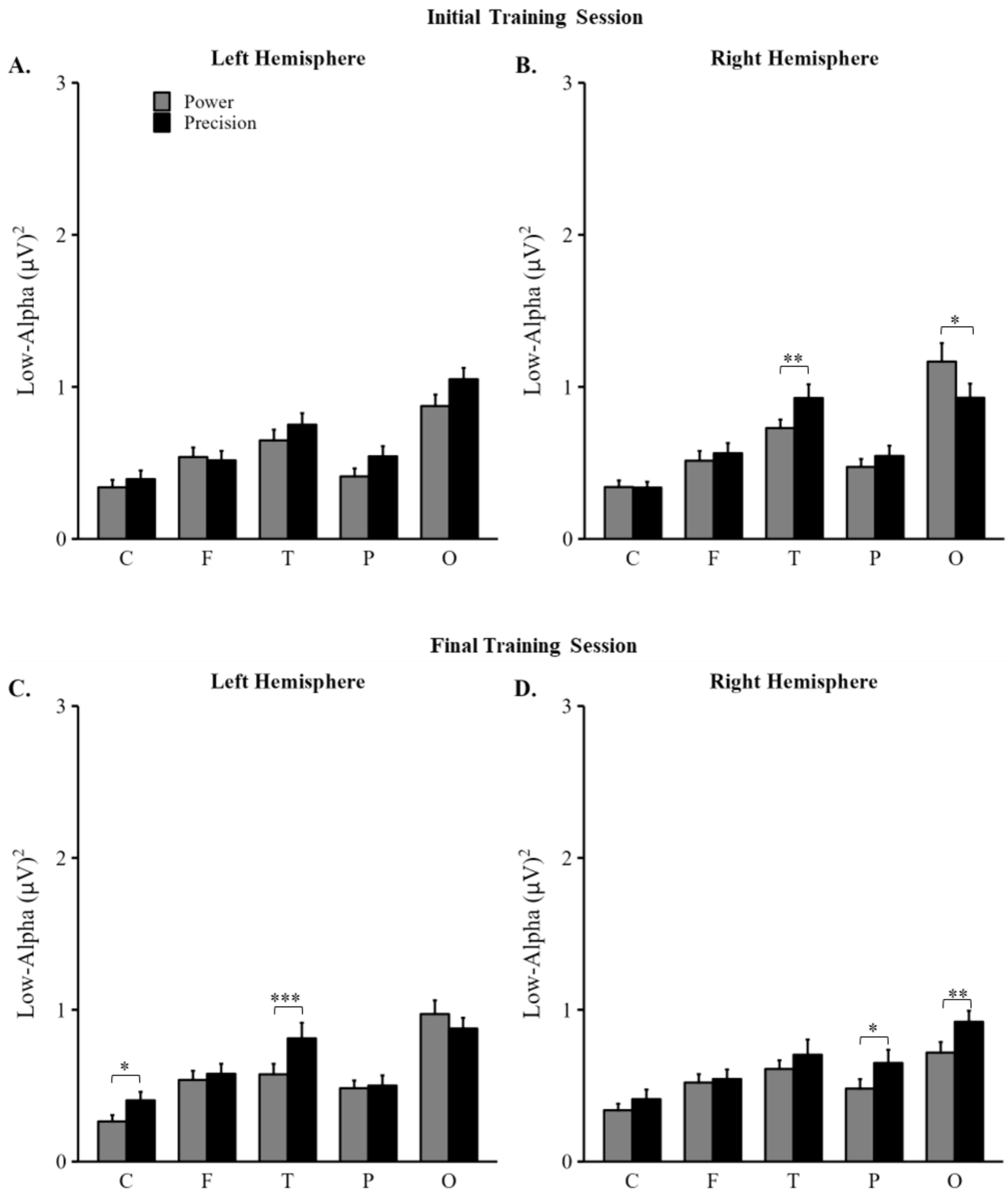
The post-hoc analysis revealed that when the prosthesis users manipulated the precision grip objects when compared to the power grip objects, they experienced greater low-alpha power in the right temporal ($p = 0.004$, $d = 0.622$) and attenuated low-alpha power in the right occipital region ($p = 0.013$, $d = 0.639$).

Final Training Session

The post-hoc analysis revealed that when the prosthesis users manipulated the precision grip objects when compared to the power grip objects, they experienced greater low-alpha power in the right temporal ($p = 0.002$, $d = 0.295$), parietal ($p = 0.011$, $d = 0.513$), occipital ($p = 0.003$, $d = 0.693$) regions and the left temporal ($p < 0.001$, $d = 0.732$) and central ($p = 0.032$, $d = 0.647$) regions.

Retention Session

The post-hoc analysis revealed that when the prosthesis users manipulated the precision grip objects when compared to the power grip objects, they experienced greater low-alpha power in the left occipital region ($p = 0.012$, $d = 0.993$) and left parietal ($p = 0.047$, $d = 0.453$) regions. When the prosthesis users manipulated the precision grip objects when compared to the power grip objects, they experienced greater low-alpha power in the right frontal ($p = 0.045$, $d = 0.520$) and parietal ($p = 0.032$, $d = 0.524$) regions.


Initial Training Session
A.
Left Hemisphere
Power
Precision
Low-Alpha (μV)²
0
1
2
3
C
F
T
P
O
B.
Right Hemisphere
Low-Alpha (μV)²
**
*
Final Training Session
C.
Left Hemisphere
Low-Alpha (μV)²
*
***
D.
Right Hemisphere
Low-Alpha (μV)²
*
**

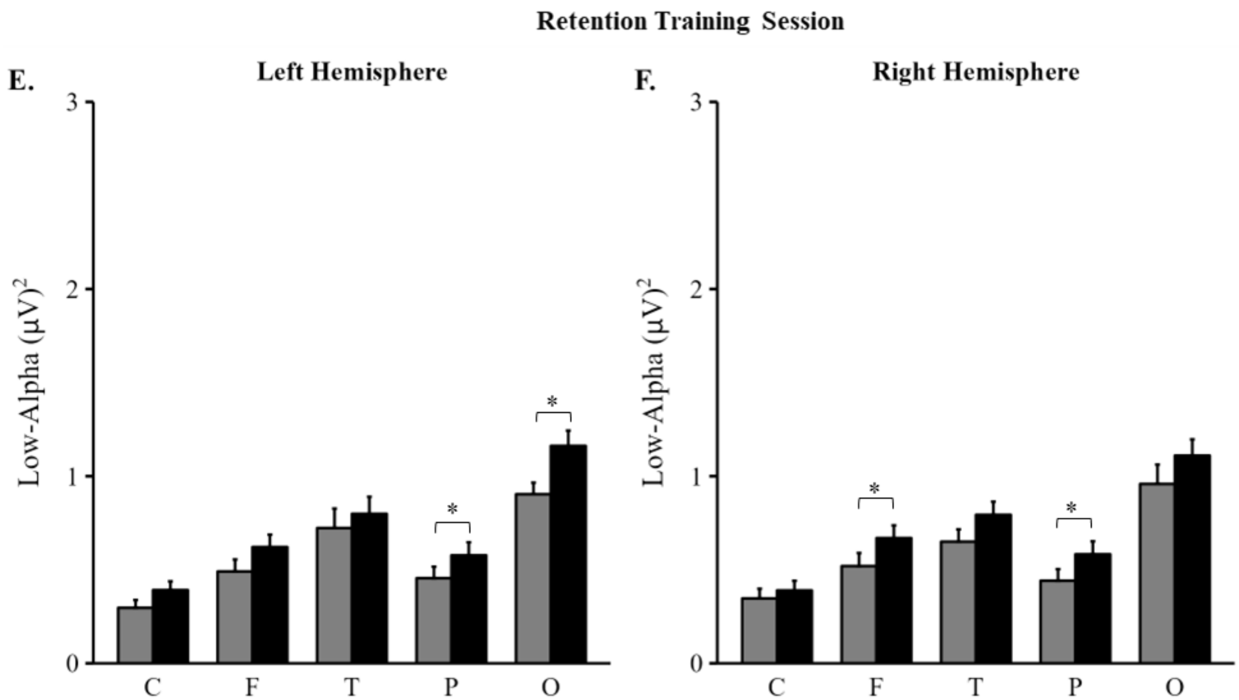


Fig. 11. A. Low-alpha power for each grip type across regions in the left hemisphere during the initial training session. **B.** Low-alpha power for each grip type across regions in the right hemisphere during the initial training session. **C.** Low-alpha power for each grip type across regions in the left hemisphere during the final training session. **D.** Low-alpha power for each grip type across regions in the right hemisphere during the final training session. **E.** Low-alpha power for each grip type across regions in the left hemisphere during the retention training session. **F.** Low-alpha power for each grip type across regions in the right hemisphere during the retention training session. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. S2-Initial training session. S11-Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

A Prosthesis x Grip Type interaction was revealed ($F(1, 901) = 24.502$, $p < 0.001$, $\eta p^2 = 0.0265$). The post-hoc analysis revealed that the BP group produced greater low-alpha power when compared to the MYO grip during the power grip tasks ($p = 0.046$, $d = 0.583$). The MYO group produced greater low-alpha power during the precision grip tasks when compared to the power grip tasks ($p = 0.001$, $d = 0.494$).

A Prosthesis x Region x Hemisphere interaction was revealed ($F(4, 901) = 10.574$, $p < 0.001$, $\eta p^2 = 0.048$). The post-hoc analysis revealed that that the BP users produced greater low-alpha power over the left temporal region ($p = 0.003$, $d = 1.067$) and right occipital region ($p = 0.011$, $d = 0.727$) when compared to the MYO users.

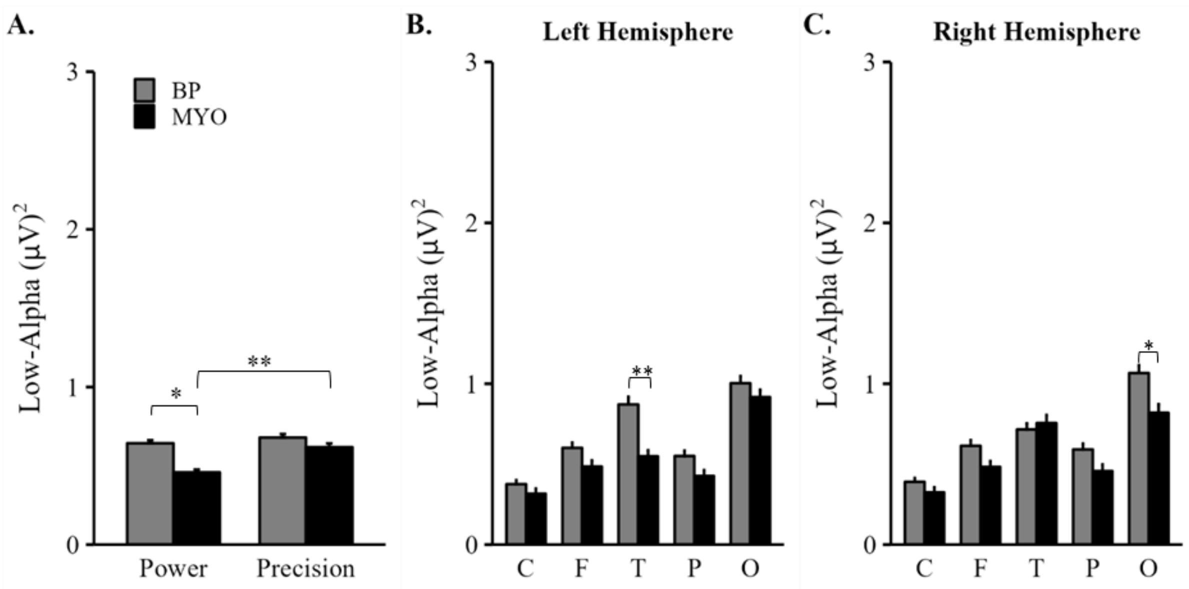


Fig. 12. A. Low-alpha power for each grip type. **B.** Low-alpha power across regions in the left hemisphere during the initial training session. **C.** Low-alpha power across regions in the right hemisphere during the initial training session. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. S2-Initial training session. S11-Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

High-Alpha Power

Main effects were revealed for Session ($F(2, 909) = 5.542$, 0.004, $\eta p^2 = 0.012$) and Grip Type ($F(1, 908) = 5.542$, $p = 0.004$, $\eta p^2 = 0.011$).

The Session main effect was superseded by a Prosthesis x Session interaction ($F(2, 909) = 7.682$, $p < 0.001$, $\eta p^2 = 0.017$). The post-hoc analysis revealed that the BP users experienced lower high-alpha power in the retention session when compared to the MYO users ($p = 0.033$, $d = 0.495$). When compared to the initial session, the MYO group experienced an attenuation in high-alpha power during the final training session (p = 0.020, d = 0.223) and retention (p < 0.001, d = 0.247) while the BP group experienced an elevation of high-alpha power (p = 0.006, d = 0.172) during the retention session when compared to the initial session.

The Session main effect was also superseded by a Session x Region x Hemisphere interaction ($F(8, 908) = 2.576$, $p = 0.009$, $\eta p^2 = 0.022$). The prosthesis users experienced an attenuation in high-alpha power in the right occipital (p < 0.001, d = 0.893) and right temporal (p = 0.001, d = 0.533) regions during the final training session when compared to the initial training session. The prosthesis users experienced an attenuation of high-alpha power in the right temporal region (p = 0.001, d = 0.612) in the retention session when compared to the initial training session.

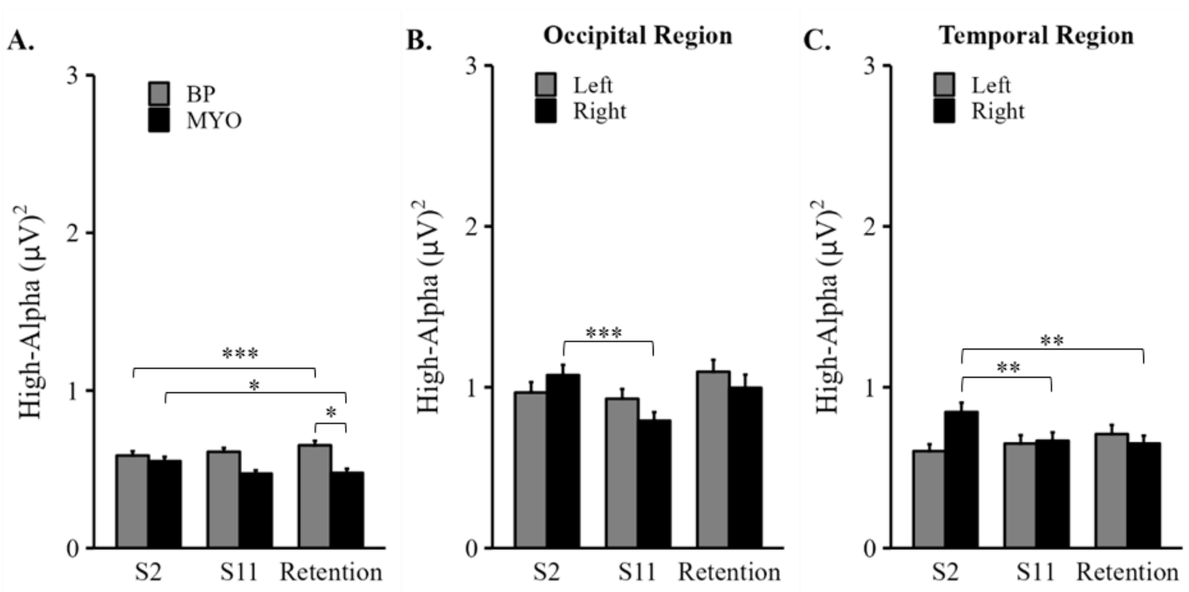


Fig. 13. A. High-alpha power across sessions. **B.** High-alpha power across sessions for the occipital region in each hemisphere. **C.** High-alpha power across sessions for the temporal region in each hemisphere. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. S2-Initial training session. S11- Final Training Session. Ret-Retention session. * p < 0.05, ** p < 0.01, *** p < 0.001.

A Prosthesis x Region x Hemisphere interaction was revealed ($F(4, 908) = 6.272$, $p < 0.001$, $\eta p^2 = 0.027$). The post-hoc analysis revealed that the MYO users experienced lower high-alpha power in the left temporal ($p = 0.008$, $d = 0.829$) and the right occipital ($p < 0.001$, $d = 0.924$) regions when compared to the BP users.

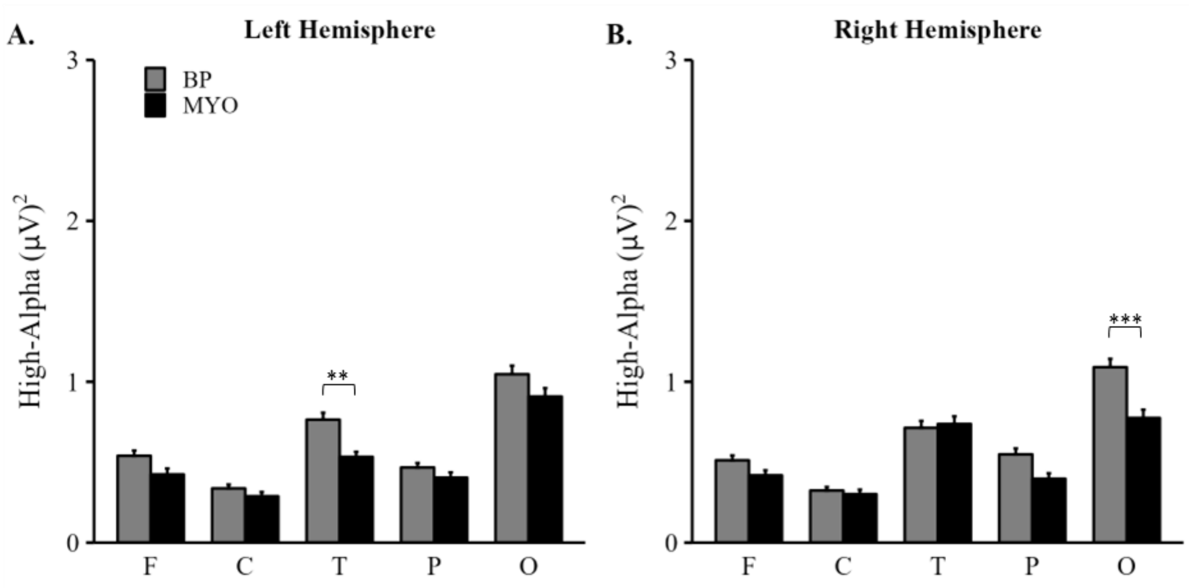


Fig. 14. A. High-alpha power across regions in the left hemisphere. **B.** High-alpha power across sessions in the right hemisphere. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. S2-Initial training session. S11- Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

A Prosthesis x Region x Grip Type interaction was revealed ($F(4, 908) = 3.193$, 0.012, $\eta p^2 = 0.014$). The post-hoc analysis revealed that the BP users experienced greater high-alpha power in the occipital region when manipulating the power grip objects when compared to the precision grip objects ($p < 0.001$, $d = 0.480$). On the contrary, the MYO users experienced greater high-alpha power when manipulating the precision grip objects when compared to the power grip objects in the occipital ($p = 0.005$, $d = 0.747$), central ($p = 0.041$, $d = 0.458$), and temporal ($p < 0.001$, $d = 0.609$) regions. For the power grip tasks, the BP users produced greater high-alpha power in the occipital ($p < 0.001$, $d = 1.272$) and temporal ($p = 0.042$, $d = 0.636$) regions when compared to the MYO users.

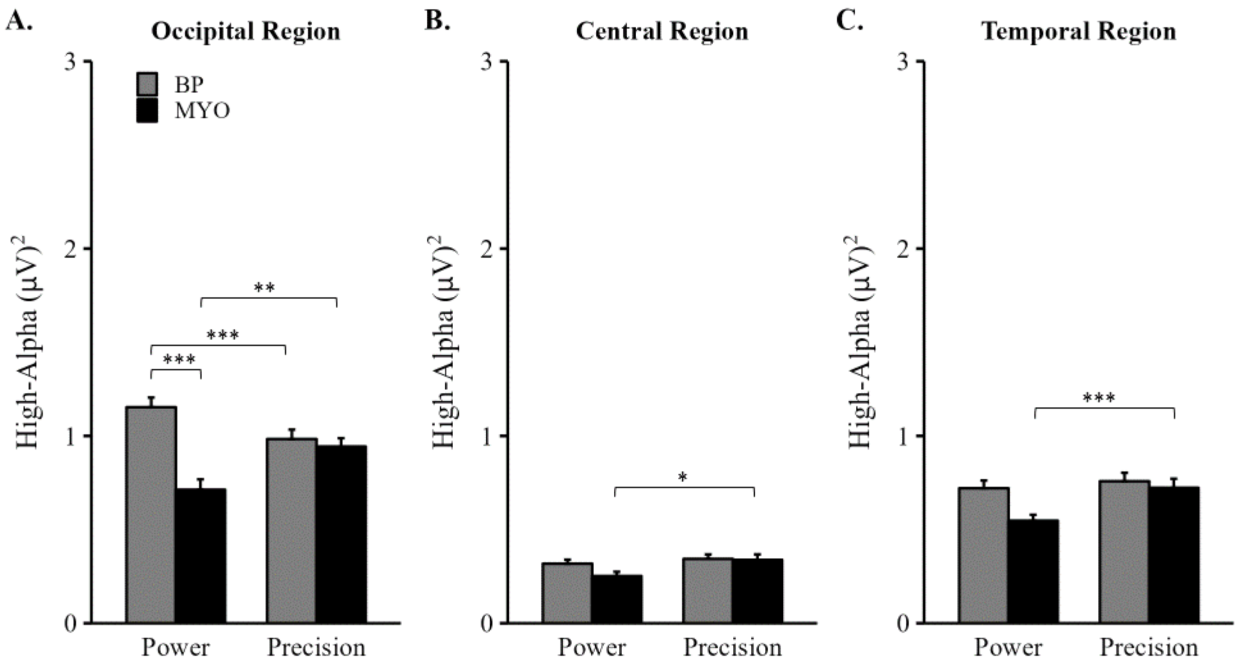


Fig. 15. A. High-alpha power across grips in the occipital region. **B.** High-alpha power across grips in the central region. **C.** High-alpha power across grips in the temporal region. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. S2-Initial training session. S11- Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Beta

A main effect was revealed for Session ($F(2, 900) = 15.685$, $p < 0.001$, $\eta p^2 = 0.012$). This main effect was superseded by a Session x Hemisphere interaction ($F(2, 900) = 4.123$, $p = 0.016$, $\eta p^2 = 0.008$).The post-hoc analysis revealed that in the left hemisphere, higher beta was produced by the prosthesis users during the initial session when compared to the final training session ($p = 0.024$, $d = 0.112$). In the right hemisphere higher beta was produced by the prosthesis users during the initial training session when compared to the final training session ($p < 0.001$, $d = 0.248$) and the retention session($p < 0.001$, $d = 0.206$).

The Session main effect was also superseded by a Prosthesis x Session interaction ($F(2, 901) = 4.125$, $p = 0.016$, $\eta p^2 = 0.023$). The post-hoc analysis revealed that when compared to the initial session, the MYO users experienced an attenuation of beta power during the final training session ($p < 0.001$, d =

0.267) and retention session ($p < 0.001$, $d = 0.308$). When compared to the initial session, the BP users experienced an attenuation of beta power during the final training session ($p = 0.003$, $d = 0.129$).

The Session main effect was also superseded by a Session x Region x Grip Type interaction ($F(8, 900) = 2.374$, $p = 0.016$, $\eta p^2 = 0.019$). The post-hoc analysis revealed that during the initial session, greater beta power was produced during the precision grip tasks when compared to the power grip tasks in the temporal ($p = 0.028$, $d = 0.342$), occipital ($p = 0.008$, $d = 0.505$) and frontal regions ($p = 0.020$, $d = 0.508$). During the final training session, greater beta power was detected during the precision grip task in the temporal ($p = 0.004$, $d = 0.433$) and central ($p = 0.028$ $d = 0.491$) regions when compared to the power grip task. No differences in beta power between grip types were noted during the retention session.

The post-hoc analysis revealed that when compared to the initial session, during the final training session, the prosthesis users experienced an attenuation in beta power when transporting the power grip objects in the central ($p = 0.045$, $d = 0.538$), occipital ($p < 0.001$, $d = 0.892$) and temporal ($p = 0.006$, $d = 0554$) regions. When compared to the initial session, during the final training session, the prosthesis users experienced an attenuation in beta power when transporting the precision grip objects in the occipital ($p = 0.0140$, $d = 0.662$) and temporal ($p = 0.027$, $d = 0.412$) regions. When compared to the initial session, during the retention session, the prosthesis users experienced an attenuation in beta power when transporting the precision grip objects in the temporal region ($p < 0.001$, $d = 0.703$). When compared to the initial session, during the retention session, the prosthesis users experienced an attenuation in beta power when transporting the power grip objects in the occipital region ($p = 0.049$, $d = 0.480$).

A significant Prosthesis x Grip Type interaction was detected ($F(1, 900) = 35.980$, $p < 0.001$, $\eta p^2 = 0.041$). When compared to the power grip objects, the MYO group produced higher beta power when completing the precision task ($p < 0.001$, $d = 0.258$). For the BP users, higher beta power was produced for the power grip tasks when compared to the precision grip tasks ($p < 0.001$, $d = 0.165$).

A significant Prosthesis x Region x Hemisphere interaction was revealed (F(4, 900) = 10.381, $p < 0.001$, $\eta p^2 = 0.041$). The post-hoc analysis revealed that the MYO group experienced higher beta power in the right temporal region when compared to the BP users (p = 0.045, d = 0.518).

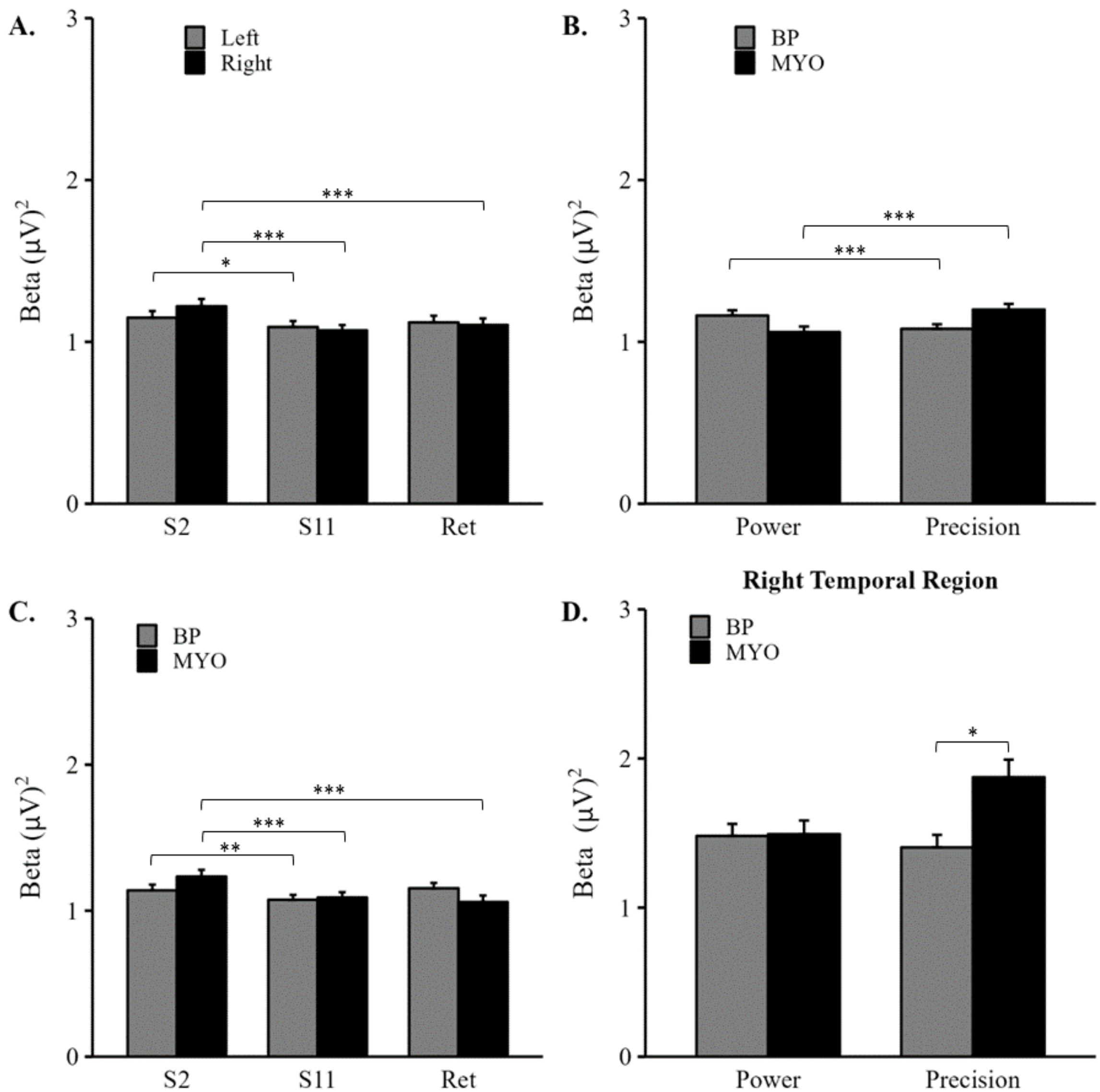


Fig. 16. A. Beta power in each hemisphere across sessions. **B.** Beta power for each grip. **C.** Beta power across sessions. **D.** Beta power for each grip type in the right temporal region. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. S2-Initial training session. S11- Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

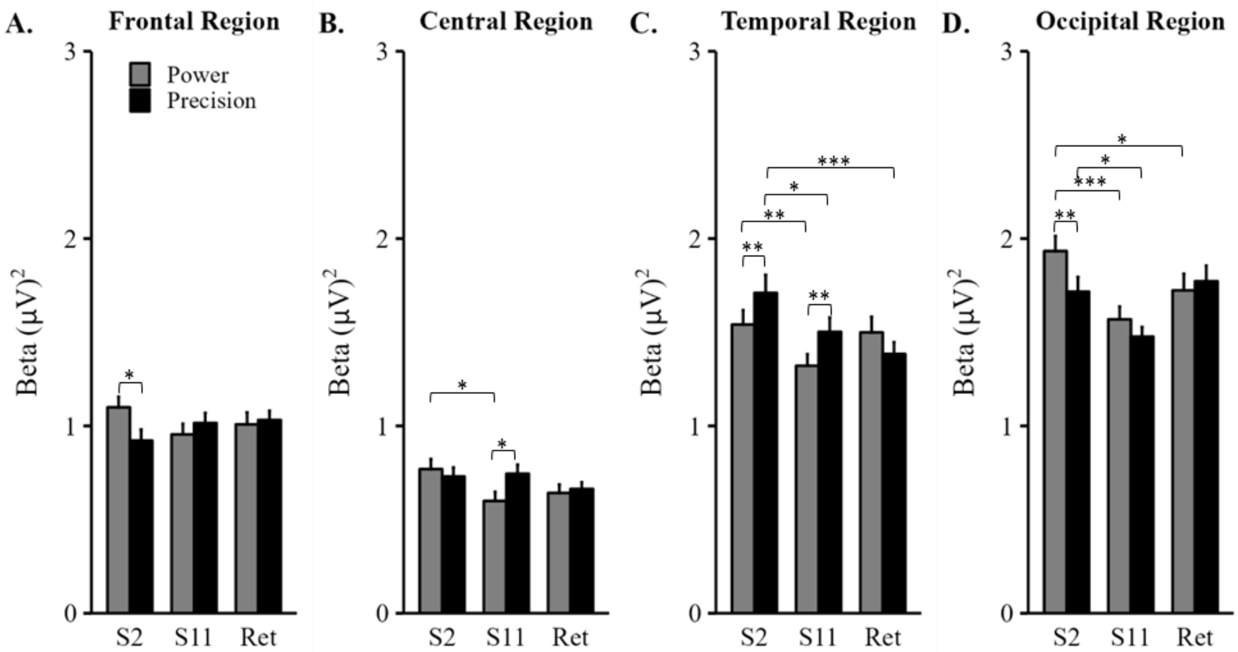


Fig. 17. A. Beta power for each grip type in the frontal region across sessions. **B.** Beta power for each grip type in the central region across sessions. **C.** Beta power for each grip type in the temporal region across sessions. **D.** Beta power for each grip type in the occipital region. BP- Body-powered prosthesis users. MYO- Myoelectric prosthesis users. S2-Initial training session. S11- Final Training Session. Ret- Retention session. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Discussion

This work extends past efforts in upper limb prosthetic performance research (Bloomer et al., 2018, 2020; Bouwsema et al., 2008, 2014; Huinink et al., 2016; H. E. Williams et al., 2021), by systematically manipulating prehensile demands to examine differences in prosthetic performance and mental workload between BP and MYO users when grasping power grip objects or precision grip objects.

General Prosthetic Practice and Learning Effects on Mental Workload and Performance

In line with our predictions, both prosthetic groups transported the power and precision grip objects significantly faster with concurrent improvements in movement quality (increased movement smoothness) by the end of training. Permanent refinements in grip skill acquisition, collectively indexed by improvements in performance and movement smoothness improvements were observed during the retention session thus indicating a learning effect (Fig.6). These results are in alignment with past upper limb prosthesis performance literature showing no clear differences in performance advantages between BP and MYO prostheses (Carey et al., 2015a; Resnik et al., 2019). While no differences in grip type performance or kinematics were observed between the prosthetic groups, the incorporation of mental workload assessment revealed marked differences between prosthetic groups during motor performance. Both groups perceived a significant attenuation of perceived mental workload as a result of training. This reduction in perceived mental workload was sustained during the retention session (Fig.8). The MYO group encountered higher perceived performance demands at the beginning of training when compared to the BP users; however, this discrepancy in perceived performance demands diminished throughout training such that both groups had similar perceptions of performance after completion of the training program. This early discrepancy in perceived performance may reflect early challenges associated with MYO control and interfering co-contractions may have influenced the poorer perception of performance when compared to the BP users (A. Chadwell et al., 2021; Alix Chadwell et al., 2016).

Spectral EEG revealed distinct patterns of cortical activation between the prosthetic groups in response to training. As a result of training, the BP users produced greater whole scalp high-alpha power from the initial to the retention session indicating a reduction in cognitive-motor processing in response to training while the MYO users produced more cognitive-motor processing (attenuated low and high-alpha power), particularly in the left temporal and right occipital regions in response to training (Fig.13). This may suggest that the BP users produced less task-relevant cognitive-motor resources to obtain similar permanent improvements in performance and kinematics to that of the MYO users. For the MYO users, an attenuation of low and high alpha power and beta power during training may imply a progression from a state of inhibition to suppress less unpredictable and unintended prosthetic hand movements at the beginning of training to a release from this inhibitive state, thus allowing for an increased recruitment of the task relevant cognitive-motor resources over time. The stronger cortical activation over the left temporal region experienced by the MYO users may reflect more reliance on declarative knowledge processing that is typically engaged in the early stages of motor learning processing (Hatfield et al., 2004;

Johnny V.V. Parr et al., 2020). However, this interpretation should be met with caution since the MYO users produced less theta power over the left temporal region when compared to BP users during the training program (Fig.9C). Past work has suggested that theta desynchrony may suggest a reduction in working memory resources (Fellner et al., 2016). Additionally, this evidence may support past findings from the literature that suggests that the MYO users required more visual attention to their prosthetic hand due to line of sight occlusion and lack or proprioceptive feedback of these devices (Carey et al., 2015; J. V.V. Parr et al., 2019; J. V. V Parr et al., 2018) While differences (main effects) in beta power were not observed between groups, the MYO group progressively experienced an elevation of sensorimotor processing that persisted during the retention session (Fig.16A). The BP group also experienced an attenuation of beta power during training, but this change did not persist during the retention session (Fig.16A). Collectively, these results may suggest that the BP group produced enhanced cognitive-motor efficiency as indexed by a reduction in cortical engagement improvement in motor performance and movement smoothness. In contrast, the MYO users engaged more cognitive-motor processes to produce similar performance and movement smoothness. Sensorimotor efficiency, marked by a reduction in sensorimotor processing and improvement in performance was not observed for either group. Furthermore, the MYO group deployed increased cognitive-motor and sensorimotor resources as a result of training that persisted during the retention session which may suggest the MYO users may still be in the cognitive stage of motor learning (Fig. 16C). The BP group exhibited signs of cognitive-motor efficiency while increased engagement of sensorimotor resources as a result of training did not persist during the retention training, which may represent beginnings of an emergence from the cognitive stage of learning for the BP group (Fig.16C) (Fitts & Posner, 1967). This confirms and extends previous findings from the first study by presenting evidence that when BP users grasp objects that require various prehensile patterns, they are in learning stage (cognitive-associative stage) in which the human-device sensorimotor map is better encoded into their internal model compared to MYO users who are still early in the learning process (cognitive stage).

Power vs. Precision Grip Tasks

While performance and kinematics were similar between both grips, prosthesis users experienced more frustration during the precision grip tasks when compared to the power grip tasks (Fig.8). Additionally, the MYO group perceived poorer performance during the precision grip tasks when compared to the power grip tasks (Fig.8). The higher levels of frustration during the precision grip tasks were accompanied by an emergence of higher working memory, attentional and error-monitoring processing (greater theta power) for precision grip tasks when compared to power grip tasks for the MYO group during the final training session and the BP group during the retention session (Fig.9E-F). This may suggest that as a result of training, the BP users produced a permanent change in theta power. This change may suggest they required fewer working memory, attentional and error monitoring resources for grasping power grip objects when compared to precision grip objects. In the occipital region, the MYO users experienced greater high-alpha power during the precision grip tasks when compared to the power grip tasks (Fig.15A). For the MYO group, greater high-alpha power over the central and temporal region during the precision grip tasks when compared to power grip tasks was also revealed (Fig.15B-C). While past mental workload has suggested that alpha synchrony along with enhanced or maintained performance indicated improved cognitive-motor efficiency (Gentili et al., 2011; Pruziner et al., 2019; Shaw et al., 2018), a different explanation may be warranted in the present study. As evidenced by the NASA-TLX, both groups perceived more frustration during the precision grip tasks and the MYO group perceived poorer performance during the precision grip tasks when compared to the power grip tasks (Fig.8). Such changes in cortical dynamics observed in the MYO users when manipulating the precision grip objects when compared to the power grip objects may reflect a greater inhibition of non-essential visual, motor processing and working memory resources during the manipulation of the precision grip objects when compared to the power-grip objects. These results are in line with past studies, that have shown more cortical inhibition during precision grip tasks when compared to power grip tasks (Iñaki Iturrate et al., 2018; Tazoe & Perez, 2017). This greater cortical inhibition observed in the present study may reflect increased inhibition of unwanted co-contractions of the agonist-antagonist pair to reduce the chance of unexpected terminal device movements as well as inhibition of competing, non-essential visual information such as bypassing visual occlusions elicited by the myoelectric hand. Specifically, when engaging a pinch or 3-jaw chuck grasp frequently used by the MYO users to grasp smaller diameter objects, , the 4^{th} and 5^{th} digits of the hand were in a closed position and may have inadvertently created a visual barrier to grasping objects. In contrast, the BP users produced a greater engagement of task relevant cognitive-motor processes (attenuation of high-alpha power) during the precision grip tasks when compared to the power grip (Fig.15A). When considering the perception of higher frustration during the precision grip tasks, it is possible that the attenuation of high-alpha power during the precision grip tasks reflects an increased effort to inhibit non-essential cognitive-motor processes to successfully grasp the precision grip objects. These results coincide with both groups deploying less sensorimotor resources during the precision grip tasks when compared to the power grip tasks over the temporal and central regions by the end of training; however, these sensorimotor changes were not permanent, as these changes vanished during the retention session.

Mental Workload Differences Between Prosthetic Groups During Power Grip Tasks

While both groups experienced a reduction in perceived mental workload as a result of training (Fig.8), the BP users perceived greater physical demand when grasping power grip objects at the beginning of training when compared to the MYO users (Fig.7). This early difference in physical demand between prosthetic groups may have been attributed to the BP users learning to modulate the aperture of the hook to utilize the inner rubber grip contacts on the inside of the hook for a more secure grasp. Sustaining a wide aperture to grasp larger diameter objects, may have required stronger and longer muscle contractions that was not required for the MYO users. Additionally, the grip strength of a body-powered voluntary opening terminal device has been evidenced to be much weaker than a myoelectric terminal device (Uellendahl, 2017). However, by the end of training, this difference in perception of physical demand between the prosthetic groups had diminished.

The BP group deployed fewer visual resources (high-alpha synchrony over the occipital region) when compared to the MYO users when completing the power grip tasks (Fig.15A). Specifically, the increase in high-alpha power over the occipital region may reflect decreased visual processing possibly due to fewer prosthesis contact points on the larger diameter power grip objects while the MYO users typically used a composite grip that required visual fixation on all prosthetic digits and the thumb on the object of interest. The BP group also deployed greater theta power during the final training session, which may reflect increased processing of working memory, attentional and error monitoring resources when compared to the MYO users when completing the power grip tasks; however, this change did not persist during the retention session (Fig.9E). The MYO users progressively produced less theta power as a result of training (Fig.9A). Past research has been mixed on the effects of theta in response to practice and learning. Some work suggests an elevation of theta in response to practice reflects enhanced working memory engagement, attentional control and error monitoring (Jaquess et al., 2018). In contrast, some authors suggest a reduction may reflect less top-down control of attention and reflects skill acquisition with diminishing effort (Kao et al., 2013). The latter position may suggest that the reduction in theta power over time in the MYO group may reflect a refinement in the precision of agonist muscle contraction with reduction in co-contraction and resultant decrease in unexpected prosthetic movements. Since the BP users control mechanism was not as complex as the MYO users, the sustained theta power throughout training may reflect a more stable control strategy that required similar attentional resources throughout training for the BP users.

Mental Workload Differences Between Prosthetic Groups During Precision Grip Tasks

The MYO users perceived greater performance demands when compared to the BP users, which may be driven by the perception of poorer performance when grasping the precision grip objects when compared to the BP users (Fig.8). Cortical dynamics between prosthesis users were mostly similar between both groups during the precision grip tasks. Neither group exhibited changes in theta power for the precision grip tasks during training which may reflect consistent levels of attentional, working memory and error-monitoring processing (Fig.9B). This may be due to difficulty refining approaches to grasp the precision grip objects thus an elevation of theta representative of an enhancement of attentional resources did not occur (Jaquess et al., 2018). Additionally, the BP group produced less beta power over the right temporal region when compared to the MYO users which may reflect represent greater engagement of sensorimotor integration required to complete the precision grip tasks for the BP users (Fig.16D). Collectively, this suggests that BP users deployed more resources to meet the precision grip task demands while the MYO users deployed less resources and engaged inhibitory processes to potentially reduce the signal to noise ratio to refine muscle contractions to close the fingers around the precision grip objects without elicit a sustained contraction which may result in more hand closure which may inadvertently reposition the object or drop it the object.

Conclusion, Limitations and Future Directions

Our results revealed that across multiple training sessions, prosthesis users had similar improvements in prehensile performance and movement quality for both grip types. While the EEG results of this study offered complex and many nuanced spectral EEG findings, common themes emerge that suggest different patterns of activation between prosthetic groups. Overall, although spectral EEG may suggest both prosthetic groups were still strongly engaged in motor learning, the BP users exhibited signs of an emergence of cognitive-motor efficiency as revealed by a reduction in cognitive-motor processing while the MYO users further engaged cognitive-motor resources as training progressed. Both groups exhibited increases in sensorimotor processing as a result of training which suggests that sensorimotor efficiency was not present and that both groups were ultimately still learning to engage the necessary sensorimotor resources to meet task demands. These results confirm and extend prior results from the first study while accounting to prehensile differences. The evidence suggests that the BP users may be more advanced (possibly in the cognitive-associative stage) with a better encoding of the human-device sensorimotor map into its internal model relative to the MYO group for which this encoding is likely still in its early form (cognitive stage).

When examining differences between grip types, the evidence revealed that for precision grip tasks, MYO users produced greater high-alpha power during the precision grip tasks, particularly in the temporal, occipital and temporal regions. This result combined with greater frustration for both groups and a poorer perception of performance by the MYO users during precision when compared to power grip tasks, and also poorer performance perception by the MYO users during precision grip tasks when compared to the BP group during precision grip tasks, this elevation in alpha-power may reflect the engagement of an inhibitory process to reduce unwanted muscle co-contraction that may negatively impact performance (A. Chadwell et al., 2021; Alix Chadwell et al., 2016). The MYO users also produced less beta processes particularly in the right temporal region which may reflect a reduction of sensorimotor integration processing and greater inhibition. On the contrary, BP users revealed greater high-alpha power over the occipital region during the power grip tasks when compared to the precision grip tasks. When interpreted in conjunction with both groups experiencing greater frustration during the precision tasks, BP users may have engaged more visual resources due to greater visual demands from the precision compared to the power grip tasks. Additionally, the BP users deployed fewer visual resources when compared to the MYO users during the power grip tasks while maintaining similar kinematic and performance improvements. Collectively, this may suggest that compared to the MYO group, the BP users may have slightly more efficient cognitive-motor processes for power grip tasks. In summary, the different underling cortical activation patterns between prosthesis users and grip types may suggest that MYO users engaged more inhibitory cortical processes and less working memory, attentional and error monitoring processes when manipulating precision grip objects while BP users deployed fewer visual resources to complete the power grip tasks when compared to precision grip tasks and the MYO users.

While this work is informative, there are several limitations. While we accounted for various grip types within the broader power(spherical, cylindrical, extension) and precision(tripod, tip, lateral) grip categories, due to the design of the SHAP assessment, prosthesis users only completed one trial of each grip type per measurement session. Overall, participants repeated each grip subtask only five times throughout the entire training program and retention session. The design of the assessment may have not allowed for enough trials to reveal differences in the acquisition of the power and precision grip skills. Secondly, our measurement periods involved pressing the timer button at the beginning and end of trials. While pressing of the timer button was included consistently across all tasks and participants, this may have introduced increased variability into our measurements since users varied in the force and speed in which they pressed the button. Another potential limitation is that prosthesis users were not explicitly told what grip or terminal device position to use when grasping each object. During training, participants had the opportunity to refine their grip approach for grabbing items of various shapes and sizes and received grip suggestions based upon their performance. Specifically for the MYO users, while there may have been some variation within grip type (e.g., using a pincer grasp to grab the tripod object), using a grip from a different grip type (e.g., using a tip pinch grip to grasp a cylinder) was seldomly observed and was not thought to impact the results of the study. Lastly, MYO users did encounter more prosthesis control malfunctions when compared to the BP users and one participant's data was fully removed from the study. Some of these malfunctions included signal quality issues, delayed motor responses and digit immobilizations. While to some degree technical issues with the myoelectric device was anticipated and we purposely wanted to incorporate the unpredictability of the MYO devices into the study to reflect real world myoelectric problems that are frequently cited (Biddiss & Chau, 2007; Rackerby et al., 2022; Resnik et al., 2019), this limitation must be acknowledged. Lastly, due to recruitment challenges and varying amounts of use and familiarity of BP and MYO reported individuals living with upper limb amputations, we decided to train individuals with intact limbs on how to use a bypass prosthesis in order to capture the novelty of skill acquisition. While bypass prosthesis users have been shown to have similar kinematic patterns as actual prosthesis users (H. E. Williams et al., 2021), it is not clear how if the cortical dynamics observed in this study are truly representative of the cortical dynamics in an upper limb prosthesis user who experienced an amputation.

Despite the study limitations, to the author's knowledge, this study is the first to systematically assess prehensile performance and mental workload between BP and MYO users. This work may inform upper limb device prescriptive decision making, prosthesis rehabilitation program development and prosthetic design. To increase the ecological validity of this study, future directions of this work may include examination of cortical dynamics in prosthesis users with upper limb amputations. Additionally, since some work indicates stronger fronto-parietal communication during precision grip tasks (Inaki Iturrate et al., 2018) when compared to power grip tasks, the examination of corticocortical communication via functional connectivity analysis may reveal more about the interregional communication differences between grip and prosthetic types.

References

Balasubramanian, S., Melendez-Calderon, A., Roby-Brami, A., & Burdet, E. (2015). On the analysis of movement smoothness. *Journal of NeuroEngineering and Rehabilitation*, *12*(1), 1–11. https://doi.org/10.1186/s12984-015-0090-9

Beck, M. M., Spedden, M. E., Dietz, M. J., Karabanov, A. N., Christensen, M. S., & Lundbye-Jensen, J. (2021). Cortical signatures of precision grip force control in children, adolescents, and adults. *ELife*, *10*, 1–22. https://doi.org/10.7554/eLife.61018

Biddiss, E., & Chau, T. (2007). Upper limb prosthesis use and abandonment: A survey of the last 25 years. *Prosthetics and Orthotics International*, *31*(3), 236–257. https://doi.org/10.1080/03093640600994581

Bloomer, C., Wang, S., & Kontson, K. (2020). Kinematic analysis of motor learning in upper limb body-powered bypass prosthesis training. *PLoS ONE*, *15*(1), 1–16. https://doi.org/10.1371/journal.pone.0226563

Bloomer, C., Wang, S., & Kontson, K. L. (2018). Creating a standardized , quantitative training protocol for upper limb bypass prostheses. *Physical Medicine and Rehabilitation Research*.

Boser, Q. A. (2019). *Characterizing the Visuomotor Behaviour of Upper Limb Body-Powered Prosthesis Users*. University of Alberta.

Bouwsema, H., Van Der Sluis, C. K., & Bongers, R. M. (2008). *The Role of Order of Practice in Learning to Handle an Upper-Limb Prosthesis*. https://doi.org/10.1016/j.apmr.2007.12.046

Bouwsema, H., Van Der Sluis, C. K., & Bongers, R. M. (2014). Changes in performance over time while learning to use a myoelectric prosthesis. *Journal of NeuroEngineering and Rehabilitation*. https://doi.org/10.1186/1743-0003-11-16

Brinkman, L., Stolk, A., Dijkerman, H. C., de Lange, F. P., & Toni, I. (2014). Distinct Roles for Alpha- and Beta-Band Oscillations during Mental Simulation of Goal-Directed Actions. *Journal of Neuroscience*, *34*(44), 14783–14792. https://doi.org/10.1523/JNEUROSCI.2039-14.2014

Brinkman, L., Stolk, A., Marshall, T. R., Esterer, S., Sharp, P., Dijkerman, H. C., de Lange, F. P., & Toni,

I. (2016). Independent causal contributions of Alpha- and Beta-band oscillations during movement selection. *Journal of Neuroscience*, *36*(33), 8726–8733. https://doi.org/10.1523/JNEUROSCI.0868-16.2016

Butkus, J., Dennison, C., Orr, A., & Laurent, M. St. (2014). Occupational Therapy with the Military Upper Extremity Amputee: Advances and Research Implications. *Current Physical Medicine and Rehabilitation Reports*, *2*(4), 255–262. https://doi.org/10.1007/s40141-014-0065-y

Carey, S. L., Lura, D. J., & Highsmith, M. J. (2015a). *Differences in myoelectric and body- powered upper-limb prostheses: Systematic literature review*. *52*(3), 247–262.

Carey, S. L., Lura, D. J., & Highsmith, M. J. (2015b). *Differences in myoelectric and body-powered upper-limb prostheses: Systematic literature review*. *52*(3), 247–262. https://doi.org/10.1682/JRRD.2014.08.0192

Chadwell, A., Kenney, L., Thies, S., Head, J., Galpin, A., & Baker, R. (2021). Addressing unpredictability may be the key to improving performance with current clinically prescribed myoelectric prostheses. *Scientific Reports*, *11*(1), 1–15. https://doi.org/10.1038/s41598-021-82764-6

Chadwell, Alix, Kenney, L., Thies, S., Galpin, A., & Head, J. (2016a). The reality of myoelectric prostheses: Understanding what makes these devices difficult for some users to control. *Frontiers in Neurorobotics*, *10*(AUG), 1–21. https://doi.org/10.3389/fnbot.2016.00007

Chadwell, Alix, Kenney, L., Thies, S., Galpin, A., & Head, J. (2016b). The reality of myoelectric prostheses: Understanding what makes these devices difficult for some users to control. *Frontiers in Neurorobotics*, *10*(AUG), 1–21. https://doi.org/10.3389/fnbot.2016.00007

Cook, R. D. (1977). Detection of Influential Observation in Linear Regression. *Technometrics*, *19*(1), 15–18. https://doi.org/10.2307/1268249

Deeny, S., Chicoine, C., Hargrove, L., Parrish, T., & Jayaraman, A. (2014). A Simple ERP Method for Quantitative Analysis of Cognitive Workload in Myoelectric Prosthesis Control and Human-Machine Interaction. *PLoS ONE*, *9*(11), e112091. https://doi.org/10.1371/JOURNAL.PONE.0112091

Ehrsson, H. H., Fagergren, A., Jonsson, T., Westling, G., Johansson, R. S., & Forssberg, H. (2000). Cortical activity in precision- versus power-grip tasks: An fMRI study. *Journal of Neurophysiology*, *83*(1), 528–536. https://doi.org/10.1152/jn.2000.83.1.528

El Hayek, M., Lobo Jofili Lopes, J. L. M., Lelaurin, J. H., Gregory, M. E., Abi Nehme, A. M., McCall-Junkin, P., Au, K. L. K., Okun, M. S., & Salloum, R. G. (2023). Type, Timing, Frequency, and Durability of Outcome of Physical Therapy for Parkinson Disease: A Systematic Review and Meta-Analysis. *JAMA Network Open*, *6*(7), E2324860. https://doi.org/10.1001/jamanetworkopen.2023.24860

Feix, T., Romero, J., Schmiedmayer, H.-B., Dollar, A. M., & Kragic, D. (2016). The GRASP Taxonomy of Human Grasp Types. *IEEE Transactions on Human-Machine Systems*, *46*(1), 66–77. https://doi.org/10.1109/THMS.2015.2470657

Fellner, M., Volberg, G., Hanslmayr, S., Wimber, M., Goldhacker, M., & Mark, W. (2016). *Spatial Mnemonic Encoding : Theta Power Decreases and Medial Temporal Lobe BOLD Increases Co-Occur during the Usage of the Method of Loci*. *3*(December), 1–16.

Fitts, P. M., & Posner, M. I. (1967). Human performance. In *Human performance.* Brooks/Cole.

Geevasinga, N., Menon, P., Kiernan, M. C., & Vucic, S. (2014). Motor cortical function and the precision grip. *Physiological Reports*, *2*(12), 1–10. https://doi.org/10.14814/phy2.12120

Gentili, R. J., Bradberry, T. J., Oh, H., Costanzo, M. E., Kerick, S. E., Contreras-Vidal, J. L., & Hatfield, B. D. (2015). Evolution of cerebral cortico-cortical communication during visuomotor adaptation to a cognitive-motor executive challenge. *Biological Psychology*, *105*, 51–65. https://doi.org/10.1016/j.biopsycho.2014.12.003

Gentili, R. J., Bradberry, T. J., Oh, H., Hatfield, B. D., & Contreras Vidal, J. L. (2011). Cerebral cortical dynamics during visuomotor transformation: Adaptation to a cognitive-motor executive challenge. *Psychophysiology*, *48*(6), 813–824. https://doi.org/10.1111/j.1469-8986.2010.01143.x

Gentili, R. J., Jaquess, K. J., Shuggi, I. M., Shaw, E. P., Oh, H., Lo, L. C., Tan, Y. Y., Domingues, C. A., Blanco, J. A., Rietschel, J. C., Miller, M. W., & Hatfield, B. D. (2018). Combined assessment of attentional reserve and cognitive-motor effort under various levels of challenge with a dry EEG system. *Psychophysiology*, *55*(6), 1–17. https://doi.org/10.1111/psyp.13059

Gentili, R. J., Rietschel, J. C., Jaquess, K. J., Lo, L. C., Prevost, M., Miller, M. W., Mohler, J. M., Oh, H., Tan, Y. Y. ing, & Hatfield, B. D. (2014). Brain biomarkers based assessment of cognitive workload in pilots under various task demands. *Conference Proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference*, *2014*, 5860–5863. https://doi.org/10.1109/EMBC.2014.6944961

Gevins, A, & Smith, M. E. (2003). Neurophysiological measures of cognitive workload during human-computer interaction. *Theoretical Issues in Ergonomic Science*, *4*, 113–131. https://doi.org/10.1080/14639220210159717

Gevins, Alan, Smith, M. E., McEvoy, L., & Yu, D. (1997). High-resolution EEG mapping of cortical activation related to working memory: Effects of task difficulty, type of processing, and practice. *Cerebral Cortex*, *7*(4), 374–385. https://doi.org/10.1093/cercor/7.4.374

Gonzalez, J., Soma, H., Sekine, M., & Yu, W. (2012). Psycho-physiological assessment of a prosthetic hand sensory feedback system based on an auditory display: A preliminary study. *Journal of NeuroEngineering and Rehabilitation*, *9*(1), 1–14. https://doi.org/10.1186/1743-0003-9-33

H. Yan, J., Hinrichs, R., Gregory Payne, V., & Thomas, J. (2000). Normalized Jerk: A Measure to Capture Developmental Characteristics of Young Girls' Overarm Throwing. *Journal of Applied Biomechanics*, *16*, 196–203. https://doi.org/10.1123/jab.16.2.196

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*, *52*, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9

Hatfield, B. D., Haufler, A. J., Hung, T.-M., & Spalding, T. W. (2004a). Electroencephalographic studies of skilled psychomotor performance. LK - https://umaryland.on.worldcat.org/oclc/110223290. *Journal of Clinical Neurophysiology : Official Publication of the American*

Electroencephalographic Society TA - TT -, *21*(3), 144–156.

Hatfield, B. D., Haufler, A. J., Hung, T.-M., & Spalding, T. W. (2004b). Electroencephalographic Studies of Skilled Psychomotor Performance. *Journal of Clinical Neurophysiology*, *21*(3).

Huinink, L. H. B., Bouwsema, H., Plettenburg, D. H., Van Der Sluis, C. K., & Bongers, R. M. (2016). *Learning to use a body-powered prosthesis: changes in functionality and kinematics*. https://doi.org/10.1186/s12984-016-0197-7

Iturrate, Inaki, Chavarriaga, R., Pereira, M., & Zhang, H. (2018). Human EEG reveals distinct neural correlates of power and precision grasping types. *NeuroImage*, *July*. https://doi.org/10.1016/j.neuroimage.2018.07.055

Iturrate, Iñaki, Chavarriaga, R., Pereira, M., Zhang, H., Corbet, T., Leeb, R., & Millán, J. del R. (2018). Human EEG reveals distinct neural correlates of power and precision grasping types. *NeuroImage*, *181*(July), 635–644. https://doi.org/10.1016/j.neuroimage.2018.07.055

Jaquess, K. J., Gentili, R. J., Lo, L. C., Oh, H., Zhang, J., Rietschel, J. C., Miller, M. W., Tan, Y. Y., & Hatfield, B. D. (2017). Empirical evidence for the relationship between cognitive workload and attentional reserve. *International Journal of Psychophysiology*, *121*(February), 46–55. https://doi.org/10.1016/j.ijpsycho.2017.09.007

Jaquess, K. J., Lo, L. C., Oh, H., Lu, C., Ginsberg, A., Tan, Y. Y., Lohse, K. R., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Changes in Mental Workload and Motor Performance Throughout Multiple Practice Sessions Under Various Levels of Task Difficulty. *Neuroscience*, *393*, 305–318. https://doi.org/10.1016/j.neuroscience.2018.09.019

Kao, S. C., Huang, C. J., & Hung, T. M. (2013). Frontal midline theta is a specific indicator of optimal attentional engagement during skilled putting performance. *Journal of Sport and Exercise Psychology*, *35*(5), 470–478. https://doi.org/10.1123/jsep.35.5.470

Landsmeer, J. M. (1962). Power grip and precision handling. *Annals of the Rheumatic Diseases*, *21*, 164–170. https://doi.org/10.1136/ard.21.2.164

Light, C. M., Chappell, P. H., & Kyberd, P. J. (2002). Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity. *Archives of Physical Medicine and Rehabilitation*, *83*(6), 776–783. https://doi.org/10.1053/apmr.2002.32737

Long, C. I. I., Conrad, P. W., Hall, E. A., & Furler, S. L. (1970). Intrinsic-Extrinsic Muscle Control of the Hand in Power Grip and Precision Handling: AN ELECTROMYOGRAPHIC STUDY LK - https://umaryland.on.worldcat.org/oclc/7008000999. *The Journal of Bone & Joint Surgery TA - TT -* , *52*(5), 853–867.

Lu, Y., Bilaloglu, S., Aluru, V., & Raghavan, P. (2015). Quantifying feed forward control: A linear scaling model for fingertip forces and object weight. *Journal of Neurophysiology*, *114*(1), 411–418. https://doi.org/10.1152/jn.00065.2015

Noble, J. W., Eng, J. J., & Boyd, L. A. (2014). Bilateral motor tasks involve more brain regions and higher neural activation than unilateral tasks: An fMRI study. *Experimental Brain Research*, *232*(9), 2785–2795. https://doi.org/10.1007/s00221-014-3963-4

Parr, J. (2018). *Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand*. *50*(4).

Parr, J. V.V., Vine, S. J., Wilson, M. R., Harrison, N. R., & Wood, G. (2019). Visual attention, EEG alpha power and T7-Fz connectivity are implicated in prosthetic hand control and can be optimized through gaze training. *Journal of NeuroEngineering and Rehabilitation*, *16*(1), 1–20. https://doi.org/10.1186/s12984-019-0524-x

Parr, Johnny V.V., Gallicchio, G., Harrison, N. R., Johnen, A. K., & Wood, G. (2020). All talk? Challenging the use of left-temporal EEG alpha oscillations as valid measures of verbal processing and conscious motor control. *Biological Psychology*, *155*(May), 107943. https://doi.org/10.1016/j.biopsycho.2020.107943

Parr, J. V. V, Vine, S. J., Harrison, N. R., & Wood, G. (2018). Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand. *Journal of Motor Behavior*, *50*(4), 416–425. http://10.0.4.56/00222895.2017.1363703

Pruziner, A. L., Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Miller, M. W., Wolf, E. J., Hatfield, B.

D., Dearth, C. L., & Gentili, R. J. (2019). Biomechanical and neurocognitive performance outcomes of walking with transtibial limb loss while challenged by a concurrent task. *Experimental Brain Research*, *237*(2), 477–491. https://doi.org/10.1007/s00221-018-5419-8

Rackerby, R., Lukosch, S., & Munro, D. (2022). Understanding and Measuring the Cognitive Load of Amputees for Rehabilitation and Prosthesis Development. *Archives of Rehabilitation Research and Clinical Translation*, *4*(3), 100216. https://doi.org/10.1016/j.arrct.2022.100216

Resnik, L., Adams, L., Otr, L., Borgia, M., Delikat, J., Otr, L., Disla, R., Ebner, C., Walters, L. S., & Otr, L. (2013). Development and Evaluation of the Activities Measure for Upper Limb Amputees. *Archives of Physical Medicine and Rehabilitation*, *94*(3), 488-494.e4. https://doi.org/10.1016/j.apmr.2012.10.004

Resnik, L., Borgia, M., Cancio, J., Heckman, J., Highsmith, J., Levy, C., Phillips, S., & Webster, J. (2022). Dexterity, activity performance, disability, quality of life, and independence in upper limb Veteran prosthesis users: a normative study. *Disability and Rehabilitation*, *44*(11), 2470–2481. https://doi.org/10.1080/09638288.2020.1829106

Resnik, L., Ekerholm, S., Borgia, M., & Clark, M. A. (2019). A national study of Veterans with major upper limb amputation: Survey methods, participants, and summary findings. *PLoS ONE*, *14*(3), 1–24. https://doi.org/10.1371/journal.pone.0213578

Rietschel, J. C., Miller, M. W., Gentili, R. J., Goodman, R. N., McDonald, C. G., & Hatfield, B. D. (2012). Cerebral-cortical networking and activation increase as a function of cognitive-motor task difficulty. *Biological Psychology*, *90*(2), 127–133. https://doi.org/10.1016/j.biopsycho.2012.02.022

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological Psychology*. https://doi.org/10.1016/j.biopsycho.2018.01.009

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Wolf, E. J., Dearth, C. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2019). *A Comparison of Mental Workload in Individuals with*

Transtibial and Transfemoral Lower Limb Loss during Dual-Task Walking under Varying Demand. 1–13. https://doi.org/10.1017/S1355617719000602

Shim, J., Kim, H., Lee, S., Park, M., & Lee, M. (2011). Comparison of hand power and muscle activation during power grip and pinch grip. *Journal of Physical Therapy Science*, *23*(3), 459–461. https://doi.org/10.1589/jpts.23.459

Shuggi, I. M., Oh, H., Shewokis, P. A., & Gentili, R. J. (2017). Mental workload and motor performance dynamics during practice of reaching movements under various levels of task difficulty. *Neuroscience*. https://doi.org/10.1016/j.neuroscience.2017.07.048

Shuggi, I. M., Oh, H., Wu, H., Ayoub, M. J., Moreno, A., Shaw, E. P., Shewokis, P. A., & Gentili, R. J. (2019). Motor Performance, Mental Workload and Self-Efficacy Dynamics during Learning of Reaching Movements throughout Multiple Practice Sessions. *Neuroscience*, *423*, 232–248. https://doi.org/10.1016/j.neuroscience.2019.07.001

Takasawa, M., Oku, N., Osaki, Y., Kinoshita, H., Imaizumi, M., Yoshikawa, T., Kimura, Y., Kajimoto, K., Sasagaki, M., Kitagawa, K., Hori, M., & Hatazawa, J. (2003). Cerebral and Cerebellar Activation in Power and Precision Grip Movements: An H215O Positron Emission Tomography Study. *Journal of Cerebral Blood Flow and Metabolism*, *23*(11), 1378–1382. https://doi.org/10.1097/01.WCB.0000091258.83091.C2

Tazoe, T., & Perez, M. A. (2017). Cortical and reticular contributions to human precision and power grip. *The Journal of Physiology*, *595*(8), 2715–2730. https://doi.org/10.1113/JP273679

Uellendahl, J. (2017). Myoelectric versus Body-Powered Upper-Limb Prostheses: A Clinical Perspective. *JPO Journal of Prosthetics and Orthotics*, *29*(4S), P25–P29. https://doi.org/10.1097/jpo.0000000000000151

van der Cruijsen, J., Manoochehri, M., Jonker, Z. D., Andrinopoulou, E. R., Frens, M. A., Ribbers, G. M., Schouten, A. C., & Selles, R. W. (2021). Theta but not beta power is positively associated with better explicit motor task learning. *NeuroImage*, *240*(July), 118373. https://doi.org/10.1016/j.neuroimage.2021.118373

Van Ede, F., De Lange, F., Jensen, O., & Maris, E. (2011). Orienting attention to an upcoming tactile event involves a spatially and temporally specific modulation of sensorimotor alpha- and beta-band oscillations. *Journal of Neuroscience*, *31*(6), 2016–2024. https://doi.org/10.1523/JNEUROSCI.5630-10.2011

van Ede, F., & Maris, E. (2013). Somatosensory demands modulate muscular beta oscillations, independent of motor demands. *Journal of Neuroscience*, *33*(26), 10849–10857. https://doi.org/10.1523/JNEUROSCI.5629-12.2013

van Ede, F., Winner, T., & Maris, E. (2015). Touch automatically upregulates motor readiness in humans. *Journal of Neurophysiology*, *114*(6), 3121–3130. https://doi.org/10.1152/jn.00504.2015

Williams, H. E., Chapman, C. S., Pilarski, P. M., Vette, A. H., & Hebert, J. S. (2021). Myoelectric prosthesis users and non-disabled individuals wearing a simulated prosthesis exhibit similar compensatory movement strategies. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 1–15. https://doi.org/10.1186/s12984-021-00855-x

Yu, Z., Guindani, M., Grieco, S. F., Chen, L., Holmes, T. C., & Xu, X. (2022). Beyond t test and ANOVA: applications of mixed-effects models for more rigorous statistical analysis in neuroscience research. *Neuron*, *110*(1), 21–35. https://doi.org/10.1016/j.neuron.2021.10.030

Zaepffel, M., Trachel, R., Kilavik, B. E., & Brochier, T. (2013). Modulations of EEG Beta Power during Planning and Execution of Grasping Movements. *PLoS ONE*, *8*(3). https://doi.org/10.1371/journal.pone.0060060

Chapter 4: Mental Workload and Performance Under Contextual Demands

Abstract

The use of performance outcome measures with insufficient ecological validity to assess motor performance may not reflect the multi-faceted motor demands encountered in activities of daily living and may not challenge the prosthesis user with attentional, working memory and executive functioning demands elicited by real-life scenarios, therefore resulting in poor translation of motor skills to more complex environments. To determine the effects of situational cognitive-motor demands on more ecological valid daily activities, we designed and implemented a novel performance outcome measure, the Household Item Transport Test (HITT) to assess cognitive-motor performance during completion of four activities: meal preparation, beverage preparation, bookshelf organization and medical management. To manipulate situational demands that may be encountered in a real-world scenario, each activity was completed in a non-contextual condition with simplified instructions and a contextual condition that employed instructions designed to elicit executive functioning and working memory demands similar to real-world scenarios. We employed the HITT to assess cognitive-motor performance in 10 body-powered (BP) bypass prosthesis users and 10 myoelectric (MYO) bypass prosthesis users who recently completed a 10-session bypass prosthetic training program and 10 individuals using their intact dominant hand as part of a control group (CTRL). We measured performance, kinematic, perceived mental workload and spectral electroencephalography(EEG), theta (4-7 Hz), low-alpha (8-10 Hz), high-alpha (11-13 Hz), and beta(14-35 Hz) as a cortical index of mental workload. As expected, the inclusion of contextual demands generally resulted in slower activity completion times, reduction in movement smoothness and elevation of perceived mental and physical demands for all groups. However, the EEG findings generally revealed different cortical responses between the CTRL group and the prosthetic groups in response to contextual demands. The CTRL group frequently experienced greater inhibition of cognitive-motor and sensorimotor resources with fewer working memory, attentional and error monitoring resources while the cortical dynamics for the BP and MYO users were more nuanced in response to contextual demands.

Additionally, the CTRL group consistently produced significantly greater cortical activation, movement smoothness and better performance when compared to prosthesis users. To the best of our knowledge, this work is the first to examine the effects of contextual demands on cognitive-motor performance and mental workload in prosthesis users.

Introduction

It is well established that cognitive-motor performance requires efficient recruitment and allocation of underlying cognitive-motor resources to meet task demands. When task demands exceed the resource capacity, performance degrades (Gentili et al., 2018; Shaw et al., 2018; Wickens, 2008). Furthermore, if concurrent cognitive processes compete for the same resource pools (e.g. visual processing, working memory), then a resource conflict occurs which leads to degradation of cognitive-motor performance (Wickens, 2002, 2008, 2015). Mental workload, which can be defined as the amount of cognitive-motor resources required to meet task demands to successfully complete a task can be assessed to inform the underlying resources engaged to obtain a desired level of cognitive-motor performance. It is well understood that mental workload and cognitive-motor performance are inversely related and has been well examined in ergonomics (Fallahi et al., 2016; Garde et al., 2002; A Gevins & Smith, 2003), aviation (Gentili et al., 2014; Jaquess et al., 2017), medical surgery (M. R. Wilson et al., 2011; J. Y. Zhang et al., 2017; Zheng et al., 2010) and rehabilitation (Deeny et al., 2014; Gonzalez et al., 2012; J. Parr et al., 2020; Pruziner et al., 2019; Shaw et al., 2019). Regarding the latter, mental workload assessment for upper limb device use is growing more interest due to the need to understand demands associated with technological integration into rehabilitation devices such as prostheses and powered orthoses (Marchand et al., 2021; Park & Zahabi, 2022; J. Parr et al., 2020; Johnny V.V. Parr et al., 2023; Zahabi et al., 2019; W. Zhang et al., 2017). In this body of work, mental workload is typically assessed in upper limb device users as they perform a performance outcome measure or task that is typically used in rehabilitation such as the Southampton Hand Assessment Procedure (J. V.V. Parr et al., 2019; Johnny V.V. Parr et al., 2023) and the Clothespin Relocation Task (Zahabi et al., 2019; W. Zhang et al., 2017) using assessment tools such as spectral electroencephalography (EEG), self-report measures and eye tracking. Spectral EEG is of particular interest for this study since it has been evidenced that mental workload modulates spectral power within various bands. Specifically, alpha power, which can be split into low-alpha power (8-10Hz) and high-alpha power (11-13Hz) have been shown to reliably index changes in mental workload. An attenuation of low-alpha power has been associated with increased mental workload and is thought to reflect an increase in general arousal while an attenuation of high-alpha power has also been associated with elevations in mental workload and is thought to reflect an increased recruitment of task relevant cognitive-motor resources. Synchronization of theta power(4-7Hz) has been associated with increased recruitment of working memory, error monitoring and attentional resources. Lastly, desynchrony of beta power (14-35 Hz) has been associated with increased sensorimotor processing. Various studies have provided evidence to support the relationship of these spectral biomarkers to mental workload (Gentili et al., 2014, 2015, 2018; Jaquess et al., 2018; Rietschel et al., 2012; Shaw, Rietschel, Hendershot, Pruziner, Miller, Hatfield, et al., 2018). The National Aeronautics Space Administration Task Load Index (NASA-TLX) questionnaire has served as a companion simple to use mental workload tool to neuroimaging techniques such as EEG to capture mental workload (Gentili et al., 2018; Gonzalez et al., 2012; Hart & Staveland, 1988; Shaw et al., 2018). While these assessment tools have been shown to reliably index mental workload in prosthesis users (Marchand et al., 2021; Park & Zahabi, 2022), the failure to systematically manipulate cognitive-motor demands in performance outcome measure may make it more difficult precisely extract the sources of mental workload for in-depth analysis in prosthesis users. While a limited effort has systematically manipulated cognitive demand during assessment of lower and upper limb prosthesis users by manipulation of time pressure (Johnny V.V. Parr et al., 2023), visual discrimination (Pruziner et al., 2019; Shaw et al., 2019) and cognitive demand in a virtual environment (Deeny et al., 2014), these manipulations likely did not reflect attentional and working memory demands elicited in a real-word environment.

Generalization of motor skills is defined as the ability to transfer knowledge and skills learned in one context to another context (Krakauer et al., 2006). The ability of the individual to apply skills learned across varying contexts is a critical component of a rehabilitation program to successfully facilitate the transfer of task performance from a clinical setting to everyday living (Babulal et al., 2017). However, performance outcome measures used in upper limb rehabilitation typically assess motor performance doing fairly rudimentary tasks that are not commonly performed in real world environments (Desrosiers et al., 1994; Feys et al., 2017; Haverkate et al., 2016) therefore, may not reflect the skill required to manipulate objects that are used in everyday life. The assessment of cognitive-motor performance as individuals complete client-centered types of activities such as instrumental activities of daily living (iADLs) or health management activities may better reflect engagement in daily activities that are salient to the individual. iADLs are defined as activities that support daily life within the home and community and health management activities are activities related to developing, managing and maintaining health and wellness routines (Boop et al., 2020). Some performance outcome measures assess performance of iADLs (Davis Sears & Chung, 2010; Light et al., 2002; Resnik, Adams, Borgia, et al., 2013); however, these measures do not capture how varying contexts affect motor performance. The understanding of how context variation affects cognitive-motor performance may better inform cognitive-motor performance in real world scenarios compared to prior established performance outcome measures.

The aim of this study was to determine if the manipulation of contextual demands affected cognitive-motor performance and mental workload. To reach this aim, we designed the Household Item Transport Test (HITT), a novel performance outcome measure, to evaluate the influence of contextual demands on mental workload and cognitive-motor performance. The HITT consisted of four activities: i) Books on a Bookshelf, ii) Beverage Preparation, iii) Meal Preparation and iv) Medication Management. Participants completed each activity under varying levels of contextual demand. Motor performance was assessed using the time require to complete each activity, underlying movement smoothness was measured using normalized jerk and mental workload was assessed ed using the mental and physical dimensions of the NASA-TLX and the spectral EEG biomarkers, the theta, low and high-alpha, and beta bandwidths. We predicted that an increase in contextual demand would result in a decrement in motor performance and movement smoothness as well as an elevation of mental workload as indexed by an increase of perceived physical and mental demands, an attenuation in low-alpha, high-alpha and beta power along with an elevation of theta power. We also predicted that the CTRL group would exhibit better motor performance, increased movement smoothness and decrease in mental workload as indicated by a greater attenuation of perceived physical and mental demands, greater low-alpha, high-alpha and beta power along with attenuated theta power when compared to the BP and MYO groups. Lastly, we predicted that the BP group would exhibit better motor performance, increased movement smoothness and decrease in mental workload as indicated by a greater attenuation of perceived physical and mental demands, greater low-alpha, high-alpha, beta power along with greater attenuated theta power when compared to the MYO group.

Methods

Participants

A convenience sample of 30 right-handed participants (16 males, 15 females) with intact upper limbs between the ages of 19 and 58 (mean = 26.27, SD = 9.35) without any upper limb impairment or neurological conditions and with normal or corrected- to normal vision were selected for the study. 10 participants were selected to be in the CTRL group based upon participant time availability. 20 participants who previously completed a 10-session standardized bypass prosthetic training program (Bloomer et al., 2018) to learn to use a BP (n = 10) or MYO (n = 10) bypass prosthesis participated in this study. On average, prosthesis users had 14.65 days between their training program and participation in this study. All participants were current or former University of Maryland, College Park students or faculty. The sample size was determined based upon a prior upper limb prosthetic training study (J. V.V. Parr et al., 2019). All participants provide their informed consent prior to participating in the study. The Institutional Review Board at the University of Maryland- College Park approved this study.

HITT Design

The HITT is comprised of three functional targets: Object Grasping, Object Placement, and Contextual Demands. The Object Grasping and Object Placement functional targets were included in Part I of the HITT while the Contextual Demand functional target was Part II of the HITT. This study is solely focused on Part II of the HITT (Contextual Demand functional target) and will be discussed in detail.

Six activities were originally selected based upon classification of iADLs and health management activities from the Occupational Therapy Framework 4th Edition (Boop et al., 2020) (Table 1). Two activities were removed. The Household Supplies activity, which required participants to place cylindrical shaped household cleaning supplies into a cupboard was removed due to inconsistency in the weight, diameter, and cleaning spouts of the objects. The Financial Management activity, which was trialed by two BP users, required participants to place coins in a piggy bank was removed due to significant difficulty to use a prosthesis to place the coins in the slot and due to lack of ecological validity since piggy banks are not commonly used for adults. The Beverage Preparation activity was added to the HITT after two BP users completed the study, therefore only eight BP users completed this activity. The rationale for activity selection was to select activities that are used in daily living that require a progression of grips from power to precision grips. It was predicted that precision grips and activities that were loaded on working memory demands would have the most significant negative effect on cognitive-motor performance and mental workload. It is important to note that all activities required some degree of decision making and visual search and discrimination; however, to some degree these demands were more constant across activities in comparison to the sequencing and working memory demands(Table 3). These predictions were critical to the design of the HITT to ensure various levels of motor and contextual difficulty were elicited by the activity demands in order to address the lack of systematic manipulation of cognitive-motor demands in upper limb performance outcome measures.

Table 1. HITT Activity Classification

Activity	**Activity Classification**	**Grip Class**	**Grip Sub-Category**	**Maintained in Final Iteration**
Books on a Bookshelf	iADL-Home Establishment and Management	Power	Extension	Yes
Meal Preparation	iADL- Meal Preparation and Cleanup	Power, Precision	Extension, Tripod	Yes
Beverage Preparation	iADL- Meal Preparation and Cleanup	Power	Cylindrical, Hook	Yes
Financial Management	iADL- Financial Management	Precision	Pinch	No
Household Supplies	iADL-Home Establishment and Management	Power	Cylindrical	No
Medication Management	Health Management-Medication Management	Precision	Pinch	Yes

The Books on a Bookshelf activity consisted of two paperback and two hardback books that were stacked horizontally 8 inches in front of the participant. Participants were instructed to place the books upright on a bookstand on the bottom shelf of a two-compartment bookshelf. The Meal Preparation activity consisted of a plate with wooden like replicas of a fast food meal (cheeseburger with lettuce and tomato, French fries, fish nuggets and a ketchup and mustard packet). Participants were instructed to prepare a fast food order. The Beverage Preparation activity required participants to distribute 16 ounces of water from a plastic water bottle to a measuring cup. The participants were then required to pour water into four paper cups based upon the activity instructions. The Medication Management task consisted of a 7-day color coded pillbox and 3 small pill bottles without caps with equal amounts plastic replicas of medication pills. Based upon instructions the participants emptied the bottles and placed the pills in the specified location in the pillbox (See Table 3 for specific activity instructions and Figure 1 for the activity set-up).

Participants completed each of the final four activities in a contextual and non-contextual condition (Table 2). The activity order and experimental condition order were counterbalanced to reduce the chance of an order effect. Participants sat in a chair with back support with both forearms resting on a table with their arms at a 90-degree angle and their feet flat on the floor. The table height and chair distance were adjusted per participant to ensure comfort and standardization of the arm angle. Participants were required to sit upright and not lean on the back of the chair when completing an activity but were allowed to use the back support to rest between activities.

Table 2. Instructions for each activity.

Activity/Primary Cognitive Demand	**Non-Contextual Instruction**	**Contextual Instruction**
Books on a Bookshelf/ Sequencing	“Place these books on the bookshelf upright with the spine facing you starting from the left to the right. “	“Your significant other wants the books in alphabetical order by the author’s last name starting from the left to the right on the bookshelf. Make sure the books are upright with the spine facing you.”
Beverage Preparation/ Working Memory	“Pour water into the measuring cup as needed. Using the	“You are a barista, and you are working on new recipes. For the

	measuring cup, pour a half-cup of water into each cup. Do not pour all of the water into the measuring cup at once.”	dark roast, pour 1/2 a cup of water, for the mocha latte, pour 1/4 of water, for the vanilla latte, pour 1 cup of water, and for the espresso, pour ¼ a cup of water. For each recipe, pour the exact amount of water into the measuring cup. Do not pour all of the water into the measuring cup at once.”
Meal Preparation/Working Memory	“Make the burger using the hamburger patty, cheese, tomato, lettuce, and buns. Place the fish nuggets, French fries, and condiments on the plate.”	“You work at Junior Box, and you need to prepare the next order for the customer . Please prepare the following order and place it on the plate. Any items you don’t need, place on the table. Here is the order.” *“Let me have a burger with a hamburger patty and lettuce and tomato with no cheese. No ketchup or mustard. I want fries and a 4 fish nugget box.”*
Medication Management/Working Memory	“Place all pills into the pillbox sections according to their matching color.”	“You need to organize your grandmother’s pillbox for her. She takes her Lisinopril daily, her Colace on Fridays and Saturdays after her dinner with the neighbors and her Vitamin E supplements on Mondays, Wednesdays, and Fridays. She takes 1 pill daily for each medication.”

For the preparatory phase of the HITT, the experimenter oriented the participant to the purpose of the HITT and provided a general overview. An automated computer program prompted the participants to initiate the activity through computer speakers at a volume that was able to be clearly heard by the participant. The automated computer program was then played, and the participants practiced pressing a red button on the right side of the table to denote the beginning and end of each activity prior to beginning the HITT. Once the participants felt comfortable completing the preparatory phase, they next engaged in the practice phase. The experimenter set up materials for each activity (Table 3). The instructions for each activity were read. The experimenter then demonstrated each activity. The instructions for each activity were read again to ensure the participant understood the activity requirements. For the contextual condition, after reading the instructions the 2nd time, an opaque cover was put in front of the activity items while the experimenter randomized the order of the materials since the activities involved sequencing or memorization. This was done to ensure the novelty of the task order was preserved in order to elicit the intended cognitive demands for the contextual condition. During the execution phase of the HITT, a computer generated voice stated "Ready?" four seconds prior to the start of the activity. Participants were instructed to remain still during the ready phase and look straight ahead. At four seconds, the computer generated voice stated, "Go!" For the contextual condition, the opaque cover was lifted quickly and immediately by the experimenter once the "Go" signal was provided. Participants used their right hand or prosthesis on the right arm to press the red button to mark the beginning of movement execution. After the activity was deemed complete by the participant, they pressed the red button again with their right hand or prosthesis to denote the completion of the activity. After each activity participants completed the NASA-TLX and the Prosthesis-Orthosis Load Index (POLI) questionnaires. The questionnaires were completed in a counterbalanced order to reduce order effects. Since the NASA-TLX is validated and frequently used questionnaire in mental workload research and the POLI is a novel exploratory questionnaire, the NASA-TLX results are reported in this study. Furthermore, the mental and physical dimensions are only reported from the NASA-TLX due to the relevance of these dimensions to address the study research questions.

Figure 1. Activity set-up. *(From left to right)***.** Books on a Bookshelf. Beverage Preparation. Medication Management. Meal Preparation

Bypass Prostheses

The BP prosthesis used in this study was designed by Arm Dynamics (Dallas, TX) utilized a voluntary opening Hosmer 5X hook terminal device, with manual wrist rotation, figure eight harness and a 12 cm distal offset.

The MYO terminal device used in this study was the i-limb Ultra® created by Össur (Foothill Ranch, CA). The myoelectric terminal device was mounted to a forearm brace adapter provided by Next Step Bionics with a perpendicular handlebar with a medial offset of 15° from the participant's forearm. This device featured individualized motorized digits, compliant grip capability, direct control system using two electromyography sensors, manual thumb, and wrist rotation functionality. This prosthesis was used with a companion I-phone application (Biosim™) via Bluetooth connection. Biosim™ features a real-time EMG graph to assess muscle contraction quality and 12 automated 'quick' grips.

Procedure

Data Acquisition

EEG

EEG was recorded from 64 active electrode sites (10-20 system) at a 1000 Hz sampling rate using the Brain Vision EEG system (Brain Products GmbH, Germany). The EEG data was online referenced to the left earlobe and offline re-referenced using activity from the right earlobe. and a common ground was employed at the AFz site on the scalp. The horizontal electro-oculographic channel (HEOG) and vertical electro-oculographic channel (VEOG) was recorded by one electrode on the right outer canthus of the eye and one electrode on the superior orbital ridge of the right eye, respectively. Impedance was maintained below 10 kΩ.

EEG data was processed using the EEGlab package of Matlab®(The Mathworks Inc., USA) using custom code. Bad channels were identified and interpolated. Data was band-pass filtered with a low cut-off of 0.1 Hz and a high cut-off of 60 Hz with a 48 dB rolloff. Next, independent component analysis (ICA) was employed to remove ocular, muscle, and line noise artifacts. Data was resampled to 500Hz for synchronization with inertial measurement units (IMUs). Using a custom Matlab® script, data was epoched into early (-2 to -1 seconds) and late planning (-1 to 0 seconds) before movement onset. Movement onset was epoched from 0 seconds to the end of the trial which was marked by a manual end of movement execution trigger from the IMU system. Spectral power was calculated across 1-Hz bins and summed across theta (4-7Hz) low-alpha (8-10Hz, high-alpha (11-13 Hz) and beta (14-35 Hz) frequency bandwidths.

Kinematics

An inertial movement unit (IMU; Xsens™) was placed on the center of the participant's forehead, the right mid- humerus and distal end of the bypass prosthesis to measure change in the rate of acceleration of the head, arm, and wrist, respectively at a sampling rate of 100Hz. Data was bandpass filtered with a low cut-off of 0.01 Hz and a high cut-off of 20 Hz with an 80 dB rolloff. Data was up sampled to 500 Hz to synchronize with the EEG data. Due to the focus of this work to examine differences in upper limb movement smoothness, normalized jerk for the wrist and arm was computed to determine the rate of change in movement acceleration as an index of movement smoothness (Balasubramanian et al., 2015).

Statistical Analysis

Linear mixed effect modeling was conducted for all measures due to the model's ability to model random effects, its robustness against missing data and model flexibility. The EEG and kinematic data were natural log-transformed to reduce skewness. All data was subject to a visual inspection to assess model assumptions. Outlier removal was conducted for data points that were more than three standard deviations away from the mean to reduce the outlier influence on the model performance. Linear mixed effects models are reported with Type III ANOVA outputs to communicate the results in a more concise manner and to explain complex interactions that occurred during the study. Post-hoc analyses with a Tukey HSD correction were performed for all statistically significant main effects and interactions ($p < 0.05$). Effect sizes are reported for all statistically significant main effects and interactions. Satterthwaite's method was used to approximate degrees of freedom. All statistical analyses were performed using R Studio(RStudio Team, 2023).

Cognitive-Motor Manipulation Check

For the cognitive-motor demand manipulation check, the factor, with four levels (Books on a Bookshelf, Beverage Preparation, Meal Preparation, Medication Management) was subjected to one-way design.

Cognitive-Motor Performance

The HITT activity completion times were subjected to a 3 (Group (CTRL,BP, MYO)) x 2 (Context(Non-Context, Context)) linear mixed effects model design.

Kinematics

Normalized jerk was subjected to a 3 (Group (CTRL,BP, MYO)) x 2 (Context(Non-Context, Context)) linear mixed effects model design.

NASA-TLX

The mental and physical dimension of the NASA-TLX were subjected to a 3 (Group (CTRL,BP, MYO)) x 2(Context(Non-Context, Context)) linear mixed effects model design.

Spectral EEG

Low and high-alpha, theta and beta were subjected to a 3(Group(CTRL,BP, MYO) x 2 (Context(Non-Context, Context)) x 2 (Hemisphere(Left, Right)) design x 5 (Region(Frontal, Central, Parietal, Occipital, Temporal)) linear mixed effects model design.

For all linear mixed effects models, the Participant was the random effect to account for intersubject variances. To increase clarity in reporting, only Group and Context main effects or interactions including Prosthesis and/or Context variables are reported for all measures since these are the variables that were manipulated in the experiment.

Results

Cognitive-Motor Demand Manipulation Check

A main effect was revealed for Activity ($F(3,189) = 10.753$, $p < 0.001$, $\eta p^2 = 0.15$). The post-hoc analysis revealed that the participants took significantly longer to complete the Medication Management activity when compared to the Beverage Preparation($p = 0.028$, $d = 0.348$), Books on a Bookshelf activity($p < 0.001$, $d = 0.482$) and Meal Preparation ($p < 0.001$, $d = 0.547$) activities.

Books on a Bookshelf

Performance

A main effect was revealed for Group ($F(2, 19)) = 23.768$, $p < 0.001$, $\eta p^2 = 0.710$).The post-hoc analysis revealed that when compared to the CTRL group, the BP ($p < 0.001$, $d = 2.139$) and MYO ($p < 0.001$, $d = 2.636$) users required significantly more time to place all of the books in the bookshelf. A main effect was revealed for Context ($F(1, 18) = 5.991$, $p = 0.025$, $\eta p^2 = 0.247$) such that the participants took longer to place the books in the bookshelf with contextual instructions.

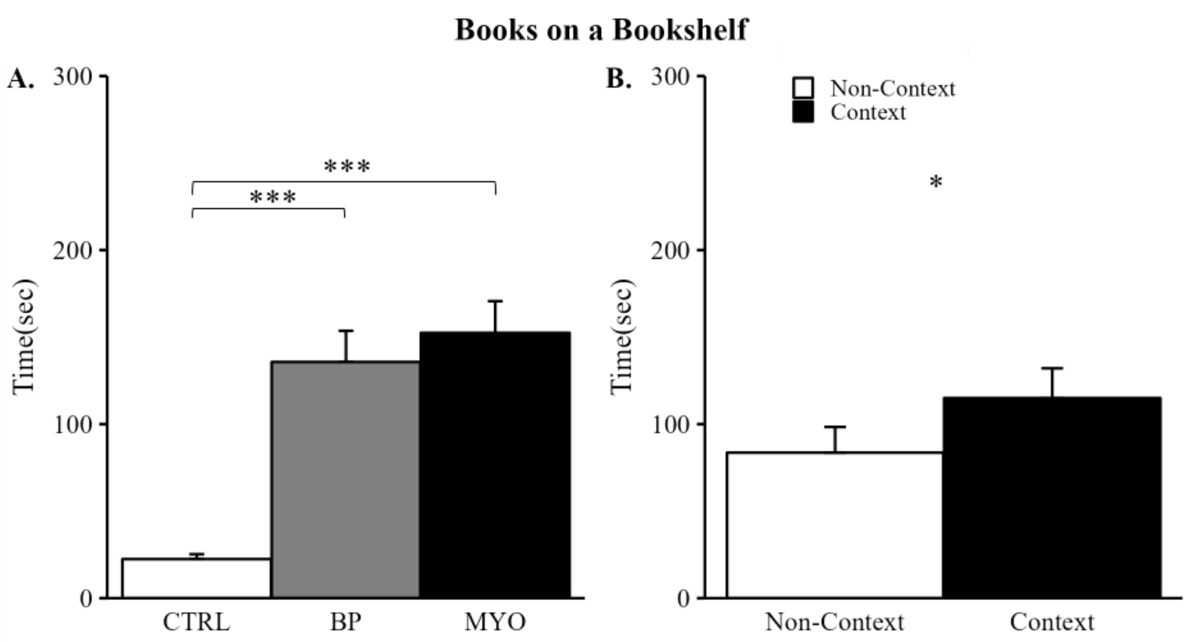


Fig. 2. Books on a Bookshelf. **A.** Performance averaged across experimental conditions for each prosthetic group . **B.** Performance averaged across groups for the non-contextual instructional and contextual conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

NASA-TLX

Mental Demand

A main effect was revealed for Group ($F(2, 25) = 4.235$, $p = 0.026$, $\eta p^2 = 0.256$). A main effect was also revealed for Context ($F(1, 24) = 21.354$, $p < 0.001$, $\eta p^2 = 0.471$). These main effects were superseded by a Group x Context interaction ($F(2, 24) = 6.681$, $p = 0.005$, $\eta p^2 = 0.358$). The post-hoc analysis revealed that the MYO group perceived higher mental demands when compared to the CTRL group ($p = 0.002$, $d = 1.899$) when placing the books on the bookshelf without contextual demands. Additionally, the CTRL group perceived higher mental demands when placing the books on the bookshelf with contextual demands when compared to without contextual demands ($p < 0.001$, $d = 1.916$).

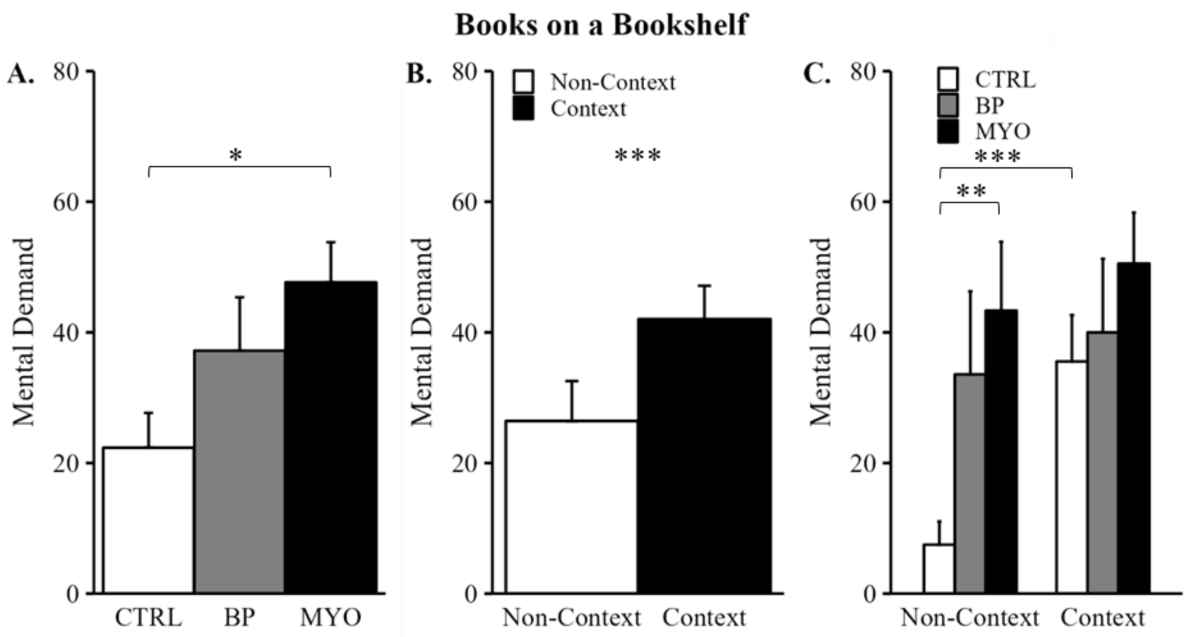


Fig. 3. Books on a Bookshelf. **A.** Perceived mental demand for each prosthetic group averaged across experimental conditions. **B.** Perceived mental demand averaged across all prosthetic groups for the non-contextual instructional and contextual conditions. **C.** Perceived mental demand in each prosthetic group for the non-contextual instructional and contextual conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * p < 0.05, ** p < 0.01, *** p < 0.001.

Physical Demand

A main effect was revealed for Group ($F(2, 24) = 5.465$, $p = 0.011$, $\eta p^2 = 0.309$) The post-hoc analysis revealed that the MYO group perceived higher physical demands when placing the books on the bookshelf when compared to the CTRL group ($p = 0.009$, $d = 1.381$). A main effect was also revealed for Context ($F(2, 24) = 7.006$, $p = 0.014$, $\eta p^2 = 0.229$) such that the participants perceived higher physical demand when placing the books on the bookshelf with contextual demands.

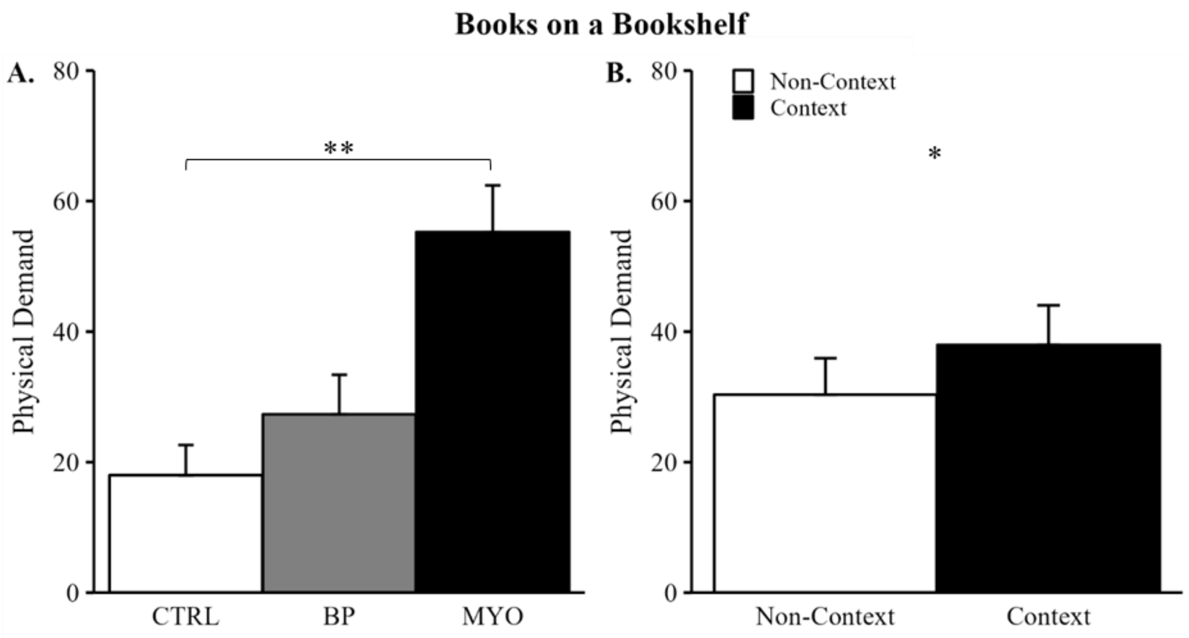


Fig. 4. Books on a Bookshelf. **A.** Perceived physical demand for each prosthetic group averaged across experimental conditions. **B.** Perceived physical demand averaged across all prosthetic groups for the non-contextual instructional and contextual conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Kinematics

Wrist

A main effect for Group ($F(2, 25) = 88.902$, $p < 0.001$, $\eta p^2 = 0.878$) was revealed. The post-hoc analysis revealed that the CTRL users had more movement smoothness when compared to the BP users ($p < 0.001$, $d = 3.062$) and MYO users ($p < 0.001$, $d = 3.643$). A main effect for Context ($F(1, 24) = 23.141$, $p < 0.001$, $\eta p^2 = 0.492$) was revealed such that participants experienced more wrist movement variability when placing the books in the cupboard with contextual instructions.

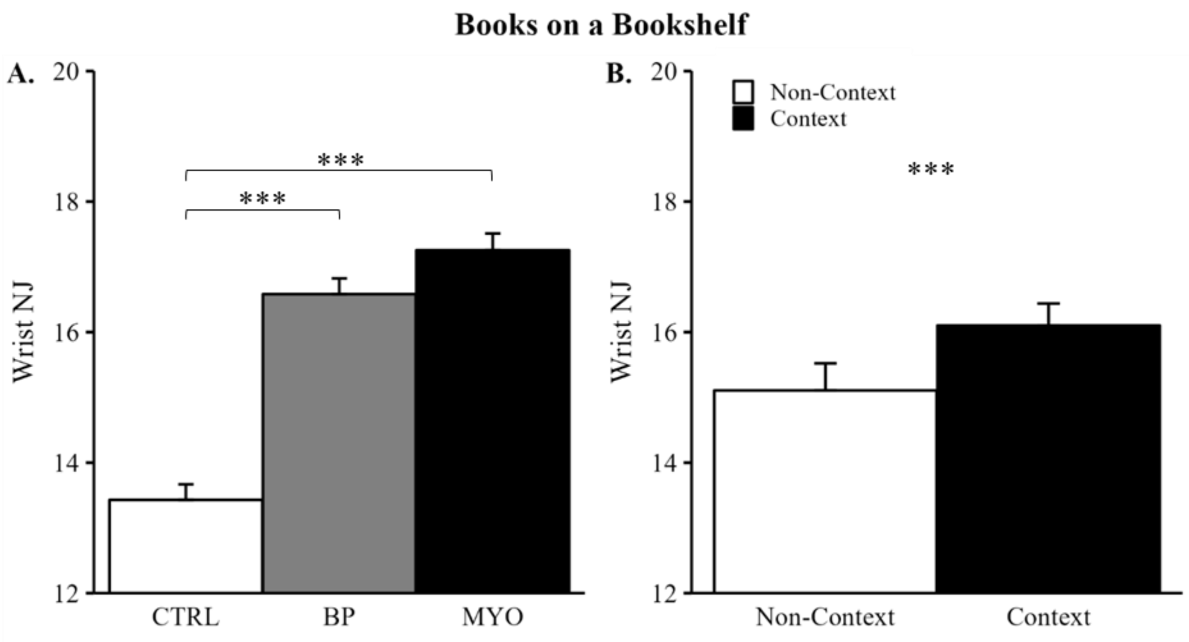


Fig. 5. Books on a Bookshelf. **A.** Wrist normalized jerk for each group averaged across experimental conditions. **B.** Wrist normalized jerk for the non-contextual instructional and contextual conditions averaged across all prosthetic groups . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Arm

A main effect for Group ($F(2, 26) = 83.539$, $p < 0.001$, $\eta p^2 = 0.867$) was revealed. Post-hoc analyses revealed that the CTRL users had more movement smoothness when compared to the BP users ($p < 0.001$, $d = 2.929$) and MYO users ($p < 0.001$, $d = 3.951$). The BP users also had more movement smoothness when compared to the MYO users ($p = 0.038$, $d = 0.824$). A main effect for Context ($F(1, 25) = 10.967$, $p = 0.030$, $\eta p^2 = 0.303$) was revealed such that participants experienced more arm movement variability when placing the books in the cupboard with contextual instructions.

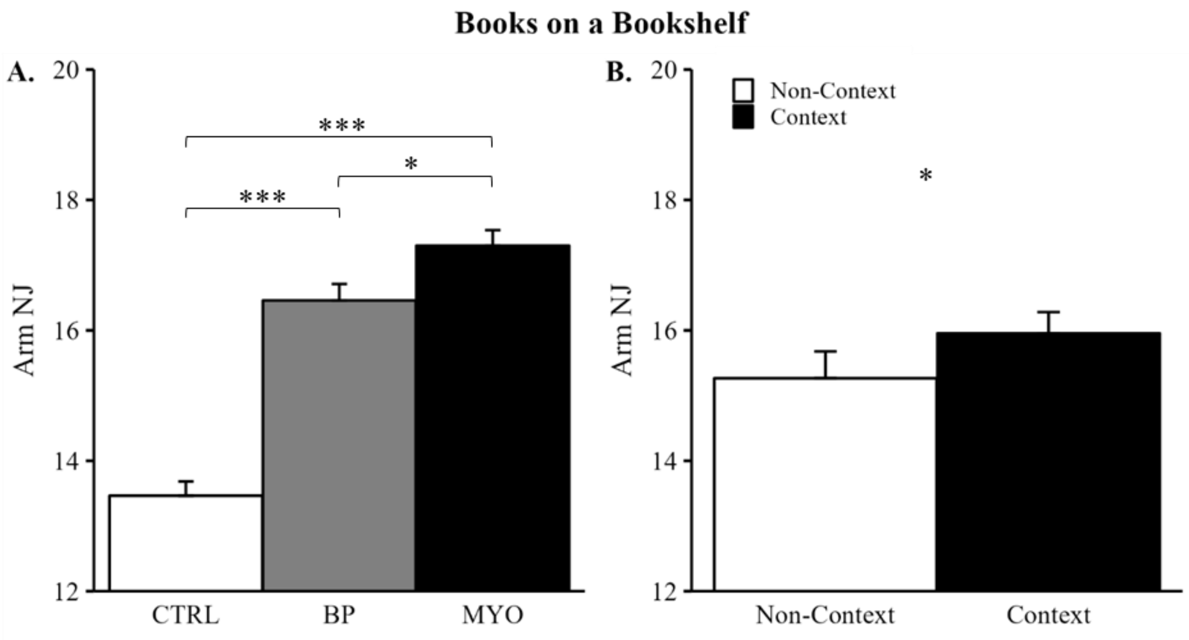


Fig. 6. Books on a Bookshelf. **A.** Arm normalized jerk for each group averaged across experimental conditions. **B.** Arm normalized jerk for the non-contextual instructional and contextual conditions averaged across all prosthetic groups . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * p < 0.05, ** p < 0.01, *** p < 0.001.

Spectral EEG

Theta

A significant Group main effect was revealed ($F(2, 27) = 8.259$, $p = 0.002$, $\eta p^2 = 0.38$). The Group main effect was superseded by a significant Group x Context interaction ($F(2, 452) = 7.183$, $p = 0.001$, $\eta p^2 = 0.031$).

With non-contextual instructions, the BP group experienced greater theta power when compared to the CTRL ($p = 0.001$, $d = 1.19$) and MYO ($p = 0.006$, $d = 0.851$) groups. Additionally, the BP users experienced higher theta power when placing the books on the bookshelf with non-contextual instructions when compared to contextual instructions ($p < 0.001$, $d = 0.184$).

The post-hoc analysis revealed that when placing the books in the cupboard with contextual instructions, the BP group experienced greater theta power when compared to the CTRL (p = 0.014 , d = 0.944) group.

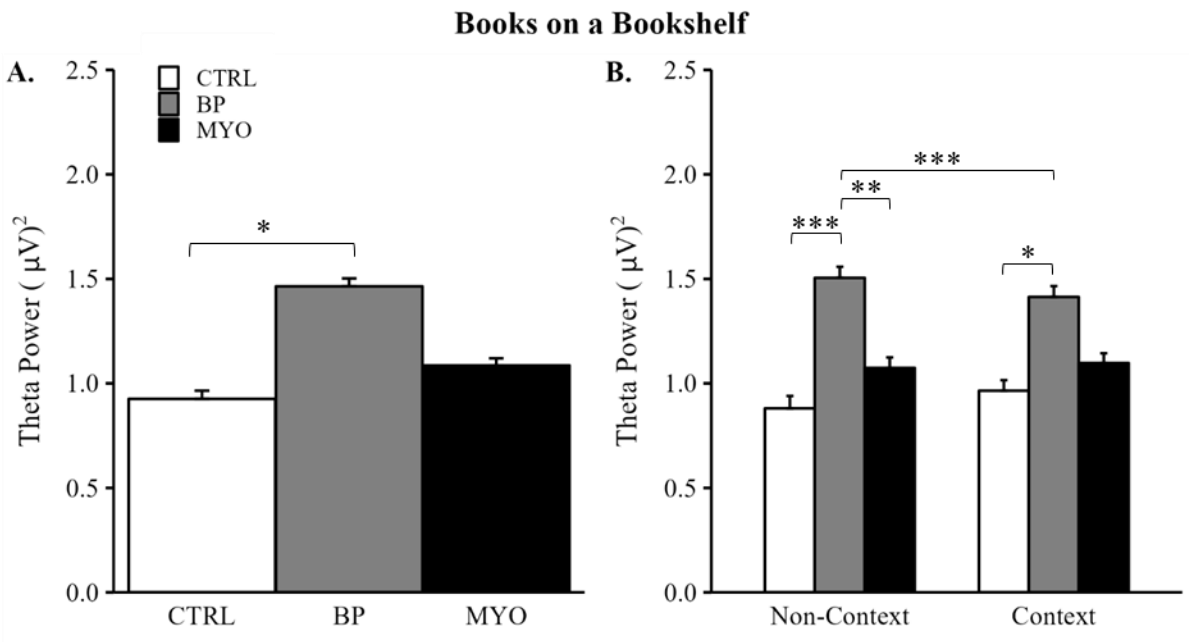


Fig. 7. Books on a Bookshelf activity. **A.** Theta power between prosthetic groups . **B.** Theta power between prosthetic groups for the non-contextual instructional and contextual conditions. BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group , CTRL- Control group. * p < 0.05, ** p < 0.01, *** p < 0.001.

Low-Alpha

A significant Group ($F(2, 27) = 8.514$, $p = 0.001$, $\eta p^2 = 0.387$) main effect was revealed. The Group main effect was superseded by a significant Group x Context interaction ($F(2, 436) = 9.086$, $p < 0.001$, $\eta p^2 = 0.040$). The post-hoc analysis revealed that when receiving contextual instructions before placing the books on the bookshelf, the BP group experienced greater low-alpha power(p = 0.010 , d = 0.958) when compared to the CTRL group. When placing the books on the bookshelf with non-contextual constructions, the BP group experienced greater low-alpha power when compared to the CTRL (p < 0.001, d = 1.414) and MYO(p = 0.035, d = 0.404) groups.

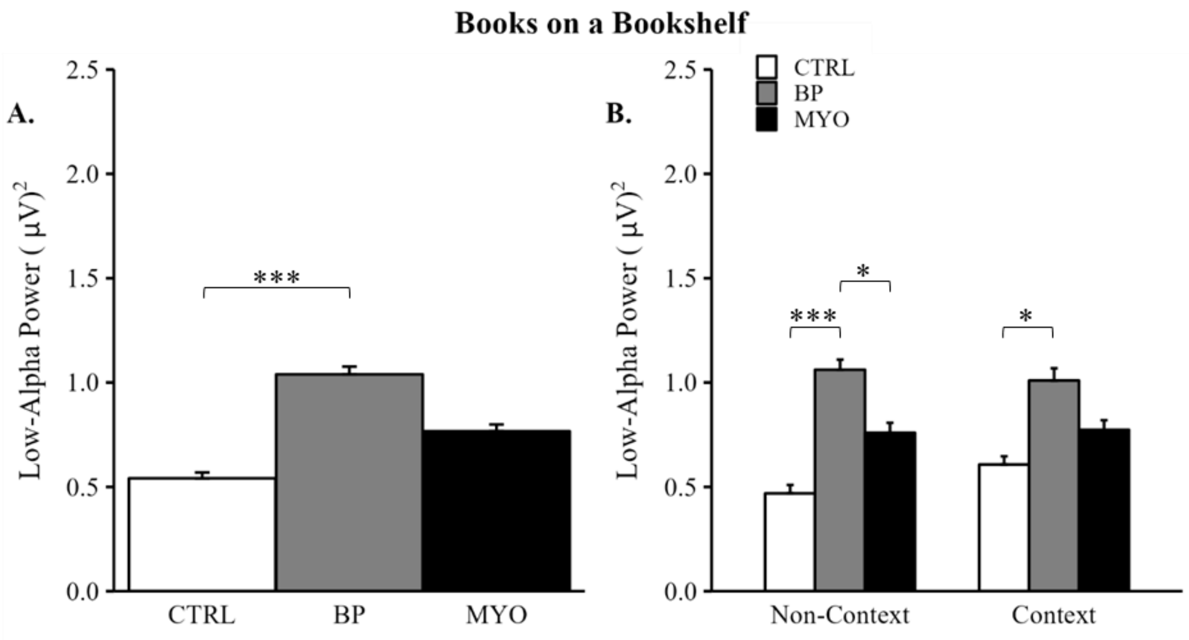


Fig. 8. Books on a Bookshelf activity. **A.** Low-alpha power between prosthetic groups . **B.** Low-alpha power between prosthetic groups for the non-contextual instructional and contextual conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The Group main effect was also superseded by a significant Group x Region x Hemi interaction ($F(8, 433) = 3.009$, $p = 0.003$, $\eta p^2 = 0.053$).

In the left hemisphere, the BP group experienced greater low-alpha power in the central($p = 0.040$, $d = 1.67$), frontal ($p = 0.020$, $d = 1.367$), occipital ($p = 0.001$, $d = 1.462$), parietal ($p = 0.008$, $d = 1.654$) and temporal ($p < 0.001$, $d = 2.567$) regions when compared to the CTRL group. In the left hemisphere, the BP group experienced greater low-alpha power in the temporal region ($p < 0.001$, $d = 1.328$) when compared to the MYO group. In the left hemisphere, the MYO group also experienced greater low-alpha power in the temporal region when compared to the CTRL group ($p = 0.014$, $d = 1.096$).

In the right hemisphere, the BP group experienced greater low-alpha power in the right central ($p = 0.0340$, $d = 1.707$), occipital ($p = 0.006$, $d = 1.719$), parietal ($p = 0.002$, $d = 2.151$) and temporal ($p = 0.004$, $d = 1.128$) regions when compared to the CTRL group. The BP group experienced greater low-alpha power in the right temporal region ($p = 0.033$, $d = 1.101$) when compared to the MYO group. The MYO group experienced greater low-alpha power in the right occipital ($p = 0.003$, $d = 1.469$) when compared to the CTRL group.

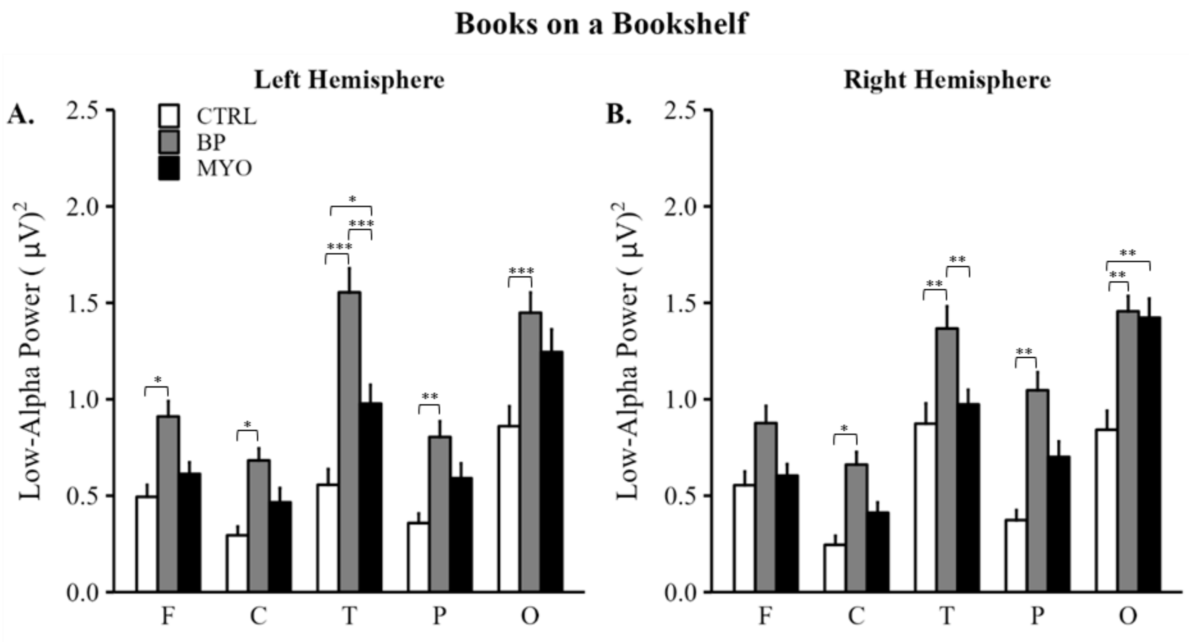


Fig. 9. Books on a Bookshelf. **A.** Low-alpha power between prosthetic groups and across regions in the left hemisphere . **B.** Low-alpha power between prosthetic groups and across regions in the right hemisphere. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

High-Alpha

A significant Group main effect was revealed ($F(2, 27) = 11.048$, $p < 0.001$, $\eta p^2 = 0.453$). This main effect was superseded by a significant Group x Context x Region interaction ($F(8, 429) = 2.338$, $p = 0.182$, $\eta p^2 = 0.007$).

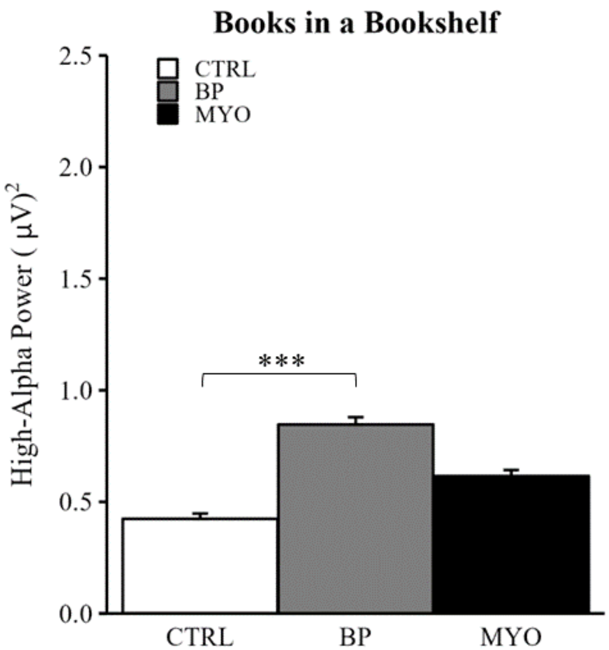


Fig. 10. Books on a Bookshelf. **A.** High-alpha power between prosthetic groups . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Within prosthetic groups, The CTRL group experienced greater high-alpha power in the occipital region during the contextual condition when compared to the non-contextual condition ($p < 0.001$, $d = 1.010$). The MYO group experienced greater high-alpha power in the occipital region power during the contextual condition when compared to the non-contextual condition ($p = 0.011$, $d = 0.527$). The MYO group experienced attenuated high-alpha power in the temporal region power during the contextual condition when compared to the non-contextual condition ($p = 0.001$, $d = 0.542$).

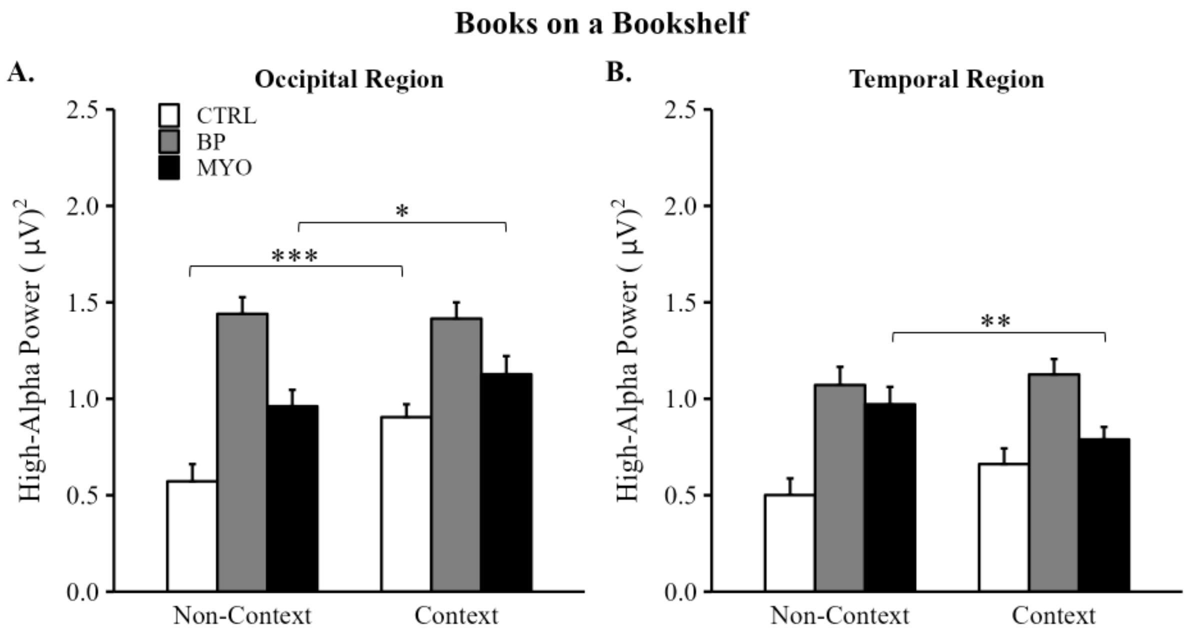


Fig. 11. Books on a Bookshelf. **A.** High-alpha power between prosthetic groups for each experimental condition . **B.** High-alpha power between prosthetic groups for each experimental group. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * p < 0.05, ** p < 0.01, *** p < 0.001.

For the non-contextual condition, the post-hoc analysis revealed that when participants received non-contextual instructions prior to placing the books on the bookshelf, the BP group experienced greater high-alpha power in the central ($p = 0.024$, $d = 1.657$), frontal ($p = 0.009$, $d = 1.575$), occipital ($p = 0.001$, $d = 2.413$), parietal ($p = 0.002$, $d = 1.994$), and temporal ($p < 0.001$, $d = 1.610$) regions when compared to the CTRL group. The MYO group experienced greater high-alpha power in the occipital ($p < 0.001$, $d = 1.124$) and temporal ($p < 0.001$, $d = 1.273$) regions when compared to the CTRL group and attenuated high-alpha power in the occipital ($p < 0.001$, $d = 1.525$) and parietal ($p = 0.045$, $d = 0.938$) regions when compared to the BP group.

The post-hoc analysis revealed that when participants received contextual instructions prior to placing the books on the bookshelf, the BP group experienced greater high-alpha power in the occipital ($p = 0.001$, $d = 1.988$), parietal ($p = 0.002$, $d = 2.17$) and temporal ($p < 0.001$, $d = 1.409$) regions when compared to the CTRL group. The BP group experienced greater high-alpha power in the temporal region when compared to the MYO group (p = 0.020, d = 1.165).

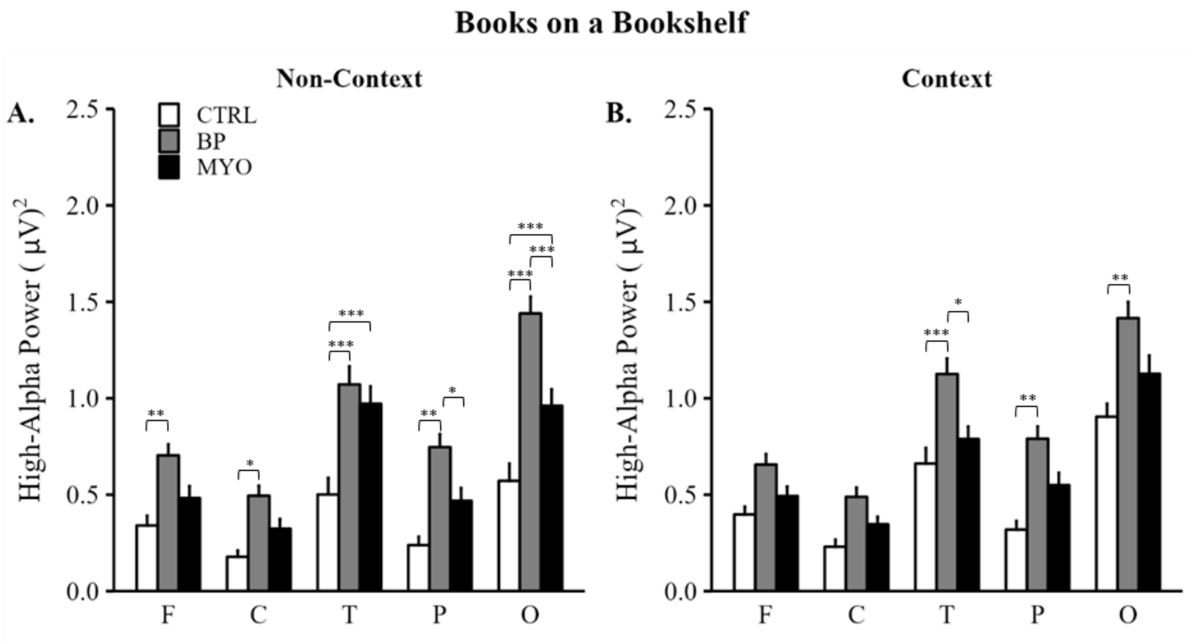


Fig. 12. Books on a Bookshelf activity. **A.** High-alpha power between prosthetic groups and across regions for the non-contextual instructions condition. **B.** High-alpha power between prosthetic groups and across regions for the contextual instructions condition. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Beta

Significant Group main effects ($F(2, 27) = 9.687$, $p < 0.001$, $\eta p^2 = 0.421$) and Context main effects ($F(1, 430) = 11.28$, $p < 0.001$, $\eta p^2 = 0.026$) were revealed.

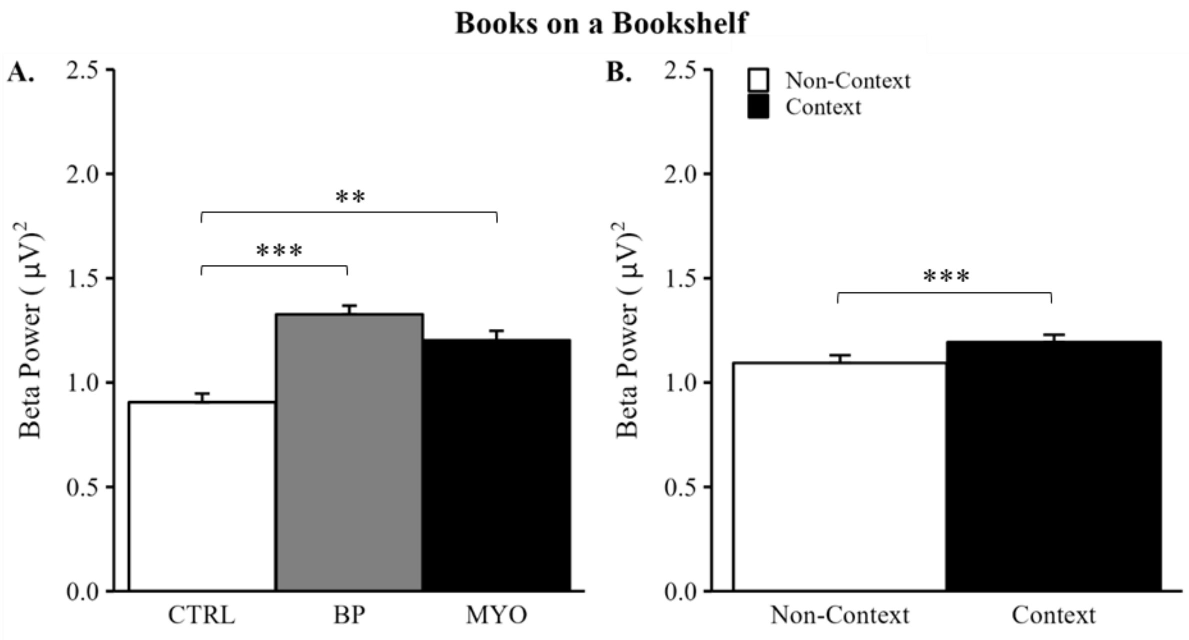


Fig. 13. Books on a Bookshelf activity. **A.** Beta power between prosthetic groups . **B.** Beta power between prosthetic groups for the non-contextual instructional and contextual conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

These main effects were superseded by a significant Group x Context interaction ($F(2, 430) = 22.017$, $p < 0.001$, $\eta p^2 = 0.093$) was revealed. Post-hoc analyses revealed that when placing the books in the bookshelf after receiving non-contextual instructions, the CTRL group experienced less beta power when compared to the BP ($p < 0.001$, $d = 1.285$) and MYO groups ($p < 0.001$, $d =0.874$). The CTRL group also experienced higher beta power when placing the books on the bookshelf after receiving contextual instructions when compared to non-contextual instructions ($p < 0.001$, $d = 0.710$).

The Group main effect was also superseded by a significant Group x Region interaction ($F(8, 422.624) = 4.031$, $p < 0.001$, $\eta p^2 = 0.071$). Post-hoc analyses revealed that the BP group experienced greater beta power in the occipital ($p < 0.001$, $d = 1.716$), parietal ($p = 0.001$, $d = 1.426$) and temporal ($p = 0.028$, $d = 0.557$) regions when compared to the CTRL group. The MYO group experienced greater beta power in the occipital ($p < 0.001$, $d = 1.353$), parietal ($p = 0.033$, $d = 0.864$) and temporal ($p = 0.004$, $d = 0.665$) regions when compared to the CTRL group.

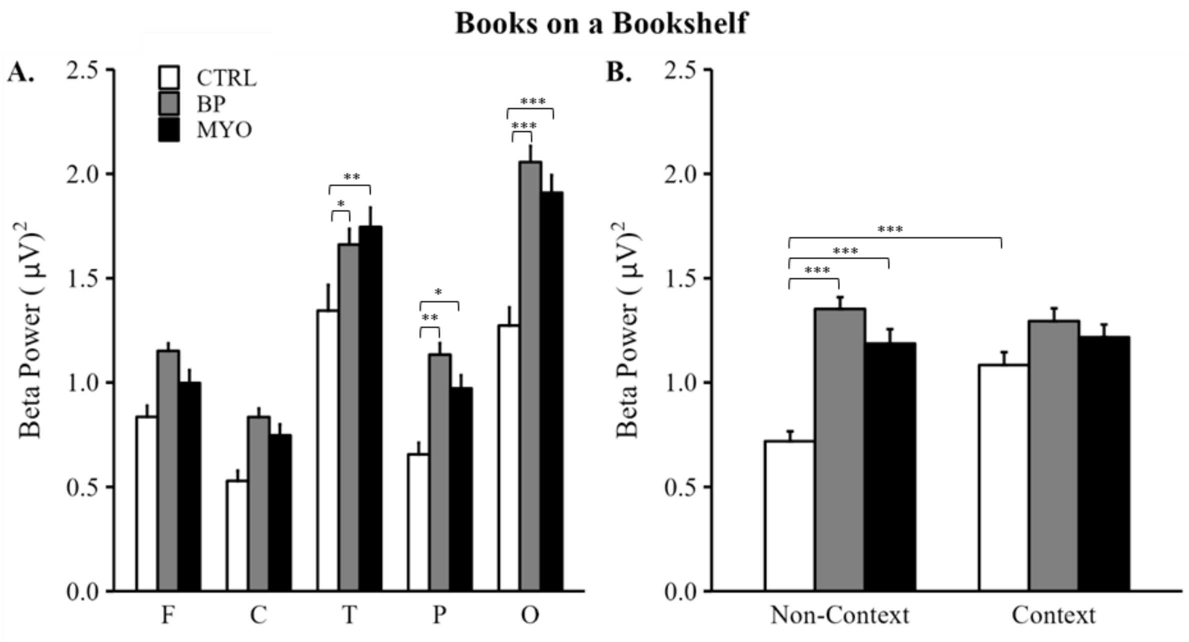


Fig. 14. Books on a Bookshelf activity. **A.** Beta power between prosthetic groups across cortical regions. **B.** Beta power between prosthetic groups for the non-contextual instructional and contextual conditions. BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group , CTRL- Control group. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Beverage Preparation

Performance

A main effect was revealed for Group ($F(2, 23) = 32.969$, $p < 0.001$, $\eta p^2 = 0.734$). The post-hoc analysis revealed that the BP ($p < 0.001$, $d = 2.861$) and MYO ($p < 0.001$, $d = 3.258$) users required significantly more time to prepare the beverages when compared to the CTRL group. A main effect was revealed for Context ($F(1, 22) = 8.500$, $p = 0.008$, $\eta p^2 = 0.275$) such that participants took more time to prepare the beverages with contextual instructions compared to non-contextual instructions.

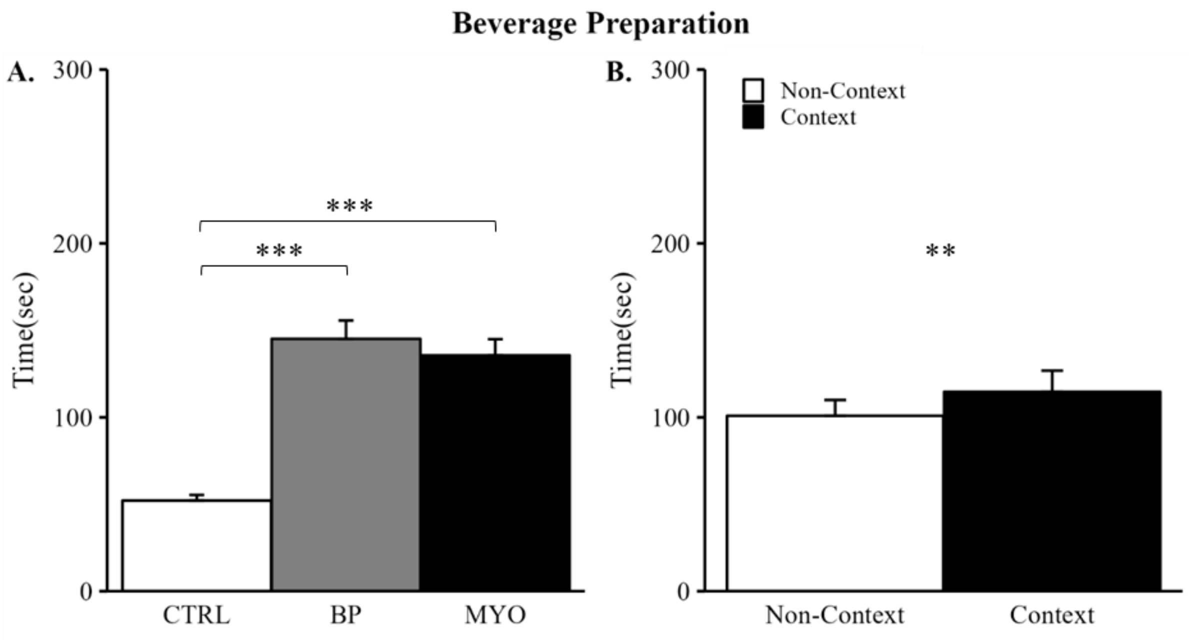


Fig. 15. Beverage Preparation. **A.** Performance averaged across groups for the non-contextual instructional and contextual conditions. **B.** Performance averaged across experimental conditions for each prosthetic group . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

NASA-TLX

Mental Demand

A Context main effect was revealed ($F(1, 146) = 17.948$, $p < 0.001$, $\eta p^2 = 0.109$). The Context main effect was superseded by a Group x Context interaction ($F(2, 146) = 4.035$, $p = 0.020$, $\eta p^2 = 0.052$). The post-hoc analysis revealed that the CTRL group experienced higher mental demand when preparing the beverage with contextual instructions when compared to the non-contextual instructions ($p < 0.001$, $d = 1.526$).

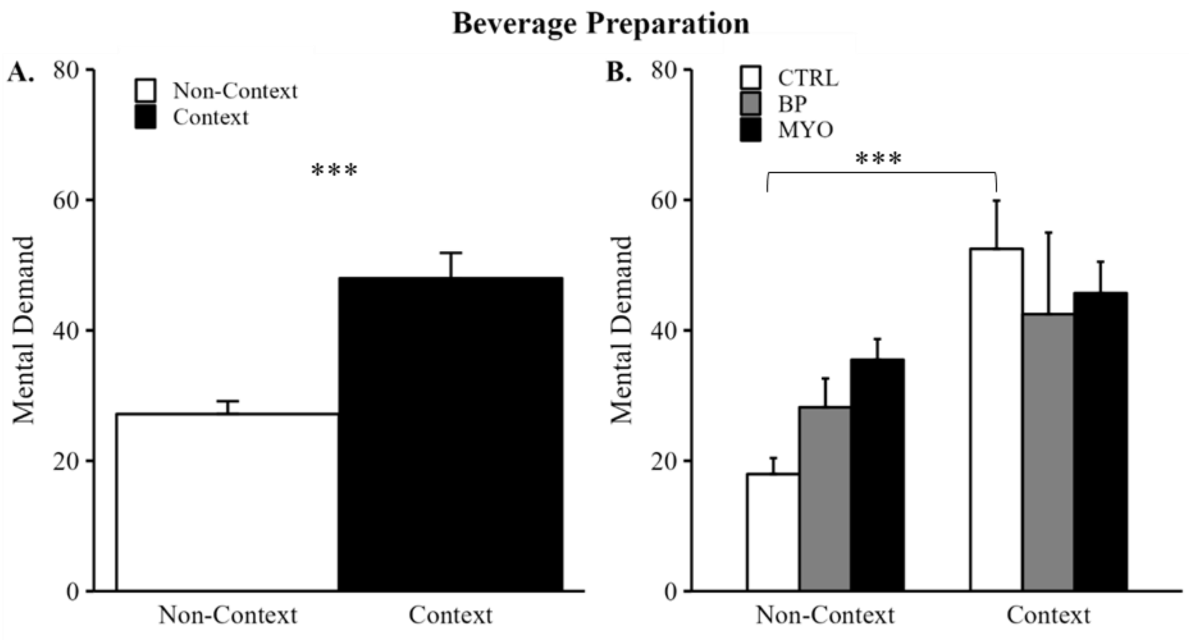


Fig. 16. Beverage Preparation. **A.** Perceived mental demand averaged across prosthetic groups . **B.** Perceived mental demand averaged for each prosthetic group for both experimental conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * p < 0.05, ** p < 0.01, *** p < 0.001.

Physical Demand

Significant main effects for Group ($F(2, 39) = 5.503$, $p = 0.008$, $\eta p^2 = 0.222$) and Context ($F(1, 148) = 4.965$, $p = 0.027$, $\eta p^2 = 0.032$) were revealed. These main effects were superseded by a Group x Context interaction ($F(2, 148) = 4.274$, $p = 0.016$, $\eta p^2 = 0.055$). The post-hoc analysis revealed that when compared to the CTRL group, the MYO group perceived greater physical demand when preparing the beverage with contextual instructions ($p < 0.001$, $d = 1.621$). Additionally, the MYO group perceived greater physical demand when preparing the beverages with contextual instructions when compared to non-contextual instructions ($p < 0.001$, $d = 838$).

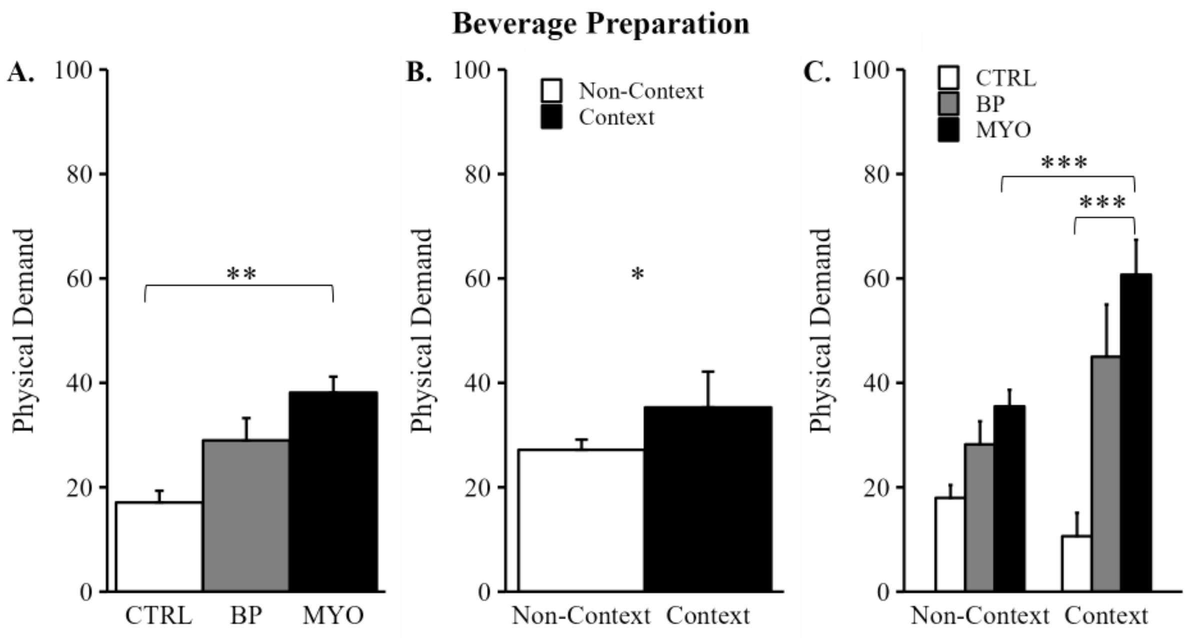


Fig. 17. Beverage Preparation. **A.** Perceived physical demand for all prosthetic groups averaged across experimental conditions. **B.** Perceived physical demand averaged across prosthetic groups . **C.** Perceived physical demand for each prosthetic group for both experimental conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Kinematics

Wrist

A main effect for Group ($F(2, 26) = 49.268$, $p < 0.001$, $\eta p^2 = 0.793$) and Context ($F(1, 23) = 10.207$, $p = 0.004$, $\eta p^2 = 0.304$) was revealed.

These main effects were superseded by a significant Group x Context interaction ($F(2, 23) = 3.529$, $p = 0.046$, $\eta p^2 = 0.233$). The post-hoc analysis revealed that when preparing the beverages after receiving non-contextual instructions, the CTRL group experienced more wrist movement smoothness when compared to the BP ($p < 0.001$, $d = 2.679$) and MYO ($p < 0.001$, $d = 3.752$) groups. The MYO group experienced less movement smoothness when preparing the beverages after receiving contextual instructions when compared to the non-contextual instructions ($p = 0.001$, $d = 1.377$).

Post-hoc analyses revealed that when preparing the beverages after receiving contextual instructions, the CTRL group experienced more wrist movement smoothness when compared to the BP ($p < 0.001$, $d = 2.679$) and MYO ($p < 0.001$, $d = 3.752$) groups. When preparing the beverages after receiving contextual instructions, the BP group experienced more wrist movement smoothness when compared to the MYO group ($p = 0.024$, $d = 1.134$).

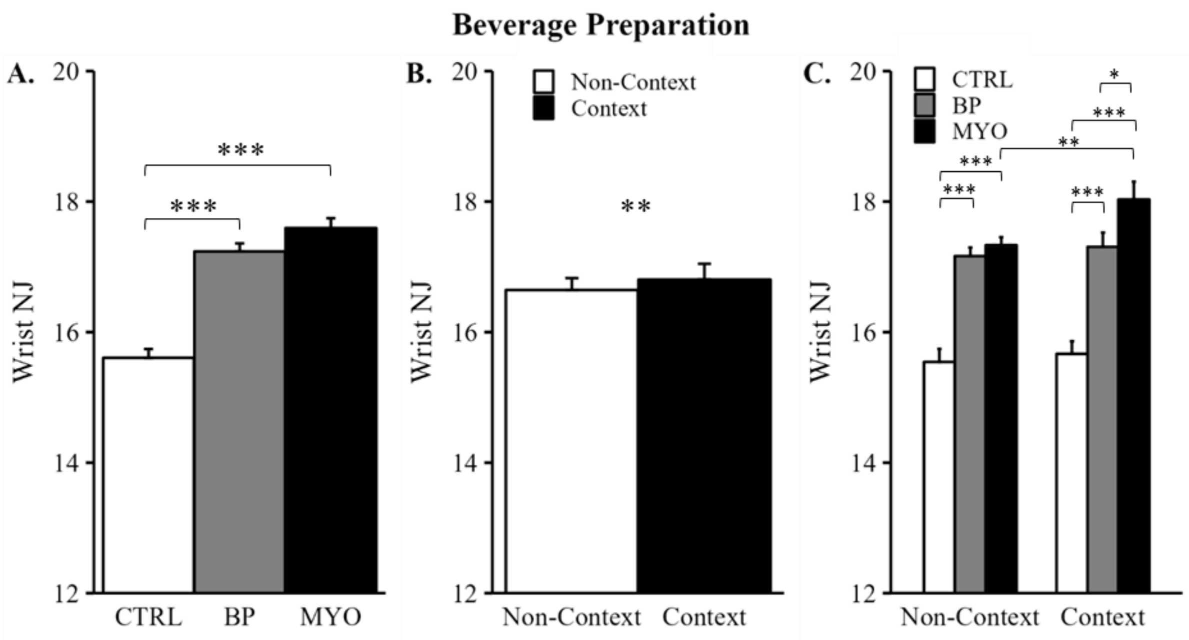


Fig. 18. Beverage Preparation. **A.** Wrist normalized jerk for each prosthetic group averaged across experimental conditions. **B.** Wrist normalized jerk for the non-contextual instructional and contextual conditions averaged across all prosthetic groups . **C.** Wrist normalized jerk for each prosthetic group for the non-contextual instructional and contextual conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Arm

A main effect for Group ($F(2, 24) = 34.036$, $p < 0.001$, $\eta p^2 = 0.737$) was revealed. Post-hoc analyses revealed that when preparing the beverages, the CTRL group exhibited more wrist movement smoothness when compared to the BP group ($p < 0.001$, $d = 2.68$) and MYO group ($p < 0.001$, $d = 2.722$). A main effect for Context ($F(1, 22) = 16.89$, $p = 0$, $\eta p^2 = 0.431$) was revealed such that participants experienced less arm movement smoothness when preparing the beverages after receiving the contextual instructions compared to the non-contextual instructions ($p < 0.001$, $d = 0.348$).

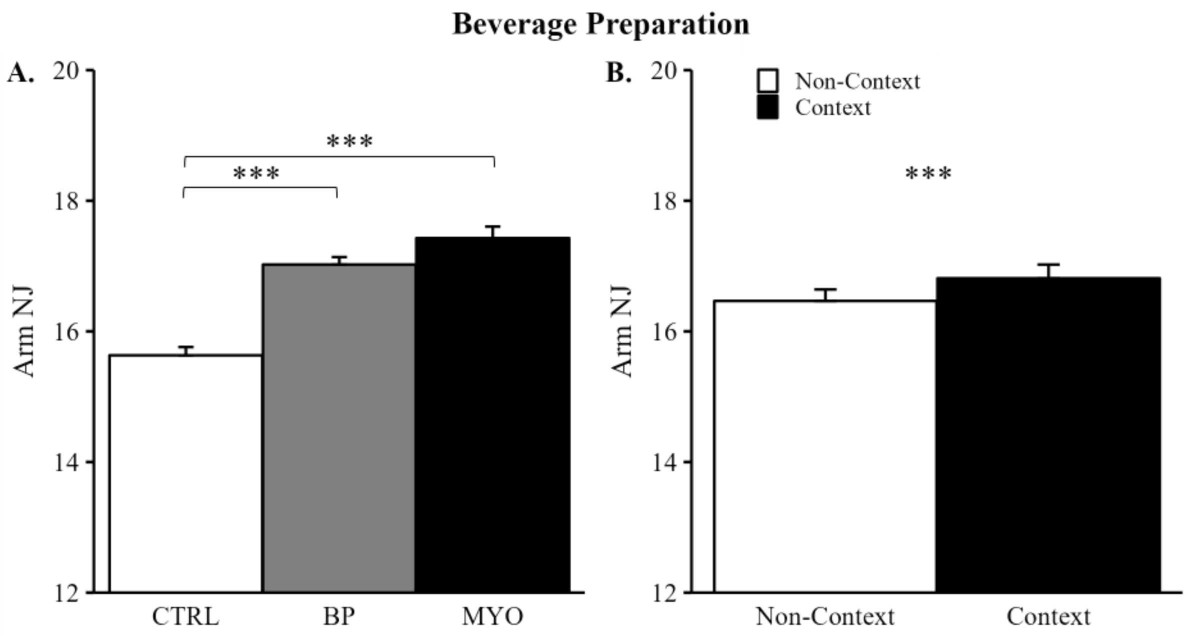


Fig. 19. Beverage Preparation. **A.** Arm normalized jerk for each prosthetic group averaged across experimental conditions. **B.** Arm normalized jerk for the non-contextual instructional and contextual conditions averaged across all prosthetic groups . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Spectral EEG

Theta

A significant Group ($F(2, 25) = 3.862$, $p = 0.035$, $\eta p^2 = 0.649$ main effect was revealed. A significant Context main effect was revealed such that theta power was significantly higher in the contextual condition when compared to the non-contextual condition ($F(1, 438) = 11.078$, $p = 0.001$, $\eta p^2 = 0.025$). The Group main effect was superseded by a significant Group x Region x Hemisphere interaction ($F(8, 438) = 2.079$, $p = 0.037$, $\eta p^2 = 0.037$). Post-hoc analyses revealed that in the left hemisphere, the CTRL group experienced lower theta power in the left occipital ($p = 0.038$, $d = 1.077$), parietal($p= 0.023$, $d = 1.198$) and temporal ($p = 0.005$, $d = 2.333$) when compared to the BP group. The

BP group experienced higher theta power in the left temporal region when compared to the MYO group (p = 0.013, d = 1.375). The BP group experienced an attenuation of theta power in the right temporal region when compared to the CTRL (p < 0.001 , d = 1.848) and MYO (p = 0.016 , d = 1.205) groups.

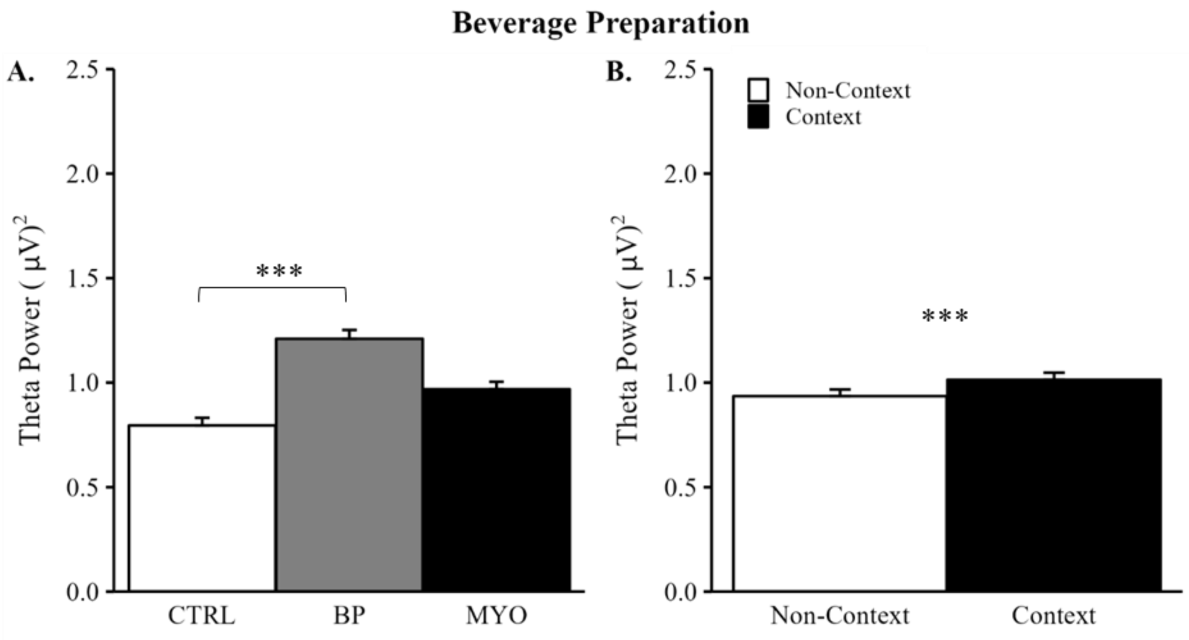


Fig. 20. Beverage Preparation. **A.** Theta power between prosthetic groups averaged across experimental conditions. **B.** Theta power in the non-contextual and contextual conditions averaged across prosthetic groups . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * p < 0.05, ** p < 0.01, *** p <

0.001.

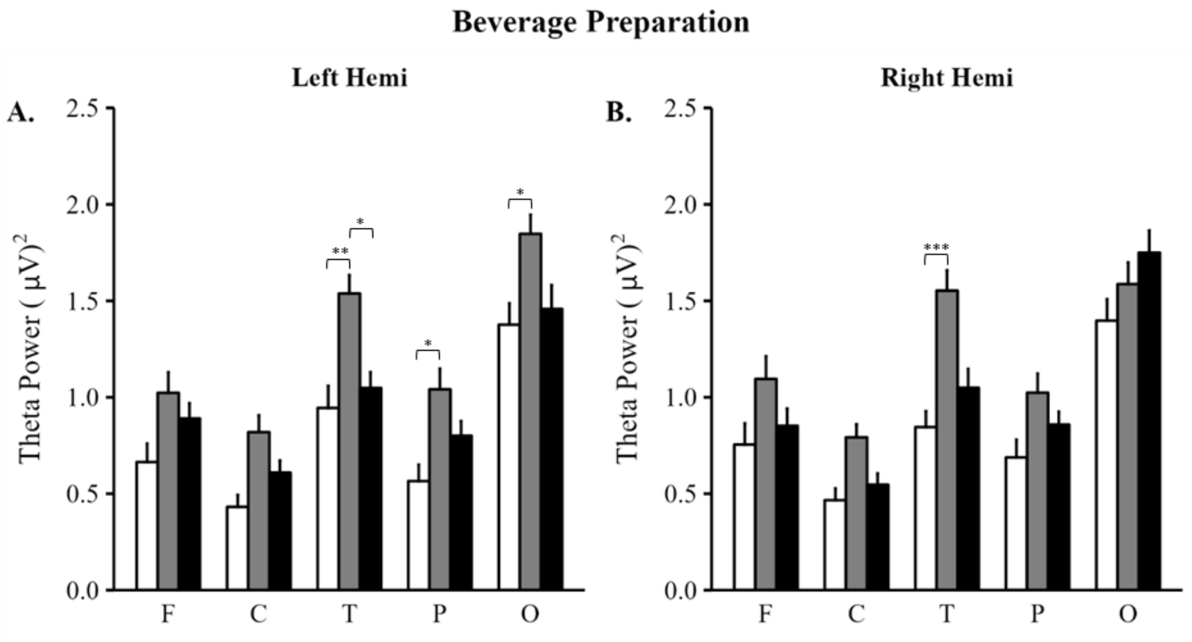


Fig. 21. Beverage Preparation. **A.** Theta power between prosthetic groups and across regions in the left hemisphere . **B.** Theta power between prosthetic groups and across regions in the right hemisphere. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group. F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Low-Alpha

A significant Group ($F(2, 25) = 4.035$, $p = 0.030$, $\eta p^2 = 0.623$) main effect was revealed. This main effect was superseded by a significant Group x Region x Hemisphere interaction ($F(8, 431) = 1.972$, $p = 0.048$, $\eta p^2 = 0.035$). The post-hoc analysis revealed that the BP group experienced greater low-alpha power in the left occipital ($p = 0.011$, $d = 0.995$) and temporal ($p < 0.001$, $d = 2.311$) regions when compared to the CTRL group. The BP group also experienced greater low-alpha power in the left temporal region ($p = 0.001$, $d = 1.728$) when compared to the MYO group. The BP group experienced greater low-alpha power in the right temporal region ($p = 0.002$, $d = 1.377$) when compared to the CTRL group.

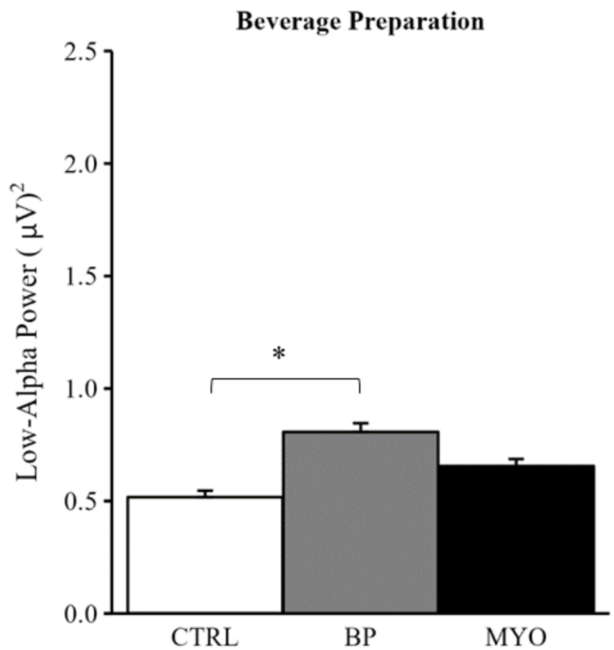


Fig. 22. Beverage Preparation. **A.** Low-alpha power between prosthetic groups . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

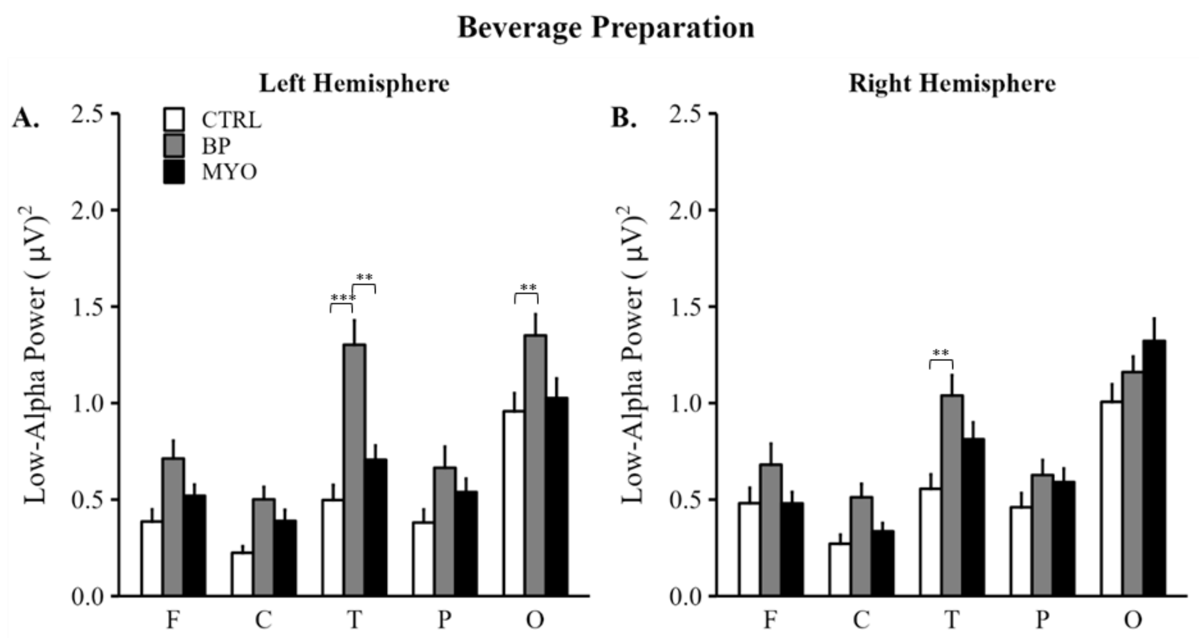


Fig. 23. Beverage Preparation. **A.** Low-alpha power between prosthetic groups and across regions in the left hemisphere . **B.** Low-alpha power between prosthetic groups and across regions in the right hemisphere. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

High-Alpha

A significant Group main effect was revealed ($F(2, 25) = 10.298$, $p < 0.001$, $\eta p^2 = 0.453$). The Group main effect was superseded by a significant Group x Region x Hemisphere interaction ($F(2, 431) = 2.134$, $p = 0.032$, $\eta p^2 = 0.038$). The post-hoc analysis revealed that in the left hemisphere, when compared to the CTRL group, the BP group exhibited greater high-alpha power in the frontal (p = 0. 0291, d = 1.349), occipital (p < 0.001 , d = 2.471), parietal (p = 0.005 , d = 1.417) and temporal (p < 0.001 , d = 2.333) regions. When compared to the MYO group, the BP exhibited greater high-alpha power in the occipital (p < 0.001, d = 1.667) and temporal regions (p < 0.001, d = 1.976). In the right hemisphere, when compared to the CTRL group, the BP group exhibited greater high-alpha power in the occipital (p < 0.001, d = 1.608), parietal (p = 0.029, d = 1.011), and temporal (p < 0.001, d = 1.993) regions. When compared to the CTRL group, the MYO group exhibited greater high-alpha power in the occipital (p < 0.001 , d = 1.239) and temporal (p = 0.004 , d = 1.15) regions.

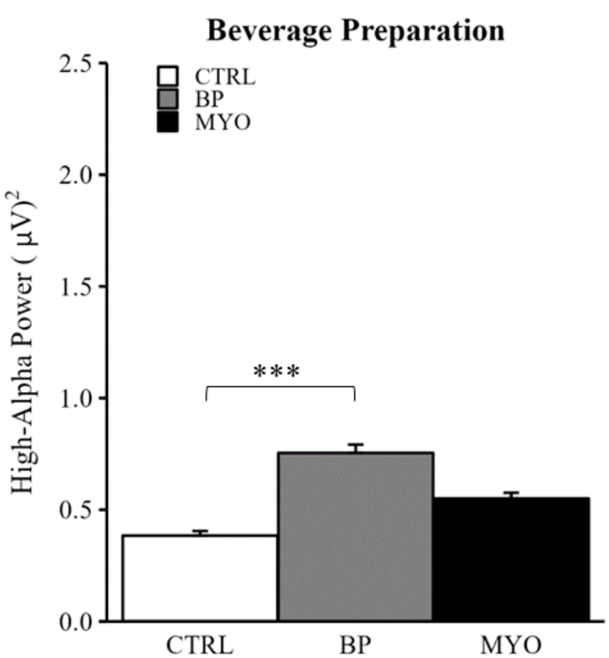


Fig. 24. Beverage Preparation. **A.** High-alpha power between prosthetic groups averaged across experimental conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * p < 0.05, ** p < 0.01, *** p < 0.001.

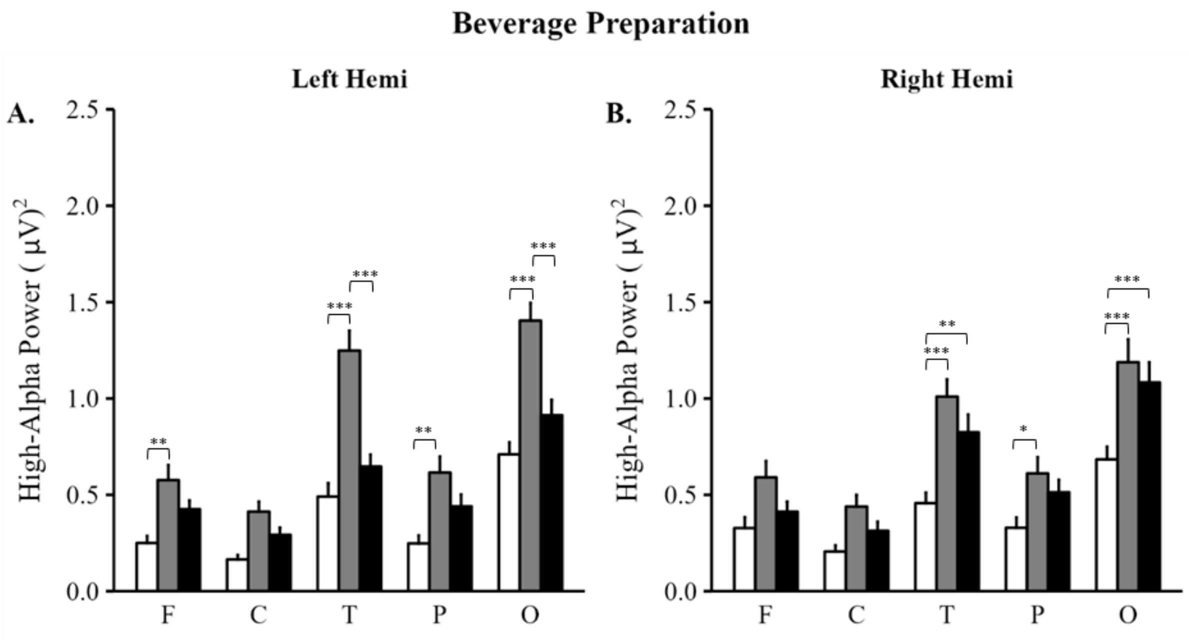


Fig. 25. Beverage Preparation. **A.** High-alpha power between prosthetic groups and across regions in the left hemisphere . **B.** High-alpha power between prosthetic groups and across regions in the right hemisphere. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Beta

A significant Group main effect was revealed ($F(2, 25) = 10.8$, $p < 0.001$, $\eta p^2 = 0.463$). The Group main effect was superseded by a significant Group x Hemisphere interaction ($F(2, 433) = 4.164$, $p = 0.016$, $\eta p^2 = 0.019$). Post-hoc analyses revealed that the BP group experienced greater beta power in the left hemisphere ($p = 0.040$, $d = 0.178$) when compared to the right hemisphere. In contrast, the MYO group experienced less beta power in the left hemisphere ($p = 0.043$, $d = 0.16$) when compared to the right hemisphere.

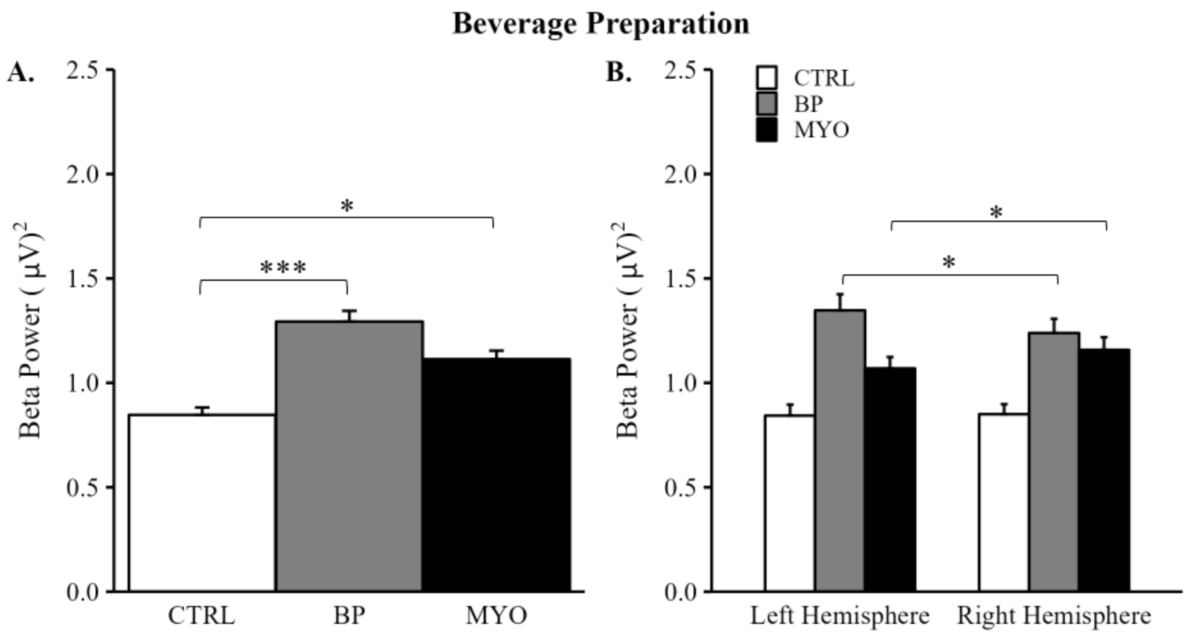


Fig. 26. Beverage Preparation. **A.** Beta power between prosthetic groups averaged across experimental conditions. **B.** Beta power between prosthetic groups for the left and right hemispheres. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The Group main effect was superseded by a significant Group x Region interaction $F(8, 434) = 4.628$, $p < 0.001$, $\eta p^2 = 0.079$). Post-hoc analyses revealed that the BP group experienced greater beta power in the central ($p = .030$, $d = 1.392$), frontal ($p = 0.048$, $d = 0.804$) and occipital($p = 0.001$, $d = 1.093$), parietal ($p = 0.006$, $d = 1.233$) and temporal ($p < 0.001$, $d = 2.012$) regions when compared to the CTRL group. The BP group experienced greater beta power in the temporal region when compared to the MYO group ($p < 0.001$, $d = 1.195$). The MYO group experienced greater beta power in the occipital ($p = 0.003$, $d = 0.981$) and temporal ($p = 0.008$, $d = 0.763$) regions when compared to the CTRL group.

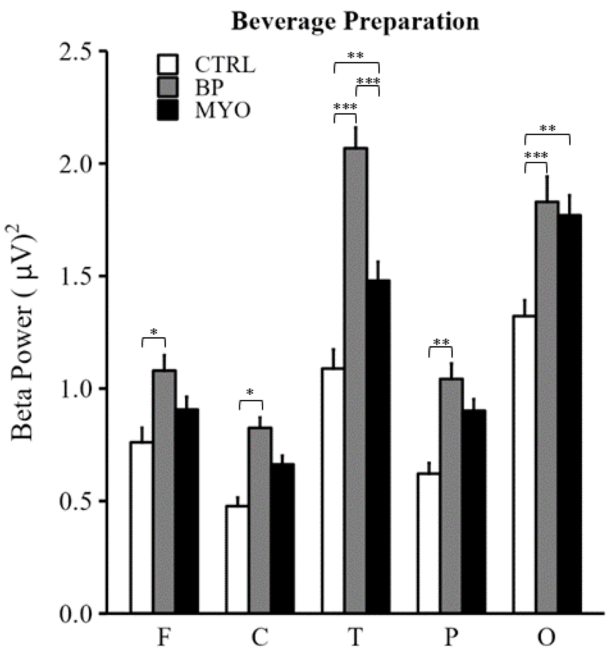


Fig. 27. Beverage Preparation. Beta power between prosthetic groups for each cortical region. CTRL- Control group, BP-Body-powered prosthetic group , MYO-Myoelectric prosthetic group . F = Frontal region, C = Central region, T = Temporal region, P = Parietal region, O = Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Meal Preparation

Performance

A main effect was revealed for Group ($F(2, 24) = 79.23$, $p < 0.001$, $\eta p^2 = 0.868$) and Context ($F(1, 22) = 40.168$, $p < 0.001$, $\eta p^2 = 0.641$).These main effects were superseded by a Group x Context interaction ($F(2, 22) = 22.237$, $p < 0.001$, $\eta p^2 = 0.666$). The post-hoc analysis revealed that the BP group took significantly longer to prepare the meal without contextual demands when compared to with contextual demands ($p < 0.001$, $d = 2.493$). During the contextual condition, the CTRL group prepared the meal significantly faster than the BP ($p < 0.001$, $d = 3.598$) and MYO ($p < 0.001$, $d = 4.544$) groups. During the non-contextual condition, the CTRL group prepared the meal significantly faster than the BP ($p < 0.001$, $d = 8.253$) and MYO ($p < 0.001$, $d = 4.523$) group. When compared to the MYO group, the BP group prepared the meal significantly slower ($p < 0.001$, $d = 1.637$).

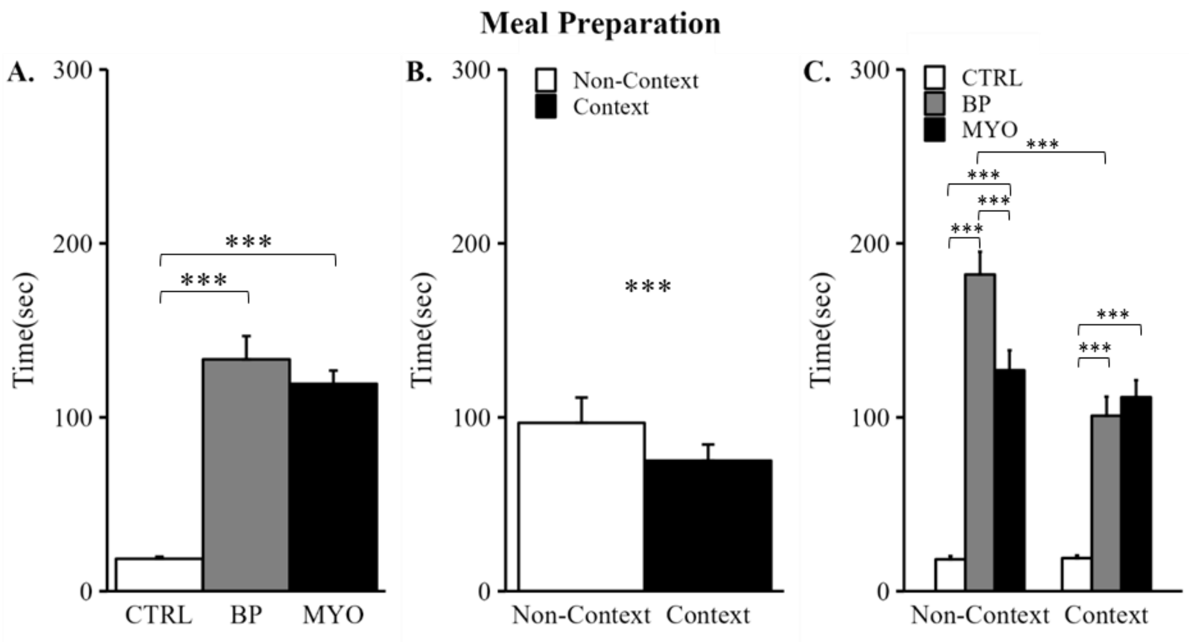


Fig. 28. Meal Preparation. **A.** Performance between prosthetic groups averaged across experimental conditions. **B.** Performance for the non-contextual condition and the contextual condition averaged across prosthetic groups . **C.** Performance for the non-contextual condition and the contextual condition for each prosthetic group . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

NASA-TLX

Mental Demand

A main effect was revealed for Group ($F(2, 45) = 3.516$, $p = 0.038$, $\eta p^2 = 0.133$). The post-hoc analysis revealed that the MYO group perceived higher mental demand than the CTRL group ($p = 0.030$, $d = 1.104$) when preparing the meal.

Physical Demand

A main effect was revealed for Group ($F(2, 61) = 5.374$, $p = 0.007$, $\eta p^2 = 0.149$) The post-hoc analyses revealed that the MYO group perceived higher physical demands when preparing the meal when compared to the CTRL group ($p = 0.010$, $d = 1.245$).

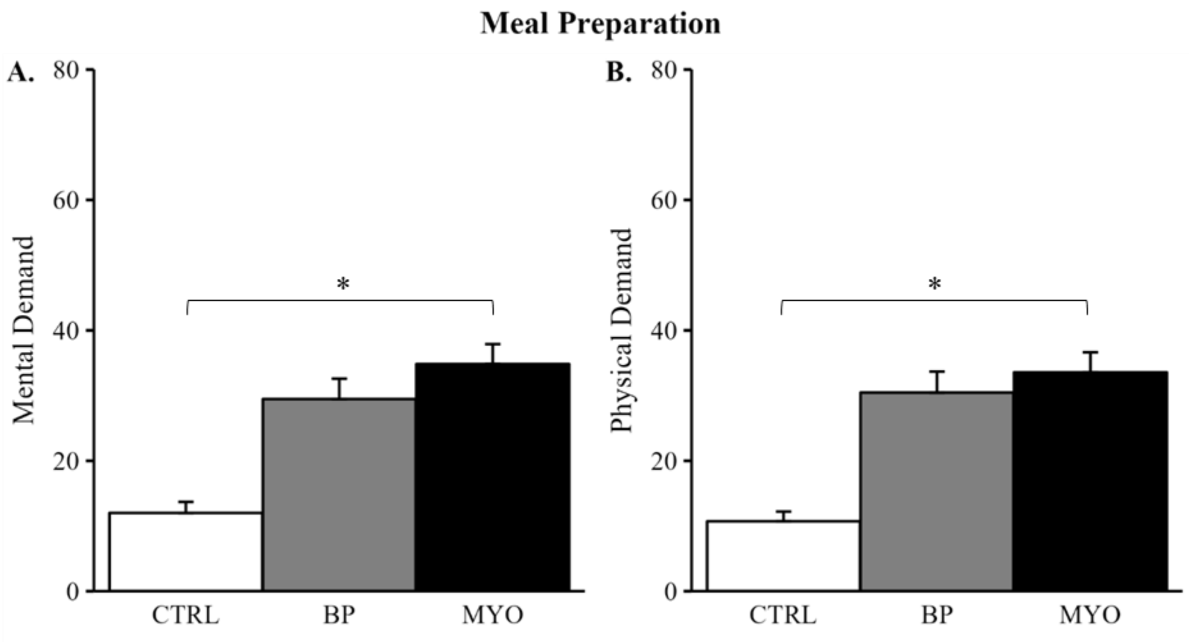


Fig. 29. Meal Preparation. **A.** Perceived mental demand between prosthetic groups averaged across experimental conditions. **B.** Perceived physical demand between prosthetic groups averaged across experimental conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Kinematics

Wrist

A main effect for Group ($F(2, 27) = 70.965$, $p < 0.001$, $\eta p^2 = 0.842$) was revealed. Post-hoc analyses revealed that the CTRL users had more movement smoothness when compared to the BP users ($p < 0.001$, $d = 3.736$) and MYO users ($p < 0.001$, $d = 4.05$). A main effect for Context ($F(1, 23) = 11.348$, $p = 0.003$, $\eta p^2 = 0.326$) was revealed such that participants experienced less movement smoothness when preparing the meal without contextual instructions.

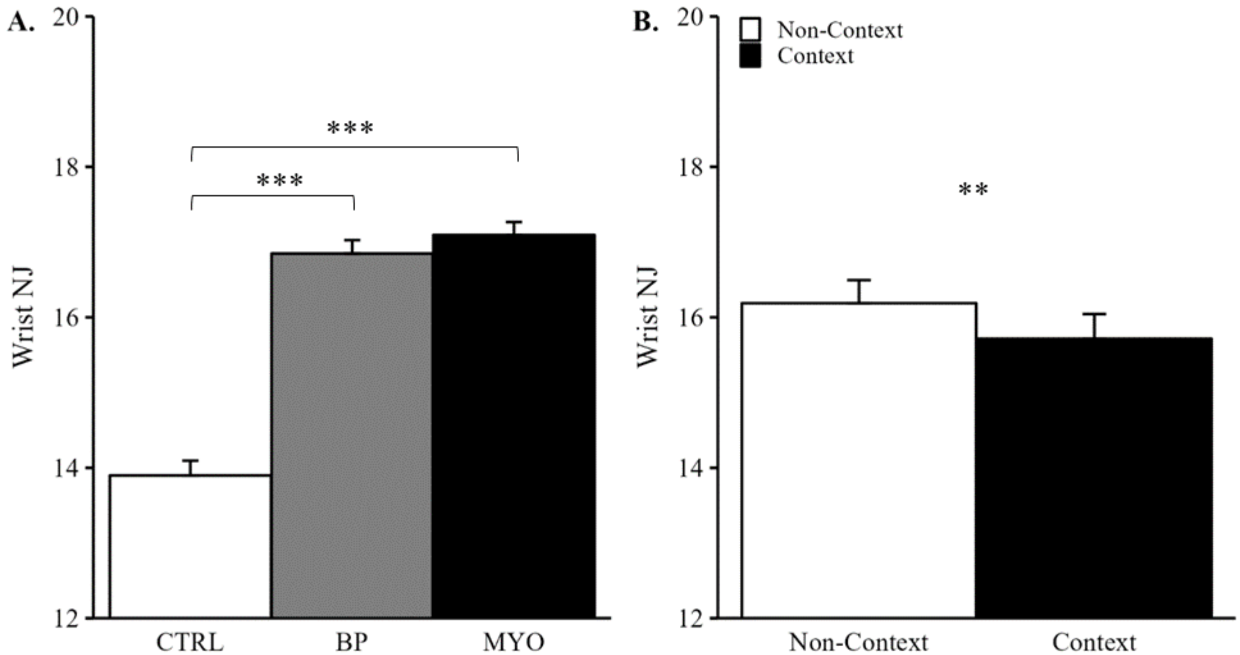


Fig. 30. Meal Preparation. **A.** Wrist normalized jerk for each prosthetic group averaged across experimental conditions. **B.** Wrist normalized jerk for the non-contextual instructional and contextual conditions averaged across all prosthetic groups . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Arm

` A main effect for Group ($F(2, 27) = 98.120$, $p < 0.001$, $\eta p^2 = 0.881$) was revealed. Post-hoc analyses revealed that the CTRL users had less arm movement variability when compared to the BP users ($p < 0.001$, $d = 4.173$) and MYO users ($p < 0.001$, $d = 5.231$). A main effect for Context ($F(1, 24) = 11.943$, $p = 0.002$, $\eta p^2 = 0.329$) was revealed such that participants experienced more arm movement variability when placing the food in the cupboard with non-contextual instructions.

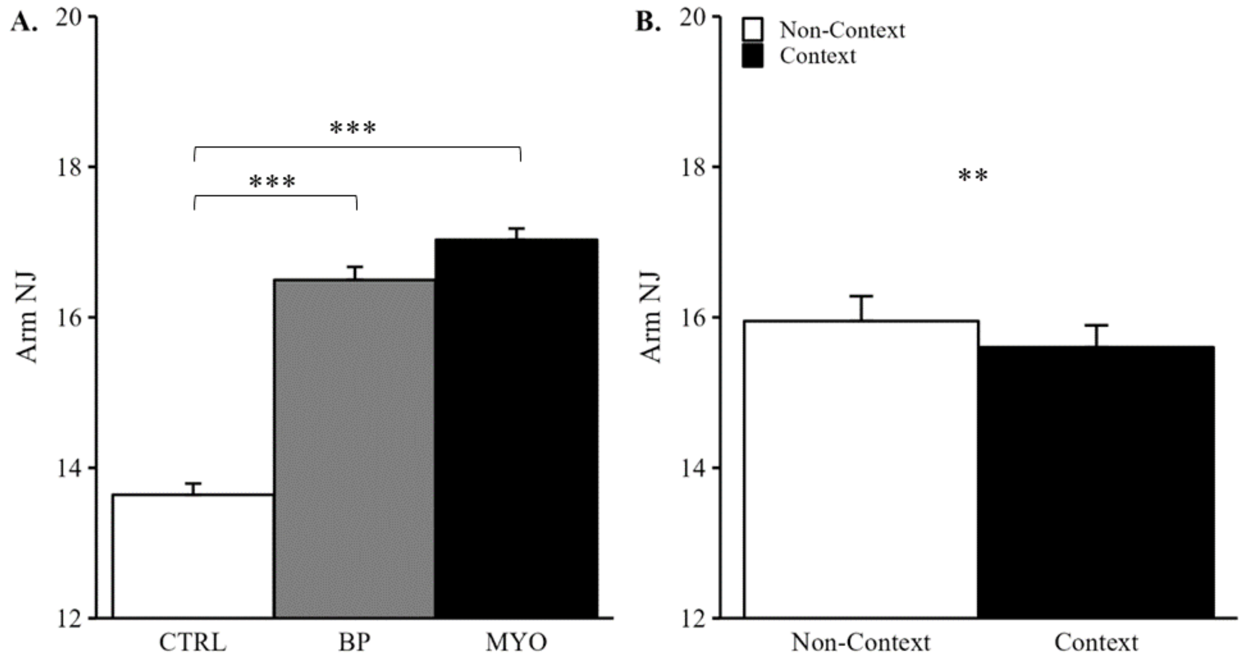


Fig. 31. Meal Preparation. **A.** Arm normalized jerk for each prosthetic group averaged across experimental conditions. **B.** Arm normalized jerk for the non-contextual instructional and contextual conditions averaged across all prosthetic groups . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Spectral EEG

Theta

A significant Group main effect was revealed ($F(2,27) = 6.738$, $p = 0.004$, $\eta p^2 = 0.335$).

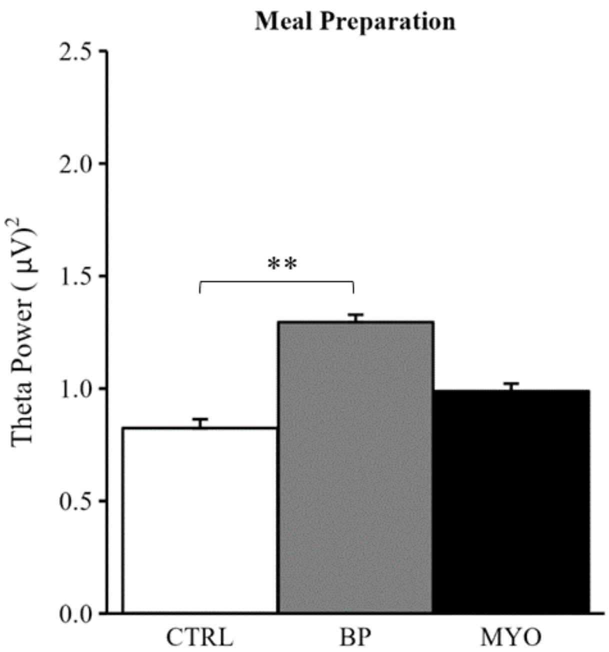


Fig. 32. Meal Preparation. Theta power for each prosthetic group averaged across experimental conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

This main effect was superseded by a significant Group x Region interaction ($F(8, 46) = 3.119$, $p = 0.002$, $\eta p^2 = 0.051$). The post-hoc analysis revealed that the CTRL group experienced an attenuation of theta power in the central ($p = 0.019$, $d = 1.211$), frontal ($p= 0.038$, $d = 1.009$), parietal ($p = 0.001$, $d = 1.414$) and temporal ($p < 0.001$, $d = 1.67$) when compared to the BP group. The BP group experienced a higher theta power in the temporal region ($p = .008$, $d = 1.127$) when compared to the MYO group.

The Group main effect was also superseded by a significant Group x Context interaction ($F(2, 464) = 6.98$, $p = 0.001$, $\eta p^2 = 0.029$). The post-hoc analysis revealed that the CTRL group experienced higher theta power during meal preparation with contextual instructions when compared to the non-contextual instructions ($p = 0.008$, $d = 0.293$). In contrast, the MYO group experienced lower theta power during meal preparation with contextual instructions when compared to the non-contextual instructions ($p = 0.017$, $d = 0.255$). When preparing the meal after receiving contextual instructions, the BP experienced higher theta when compared to the CTRL ($p = 0.020$, $d = 0.742$) and MYO ($p = 0.040$, $d = 0.746$) groups. When preparing the meal after receiving non-contextual instructions, the BP group experienced higher theta power ($p < 0.001$, $d = 1.22$) when compared to the CTRL group.

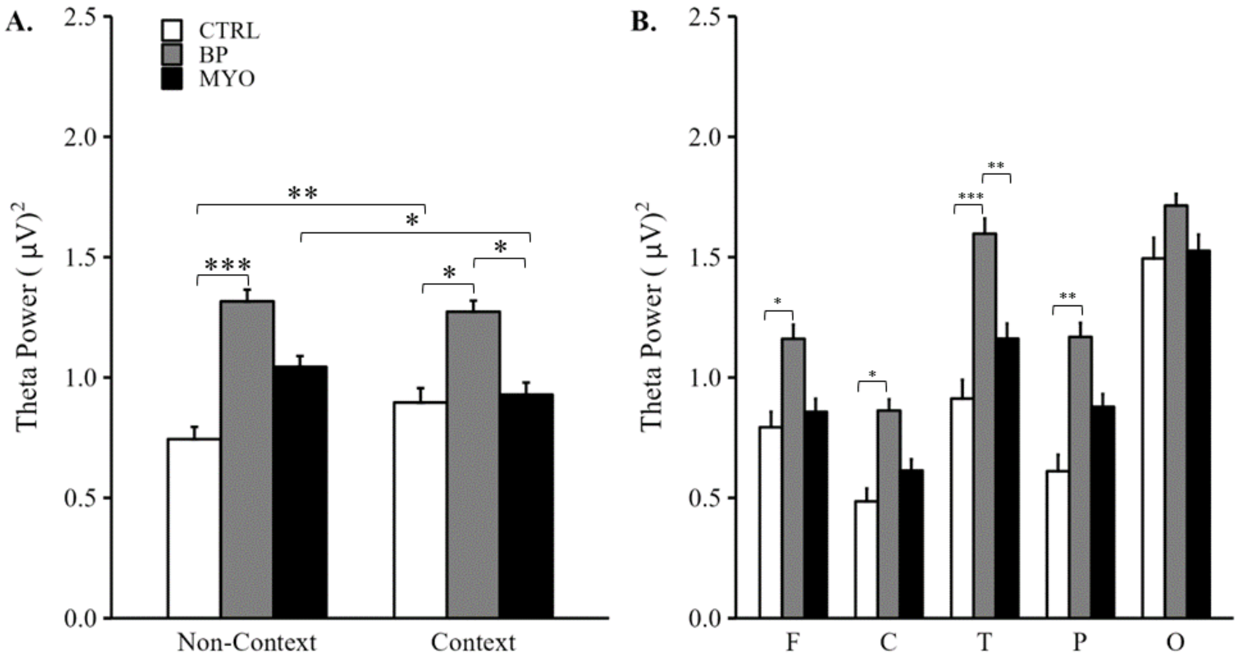


Fig. 33. Meal Preparation. **A.** Theta power between prosthetic groups for the non-contextual instructional and contextual conditions. **B.** Theta power between prosthetic groups averaged across experimental conditions for each region. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Low-Alpha

A significant Group main effect was revealed ($F(2, 27) = 9.117$, $p = 0.001$, $\eta p^2 = 0.619$). The Group main effect was superseded by a significant Group x Region x Hemisphere interaction ($F(8, 466) = 2.917$, $p = 0.003$, $\eta p^2 = 0.048$).

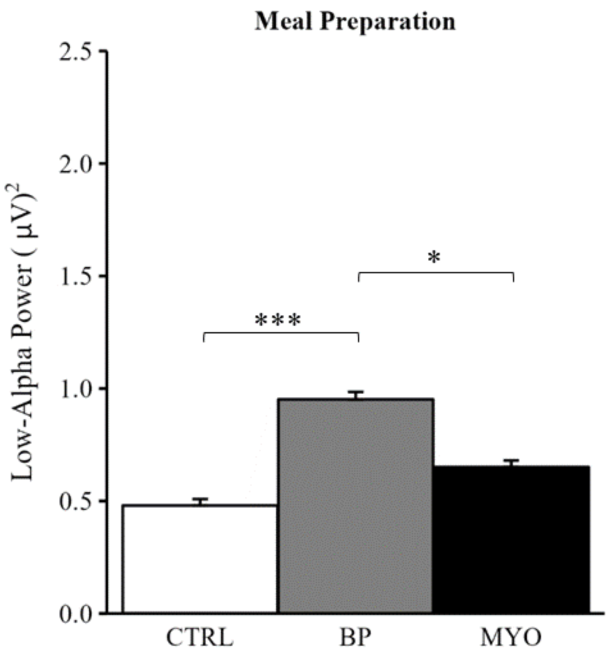


Fig. 34. Meal Preparation. **A.** Low-alpha power for each prosthetic group averaged across experimental conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The post-hoc analysis revealed that in the left hemisphere the BP group experienced greater low-alpha power in the central ($p = 0.044$. $d = 1.286$), frontal ($p = 0.022$. $d = 1.219$), parietal ($p = 0.002$, $d = 1.555$) and temporal ($p < 0.001$, $d = 3.400$) regions when compared to the CTRL group. The BP group also experienced greater low-alpha power in the left occipital ($p = 0.035$, $d = 0.889$) and left temporal ($p < 0.001$, $d = 2.178$) regions when compared to the MYO group.

The post-hoc analysis revealed that in the right hemisphere the BP group experienced greater low-alpha power in the frontal ($p= 0.034$. $d = 1.392$), occipital ($p = 0.015$, $d = 1.003$) parietal ($p = 0.001$, $d = 1.641$) and temporal ($p < 0.001$, $d = 1.911$) regions when compared to the CTRL group. The MYO group experienced greater low-alpha power in the right temporal region when compared to the CTRL group ($p = 0.006$, $d = 1.076$).

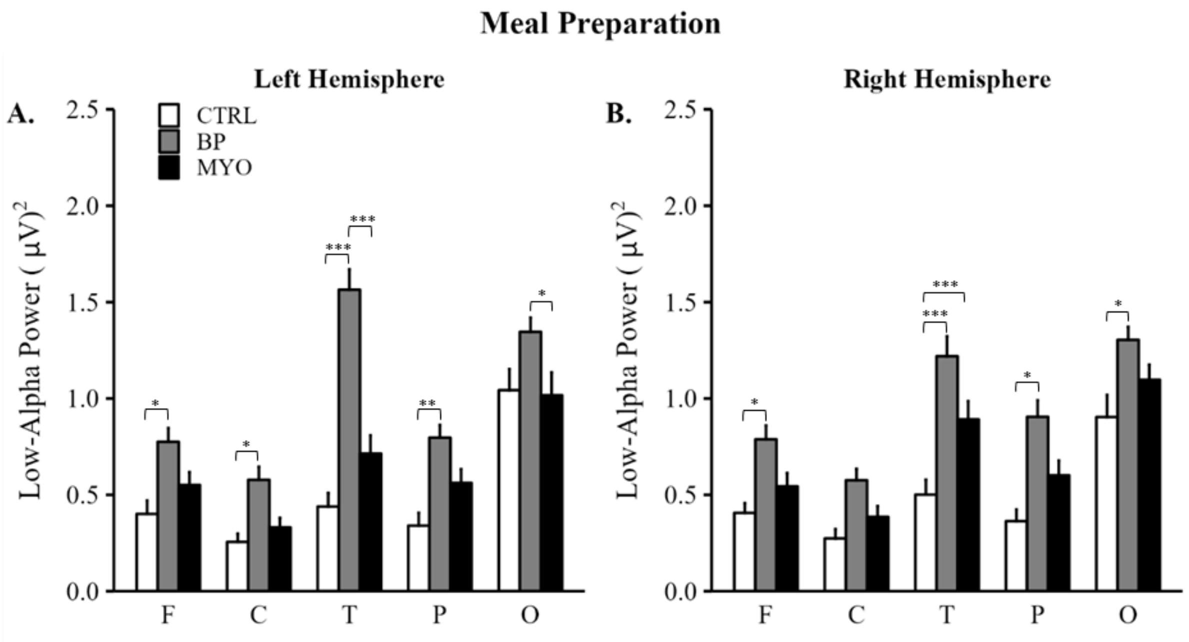


Fig. 35. Meal Preparation. **A.** Low-alpha power between prosthetic groups and across regions in the left hemisphere. **B.** Low-alpha power between prosthetic groups and across regions in the right hemisphere. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group .   F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The Group main effect was also superseded by a significant Group x Context x Region interaction ($F(8, 466) = 2.156$, $p = 0.030$, $\eta p^2 = 0.036$). The CTRL group experienced an attenuation of low-alpha power in the occipital region during the non-contextual condition when compared to the contextual instructional group ($p < 0.001$, $d = 1.197$).

The post-hoc analysis revealed that in the contextual condition, the BP group experienced greater low-alpha power in the central ($p = 0.046$, $d = 1.387$), parietal ($p = 0.007$, $d = 1.286$), and temporal ($p < 0.001$, $d = 2.191$) regions when compared to the CTRL group. The BP group experienced greater low-alpha power in the occipital ($p = 0.026$, $d = 0.946$) and temporal ($p < 0.001$, $d = 1.447$) regions when compared to the MYO group.

In the non-contextual condition, the BP group experienced greater low-alpha power in the frontal ($p = 0.005$, $d = 1.65$), occipital ($p < 0.001$, $d = 1.65$), parietal ($p = 0.007$, $d = 1.989$), temporal ($p < 0.001$, d = 2.684) regions when compared to the CTRL users. The MYO group experienced greater low-alpha power in the occipital (p = 0.040, d = 1.046), parietal (p = 0.035, d =1.253), temporal (p = 0.004, d = 1.209) regions when compared to the CTRL group. The BP group experiened greater low-alpha power in the temporal region when compared to the MYO group (p = 0.004, d = 1.314).

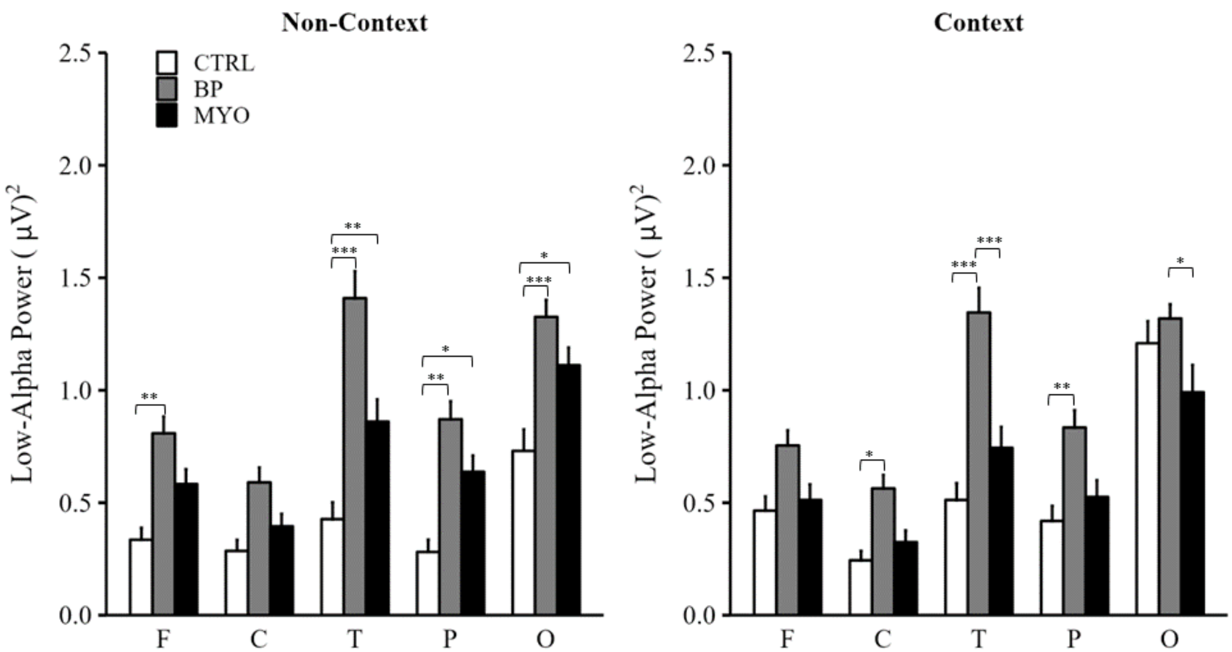


Fig. 36. Meal Preparation. **A.** Low-alpha power between prosthetic groups and across regions for the non-contextual condition. **B.** Low-alpha power between prosthetic groups and across regions for the contextual condition. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

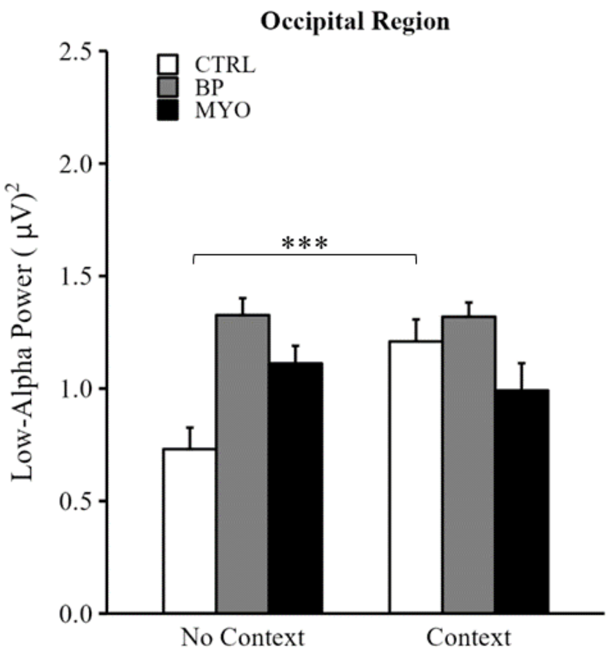


Fig. 37. Meal Preparation. Low-alpha power for each prosthetic group for the non-contextual instructional and contextual conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * p < 0.05, ** p < 0.01, *** p < 0.001.

High-Alpha

A significant main effect for Group was revealed (F(2, 27)) = 18.345, $p < 0.001$, $\eta p^2 = 0.579$).

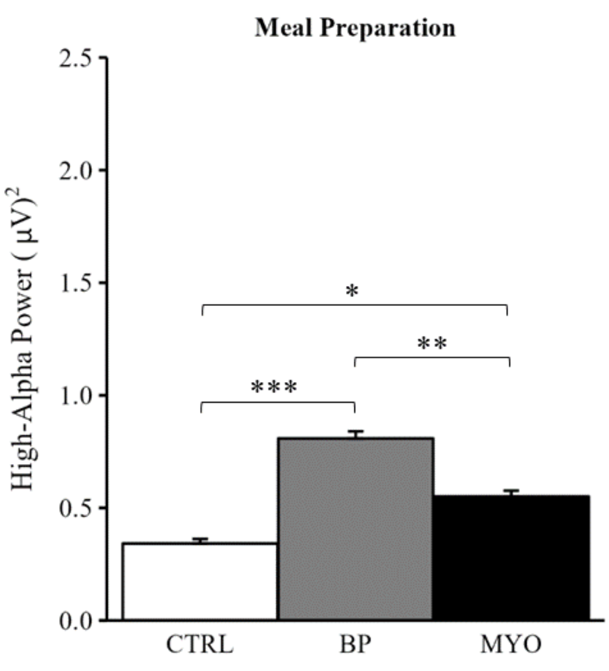


Fig. 38. Meal Preparation. High-alpha power for each prosthetic group averaged across experimental conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * p < 0.05, ** p < 0.01, *** p < 0.001.

The Group main effect was superseded by a significant Group x Region x Hemisphere interaction ($F(8, 460) = 4.261$, $p < 0.001$, $\eta p^2 = 0.069$). The post-hoc analysis revealed that in the left hemisphere, the CTRL group experienced lower high-alpha power in the left central (p = 0.031 , d = 1.389), frontal (p =

0.003, d = 1.385), occipital (p < 0.001 , d = 1.880), temporal (p < 0.001, d = 3.201) and parietal (p < 0.001 , d = 2.101) regions when compared to the BP group. The MYO group experienced lower high-alpha power in the occipital (p < 0.001 , d = 1.862) and temporal (p < 0.001 , d = 2.134) regions when compared to the BP group. In the right hemisphere the CTRL group experienced less high-alpha power in the central (p = 0.023 , d = 1.347), frontal (p = 0.029, d = 1.235), occipital (p < 0.001 , d = 2.471), temporal (p < 0.001, d = 1.931) and parietal (p < 0.001 , d = 2.181) regions. The MYO group experienced less high-alpha power in the right occipital (p = 0.015, d = 0.796), parietal (p = 0.016, d = 0.968) regions when compared to the BP group. The MYO group experienced greater alpha power in the right occipital (p < 0.001 , d = 1.692), parietal (p = 0.046 , d = 1.067) and temporal (p < 0.001 , d = 1.694) regions when compared to the CTRL group.

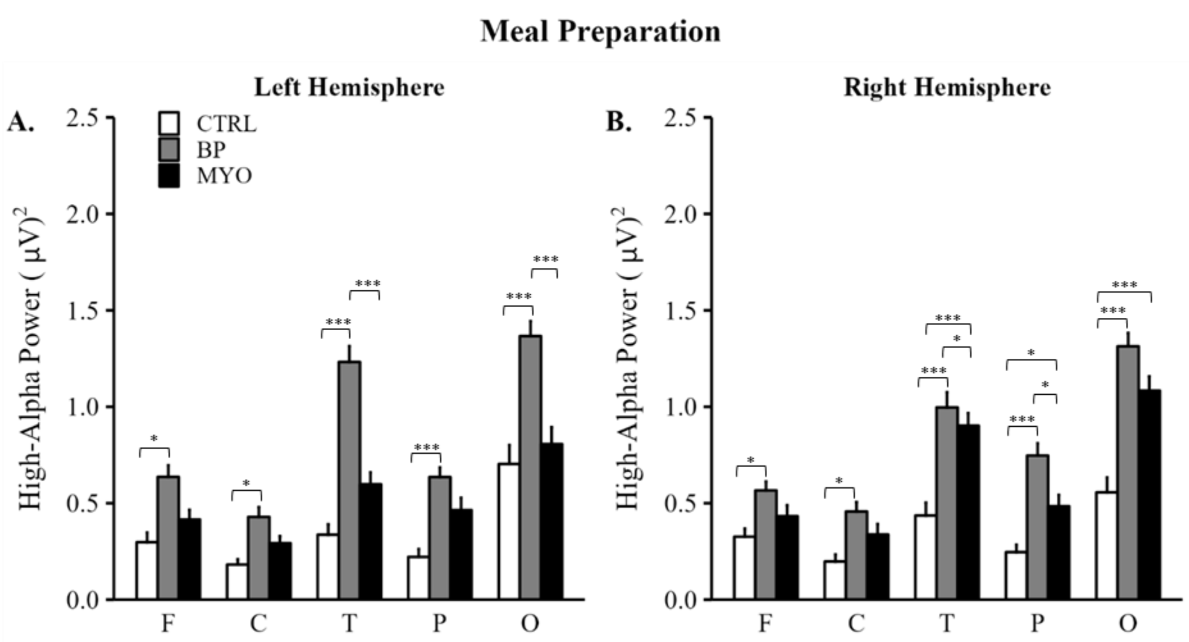


Fig. 39. Meal Preparation. **A.** High-alpha power between prosthetic groups and across regions for the left hemisphere. **B.** High-alpha power between prosthetic groups and across regions for the right hemisphere. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * p < 0.05, ** p < 0.01, *** p < 0.001.

The Group main effect was superseded by a significant Group x Context by Region interaction ($F(8, 60) = 3.108$, $p = 0.002$, $\eta p^2 = 0.05$). The CTRL group experienced an attenuation of high-alpha power in the occipital region during the non-contextual condition when compared to the contextual instructional group ($p < 0.001$, $d = 1.267$). The BP group experienced an attenuation of high-alpha power in the temporal region during the contextual condition when compared to the non-contextual instructional group ($p < 0.001$, $d = 0.849$). The MYO group experienced an attenuation of high-alpha power in the parietal ($p = 0.049$, $d = 0.416$) and occipital ($p = 0.029$, $d = 0.295$) regions during the contextual condition when compared to the non-contextual instructional group.

When comparing experimental conditions within each prosthetic group and cortical region, the post-hoc analysis revealed that the CTRL group experienced lower high-alpha power in the occipital region ($p < 0.001$, $d = 1.267$) during meal preparation with non-contextual instructions when compared to contextual instructions. The MYO group experienced lower high-alpha power in the occipital ($p = 0.029$, $d = 0.295$) and parietal ($p = 0.049$, $d = 0.416$) regions during the non-contextual condition when compared to the contextual condition. The BP group experienced lower high-alpha power in the temporal region($p < 0.001$, $d = 0.849$) during meal preparation with non-contextual instructions when compared to contextual instructions.

When comparing prosthetic groups within experimental conditions and cortical regions, the post -hoc analysis revealed that when preparing the meal with contextual instructions, the CTRL group experienced lower high-alpha power in the central ($p = 0.023$, $d = 1.488$), frontal ($p = 0.030$, $d = 1.364$), occipital ($p < 0.001$, $d = 1.502$), parietal ($p < 0.001$, $d = 1.886$), and temporal ($p < 0.001$, $d = 2.121$) regions when compared to the BP group. The CTRL group experienced lower high-alpha power in the temporal region when compared to the MYO group ($p = 0.014$, $d = 0.976$). The BP group experienced greater high-alpha power in the occipital ($p < 0.001$, $d = 1.251$), parietal ($p = 0.009$, $d = 1.034$) and temporal ($p = 0.024$, $d = 0.996$) regions when compared to the MYO group.

When preparing the meal with non-contextual instructions, the CTRL group experienced lower high-alpha power in the in the central ($p = 0.036$, $d = 1.251$), frontal ($p = 0.003$, $d = 1.315$), occipital (p

< 0.001 , d = 3.594), parietal (p < 0.001 , d = 2.407), and temporal (p < 0.001 , d = 3.071) regions when compared to the BP group. The CTRL group experienced lower high-alpha power in the occipital (p < 0.001 , d = 2.03), parietal (p = 0.004 , d = 1.657) , and temporal (p < 0.001, d = 1.489) regions when compared to the MYO group. The BP group experienced greater high-alpha power in the occipital (p = 0.008 , d = 1.197) and temporal (p < 0.001 , d = 1.620) regions when compared to the MYO group.

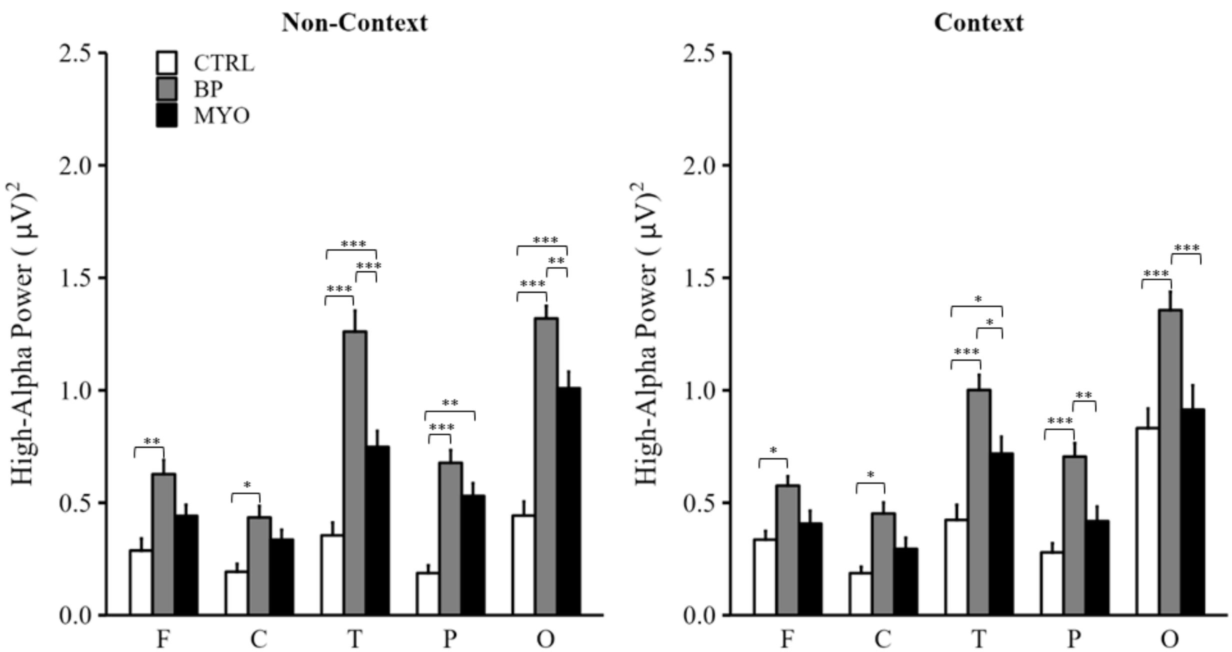


Fig. 40. Meal Preparation. **A.** High-alpha power between prosthetic groups and across regions for the non-contextual condition. **B.** High-alpha power between prosthetic groups and across regions for the contextual condition. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * p < 0.05, ** p < 0.01, *** p < 0.001.

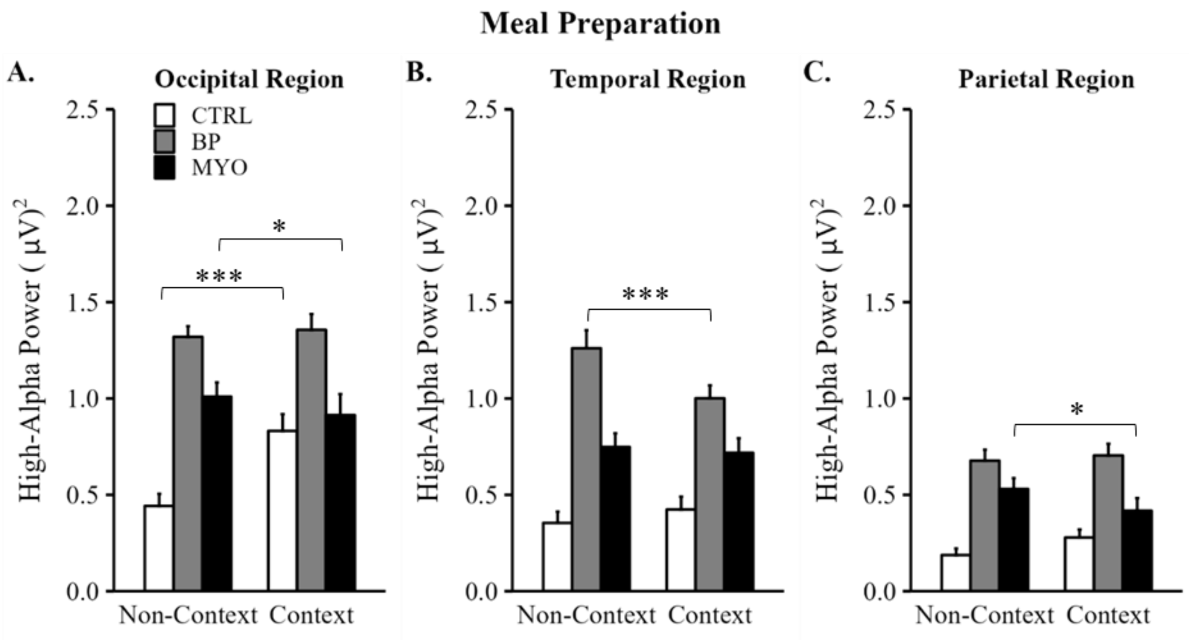


Fig. 41. Meal Preparation. **A.** High-alpha power in the occipital region between prosthetic groups for the non-contextual instructional and contextual conditions. **B.** High-alpha power in the temporal region between prosthetic groups for the non-contextual instructional and contextual conditions. **C.** High-alpha power in the parietal region between prosthetic groups for the non-contextual instructional and contextual conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Beta

A significant Group main effect was revealed ($F(2, 27)$) = 10.441, $p < 0.001$, $\eta p^2 = 0.439$).

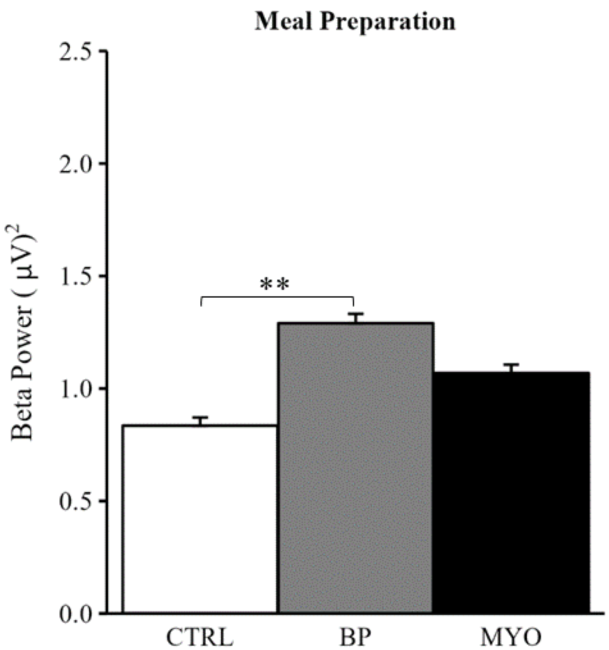


Fig. 42. Meal Preparation. Beta power for each prosthetic group averaged across experimental conditions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The Group main effect was superseded by a significant Group x Context interaction ($F(2, 468) = 19.62$, $p < 0.001$, $\eta p^2 = 0.077$). The post-hoc analysis revealed that the CTRL group experienced a reduction in beta power ($p < 0.001$, $d = 0.37$) when preparing the meal with non-contextual instructions when compared to contextual instructions. In contrast, the MYO group experienced a significant elevation in beta power when preparing the meal non-instructions when compared to contextual instructions ($p < 0.001$, $d = 0.323$). The BP group experienced higher beta power when preparing the meal after receiving contextual instructions when compared to the CTRL ($p = 0.004$, $d = 0.692$) and MYO groups ($p = 0.020$, $d = 0.592$). The CTRL group experienced lower beta power when preparing the meal after receiving non-contextual instructions when compared to the BP ($p < 0.001$, $d = 1.003$) and MYO ($p < 0.001$, $d = 0.837$) groups.

The Group main effect was also superseded by significant Group x Region interaction($F(8, 468) = 4.238$, $p < 0.001$, $\eta p^2 = 0.068$). Post-hoc analyses revealed that the BP group experienced greater beta power in the frontal ($p = 0.032$, $d = 0.861$) and occipital ($p < 0.001$, $d = 1.15$), parietal ($p = 0.001$, $d = 1.43$) and temporal ($p < 0.001$, $d = 1.546$) regions when compared to the CTRL group. The BP group experienced greater beta power in the temporal region ($p = 0.031$, $d = 0.892$) when compared to the MYO group. The MYO group experienced greater beta power in the parietal ($p = 0.023$, $d = 0.931$) and temporal ($p = 0.004$, $d = 0.734$) regions when compared to the CTRL group.

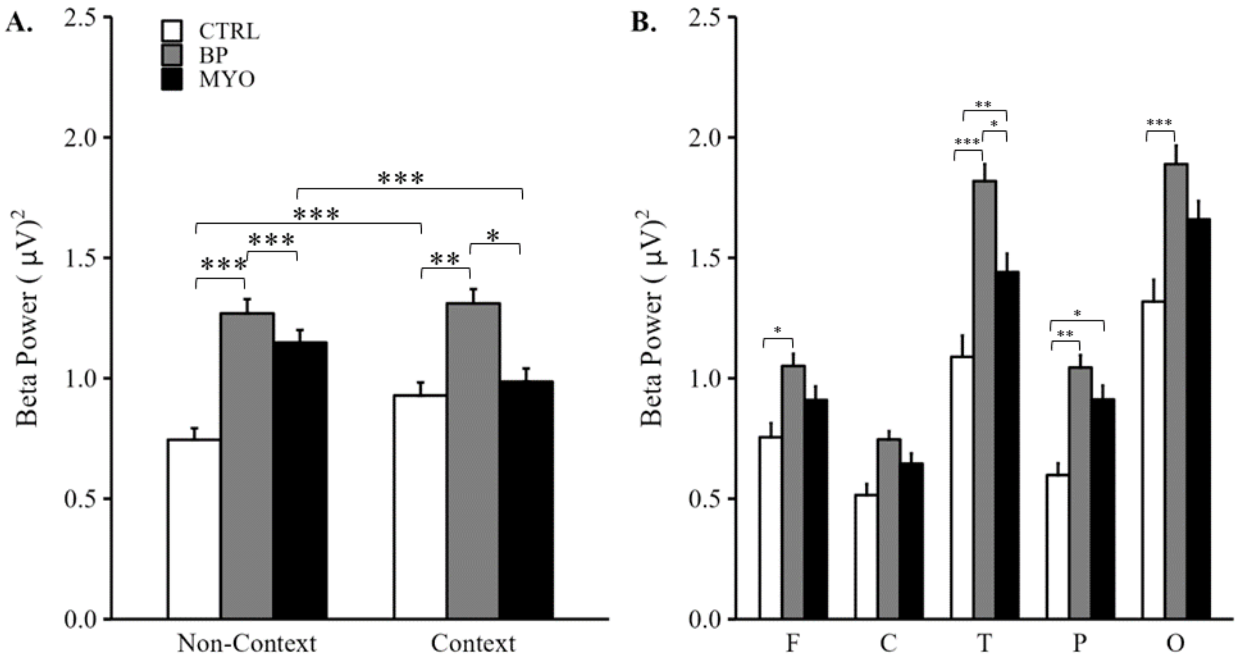


Fig. 43. Meal Preparation. **A.** Beta power between prosthetic groups for the non-contextual instructional and contextual conditions. **B.** Beta power between prosthetic groups averaged across experimental conditions for each region. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Medication Management

Performance

A main effect was revealed for Group ($F(2, 47) = 79.844$, $p < 0.001$, $\eta p^2 = 0.773$). The post-hoc analysis revealed that the BP ($p < 0.001$, $d = 2.25$) and MYO ($p < 0.001$, $d = 4.474$) users required significantly more time to prepare the pillbox when compared to the CTRL group. Additionally, the MYO group required significantly more time than the BP group to prepare the pillbox ($p < 0.001$, $d = 1.772$) A main effect was revealed for Context ($F(1, 47) = 9.578$, $p = 0.003$, $\eta p^2 = 0.169$) such that participants took significantly more time to prepare the pillbox with contextual demands compared to without contextual demands.

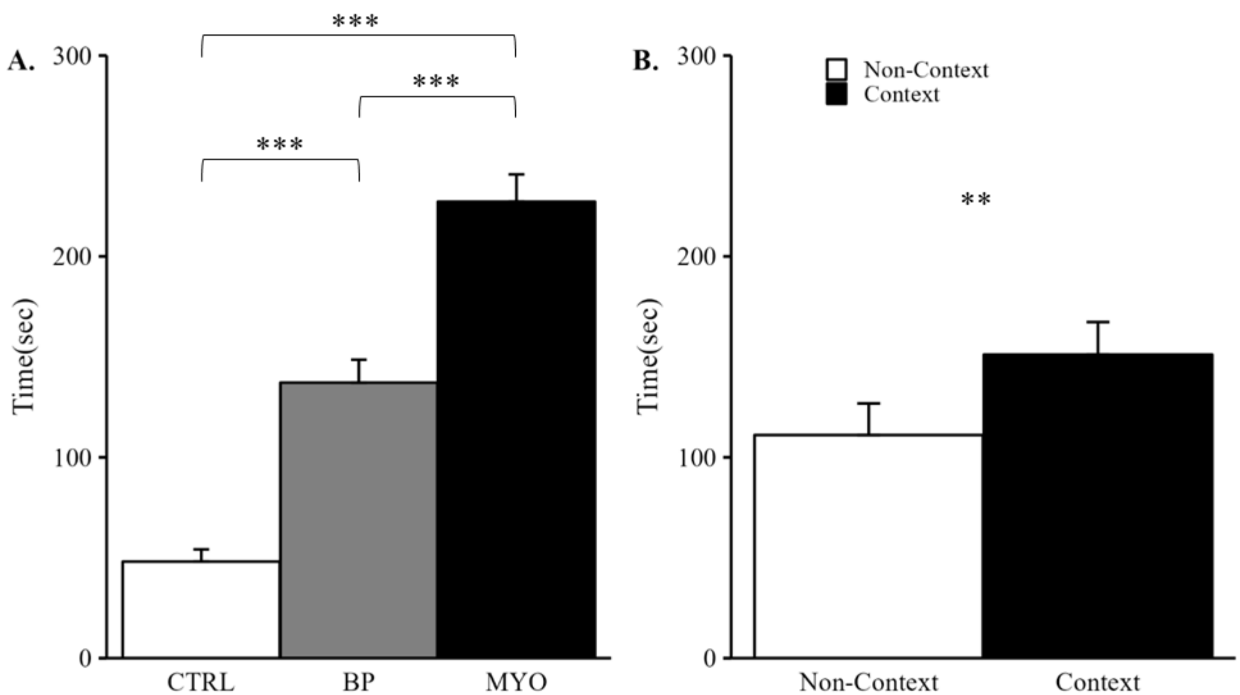


Fig. 44. Medication Management. **A.** Performance between prosthetic groups averaged across experimental conditions. **B.** Performance for the non-contextual instructional and contextual condition averaged across prosthetic groups . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

NASA-TLX

Mental Demand

A main effect was revealed for Context ($F(1, 157) = 34.761$, $p < 0.001$, $\eta p^2 = 0.181$). The main effect was superseded by a Group x Context interaction ($F(2, 157) = 4.72$, $p = 0.01$, $\eta p^2 = 0.057$). The post-hoc analysis revealed that when filling the pillbox after receiving contextual instructions, the CTRL ($p < 0.001$, $d = 1.73$) and BP ($p < 0.001$, $d = 0.651$) groups experienced more mental demand when compared to filling the pillbox after receiving the non-contextual instructions. The MYO group experienced higher perceived mental demands when compared to the CTRL group ($p = 0.002$, $d = 1.321$) when preparing the pillbox with non-contextual instructions.

Physical Demand

A main effect was revealed for Group ($F(2, 41) = 5.488$, $p = 0.008$, $\eta p^2 = 0.210$). The post-hoc analysis revealed that the MYO group perceived higher physical demands when filling the pillbox when compared to the CTRL group ($p = 0.008$, $d = 1.286$).

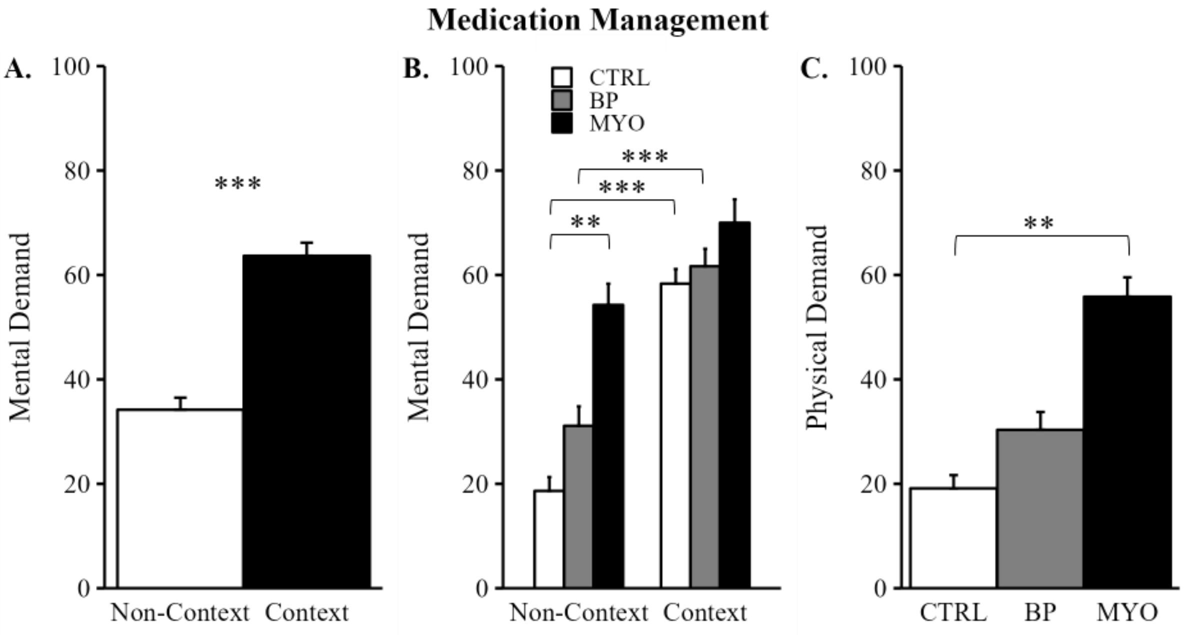


Fig. 45. Medication Management. **A.** Perceived mental demand for each for the non-contextual instructional and contextual conditions. **B.** Perceived mental demand for each prosthetic group for the non-contextual instructional and contextual conditions. **C.** Perceived physical demand averaged across the experimental conditions for each prosthetic group . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Kinematics

Wrist

A main effect for Group ($F(2, 46) = 164.658$, $p < 0.001$, $\eta p^2 = 0.877$) and Context ($F(1, 46) = 23.029$, $p < 0.001$, $\eta p^2 = 0.334$) was revealed.

The main effects were superseded by a significant Group x Context interaction ($F(2, 46) = 5.673$, $p = 0.006$, $\eta p^2 = 0.198$). Post-hoc analyses revealed that the CTRL users experienced more wrist movement smoothness during the medication task with contextual instructions when compared to the BP ($p < 0.001$, $d = 3.072$) and MYO ($p < 0.001$, $d = 5.775$) groups. Additionally, the CTRL group experienced less wrist movement smoothness when filling the pillbox after receiving contextual instructions when compared to non-contextual instructions ($p < 0.001$, $d = 2.995$). The MYO group experienced less wrist movement smoothness during the medication task with contextual instructions when compared to the BP group ($p < 0.001$, $d = 2.895$). The CTRL users experienced more wrist movement smoothness during the medication task without contextual instructions when compared to the BP ($p < 0.001$, $d = 3.072$) and MYO ($p < 0.001$, $d = 5.775$) groups. The MYO group experienced less wrist movement smoothness during the medication task with non-contextual instructions when compared to the BP group ($p = 0.001$, $d = 2.895$).

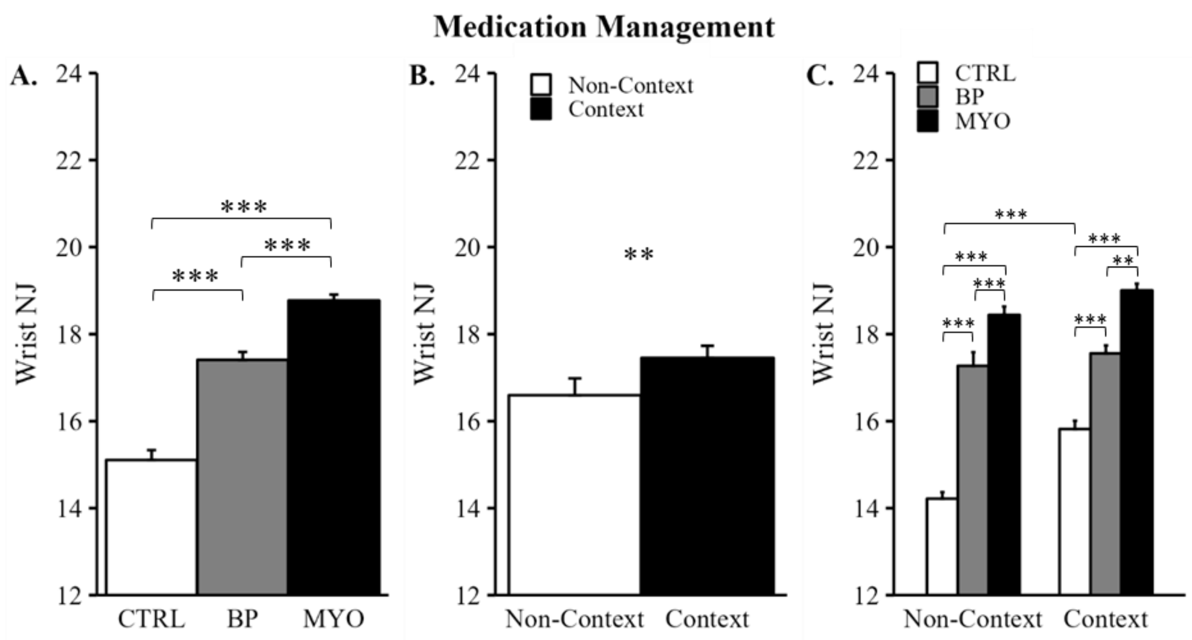


Fig. 46. Medication Management. **A.** Wrist normalized jerk for all groups without contextual demands with and with contextual demands. **B.** Wrist normalized jerk averaged across groups for the non-contextual instructional and contextual conditions. **C.** Wrist normalized jerk averaged across experimental conditions for each prosthetic group . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Arm

A main effect for Group ($F(2, 48) = 122.181$, $p < 0.001$, $\eta p^2 = 0.836$) and for Context ($F(1, 48) = 19.488$, $p < 0.001$, $\eta p^2 = 0.289$) was revealed. These main effects were superseded by a Group x Context interaction ($F(2, 48) = 5.349$, $p = 0.008$, $\eta p^2 = 0.182$). Post-hoc analyses that during the medication task with contextual instructions, the CTRL group experienced more arm movement smoothness when compared to the BP ($p = 0.001$, $d = 1.86$) and MYO ($p < 0.001$, $d = 4.613$) groups. The BP group experienced more arm movement smoothness when compared to the MYO group ($p < 0.001$, $d = 2.981$). Additionally, the CTRL group experienced less arm movement smoothness when filling the pillbox after contextual instructions when compared to non-contextual instructions ($p < 0.001$, $d = 2.242$). When filling the pillbox after receiving non-contextual instructions, the CTRL group experienced more arm movement smoothness when compared to the BP ($p < 0.001$, $d = 3.116$) and MYO ($p < 0.001$, $d = 5.915$) groups. The BP group experienced more arm movement smoothness during the medication task with non-contextual instructions when compared to the MYO group ($p < 0.001$, $d = 2.224$).

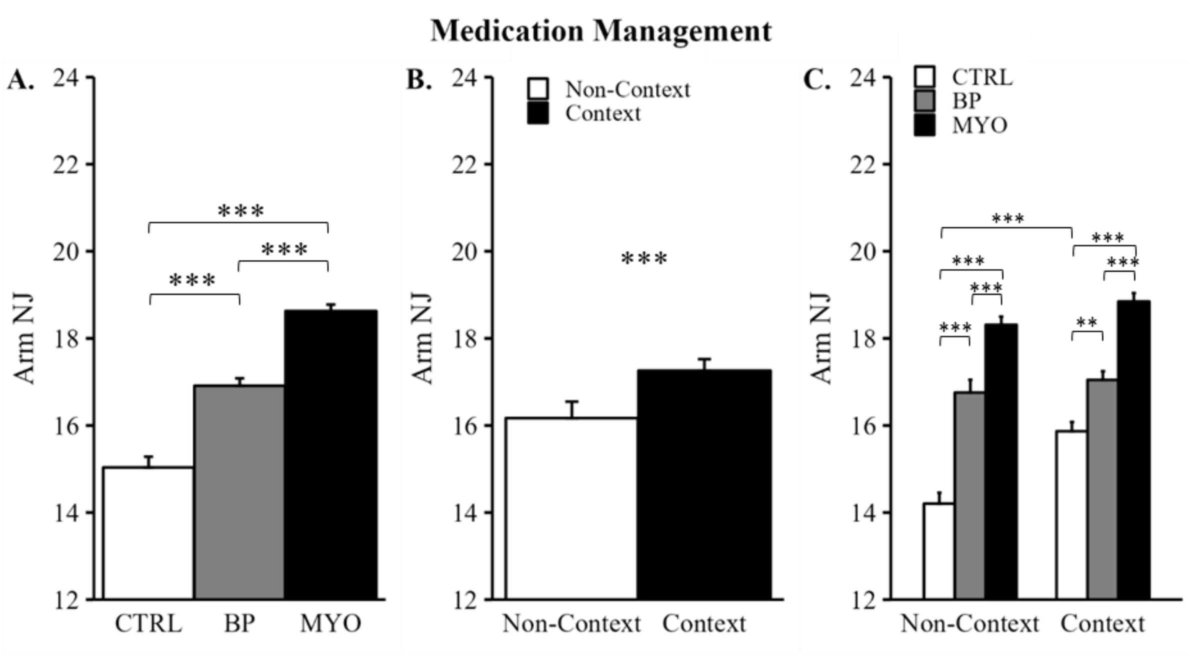


Fig. 47. Medication Management. **A.** Arm normalized jerk for all groups without contextual demands with and with contextual demands. **B.** Arm normalized jerk averaged across groups for the non-contextual instructional and

contextual conditions. **C.** Arm normalized jerk averaged across experimental conditions for each prosthetic group . CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Spectral EEG

Theta

A significant Group main effect was revealed ($F(2, 27) = 4.326$, $p = 0.023$, $\eta p^2 = 0.243$). A significant Context main effect was revealed ($F(1, 470) = 8.421$, $p = 0.004$, $\eta p^2 = 0.018$). These main effects were superseded by a significant Group x Context x Region x Hemisphere interaction ($F(8, 470) = 2.42$, $p = 0.014$, $\eta p^2 = 0.04$).

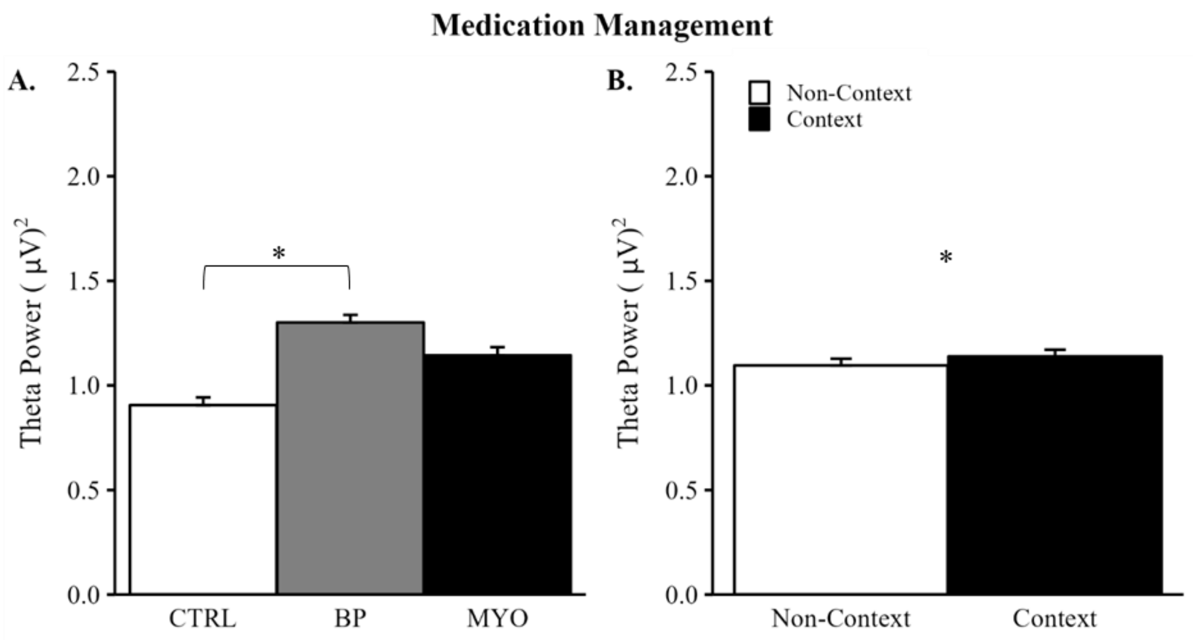


Fig. 48. Medication Management. **A.** Theta power between prosthesis groups averaged across experimental conditions. **B.** Theta power for each experimental condition averaged across prosthesis groups/ CTRL- Control group, BP- Body-powered prosthesis group, MYO- Myoelectric prosthesis group. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

For the left hemisphere, the post-hoc analysis revealed that when filling the pillbox during the non-contextual condition the CTRL group experienced an attenuation of theta power in the left occipital region ($p = 0.034$, $d = 0.548$) when compared to the contextual condition.

For the right hemisphere, the post-hoc analysis revealed that when filling the pillbox during the non-contextual condition, the CTRL group experienced an attenuation of theta power in the right occipital ($p= 0.004$, $d = 0.814$) and right temporal ($p < 0.001$, $d = 1.219$) regions when completing the task with non-contextual instructions when compared to contextual instructions. The BP group experienced an attenuation of theta power in the right temporal region ($p = 0.034$, $d = 0.757$) when completing the task with contextual instructions when compared to the non-contextual instructions.

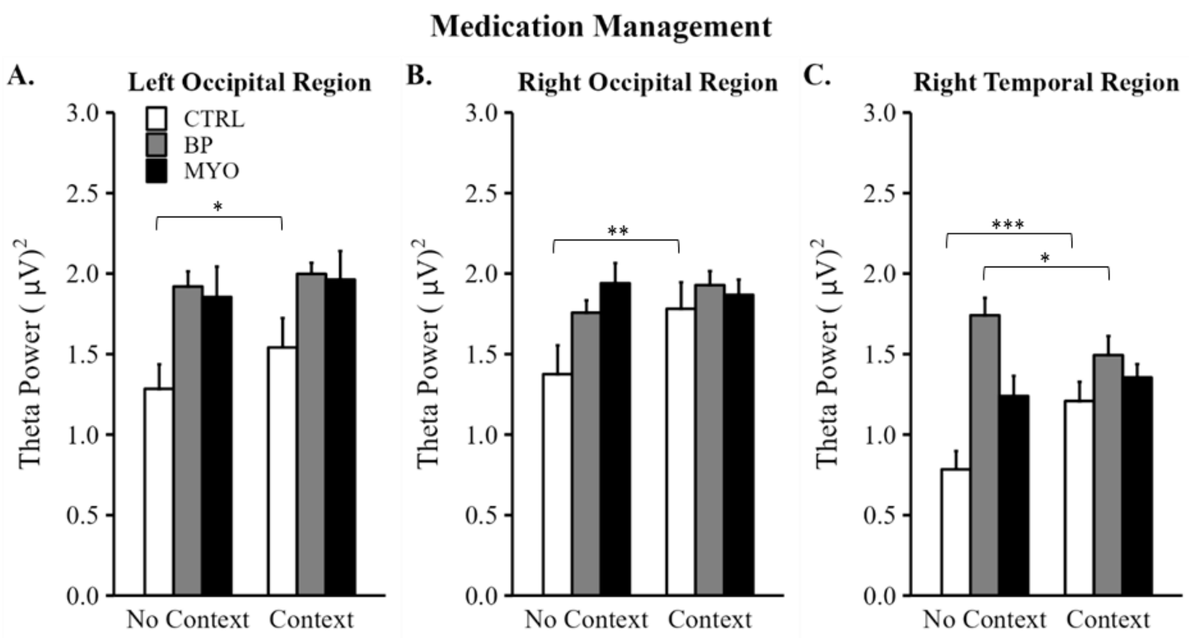


Fig. 49. Medication Management. **A.** Theta power for each experimental condition and prosthesis group for the left occipital region. **B.** Theta power for each experimental condition and prosthesis group for the right temporal region. **C.** Theta power for each experimental condition and prosthesis group for the right temporal region. CTRL- Control group, BP- Body-powered prosthesis group, MYO- Myoelectric prosthesis group. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

For the contextual condition in the left hemisphere, the BP group experienced higher theta power in the temporal region when compared to the CTRL ($p < 0.001$, $d = 2.132$) and MYO ($p = 0.006$, $d = 0.503$) groups.

For the non-contextual condition in the left hemisphere, the BP group experienced higher theta power in the occipital region when compared to the CTRL group ($p = 0.009$, $d = 0.883$).

For the contextual condition in the right hemisphere the BP group experienced higher theta power in the parietal region when compared to the CTRL group ($p = 0.015$, $d = 1.729$).

For the non-contextual condition in the right hemisphere, the CTRL group experienced lower theta power in the temporal region when compared to the BP ($p < 0.001$, $d = 2.892$) and MYO ($p = 0.009$, $d = 1.268$) groups. The BP group experienced higher theta power in the temporal region when compared to the MYO group ($p = 0.015$, $d = 1.432$).

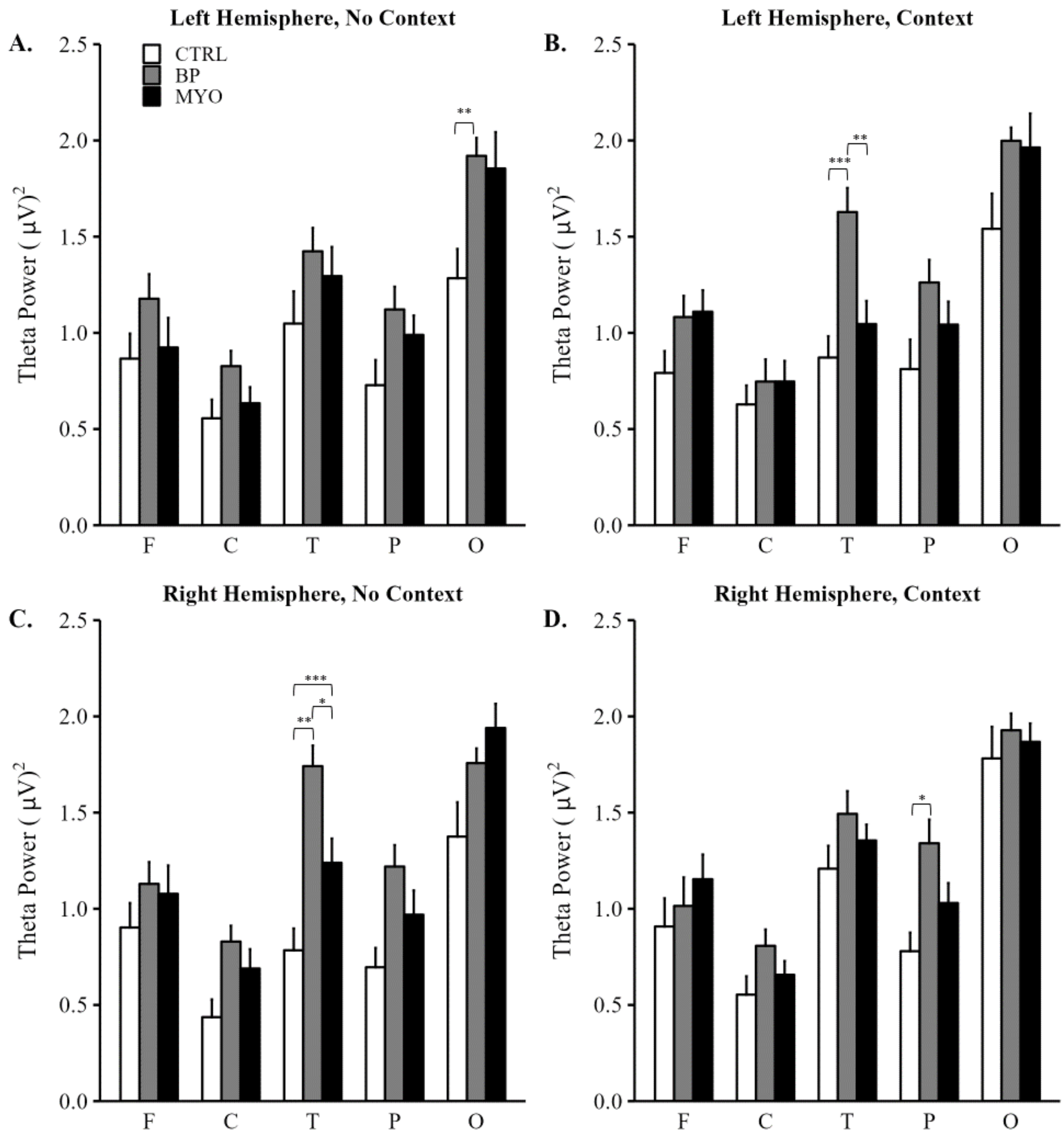


Fig. 50. Medication Management. **A.** Theta power between prosthesis groups for each cortical region in the left hemisphere during the non-contextual condition. **B.** Theta power between prosthesis groups for each cortical region in the right hemisphere during the non-contextual condition. **C.** Theta power between prosthesis groups for each cortical region in the left hemisphere during the non-contextual condition. **D.** Theta power between prosthesis groups for each cortical region in the right hemisphere during the contextual condition. CTRL- Control group, BP-

Body-powered prosthesis group, MYO- Myoelectric prosthesis group. F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Low-Alpha

A significant Group main effect was revealed ($F(2, 27) = 4.807$, $p = 0.016$, $\eta p^2 = 0.263$).

This main effect was superseded by a significant Group x Region interaction ($F(2, 467) = 5.444$, $p = 0.005$, $\eta p^2 = 0.023$). The post- hoc analysis revealed that the BP group experienced greater low-alpha power in the occipital ($p = 0.007$. $d = 1.168$) , parietal($p = 0.011$. $d = 1.213$) and temporal ($p < 0.001$. $d = 1.637$) regions when compared to the CTRL group when completing both experimental conditions of the medication management activity. The MYO group also experienced greater low-alpha power in the temporal region ($p = 0.011$. $d = 0.916$) when compared to the CTRL group.

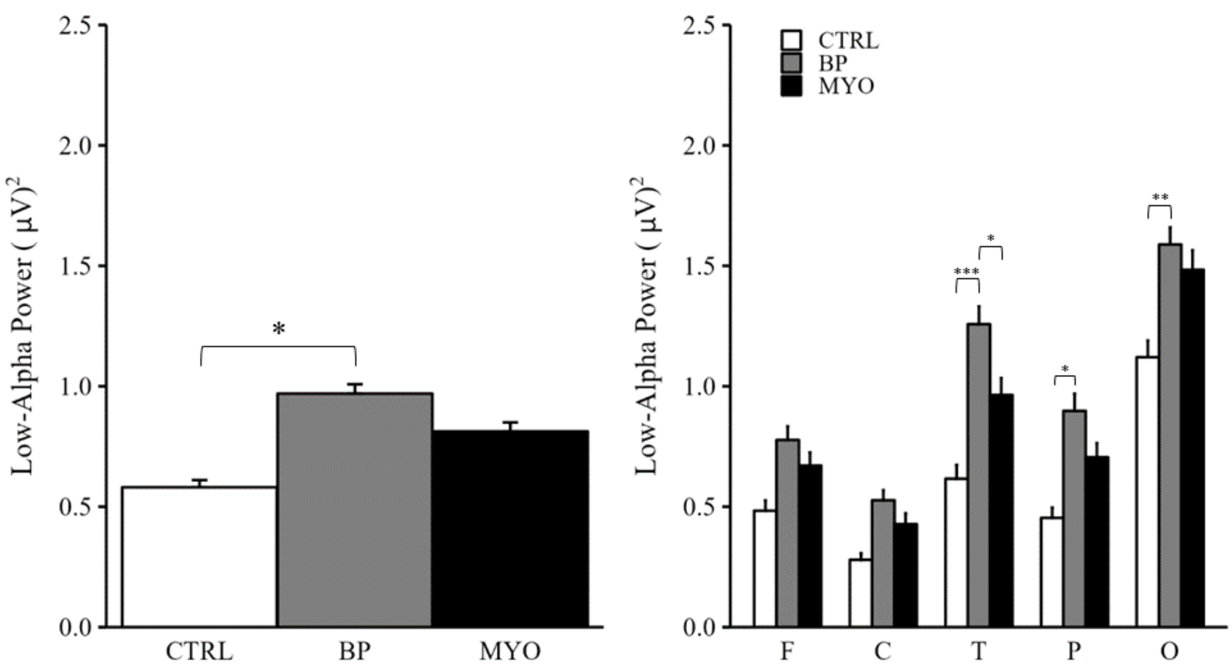


Fig. 51. Medication Management. **A.** Low-alpha power between prosthetic groups averaged across experimental conditions. **B.** Low-alpha power averaged across experimental conditions between prosthetic groups and across cortical regions. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

The Group main effect was also superseded by a significant Group x Condition x Hemisphere interaction ($F(2, 467) = 3.179$, $p = 0.043$, $\eta p^2 = 0.013$). The post-hoc analysis revealed that when the CTRL group placed the pills in the pillbox with non-contextual instructions, they experienced an attenuation of low-alpha power in the right hemisphere when compared to receiving contextual instructions ($p < 0.001$, $d = 0.311$). Conversely, the BP group experienced an attenuation of low-alpha power in the right hemisphere when they filled the pillbox with contextual instructions ($p = 0.039$, $d = 0.211$) when compared to non-contextual instructions. When filling the pillbox after receiving contextual instructions, the BP group experienced higher low-alpha power when compared to the CTRL group in the left hemisphere ($p = 0.018$, $d = 0.815$). When filling the pillbox after receiving non-contextual instructions, the BP group experienced higher low-alpha power when compared to the CTRL group in the left ($p = 0.008$, $d = 0.938$) and right ($p = 0.002$, $d = 1,059$) hemispheres.

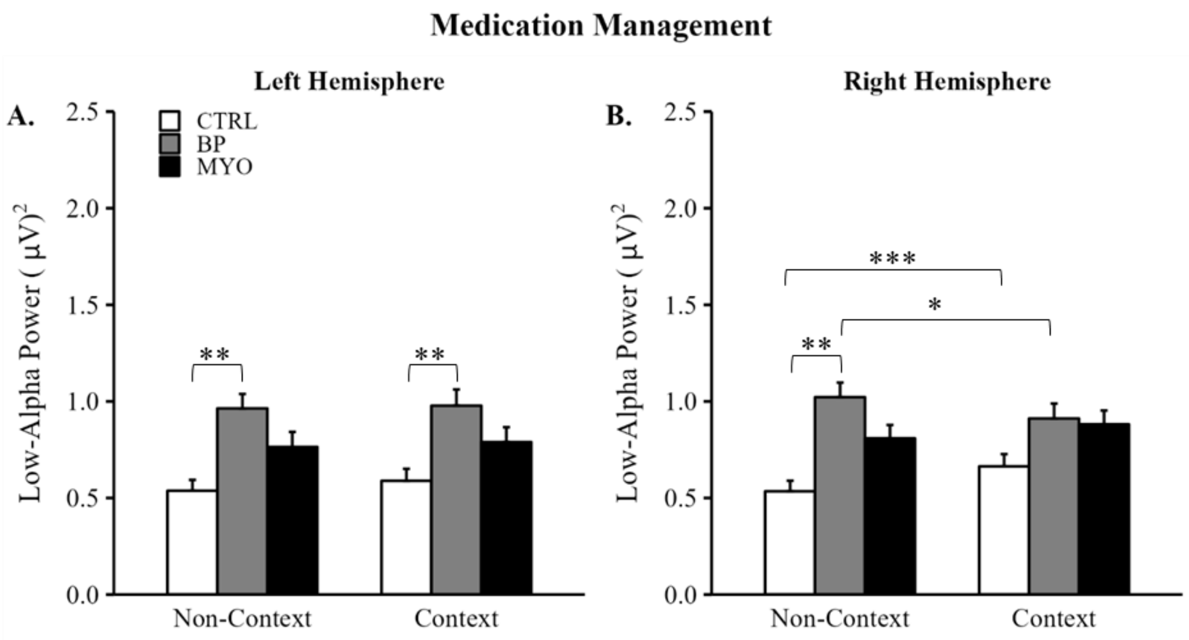


Fig. 52. Medication Management. **A.** Low-alpha power between prosthetic groups for each experimental condition in the left hemisphere. **B.** Low-alpha power between prosthetic groups for each experimental condition in the left hemisphere. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

High-Alpha

A significant Group main effect was revealed ($F(2, 27) = 10.186$, $p = 0.001$, $\eta p^2 = 0.435$). A significant Context main effect was also revealed ($F(1, 457) = 4.961$, $p = 0.026$, $\eta p^2 = 0.011$). These main effects were superseded by a significant Context x Group x Region x Hemisphere interaction ($F(8, 457) = 2.268$, $p = 0.022$, $\eta p^2 = 0.038$).

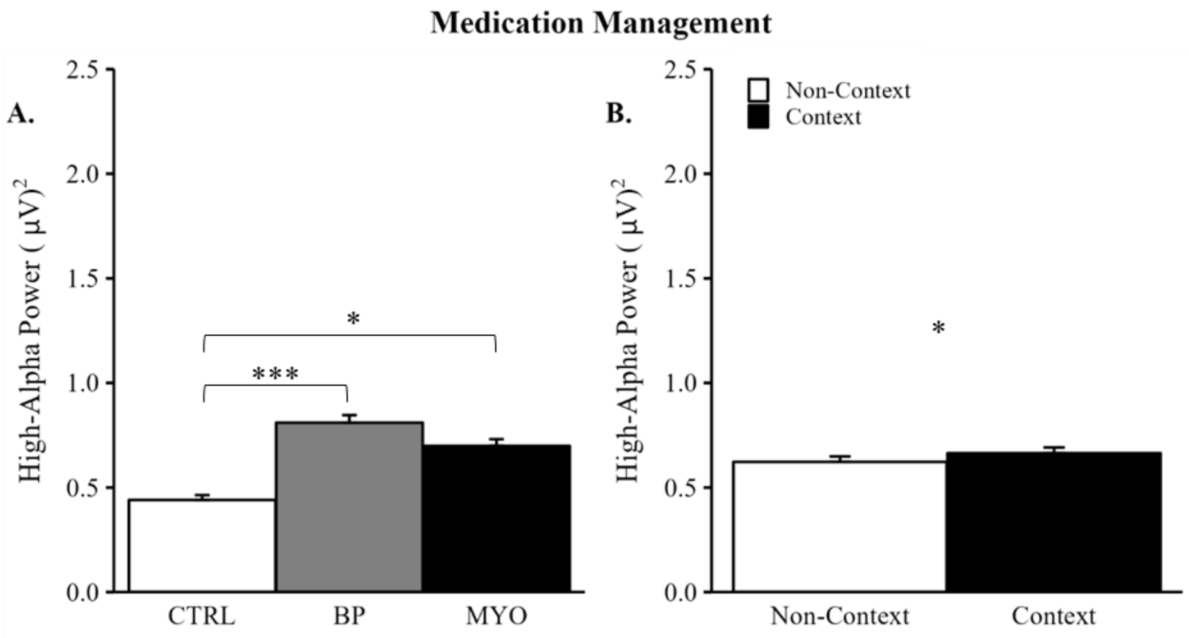


Fig. 53. Medication Management. **A.** High-alpha power between prosthetic groups averaged across experimental conditions. **B.** High-alpha power for each experimental condition averaged across prosthetic groups / CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

In the left hemisphere, the CTRL group exhibited greater alpha power in the occipital ($p < 0.001$, $d = 1.279$) region in the left hemisphere when filling the pillbox during the contextual condition when compared to the non-contextual condition. The MYO group exhibited greater alpha power in the occipital ($p = 0.010$, $d = 0.985$) and temporal ($p = 0.017$, $d = 0.700$) regions in the left hemisphere when filling the pillbox during the non-contextual condition when compared to the contextual condition.

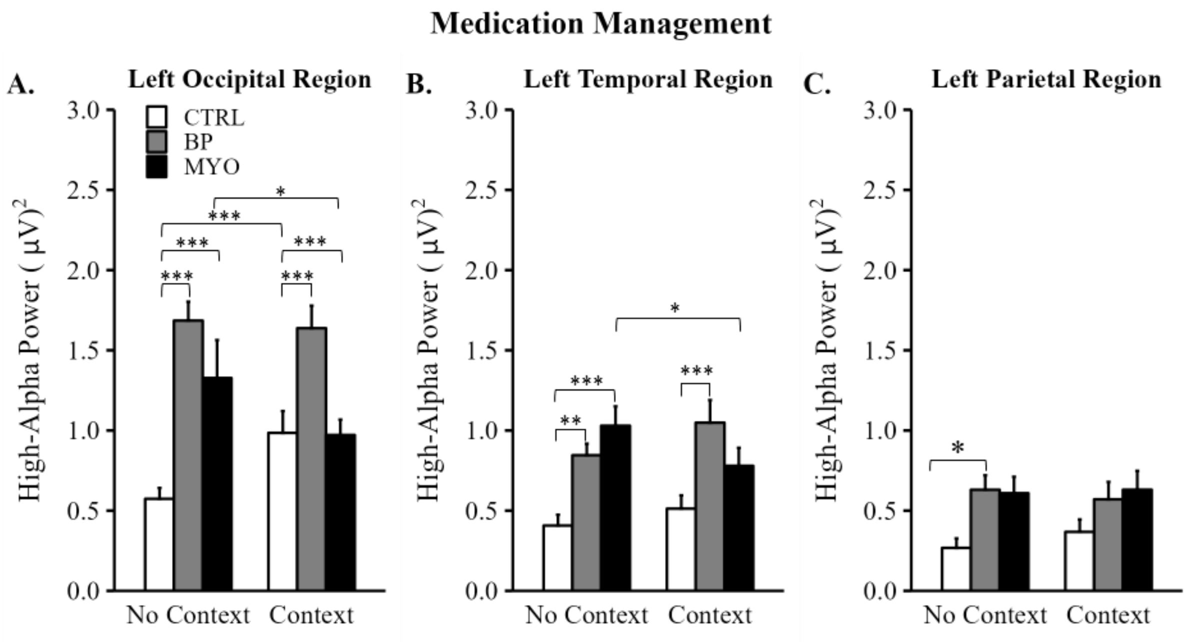


Fig. 54. Medication Management. **A.** High-alpha power for each experimental condition and prosthetic group for the left occipital region. **B.** High-alpha power for each experimental condition and prosthetic group for the left temporal region. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

For the right hemisphere, the CTRL group exhibited greater alpha power in the occipital ($p = 0.004$, $d = 0.818$) and temporal ($p < 0.001$, $d = 1.06$) regions in the right hemisphere when filling the pillbox during the contextual condition when compared to the non-contextual condition.

For the left hemisphere in the non-contextual condition, the BP group experienced greater high-alpha power in the occipital ($p < 0.001$, $d = 4.649$), parietal ($p = 0.006$, $d = 1.58$) and temporal ($p = 0.002$, $d = 2.102$) regions when compared to the CTRL group. The MYO group experienced greater high-alpha power in the occipital ($p < 0.001$, $d = 2.499$), parietal ($p = 0.028$, $d = 1.293$) and temporal ($p < 0.001$, $d = 2.128$) regions when compared to the CTRL group.

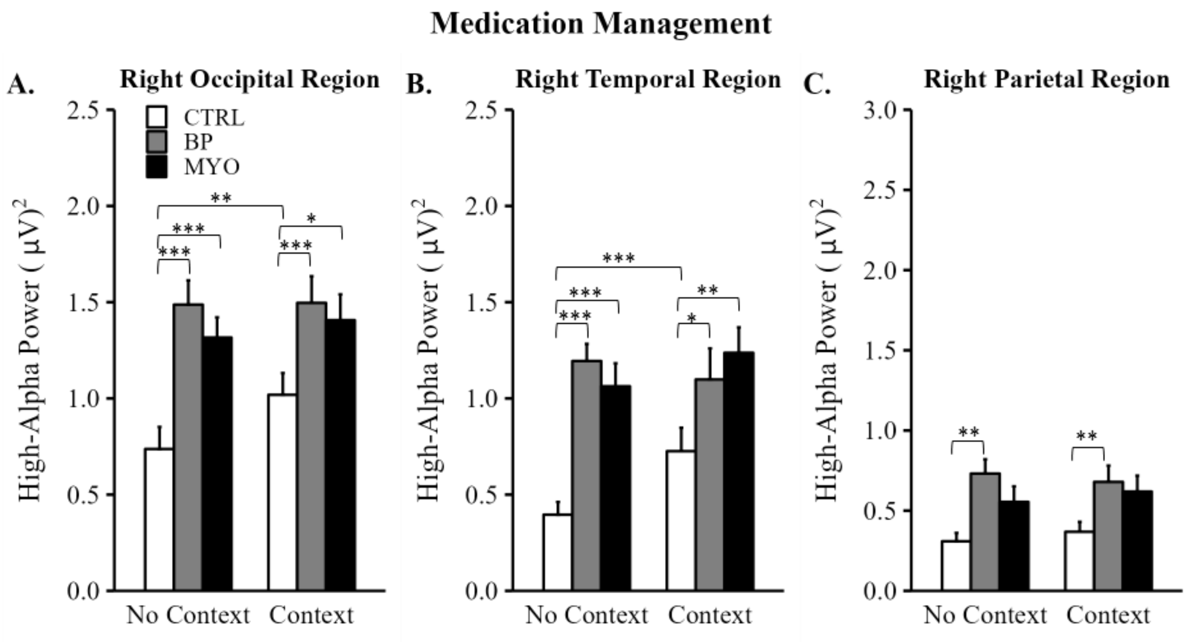


Fig. 55. Medication Management. **A.** High-alpha power for each experimental condition and prosthetic group for the right occipital region. **B.** High-alpha power for each experimental condition and prosthetic group for the right temporal region. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

For the left hemisphere during the contextual condition, the post-hoc analysis revealed that for the left hemisphere, when filling the pillbox after receiving contextual instructions, the BP group experienced greater high-alpha power in the occipital ($p < 0.001$, d= 1.701) and temporal ($p < 0.001$, d = 0.669) regions when compared to the CTRL group. The BP group experienced greater high-alpha power in the occipital region when compared to the MYO users ($p < 0.001$, d = 2.254).

For the right hemisphere for the non-contextual condition, the post-hoc analysis revealed that the BP group experienced greater high-alpha power in the occipital ($p < 0.001$, d = 2.031), parietal ($p = 0.001$, d = 1.936) and temporal ($p < 0.001$, d = 3.555) regions when compared to the CTRL group. The MYO group experienced greater high-alpha power in the occipital ($p < 0.001$, d = 1.763) and temporal($p < 0.001$, d = 2.450) regions when compared to the CTRL group.

For the right hemisphere during the contextual condition the post-hoc analysis revealed that the BP group experienced greater high-alpha power in the occipital ($p < 0.001$, $d = 1.514$), parietal ($p = 0.017$, $d = 1.213$), and temporal ($p = 0.015$, $d = 0.892$) regions when compared to the CTRL group. The MYO group experienced greater high-alpha power in the occipital ($p = 0.023$, $d = 1.107$) and temporal ($p = 0.002$, $d = 1.311$) regions when compared to the CTRL group.

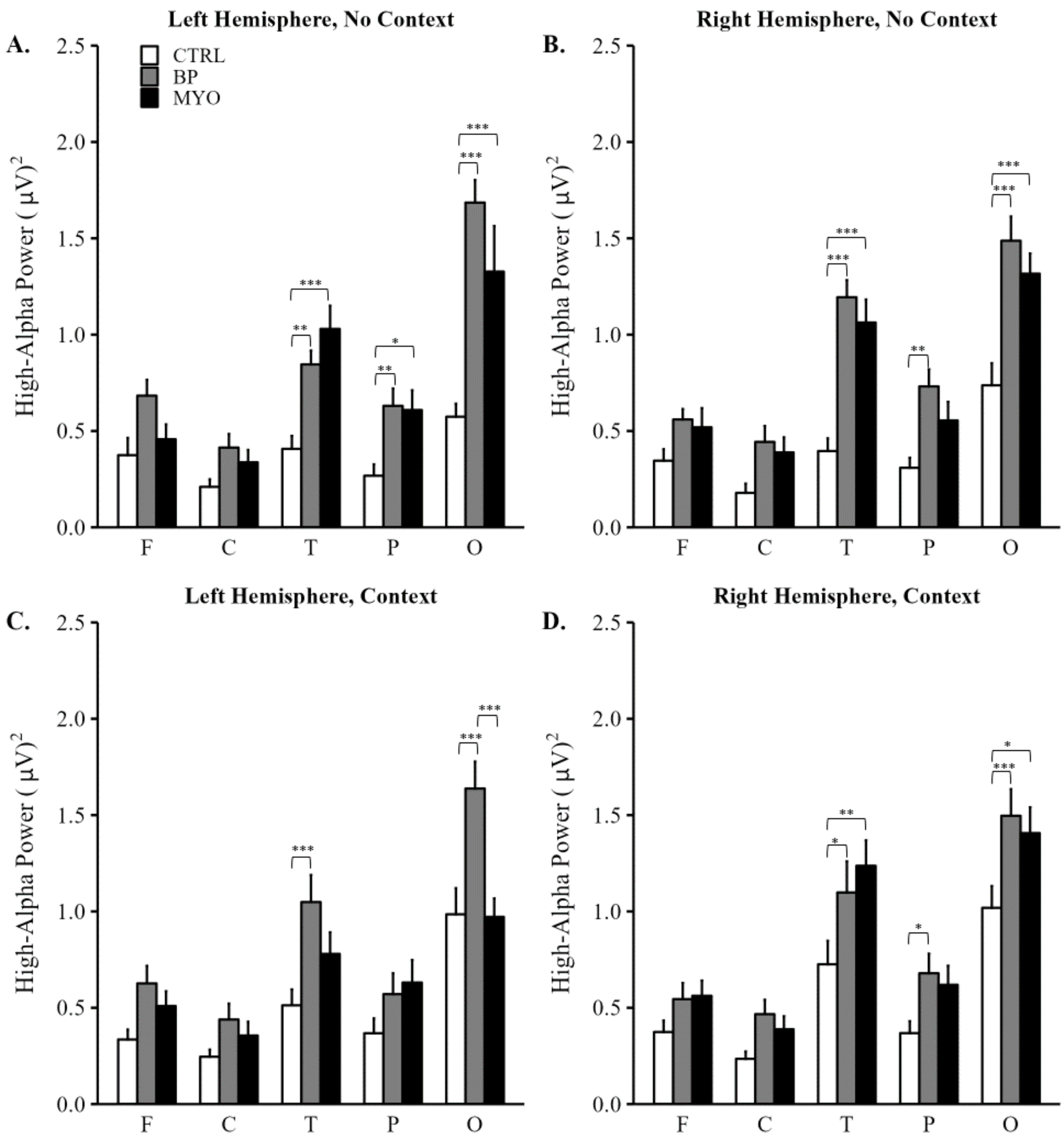


Fig. 56. Medication Management. **A.** High-alpha power between prosthetic groups for each cortical region in the left hemisphere during the non-contextual condition. **B.** High-alpha power between prosthetic groups for each cortical region in the right hemisphere during the non-contextual condition. **C.** High-alpha power between prosthetic groups for each cortical region in the left hemisphere during the non-contextual condition. **D.** High-alpha power between prosthetic groups for each cortical region in the right hemisphere during the contextual condition. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

A significant Group main effect was revealed ($F(2, 27) = 4.326$, $p = 0.023$, $\eta p^2 = 0.243$). A significant Context main effect was revealed ($F(1, 470) = 8.421$, $p = 0.004$, $\eta p^2 = 0.018$). These main effects were superseded by a significant Group x Context x Region x Hemisphere interaction ($F(8, 470) = 2.42$, $p = 0.014$, $\eta p^2 = 0.04$).

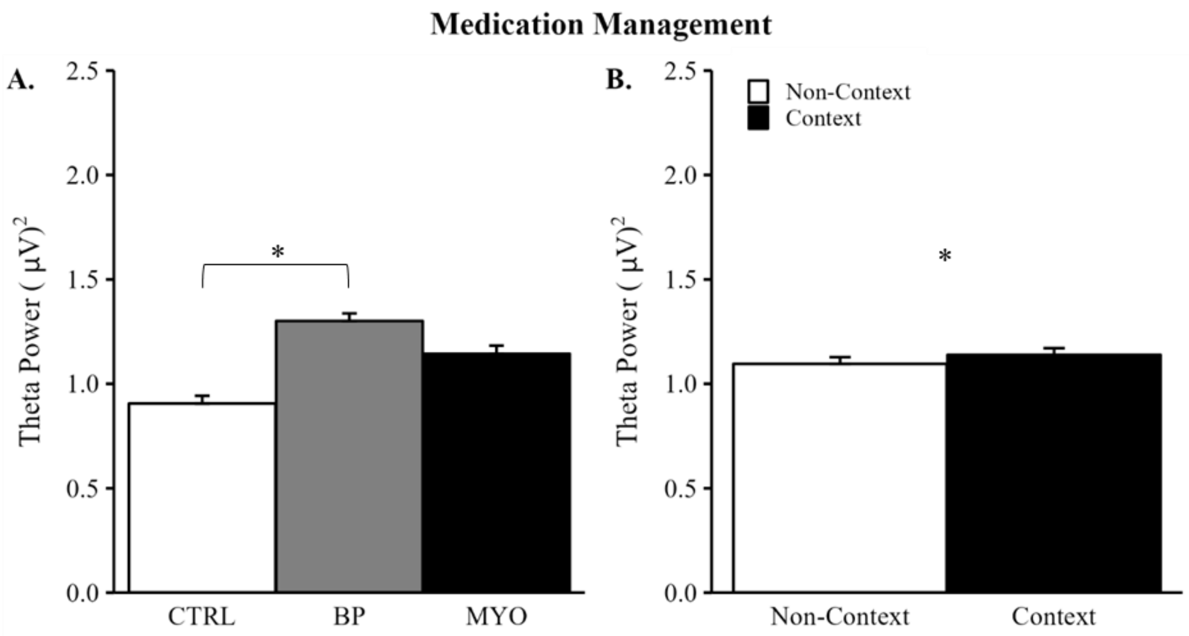


Fig. 57. Medication Management. **A.** Theta power between prosthetic groups averaged across experimental conditions. **B.** Theta power for each experimental condition averaged across prosthetic groups. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group .   * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

For the left hemisphere, the post-hoc analysis revealed that when filling the pillbox during the non-contextual condition the CTRL group experienced an attenuation of theta power in the left occipital region (p = 0.034, d = 0.548) when compared to the contextual condition.

For the right hemisphere, the post-hoc analysis revealed that when filling the pillbox during the non-contextual condition, the CTRL group experienced an attenuation of theta power in the right occipital (p= 0.004, d = 0.814) and right temporal (p < 0.001, d = 1.219) regions when completing the task with non-contextual instructions when compared to contextual instructions. The BP group experienced an attenuation of theta power in the right temporal region (p = 0.034 , d = 0.757) when completing the task with contextual instructions when compared to the non-contextual instructions.

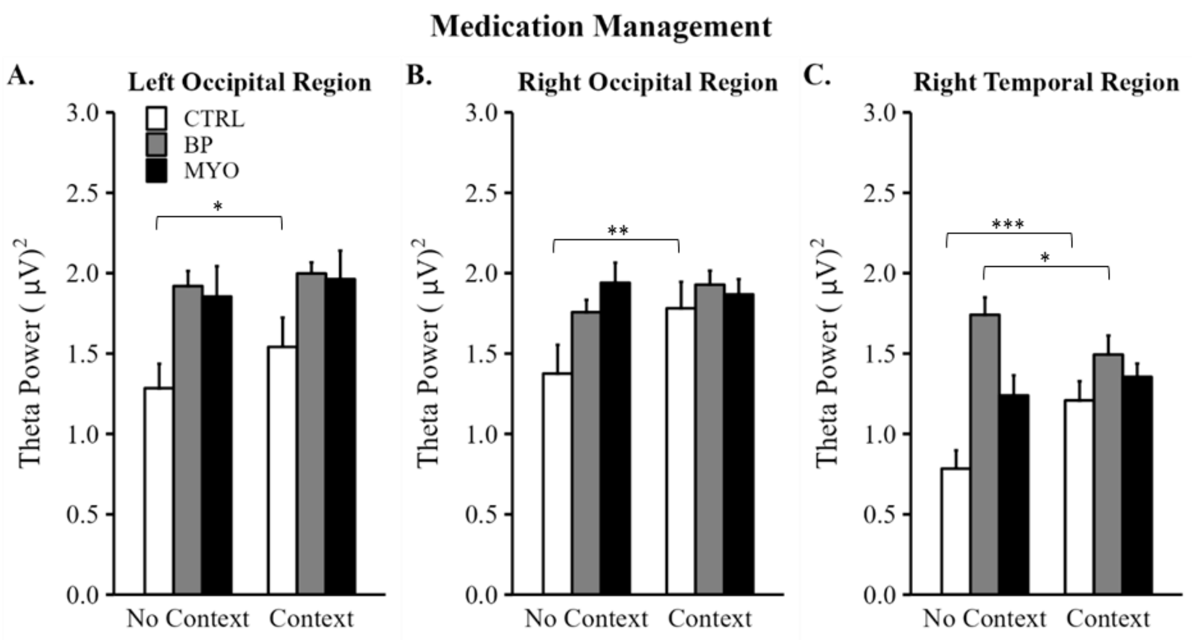


Fig. 58. Medication Management. **A.** Theta power for each experimental condition and prosthetic group for the left occipital region. **B.** Theta power for each experimental condition and prosthetic group for the right temporal region. **C.** Theta power for each experimental condition and prosthetic group for the right temporal region. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . * p < 0.05, ** p < 0.01, *** p < 0.001.

For the contextual condition in the left hemisphere, the BP group experienced higher theta power in the temporal region when compared to the CTRL ($p < 0.001$, $d = 2.132$) and MYO ($p = 0.006$, $d = 0.503$) groups.

For the non-contextual condition in the left hemisphere, the BP group experienced higher theta power in the occipital region when compared to the CTRL group ($p = 0.009$, $d = 0.883$).

For the contextual condition in the right hemisphere the BP group experienced higher theta power in the parietal region when compared to the CTRL group ($p = 0.015$, $d = 1.729$).

For the non-contextual condition in the right hemisphere, the CTRL group experienced lower theta power in the temporal region when compared to the BP ($p < 0.001$, $d = 2.892$) and MYO ($p = 0.009$, $d = 1.268$) groups. The BP group experienced higher theta power in the temporal region when compared to the MYO group ($p = 0.015$, $d = 1.432$).

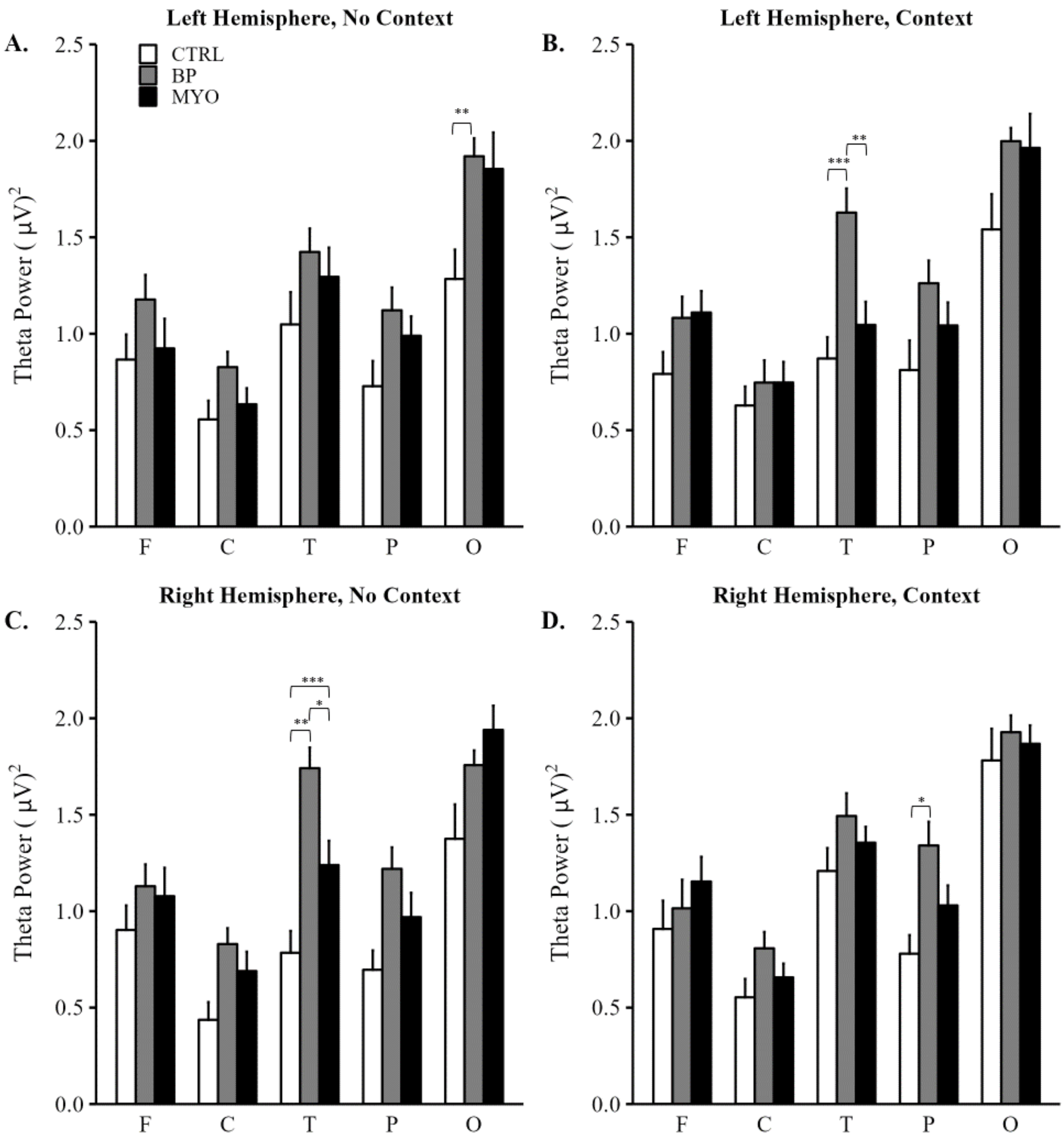


Fig. 59. Medication Management. **A.** Theta power between prosthetic groups for each cortical region in the left hemisphere during the non-contextual condition. **B.** Theta power between prosthetic groups for each cortical region in the right hemisphere during the non-contextual condition. **C.** Theta power between prosthetic groups for each cortical region in the left hemisphere during the non-contextual condition. **D.** Theta power between prosthetic groups for each cortical region in the right hemisphere during the contextual condition. CTRL- Control group, BP-

Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * p < 0.05, ** p < 0.01, *** p < 0.001.

Beta

A significant Group main effect was revealed ($F(2, 27) = 10.186$, $p = 0.001$, $\eta p^2 = 0.385$). A significant Context main effect was revealed ($F(1, 457) = 4.961$, $p = 0.026$, $\eta p^2 = 0.03$). These main effects were superseded by a significant Group x Context x Region interaction ($F(8, 462) = 2.173$, $p = 0.028$, $\eta p^2 = 0.036$).

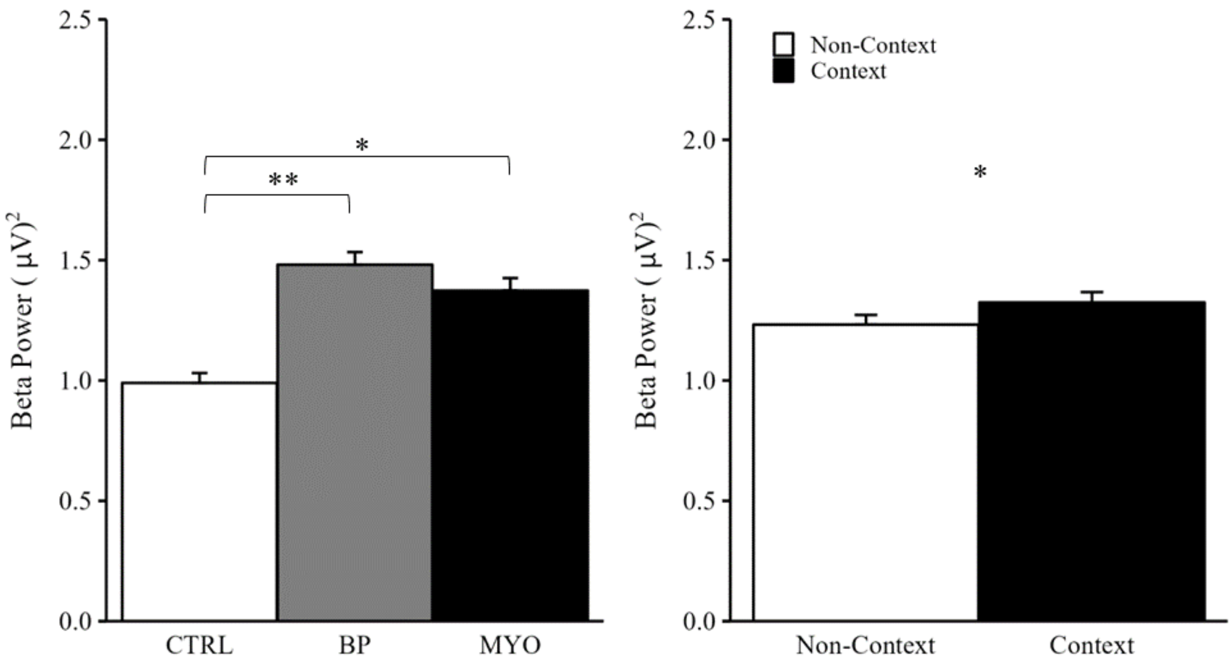


Fig. 60. Medication Management. **A.** Beta power between prosthetic groups averaged across both experimental conditions. **B.** Beta power averaged across prosthetic groups for each experimental condition. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * p < 0.05, ** p < 0.01, *** p < 0.001.

For the prosthetic groups , the post-hoc analysis revealed that the CTRL group experienced greater beta power in the occipital ($p < 0.001$, $d = 1.187$) and temporal ($p < 0.001$, $d = 0.804$) regions when completing the task with contextual instructions compared to without instructions.

For the non-contextual condition, the post- hoc analysis revealed that the BP group experienced higher beta power in the occipital ($p < 0.001$, $d = 2.357$), parietal ($p = 0.001$, $d = 1.630$), and temporal (p

< 0.001 , d = 1.972), regions when compared to the CTRL users. The MYO group experienced higher beta power in the occipital ($p < 0.001$, d = 2.068), parietal (p = 0.044 , d = 1.100), and temporal ($p < 0.001$, d = 2.049) regions when compared to the CTRL group.

For the contextual instructions, the post- hoc analysis revealed that the BP group experienced higher beta power in the occipital(p = 0.002 , d = 1.213) and temporal (p = 0.008 , d = 0.923) regions when compared to the CTRL group. The MYO group experienced higher beta power in the temporal region when compared to the CTRL group (p = 0.018 , d = 0.749).

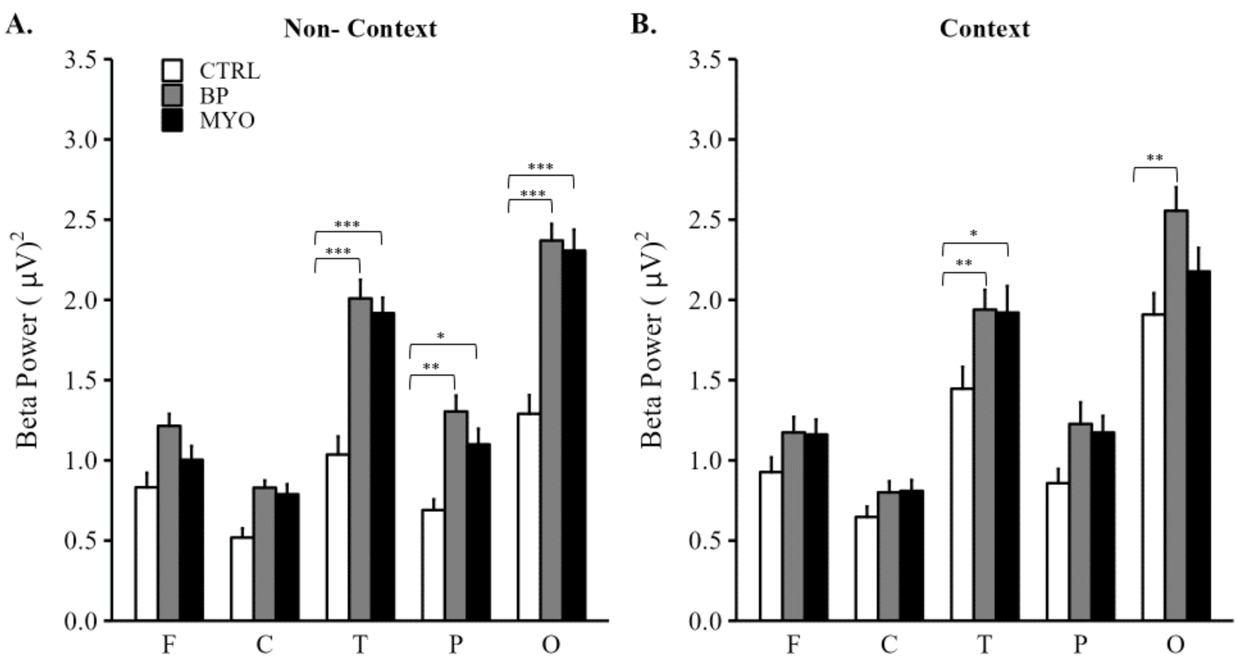


Fig. 61. Medication Management. **A.** Beta power between prosthetic groups for each cortical region during the non-contextual condition. **B.** Beta power between prosthetic groups for each cortical region during the non-contextual condition. CTRL- Control group, BP- Body-powered prosthetic group , MYO- Myoelectric prosthetic group . F - Frontal region, C - Central region, T - Temporal region, P - Parietal region, O - Occipital region. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Discussion

Several main results emerge from the present study. First, relative to both prosthesis groups, the CTRL group consistently produced a much higher performance for all activities such that the activities were executed with much faster and smoother movements. The BP completed all the activities with a similar duration or faster (except in for the meal execution under the non-contextual condition) than the MYO users. Also, the BP completed all the activities with similar or greater movement smoothness compared to the MYO users. Regardless of the type of prosthesis, the performance decreased a(i.e., slower, and jerkier movement) from the non-contextual to the contextual condition for all activities except for the meal preparation activity, in which an enhanced movement smoothness was observed.

Second, relative to the BP group, the CTRL group revealed smaller theta, low-alpha, high-alpha and beta power for the four activities. This was observed fairly independently of the context although the scalp distribution of these dynamics was modulated by the type activities. Namely, the CTRL group revealed a smaller theta power which was widely observed over the scalp for the book, beverage, and meal activities, but more localized in the temporal, parietal, and occipital regions for the medication activity. In addition, compared to the BP group, the CTRL group revealed a smaller low-alpha power observed across most cortical regions for the book, meal activity and medication but more focused in the temporal regions for the beverage activity. For the high-alpha and beta bandwidths, the CTRL group revealed a smaller power relative to the BP group in these frequencies across most cortical regions for all four activities although these changes were more robust in the temporal, parietal, and occipital regions. Furthermore, compared to the MYO users, the CTRL group revealed smaller theta, low-alpha, high-alpha and beta power although such differences were much less systematic (particularly in the theta and low-alpha bandwidth) than those observed between the CTRL and BP users. Namely, relative to the MYO users, the CTRL group revealed a smaller theta power mainly in the temporal regions for the medication activity and a reduced low-alpha power for the book and meal activity. These differences were more consistently observed for the high-alpha and beta power in the temporal and occipital regions. In addition, although the BP and MYO users revealed similar cortical dynamics for the medication activity, the BP users revealed a greater theta, low-alpha, high-alpha and beta power mainly localized in the temporal regions and to a lesser extent in the occipital region for the book, beverage, and meal activities.

Third, contextual demands across the activities yielded varying cortical activation patterns. Specifically, the CTRL group frequently exhibited greater cortical inhibition during the contextual condition when compared to the non-contextual condition, while the prosthesis groups produced varying cortical activation patterns that was more sensitive to the interaction of the motor demand of the activity and the contextual instructions for the activity. Additionally, the cortical dynamics of the prosthesis users between the non-contextual and contextual conditions were often similar which may reflect an inability to deploy adequate cortical resources to the added executive functioning demands in the contextual condition, due to significant resources being allocated to the physical demand of the activities. The manipulation of contextual demands during the beverage preparation activity was the only activity that did not reveal differences in cortical dynamics between the groups.

Effects of the Prosthesis Type on Cognitive-Motor Performance and Mental Workload

Performance

The fact that relative to the prosthesis users, the CTRL group produced a much faster and smoother motion when performing all the activities was expected since individuals of this group have very well encoded internal models of their upper limb allowing them to execute motion with limited use of peripheral feedback leading to fast and smooth movements. In contrast, the prothesis users have only practiced operating their device for an average of 1-2 months which likely does not allow for high quality encoding of the internal model. This may be due to the novel and unusual sensorimotor mapping of learning to use a prosthesis that further relies on peripheral feedback to guide the performance which resulted in slower execution of activities and lower movement smoothness (Lum et al., 2014b; Shuggi et al., 2017, 2019). In addition, it is also possible that the prosthesis users(especially the MYO group) experienced higher levels of physical demand for both activity conditions and in response, may have deployed more variable movement strategies leading to higher levels of arm movement jerkiness when compared to the CTRL group.

Theta Power

Interestingly, relative to the BP users, individuals of the CTRL group using their ‘intact’ limb revealed a lower level of theta power for both contexts but similar to that observed in the MYO prosthesis users. This was surprising as it was expected that the theta power would be higher for the MYO (either similar or higher to the BP group) users. Although various neural functions have been associated to these theta power changes and that several competing mechanisms can be considered here, a possible explanation could be related to the engagement of error processes since it was suggested that theta power would reflect error processing (Arrighi et al., 2016; Cavanagh et al., 2012; Dufour et al., 2018; Harper et al., 2017; Margraf et al., 2023; Tombini et al., 2009). In particular, prior works from the cognitive and motor domain have suggested that greater error detection, correction and prediction in response to higher task demands would lead to enhanced theta power (Arrighi et al., 2016; Cavanagh et al., 2012; Dufour et al., 2018; Gentili et al., 2011, 2014, 2018; Gevins & Smith, 2000; Jaquess et al., 2017; Shaw et al., 2018; Tombini et al., 2009). Importantly, experimental, and computational studies collectively suggest that the error signals that drive the performance is a combination of three types of error that arise from the discrepancy between: i) the predicted and actual sensory state (prediction error), ii) the predicted and desired sensory state as well as iii) desired and actual sensory state (Blakemore & Sirigu, 2003; Morehead et al., 2017; Wolpert & Miall, 1996). In addition, evidence from this literature suggests that the prediction error (which is heavily involved in two out of three comparisons) is a main driver of error processing and is critical to activate movement correction (Alexander & Brown, 2019; Arrighi et al., 2016; Desmurget & Grafton, 2000; Krakauer et al., 2006). This prediction error is generated by an internal forward model which is acquired during learning to predict the sensory state by employing an efference copy of the motor command (Desmurget & Grafton, 2000; Franklin & Wolpert, 2011; Niziolek et al., 2013; Wolpert & Miall, 1996). However, as suggested by the results from chapters 2 and 3, the prosthetic learning was still at its early stage although BP users exhibited more characteristics of cognitive-motor efficiency when compared to the MYO users. Thus, computationally this would suggest that the encoding of the internal forward model of the sensorimotor mapping to control the prosthesis was only partial (in particular for the MYO group) in contrast to individuals of the CTRL group who would be able to engage a very robust internal model of their upper limb acquired and highly refined over years/decades. Thus, the neurocontrol system of individuals of the MYO group would likely have access to a partially encoded internal forward model (of the prosthesis) therefore rendering a flawed computation of the error with a minimal resolution to guide the movement. This ultimately may have led to a lower theta power and greater use of peripheral feedback which ultimately resulting in a poor performance. In contrast, individuals of the CTRL group employed a very well-established internal model and thus could accurately generate prediction resulting very low prediction error leading to a lower theta power and superior performance. Therefore, the similarly low level of theta power observed in the CTRL group may index the quasi-null prediction error due to highly accurate predictive resources whereas for the MYO group this would reflect the inability to engage their forward models to generate error computation to guide the movement resulting in a drastic difference of performance between both groups.

The same mechanism could also explain the differences between the CTRL and BP groups as well as between the BP and MYO users. Compared to the CTRL group who would have a very small prediction error due to a highly refined internal model, the BP group would not have such an accurate internal forward model resulting thus in larger prediction error and thus a larger theta power (Arrighi et al., 2016; Cross-Villasana et al., 2018; Dufour et al., 2018; Gentili et al., 2011, 2014; Shaw et al., 2018). However, as mentioned previously, the BP group would have likely benefited more from learning than the MYO (with an enhanced cognitive-motor efficiency in retention, see chapters 2 and 3) and thus would have a better internal forward model (albeit not as optimized as the CTRL group) enabling to engage in error processing to guide the movement and thus generating higher level of theta power than the MYO group ultimately contributing to similar or even greater movement smoothness (Baumeister et al., 2008; Franklin & Wolpert, 2011; Jaquess et al., 2018).

Low-Alpha, High-Alpha, and Beta Power

When comparing the cognitive-motor performance between the types of prosthesis, the BP users consistently revealed a similar or better performance compared to the MYO users. In addition, the current findings here suggest that relative to the MYO users, the BP users revealed a greater EEG power in the low-alpha, high-alpha and beta bandwidth in particular for the temporal and occipital region. Considering the collective differences in performance and cortical dynamics between the BP and MYO, the MYO user would recruit further temporally(attentional, memory processes) and occipitally (visual feedback processing for movement regulation leading) compared to the BP users (Gentili et al., 2011; Johnny V.V. Parr et al., 2020; J. V. V Parr et al., 2018). Interestingly. this is consistent with the finding previously described in chapters 2 and 3 which revealed that learning of BP was superior to that of the MYO as indicated by similar performance along with lower engagement of the cognitive-motor processes and thus higher neural efficiency for the former compared to the later during the retention period. In particular, this supports the notion previously discussed that although both prothesis groups would have a limited encoding of the internal models of the device to control, the MYO group will likely have an even poorer encoding of these internal models relying thus on the peripheral visual feedback for operating the device. Relative to the BP group, the MYO users would further rely on visual feedback would requiring thus further attentional and visual processing for movement regulation leading to a lower high-alpha and beta power (particularly observed in the temporal and occipital regions) along with a similar or even degraded smoothness. In other words, the lower cognitive-motor efficiency observed during the retention period (chapters 2 and 3) for the MYO users relative to the BP users was also observed during the activities in the present study. Interestingly, no difference in high-alpha and beta power between the BP and MYO users was observed for the medication activity which involved a precision grip which possibly was very challenging for both the BP and the MYO users leading to similar cortical dynamics.

When comparing the CTRL group to the prosthesis users, the findings revealed a smaller level of low-alpha and high-alpha power suggesting a greater arousal and engagement of the task specific cognitive-motor resources in the CTRL relative to the BP group and to a lesser extent the MYO group. In particular, it appears that the CTRL group exhibited a lower level of temporal, parietal and occipital high-alpha power across the various activities compared to the prosthesis users suggesting that the former further engaged the corresponding neural processes compared to the latter (Gentili et al., 2014, 2018; Pruziner et al., 2019; Shaw et al., 2018). This was contrary to expectation since it would have been expected that the CTRL group would reveal a higher degree of alpha power as indicative of a lower mental workload. However, once again, the performance for the CTRL relative to both prosthesis groups was drastically superior. A possible explanation would be that the CTRL group was able to recruit the cognitive-motor resources that are needed to be deployed to perform the activity with an optimal performance whereas such similar modulation to reach a comparable performance was not possible for the BP and MYO users. This is consistent with the notion that was mentioned above which suggests that the CTRL group benefiting from very robust and accurate internal models that could be engaged to perform the activities. Interestingly, the temporal and parietal regions have been proposed as having a significant role in the acquisition, implementation, and retrieval of action selection strategies while the parietal cortex has been considered as a likely neural site to encode internal models (Desmurget & Grafton, 2000; Franklin & Wolpert, 2011; Wolpert & Miall, 1996). Thus, it is not surprising that these two regions would be recruited during performance along with the occipital regions which are important to access the actual state which as mentioned above is compared to the predicted state to compute the prediction error that is critical for movement execution (Arrighi et al., 2016; Desmurget & Grafton, 2000). This could also explain the similar differences observed between the CTRL and prosthesis users in the beta band which revealed similarly that the former had a smaller beta power compared to the latter suggesting that the CTRL group would be able to engage more sensorimotor processing resources (Espenhahn et al., 2019; Teodoro et al., 2018; Zaepffel et al., 2013). Likely the engagement of such sensorimotor resources would be enabled by the capability to recruit more robustly encoded internal models.

Effects of Contextual Demands on Cognitive-Motor Performance and Mental Workload

CTRL Group

The manipulation of contextual demands in the activities led to a consistent pattern of change for the CTRL group. Specifically, compared to a non-contextual, when the CTRL group executed the book activity with a context, an increase of high-alpha (in particular, over the occipital region) and beta power was revealed along with a reduction of performance (Figures 11 and 14). This suggests a decrease of the engagement of task-specific and sensorimotor resources resulting in an elevation of the time to complete the activity and a reduction of smoothness. A possible explanation may be that the elevation of high-alpha power produced in the occipital region during the contextual condition may reflect a strategy to inhibit irrelevant visual stimuli, such as the names of the authors of the books that were not in alphabetical order. This visual selective strategy may have contributed to the longer activity completion time and mental workload as evidenced by the CTRL group's elevation in perceived mental workload during the contextual condition. The filtering of author's names that were not in alphabetical order may also have prompted more jerky movements to temporally displace books not in sequential order out of the movement path while searching for the next book in alphabetical order. Similarly, to the book activity, the CTRL group revealed an increase of theta, low-alpha and high-alpha power generally detected in the temporal and occipital regions when executing the medication activity. This suggests a greater engagement of the theta-related resources such as error processes along with a disengagement of task-specific resources associated with slower and with jerkier motion. A possible explanation extends the prior position that the CTRL users engaged a visual filtering mechanism to inhibit non-essential visual information. This inhibition of non-essential visual information(e.g., medication names not of interest during the movement sequence, selective filtering of the days of the week specified on the pillbox) likely increased error monitoring and attentional processes to ensure pills were placed in the proper section of the pillbox. The same changes for theta, low-alpha and high-alpha power were also observed for the meal activity which likely suggest a similar visual filtering/error monitoring strategy but also with an elevation of beta power. The elevation in beta power produced by the CTRL group accompanied general improvements in movement smoothness and faster activity completion times in the contextual condition when compared to the non-contextual condition likely reflects sensorimotor efficiency. This may be partially explained by the condition instructions which instructed less items to be used to make the burger and prepare the meal during the contextual condition.

Prosthetic Groups

When considering the prosthesis group, the effect of context revealed a more nuanced pattern of cortical dynamics. Specifically, for the book activity, relative to the non-contextual condition, the BP group exhibited a reduction of theta power over the entire scalp whereas the MYO group revealed an elevation of occipital high-alpha power under the context condition (Figures 7 and 11). The disengagement of the occipital region observed in the MYO group may indicate that the MYO users engaged in a similar visual filtering process to inhibit non-essential visual information. In addition to filtering author names in search for the author's name that was next in alphabetical order, it is plausible that the MYO hand bypass position was occluded This may reflect a design issue of the bypass device which offsets the myoelectric hand in a ventral position underneath the participant's arm. Ventral offsets for bypass prosthesis has been cited to occlude the myoelectric hand thus potentially causing increased hand-eye coordination challenges (A. W. Wilson et al., 2017). The interaction of these visual demands may have resulted in increased difficulty to deploy the essential visual resources and potentially an inhibitory process reflective of filtering out non-essential visual information.

Relative to the non-contextual condition, when the MYO group executed the meal activity with contextual instructions, a reduction of theta and beta power as well as of parietal and occipital high-alpha power was observed. For the same activity, the BP group revealed a reduction of temporal high-alpha power from the non-contextual to the context condition (Fig.41). A plausible reason for the differences in cortical processing between the prosthetic groups may be that the BP users had depleted most resources during the non-contextual condition. For example, in the non-contextual condition, participants make a burger with all ingredients while placing both side dishes and condiments on the plate. However, in the contextual condition, the participants were instructed to omit one topping, and they were not required to put the condiments on the plate. Thus the higher number of items to manipulate may have contributed to similar motor performances between both conditions of the CTRL group and MYO group but significantly longer times for the BP group to complete the non-contextual condition when compared to the contextual condition. It is hypothesized that the BP group was impacted by the reduction in items in the contextual condition due to the grip demand elicited by the food items that had smooth wooden-like surfaces that were slippery. Due to the tactile proprioceptive feedback elicited by the CTRL group's sensory receptors in the fingertips, the slippery nature of the food items likely did not impact the CTRL group as significantly. For the MYO users, the rubber coverage of the myoelectric hand likely aided secure grasp of smooth items. Additionally, the compliant grip function of the myoelectric device provided vibratory stimulus when maximal grip force had been achieved as a form of afferent sensory feedback. The BP users had rubber material on the inside of the hooks to improve grip, however, this material did not exist along all contact points including the tips of the terminal device. Since many of the food items had small diameters in addition to being slippery and the BP users did not have an afferent sensory system integrated into the end effector like the CTRL and MYO groups, the BP group likely experienced more difficulty grasping the items when compared to the other groups.

During the medication activity, the BP group revealed an attenuation of theta and low-alpha power while the MYO users experienced an attenuation in high-alpha power over the left occipital and right temporal regions during the contextual condition when compared to the non-contextual condition. This likely reflects increased cortical activation to address the contextual demands for both groups. In addition, the reduction in theta power observed in the BP group may not reflect working memory demands since working memory demands were systematically increased in the contextual condition(which was marked by a significant elevation of perceived mental demand in this condition). Instead, the attenuation in theta power may reflect less monitoring of movements that was accompanied by slower movement times during the contextual condition. Due to the significant physical demands of grasping the small medication pills, it is likely that the contextual demand forced the prosthesis users to devote more resources to filling the pillbox properly thus maintain similar levels of movement quality to that of the non-contextual condition. For the BP users, this may have decreased error monitoring resources while the MYO users still had to engage error monitoring and attentional resources(and possibly working memory resources) that were similar to the non-contextual condition.

Conclusions, Limitations and Future Directions

In summary, contextual demands generally led to decrements in motor performance as noted by an increase in time required to complete activities and a reduction in movement smoothness with the exception of the meal preparation activity in which the opposite was observed. Contextual demands generally resulted in an elevation of mental workload as collectively indexed by the NASA-TLX and increased cortical activation(low and high-alpha, beta desynchrony) and increased attentional, working memory and error monitoring resources (theta synchrony). The CTRL group typically exhibited an increased engagement of inhibitory cortical processes in response to contextual demands while the BP and MYO users produced varied cortical dynamics in response to contextual demands. This may indicate that the CTRL group was able to more effectively deploy a visual strategy to inhibit non-essential information thus increasing the signal to noise ratio of the executive functioning demands of the contextual condition, therefore resulting in significantly enhanced performance and kinematics when compared to the prosthetic groups. This is partially in line with past efforts that have demonstrated increased cortical engagement in response to elevations in cognitive-motor demands (Gentili et al., 2014, 2018; Jaquess et al., 2017; Shaw, Rietschel, Hendershot, Pruziner, Miller, Hatfield, et al., 2018); however, our evidence also presents a divergence from these prior works. Furthermore the results provide empirical support for the theoretical 4-D multiple resource model which states that when demand is greater than the amount of resource availability, mental workload exceeds resource capacity and performance degrades (Wickens, 2008). Additionally, the model states that when there is demand for common cortical resources and a resource overlap ensues, performance is degraded. While this model was designed to predict workload overload during multi-tasking, the model can still inform the present study. Specifically, various contextual demands such as sequencing (e.g. Books on a Bookshelf), working memory (e.g. Meal Preparation, Beverage Preparation, Medication Management), visual search and decision making(all activities) onto the cognitive-motor activities in this study likely elicited elevations in mental workload that required cortical inhibitory and facilitatory processes in response to elevations in task demands.

When examining differences between prosthetic groups, the CTRL group was predicted to produce less cortical activation when compared to the prosthesis users. However, our results revealed that the CTRL group using their intact and able hands, experienced increased cortical activation when compared to the prosthesis users. However, the performance from the CTRL group as much higher than that from the BP and MYO users. Our results suggest that the CTRL group was able to recruit their cognitive-motor resources and engage robust internal models of their end effector to generate a superior performance whereas due to the novelty of prosthesis operation (participants only had 10 sessions of practice prior to this study) the prosthesis users were not able to engage these neural processes in a similar manner which leading to longer activity completion times, elevation in movement jerkiness and perceived mental and physical demand. Instead, this lower cortical activation in the prosthesis users may possibly reflect increased inhibition of interfering cortical processes associated with the novelty of the prosthesis and ongoing adaptations as the prosthesis users encountered novel cognitive-motor demands that may not have been present during training. Greater cortical activation in the CTRL group may reflect a release from inhibition to engage relevant resources to complete the activities (Klimesch, 2012). Additionally, the CTRL group frequently engaged more inhibitive cognitive-motor and sensorimotor resources along with an elevation of theta power in response to contextual demands. This may suggest that the CTRL group were more effectively able to inhibit non-essential cognitive-motor information while effectively deploying necessary working memory, attentional and error-monitoring resources to meet contextual demands.

While this work is informative, there are limitations. First, the creation of the activity instructions could have been refined more carefully to reflect the same number of steps required to complete the task in both experimental conditions. For example, the contextual instructions of the meal preparation task invertedly reduced the number of items the experimental groups had to manipulate, thus potentially contributing to faster performance times in the contextual condition, which was in opposition to the study’s hypothesis. Secondly, the contextual demands across the activities were primarily designed to elevate working memory demand. This was done intentionally since mental workload has been shown to have a strong inverse relationship to the amount of information processing capacity(Kahneman, 1974). However, designing the contextual instructions to integrate a diversity of executive functioning demands such as decision making, calculations, and inhibition may have increased the generalizability of the HITT assessment to cognitive-motor performance in real-life scenarios. Lastly, the meal preparation utilized wooden-like models of fast food ingredients. This created unintended slippery conditions that made it difficult to stack the food ingredients to make a burger. While to some degree, the friction between food items was improved using the application of felt material on the items, the residual slippery conditions did not fully reflect the preparation of a burger using actual food ingredients. As a result, the generalization of the meal preparation performance in the HITT to the real-world experience of preparing a burger may be somewhat limited.

Despite these limitations, this work successfully designed a novel performance outcome measure, the HITT, to assess the influence of contextual demands on cognitive-motor performance and mental workload. The HITT addresses the paucity of performance outcome measures in upper limb rehabilitation that do not assess the impact of cognitive demands on motor performance (Murphy et al., 2015; Wang et al., 2018) despite it being well-evidenced that elevations of mental workload is often associated with decrements in motor performance (Gentili et al., 2015; Miller et al., 2011; Shaw et al., 2018). This study confirmed that contextual demands introduced to cognitive-motor activities degrade motor performance and increase mental workload. The study provides evidence that cognitive-motor performance in controlled environments may not translate to performance in real world scenarios that are richer in complexity, variability, and cognitive-motor demands. Integration of contextual demands that simulate daily activities in the home or community environment may increase the ecological validity of cognitive-motor activities selected in a rehabilitation setting and may prepare individuals who have recently learned to use a new upper limb device for functional re-integration into the community.

Due to the complexity of spectral interactions observed in this study, a future direction of this work would be to assess cognitive-motor performance using cerebral cortical networking to examine interregional communication during activity performance. Such work may enhance the understanding of the interactions between brain regions during cognitive-motor activities with more complex cognitive demands. Additionally, a computational approach traditionally used in information theory called Levenshtein's distance, could be employed in this study to quantify the deletions, insertions, or substitutions of motor sequences of the non-contextual and contextual conditions of this study(Hauge et al., 2020; Po, 2020). Employment of this approach may reduce potential study confounds by ensuring the same number of steps exists for both experimental conditions. Lastly, the extension of this work to examine cognitive-motor performance and mental workload in patient populations may help inform the design of rehabilitation programs that aim to increase the translation of cognitive-motor skills acquired in the clinic to the patients' homes and communities.

References

Alexander, W. H., & Brown, J. W. (2019). The Role of the Anterior Cingulate Cortex in Prediction Error and Signaling Surprise. *Topics in Cognitive Science*, *11*(1), 119–135. https://doi.org/10.1111/tops.12307

Arrighi, P., Bonfiglio, L., Minichilli, F., Cantore, N., Carboncini, M. C., Piccotti, E., Rossi, B., & Andre, P. (2016). EEG theta dynamics within frontal and parietal cortices for error processing during reaching movements in a prism adaptation study altering visuo-motor predictive planning. *PLoS ONE*, *11*(3), 1–27. https://doi.org/10.1371/journal.pone.0150265

Babulal, G. M., Foster, E. R., & Wolf, T. J. (2017). *Therapy Practice : Practical Application of Transfer Principles*. *11*(1), 19–25. https://doi.org/10.11596/asiajot.11.19.Facilitating

Balasubramanian, S., Melendez-Calderon, A., Roby-Brami, A., & Burdet, E. (2015). On the analysis of movement smoothness. *Journal of NeuroEngineering and Rehabilitation*, *12*(1), 1–11. https://doi.org/10.1186/s12984-015-0090-9

Baumeister, J., Reinecke, K., Liesen, H., & Weiss, M. (2008). Cortical activity of skilled performance in a complex sports related motor task. *European Journal of Applied Physiology*, *104*(4), 625–631. https://doi.org/10.1007/s00421-008-0811-x

Blakemore, S. J., & Sirigu, A. (2003). Action prediction in the cerebellum and in the parietal lobe. *Experimental Brain Research*, *153*(2), 239–245. https://doi.org/10.1007/s00221-003-1597-z

Bloomer, C., Wang, S., & Kontson, K. L. (2018). Creating a standardized , quantitative training protocol for upper limb bypass prostheses. *Physical Medicine and Rehabilitation Research*.

Boop, C., Cahill, S. M., Davis, C., Dorsey, J., Gibbs, V., Herr, B., Kearney, K., Liz Griffin Lannigan, E., Metzger, L., Miller, J., Owens, A., Rives, K., Synovec, C., Winistorfer, W. L., & Lieberman, D. (2020). Occupational therapy practice framework: Domain and process fourth edition. In *American Journal of Occupational Therapy* (Vol. 74, Issue August). https://doi.org/10.5014/ajot.2020.74S2001

Cavanagh, J. F., Figueroa, C. M., Cohen, M. X., & Frank, M. J. (2012). Frontal theta reflects uncertainty and unexpectedness during exploration and exploitation. *Cerebral Cortex*, *22*(11), 2575–2586. https://doi.org/10.1093/cercor/bhr332

Cross-Villasana, F., Gröpel, P., Ehrlenspiel, F., & Beckmann, J. (2018). Central theta amplitude as a negative correlate of performance proficiency in a dynamic visuospatial task. *Biological Psychology*, *132*(April 2017), 37–44. https://doi.org/10.1016/j.biopsycho.2017.10.009

Davis Sears, E., & Chung, K. C. (2010). Validity and Responsiveness of the Jebsen-Taylor Hand Function Test. *Journal of Hand Surgery*, *35*(1), 30–37. https://doi.org/10.1016/j.jhsa.2009.09.008

Deeny, S., Chicoine, C., Hargrove, L., Parrish, T., & Jayaraman, A. (2014). A Simple ERP Method for Quantitative Analysis of Cognitive Workload in Myoelectric Prosthesis Control and Human-Machine Interaction. *PLoS ONE*, *9*(11), e112091. https://doi.org/10.1371/JOURNAL.PONE.0112091

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences*, *4*(11), 423–431. https://doi.org/10.1016/S1364-6613(00)01537-0

Desrosiers, J., Bravo, G., Hébert, R., Dutil, É., & Mercier, L. (1994). Validation of the Box and Block Test as a measure of dexterity of elderly people: Reliability, validity, and norms studies. *Archives of Physical Medicine and Rehabilitation*, *75*(7), 751–755. https://doi.org/10.5555/uri:pii:0003999394901309

Dufour, B., Thénault, F., & Bernier, P. M. (2018). Theta-band EEG Activity over Sensorimotor Regions is Modulated by Expected Visual Reafferent Feedback During Reach Planning. *Neuroscience*, *385*, 47–58. https://doi.org/10.1016/j.neuroscience.2018.06.005

Espenhahn, S., van Wijk, B. C. M., Rossiter, H. E., de Berker, A. O., Redman, N. D., Rondina, J., Diedrichsen, J., & Ward, N. S. (2019). Cortical beta oscillations are associated with motor performance following visuomotor learning. *NeuroImage*, *195*(April), 340–353. https://doi.org/10.1016/j.neuroimage.2019.03.079

Fallahi, M., Motamedzade, M., Heidarimoghadam, R., Soltanian, A. R., & Miyake, S. (2016). Assessment of operators' mental workload using physiological andsubjective measures in cement, city traffic and power plant controlcenters. *Health Promotion Perspectives*, *6*(2), 96–103. https://doi.org/10.15171/hpp.2016.17

Feys, P., Lamers, I., Francis, G., Benedict, R., Phillips, G., Larocca, N., Hudson, L. D., & Rudick, R. (2017). The Nine-Hole Peg Test as a manual dexterity performance measure for multiple sclerosis. *Multiple Sclerosis Journal*, *23*(5), 711–720. https://doi.org/10.1177/https

Franklin, D. W., & Wolpert, D. M. (2011). Computational mechanisms of sensorimotor control. *Neuron*, *72*(3), 425–442. https://doi.org/10.1016/j.neuron.2011.10.006

Garde, A. H., Laursen, B., Jørgensen, A. H., & Jensen, B. R. (2002). Effects of mental and physical demands on heart rate variability during computer work. *European Journal of Applied Physiology*, *87*(4–5), 456–461. https://doi.org/10.1007/s00421-002-0656-7

Gentili, R. J., Bradberry, T. J., Oh, H., Costanzo, M. E., Kerick, S. E., Contreras-Vidal, J. L., & Hatfield, B. D. (2015). Evolution of cerebral cortico-cortical communication during visuomotor adaptation to a cognitive-motor executive challenge. *Biological Psychology*, *105*, 51–65. https://doi.org/10.1016/j.biopsycho.2014.12.003

Gentili, R. J., Bradberry, T. J., Oh, H., Hatfield, B. D., & Contreras Vidal, J. L. (2011). Cerebral cortical dynamics during visuomotor transformation: Adaptation to a cognitive-motor executive challenge. *Psychophysiology*, *48*(6), 813–824. https://doi.org/10.1111/j.1469-8986.2010.01143.x

Gentili, R. J., Jaquess, K. J., Shuggi, I. M., Shaw, E. P., Oh, H., Lo, L. C., Tan, Y. Y., Domingues, C. A., Blanco, J. A., Rietschel, J. C., Miller, M. W., & Hatfield, B. D. (2018). Combined assessment of attentional reserve and cognitive-motor effort under various levels of challenge with a dry EEG system. *Psychophysiology*, *55*(6), 1–17. https://doi.org/10.1111/psyp.13059

Gentili, R. J., Rietschel, J. C., Jaquess, K. J., Lo, L. C., Prevost, M., Miller, M. W., Mohler, J. M., Oh, H., Tan, Y. Y. ing, & Hatfield, B. D. (2014). Brain biomarkers based assessment of cognitive workload in pilots under various task demands. *Conference Proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and*

Biology Society. Annual Conference, *2014*, 5860–5863. https://doi.org/10.1109/EMBC.2014.6944961

Gevins, a, & Smith, M. E. (2000). Neurophysiological measures of working memory and individual differences in cognitive ability and cognitive style. *Cerebral Cortex (New York, N.Y. : 1991)*, *10*(9), 829–839. https://doi.org/10.1093/cercor/10.9.829

Gevins, A., & Smith, M. E. (2003). Neurophysiological measures of cognitive workload during human-computer interaction. *Theoretical Issues in Ergonomic Science*, *4*, 113–131. https://doi.org/10.1080/14639220210159717

Gonzalez, J., Soma, H., Sekine, M., & Yu, W. (2012). Psycho-physiological assessment of a prosthetic hand sensory feedback system based on an auditory display: A preliminary study. *Journal of NeuroEngineering and Rehabilitation*, *9*(1), 1–14. https://doi.org/10.1186/1743-0003-9-33

Harper, J., Malone, S. M., & Iacono, W. G. (2017). Theta- and delta-band EEG network dynamics during a novelty oddball task. *Psychophysiology*, *54*(11), 1590–1605. https://doi.org/10.1111/psyp.12906

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*, *52*, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9

Hauge, T. C., Katz, G. E., Davis, G. P., Jaquess, K. J., Reinhard, M. J., Costanzo, M. E., Reggia, J. A., & Gentili, R. J. (2020). A novel application of levenshtein distance for assessment of high-level motor planning underlying performance during learning of complex motor sequences. *Journal of Motor Learning and Development*, *8*(1), 67–86. https://doi.org/10.1123/jmld.2018-0060

Haverkate, L., Smit, G., & Plettenburg, Di. H. (2016). Assessment of body-powered upper limb prostheses by able-bodied subjects, using the Box and Blocks Test and the Nine-Hole Peg Test. *Prosthetics and Orthotics International*, *40*(1), 109–116. https://doi.org/10.1177/0309364614554030

Jaquess, K. J., Gentili, R. J., Lo, L. C., Oh, H., Zhang, J., Rietschel, J. C., Miller, M. W., Tan, Y. Y., & Hatfield, B. D. (2017). Empirical evidence for the relationship between cognitive workload and attentional reserve. *International Journal of Psychophysiology*, *121*(February), 46–55. https://doi.org/10.1016/j.ijpsycho.2017.09.007

Jaquess, K. J., Lo, L. C., Oh, H., Lu, C., Ginsberg, A., Tan, Y. Y., Lohse, K. R., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Changes in Mental Workload and Motor Performance Throughout Multiple Practice Sessions Under Various Levels of Task Difficulty. *Neuroscience*, *393*, 305–318. https://doi.org/10.1016/j.neuroscience.2018.09.019

Kahneman, D. (1974). Attention and Effort. In *Radiobiologiya* (Vol. 14, Issue 6). https://doi.org/10.2307/1421603

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences*, *16*(12), 606–617. https://doi.org/10.1016/j.tics.2012.10.007

Krakauer, J. W., Mazzoni, P., Ghazizadeh, A., Ravindran, R., & Shadmehr, R. (2006). Generalization of motor learning depends on the history of prior action. *PLoS Biology*, *4*(10), 1798–1808. https://doi.org/10.1371/journal.pbio.0040316

Light, C. M., Chappell, P. H., & Kyberd, P. J. (2002). Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity. *Archives of Physical Medicine and Rehabilitation*, *83*(6), 776–783. https://doi.org/10.1053/apmr.2002.32737

Lum, P. S., Black, I., Holley, R. J., Barth, J., & Dromerick, A. W. (2014). Internal models of upper limb prosthesis users when grasping and lifting a fragile object with their prosthetic limb. *Experimental Brain Research*, *232*(12), 3785–3795. https://doi.org/10.1007/s00221-014-4071-1

Marchand, C., De Graaf, J. B., & Jarrassé, N. (2021). Measuring mental workload in assistive wearable devices: a review. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 1–15. https://doi.org/10.1186/s12984-021-00953-w

Margraf, L., Krause, D., & Weigelt, M. (2023). Frontal theta reveals further information about neural valence-dependent processing of augmented feedback in extensive motor practice—A secondary analysis. *European Journal of Neuroscience*, *57*(8), 1297–1316. https://doi.org/10.1111/ejn.15951

Miller, M. W., Rietschel, J. C., Mcdonald, C. G., & Hatfield, B. D. (2011). A novel approach to the physiological measurement of mental workload. *International Journal of Psychophysiology*, *80*, 75–78. https://doi.org/10.1016/j.ijpsycho.2011.02.003

Morehead, R. J., Taylor, J. A., Parvin, D. E., & Ivry, R. B. (2017). Characteristics of Implicit Sensorimotor Adaptation Revealed by Task-irrelevant Clamped Feedback. *Journal of Cognitive Neuroscience*, *29*(6), 139. https://doi.org/10.1162/jocn

Murphy, M. A., Resteghini, C., Feys, P., & Lamers, I. (2015). An overview of systematic reviews on upper extremity outcome measures after stroke. *BMC Neurology*, *15*(1). https://doi.org/10.1186/s12883-015-0292-6

Niziolek, C. A., Nagarajan, S. S., & Houde, J. F. (2013). What Does Motor Efference Copy Represent? Evidence from Speech Production. *Journal of Neuroscience*, *33*(41), 16110–16116. https://doi.org/10.1523/JNEUROSCI.2137-13.2013

Park, J., & Zahabi, M. (2022). Cognitive Workload Assessment of Prosthetic Devices: A Review of Literature and Meta-Analysis. *IEEE Transactions on Human-Machine Systems*. https://doi.org/10.1109/THMS.2022.3143998

Parr, J. V.V., Vine, S. J., Wilson, M. R., Harrison, N. R., & Wood, G. (2019). Visual attention, EEG alpha power and T7-Fz connectivity are implicated in prosthetic hand control and can be optimized through gaze training. *Journal of NeuroEngineering and Rehabilitation*, *16*(1), 1–20. https://doi.org/10.1186/s12984-019-0524-x

Parr, J., Vic, J., & Parr, V. (2020). *Evaluating and alleviating the cognitive burden associated with myoelectric prosthetic hand control Evaluating and alleviating the cognitive burden associated with myoelectric prosthetic hand control A thesis submitted in partial fulfilment of the require*. *January*. https://doi.org/10.13140/RG.2.2.26474.47048

Parr, Johnny V.V., Gallicchio, G., Harrison, N. R., Johnen, A. K., & Wood, G. (2020). All talk? Challenging the use of left-temporal EEG alpha oscillations as valid measures of verbal processing and conscious motor control. *Biological Psychology*, *155*(May), 107943. https://doi.org/10.1016/j.biopsycho.2020.107943

Parr, Johnny V.V., Galpin, A., Uiga, L., Marshall, B., Wright, D. J., Franklin, Z. C., & Wood, G. (2023). A tool for measuring mental workload during prosthesis use: The Prosthesis Task Load Index (PROS-TLX). *PLoS ONE*, *18*(5 MAY), 1–15. https://doi.org/10.1371/journal.pone.0285382

Parr, J. V. V, Vine, S. J., Harrison, N. R., & Wood, G. (2018). Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand. *Journal of Motor Behavior*, *50*(4), 416–425. http://10.0.4.56/00222895.2017.1363703

Po, D. K. (2020). Similarity Based Information Retrieval Using Levenshtein Distance Algorithm. *International Journal of Advances in Scientific Research and Engineering*, *06*(04), 06–10. https://doi.org/10.31695/ijasre.2020.33780

Pruziner, A. L., Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Miller, M. W., Wolf, E. J., Hatfield, B. D., Dearth, C. L., & Gentili, R. J. (2019). Biomechanical and neurocognitive performance outcomes of walking with transtibial limb loss while challenged by a concurrent task. *Experimental Brain Research*, *237*(2), 477–491. https://doi.org/10.1007/s00221-018-5419-8

Resnik, L., Adams, L., Borgia, M., Delikat, J., Disla, R., Ebner, C., & Walters, L. S. (2013). Development and Evaluation of the Activities Measure for Upper Limb Amputees. *Archives of Physical Medicine and Rehabilitation*, *94*, 488–494. https://doi.org/10.1016/j.apmr.2012.10.004

Rietschel, J. C., Miller, M. W., Gentili, R. J., Goodman, R. N., McDonald, C. G., & Hatfield, B. D. (2012). Cerebral-cortical networking and activation increase as a function of cognitive-motor task difficulty. *Biological Psychology*, *90*(2), 127–133. https://doi.org/10.1016/j.biopsycho.2012.02.022

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological Psychology*. https://doi.org/10.1016/j.biopsycho.2018.01.009

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Wolf, E. J., Dearth, C. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2019). *A Comparison of Mental Workload in Individuals with Transtibial and Transfemoral Lower Limb Loss during Dual-Task Walking under Varying Demand*.

1–13. https://doi.org/10.1017/S1355617719000602

Shuggi, I. M., Oh, H., Shewokis, P. A., & Gentili, R. J. (2017). Mental workload and motor performance dynamics during practice of reaching movements under various levels of task difficulty. *Neuroscience*. https://doi.org/10.1016/j.neuroscience.2017.07.048

Shuggi, I. M., Oh, H., Wu, H., Ayoub, M. J., Moreno, A., Shaw, E. P., Shewokis, P. A., & Gentili, R. J. (2019). Motor Performance, Mental Workload and Self-Efficacy Dynamics during Learning of Reaching Movements throughout Multiple Practice Sessions. *Neuroscience*, *423*, 232–248. https://doi.org/10.1016/j.neuroscience.2019.07.001

Teodoro, T., Meppelink, A. M., Little, S., Grant, R., Nielsen, G., Macerollo, A., Pareés, I., & Edwards, M. J. (2018). Abnormal beta power is a hallmark of explicit movement control in functional movement disorders. *Neurology*, *90*(3), e247–e243. https://doi.org/10.1212/WNL.0000000000004830

Tombini, M., Zappasodi, F., Zollo, L., Pellegrino, G., Cavallo, G., Tecchio, F., Guglielmelli, E., & Rossini, P. M. (2009). Brain activity preceding a 2D manual catching task. *NeuroImage*, *47*(4), 1735–1746. https://doi.org/10.1016/j.neuroimage.2009.04.046

Wang, S., Hsu, C. J., Trent, L., Ryan, T., Kearns, N. T., Civillico, E. F., & Kontson, K. L. (2018). Evaluation of Performance-Based Outcome Measures for the Upper Limb : A Comprehensive Narrative Review. *PM&R*, *10*(9), 951-962.e3. https://doi.org/10.1016/j.pmrj.2018.02.008

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, *3*(2), 159–177. http://www.ingentaconnect.com/content/tandf/ttie/2002/00000003/00000002/art00005

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394.

Wickens, C. D. (2015). *the I Ct O R Ia N I S Io N*. *Figure 1*, 1395–1399.

Wilson, A. W., Blustein, D. H., & Sensinger, J. W. (2017). A third arm - Design of a bypass prosthesis enabling incorporation. *IEEE International Conference on Rehabilitation Robotics*, 1381–1386. https://doi.org/10.1109/ICORR.2017.8009441

Wilson, M. R., Poolton, J. M., Malhotra, N., Ngo, K., Bright, E., & Masters, R. S. W. (2011). Development and validation of a surgical workload measure: The surgery task load index (SURG-TLX). *World Journal of Surgery*, *35*(9), 1961–1969. https://doi.org/10.1007/s00268-011-1141-4

Wolpert, D. M., & Miall, R. C. (1996). Forward Models for Physiological Motor Control. *Neural Networks*, *9*(8), 1265–1279.

Zaepffel, M., Trachel, R., Kilavik, B. E., & Brochier, T. (2013). Modulations of EEG Beta Power during Planning and Execution of Grasping Movements. *PLoS ONE*, *8*(3). https://doi.org/10.1371/journal.pone.0060060

Zahabi, M., White, M. M., Zhang, W., Winslow, A. T., Zhang, F., Huang, H., & Kaber, D. B. (2019). Application of Cognitive Task Performance Modeling for Assessing Usability of Transradial Prostheses. *IEEE Transactions on Human-Machine Systems*, *49*(4), 381–387. https://doi.org/10.1109/THMS.2019.2903188

Zhang, J. Y., Liu, S. L., Feng, Q. M., Gao, J. Q., & Zhang, Q. (2017). Correlative Evaluation of Mental and Physical Workload of Laparoscopic Surgeons Based on Surface Electromyography and Eye-tracking Signals. *Scientific Reports*, *7*(1), 1–7. https://doi.org/10.1038/s41598-017-11584-4

Zhang, W., White, M., Zahabi, M., Winslow, A. T., Zhang, F., Huang, H., & Kaber, D. (2017). Cognitive workload in conventional direct control vs. pattern recognition control of an upper-limb prosthesis. *2016 IEEE International Conference on Systems, Man, and Cybernetics, SMC 2016 - Conference Proceedings*, 2335–2340. https://doi.org/10.1109/SMC.2016.7844587

Zheng, B., Cassera, M. A., Martinec, D. V., Spaun, G. O., & Swanström, L. L. (2010). Measuring mental workload during the performance of advanced laparoscopic tasks. *Surgical Endoscopy*, *24*(1), 45–50. https://doi.org/10.1007/s00464-009-0522-3

Chapter 5: Preliminary Validation of a Self-Report Mental Workload Measure

Abstract

As more technological advanced rehabilitation devices such as prostheses and powered orthoses (e.g., exoskeletons) are being used by individuals with upper limb deficits, there is an increased interest in understanding how device design affects mental workload. Despite the complexity and novelty of these devices, the mental workload individuals experience when using these devices to complete daily activities is poorly understood. Patient reported outcome measures (PROMs) possess the utility to capture the mental workload in upper limb device users; however, no PROM has been fully validated for this population. Therefore, the aim of this study was to design and validate a self-report multi-dimensional mental workload questionnaire called the (Prosthesis-Orthosis Load Index(POLI) and compare the survey's sensitivity against the gold standard mental workload assessment, the National Aeronautics Task Load Index (NASA-TLX). The POLI was developed from the framework of the NASA-TLX to specifically query various sources of mental workload in prosthesis and orthosis users. As a preliminary step for scale validation, 20 individuals with intact upper limbs completed a ten session bypass prosthesis program to learn to use a body-powered (BP) or myoelectric (MYO) bypass prosthesis. At four time points during the training program and again during a retention session, prosthesis users completed the validated performance outcome measures, the Box and Block Test (BBT) and the Southampton Hand Assessment Procedure(SHAP). The POLI and NASA-TLX were administered to capture changes in perceived mental workload during completion of the performance outcome measures. As expected, prosthesis users experienced improvements in motor performance and subsequent reductions in mental workload as a result of training. The POLI had good ($\omega_{hierarchical} = 0.86$) and excellent($\omega_{hierarchical} = 0.96$) internal consistency when used to assess mental workload changes during completion of the BBT and SHAP, respectively. Criterion validity was established with the NASA-TLX when capturing mental workload during the BBT ($\beta = 0.700$, $p < 0.001$) and SHAP ($\beta = 0.880$, $p < 0.001$). Evidence also suggests that the POLI was more sensitive in detecting mental workload differences between prosthetic

groups and was similarly responsive to mental workload changes during prosthetic training when compared to the NASA-TLX. Lastly, both questionnaires had similar relationships with motor performance and movement smoothness. While these results are hopeful, further work is needed to validate the POLI in the upper limb prosthesis and orthosis clinical populations before the utility of this instrument can be fully realized.

Introduction

For individuals who are learning to use upper limb prostheses and orthoses, changes in performance are typically measured using performance outcome measures (H. Kim et al., 2012; Light et al., 2002; Mathiowetz & Weber, 1985); however, the mental workload underlying these performance changes have not been sufficiently examined. Elucidation of sources of mental workload that impede motor performance and device use may better inform prescriptive decisions for prosthesis selection, prosthetic training program and device design. As these devices have become more technologically advanced, there has been an increased interest in capturing mental workload to better understand the mental demands associated with device design (Rackerby et al., 2022). Advanced tools such as neuroimaging are being used more in human-device interaction research; however, integration of these tools in a clinical setting pose significant challenges, such as cost, set-up complexity, and data processing (Kimberley & Lewis, 2007; Soufineyestani et al., 2020). Patient reported outcome measures (PROMs), questionnaires that capture the patient's report of their health status, may serve as a useful surrogate to measure mental workload due to ease of administration, time effectiveness, interpretability, and patient-centeredness (Churruca et al., 2021; Mou et al., 2022). Additionally, there has been increased regulatory interest from the Food & Drug Administration to use PROMs in clinical trials for medical devices (Coles et al., 2021). While PROMs are increasingly used to assess the patient's experience when using upper limb devices, these measures have primarily focused on satisfaction with device use, quality of life or activity performance. To the author's knowledge, no PROMs measuring mental workload are routinely used in a clinical rehabilitation setting.

The National Aeronautics Space Administration Task Load Index (NASA-TLX) is commonly used to assess mental workload in various fields and has reliably indexed changes in mental workload in response to task demand and practice. To tailor the NASA-TLX so that it can better capture mental workload in specific fields, adaptions of the NASA-TLX has been created for fields such as medical surgery (M. R. Wilson et al., 2011) and driving (Pauzié, 2008). To address the need to specifically capture mental workload in prosthesis users, researchers created the Prosthesis Task Load Index (PROS-TLX)

(Johnny V.V. Parr et al., 2023). While this work is informative and foundational, the survey was only administered at a single timepoint thus the ability of the survey to reliably index changes in mental workload over time was unknown. Secondly, the survey was used to index mental workload during one activity, therefore it was not determined if the survey can produce comparable results across a variety of tasks. Thirdly, participants only used a myoelectric prosthesis in the study, therefore it is uncertain if the scale can distinguish the mental demands between different types of upper limb devices. Lastly, the language in the survey is specific to upper limb device prosthesis users. While there has been more interest in measuring mental workload in upper limb prosthesis users due to advances in technology, powered orthoses such as exoskeletons are becoming increasingly more advanced and may require a deeper understanding of the mental effort associated with device use (Gull et al., 2020; Marchand et al., 2021).

This study is a first step to develop and validate a multidimensional mental workload questionnaire called the Prosthesis-Orthosis Load Index (POLI) to elucidate sources of mental workload associated with task demands and device use for prosthesis and orthosis users. We retained two dimensions of the NASA-TLX and created four new dimensions to best address cognitive-motor demands associated with upper limb device use. We assessed preliminary validity (NASA-TLX, performance and normalized jerk) and internal consistency by administering the questionnaire to capture perceived mental workload during completion of the validated performance outcome measures, the Box and Block Test and the Southampton Assessment Procedure (SHAP) at various timepoints in individuals with an intact hand learning to use a body-powered (BP) or myoelectric (MYO) bypass prosthesis. While the POLI was designed with both prostheses and exoskeletons in mind, this initial effort assesses the POLI for upper limb bypass prosthesis users. Future testing of the POLI in upper limb orthotic groups is required to draw conclusions about the utility of the POLI for orthosis users.

Methods

POLI Development

We reviewed the literature to identify potential sources of mental workload associated with prosthesis and orthosis use. We modified four dimensions and retained two dimensions from the NASA-TLX (Table 1). The intention to change the *mental demand* dimension to the *mental planning* dimension was to capture the amount of cognitive-motor strategy updates in response to adjustments to task demands as a marker of mental planning efficacy. If the frequency of updating cognitive-motor strategies was high, then this may correspond to a high-level planning demand. Frequent strategy changes may indicate that the original mental plan was ill-equipped to address the task demands, which rendered the plan unstable, therefore causing the prosthesis user to update their mental plan to meet the task demands. The *physical demand* in the NASA-TLX may capture general physical demand of all engaged muscle groups and include physical effort and fatigue. We wanted to limit the reports of the effect of general physical fatigue or effort since this information may be better captured in the effort dimension. Furthermore, we specifically wanted to query the upper limb device user about device prehension performance and the challenge of using compensatory strategies to achieve the preferred device position in preparation for grasping. To do this, we bifurcated the *physical demand* dimension of the NASA-TLX into the *grasp and release demand* and the *positioning demand.* The *temporal demand* was not included in the POLI since we were not interested in the time-pressure of tasks since quality of movement is often degraded with an increased temporal demand(Heitz, 2014). Additionally, the POLI is intended to have flexibility to be administered to assess mental workload across a variety of activities some of which may not inherently prioritize task completion speed. Performance and effort were maintained from the NASA-TLX, since we were still interested in understanding the perception of overall performance success when using the upper limb device and the effort required to complete the task with the device. Lastly, a task-complexity category was included in place of the NASA-TLX frustration demand since task complexity has been shown to increase mental workload. The 20-point Likert scale was maintained from the NASA-TLX with anchors of *Very Low* and *Very High*. The performance dimension was anchored from *Perfect* to *Failure*. We also provided participants with a table of more thorough descriptions of each dimension and reviewed each dimension with the participants to ensure understanding. This descriptive table was available to participants throughout survey completion. The NASA-TLX requires participants to additionally complete a separate portion of the survey that creates weights for the dimensions to refine the most significant sources of workload; however, we omitted this step to minimize the survey completion time for the participant and assessment scoring time for the practitioner since time to administer and document findings from assessments has been identified as a major challenge for outcome measurement administration in the clinical rehabilitation setting (Stokes & O'Neill, 2008; Zidarov & Poissant, 2014).

Table 1. Dimensions of the NASA-TLX and POLI

NASA-TLX Dimensions	POLI Dimensions
Mental Demand- How mentally demanding was the task?	**Mental Planning Demand-** How frequently did you change your strategy to complete the task?
Physical Demand- How physically demanding was the task?	**Grasp and Release Demand-** How difficult was it to grasp and release during the task?
	Positioning Demand- How difficult was it to position your device in preparation for grasping?
Temporal Demand- How hurried or rushed was the pace of the task?	---
Performance- How successful were you in accomplishing what you were asked to do	**Performance-** How successful were you in accomplishing what you were asked to do?
Effort- How much effort did you use during the task?	**Effort-** How much effort did you use during the task?
Frustration- How insecure, discouraged, irritated, stressed, and annoyed were you?	**Task Complexity-** How complex was the task?

Blue and **brown** dimensions show the connection between NASA-TLX and POLI dimensions.

Participants

To participate in the study, participants were required to be right hand dominant (confirmed by the Edinburg Handedness Survey), have normal or corrected-to-normal vision, not have an upper limb injury, have no neurological disorders that would negatively influence movement and not be on psychotropic medication. A convenience sample of 28 participants volunteered to participate in the study, five participants were excluded from the study due to not meeting all inclusion criteria and three participants either signed up for the study or started the study but dropped out due to personal reasons. Thus, a final total sample of 20 right-handed participants (10 males, 10 females) with intact upper limbs between the ages of 19 and 58 (mean = 25.85, SD = 8.35) completed the 10-session bypass prosthetic training program. Participants were randomly split into the BP (4 males, 6 females, mean age = 23.5, SD = 3.77) or MYO(5 males, 5 females, mean age = 28.5, SD = 10.83) groups. Two sessions of kinematic data were not included due to IMU technical problems. During training, three MYO participants experienced a MYO device malfunction in which the index finger of the device remained in the open position during one or more assessment sessions. To determine if the malfunction had a significant effect on performance and perceived task demand, a linear mixed effect model was employed for MYO users to see if the covariate, device malfunction, significantly affected motor performance, kinematic or perception of demands using the NASA-TLX. This malfunction did not have an effect on BBT motor performance, movement smoothness or perceived mental workload (NASA-TLX) thus the BBT data for these participants were preserved. The device malfunction did not have an effect on SHAP motor performance or movement smoothness; however, the malfunction did increase the perceived physical demand ($p = 0.006$) of the MYO group during completion of the SHAP assessment. Upon further analysis, it was determined that one MYO user who experienced this malfunction for three assessment sessions was adversely affected, therefore this participant's data was removed from the SHAP dataset. Upon removal of the participant's results, device malfunction was found to not significantly impact perceived physical demand ($p = 0.446$) for the MYO users.

All participants were current or former University of Maryland, College Park students or faculty. The sample size was determined based upon a prior upper limb prosthetic training study (J. V.V. Parr et al., 2019). All participants provide their informed consent prior to participating in the study. The Institutional Review Board at the University of Maryland- College Park approved this study.

Bypass Prosthesis Donning and Operational Check

The BP bypass prosthesis used in this study was designed by Arm Dynamics (Dallas, TX) utilized a voluntary opening Hosmer 5X hook terminal device, with manual wrist rotation, figure eight harness and a 12 cm distal offset. While standing, the BP users donned the prosthesis harness on the right, dominant arm and the forearm was secured in the arm socket with straps with assistance from the experimenter. While seated, the participants demonstrated voluntary opening of the terminal device via a cable pulley system by using shoulder flexion and scapular protraction with three techniques. The bypass side technique only used the right side of the body, the sound side technique used the left side of the body and the bi-scapular technique used both scapulae to open the terminal device. Opening of the terminal device was demonstrated at a 50% and 100% aperture. The BP users also demonstrated unlocking of the wrist, manual rotation of the wrist to achieve the desired hook direction and a locking of the wrist to secure the hook positioning. The BP users pre-selected the orientation of their prosthetic hook prior to beginning each task during training and assessment.

The MYO terminal device used in this study was the i-limb Ultra® created by Össur (Foothill Ranch, CA). The myoelectric terminal device was mounted to a forearm brace adapter provided by Next Step Bionics with a perpendicular handlebar with a medial offset of 15° from the participant's forearm. This device featured individualized motorized digits, compliant grip capability, direct control system using two electromyography sensors, manual thumb, and wrist rotation functionality. This prosthesis was used with a companion I-phone application (Biosim™) via Bluetooth connection. Biosim™ features a real-time EMG graph to assess muscle contraction quality and 12 automated 'quick' grips. While the MYO users were seated, their ventral and dorsal aspect of the right forearm was cleaned using an alcohol swab prior to placing the flexor sensor on the muscle belly of the flexor carpi radialis superficialis and the extensor sensor on the muscle belly of the extensor carpi radialis. The electrodes were secured with skin tape to reduce electrode movement during the experiment. This was done to remove skin debris that may interfere with the skin/electrode connection and the electromyograph (EMG) signal. Once the prosthesis was on, participants completed repetitive hand opening and closing for approximately 5-10 seconds while viewing the EMG signal in real time to assess for contraction quality and for existence of interfering co-contraction of the flexor and extensor muscles. Knowledge of performance feedback was provided as needed until optimal muscle contractions with minimal or undetected co-contraction was detected and no significant latency was noted between the contraction and the subsequent MYO hand movement. The MYO users then selected 11 grips one at a time (Figure 1) using the Biosim™ application. They performed isometric wrist flexion to flex the digits/hand followed by isometric wrist extension to open the digits/ hand based upon the pre-selected digit operation of each grip. The thumb park quick grip was not used for the study due to usability concerns since this grip only allowed for a 1.5 second time window for the thumb to be operated via the user's input signal before returning to an open hand position. The 12th and final grip used for the MYO users was the composite grip (full fist closure) which was accessed via a double tap on any grip icon on the app. The MYO participants used the left hand to demonstrate manual rotation of the terminal device wrist and thumb opposition. If signal latency issues were detected at any time during the session, the study was paused, electrode signal quality was immediately re-inspected and position adjustments of the electrode were made as needed. The MYO users pre-selected their grip and wrist and thumb position prior to beginning each task during training and assessment.

Prosthetic Training Program

The bypass prosthetic training program was adopted from an established training protocol(Bloomer et al., 2018) with an adjustment of the frequency of performance outcome measure administration from every training session to every 3rd training session. Participants typically completed 2-3 sessions each week. This was done to more closely approximate of the frequency of practice sessions and administration of performance outcome measures typically observed in an outpatient rehabilitation setting (El Hayek et al., 2023). An experienced occupational therapist administered the prosthetic training to ensure the training was standardized and training techniques that were utilized were similar to an actual rehabilitation program (Butkus et al., 2014; Resnik et al., 2019). Participants first completed an orientation session (S1) in which the informed consent was reviewed, the prosthetic group was assigned, EEG cap size was determined, prosthesis harness fitting (BP group only) and scheduling of the first training sessions were completed. All sessions in the program were completed while seated. Customized table heights for each participant were selected so that the participants forearm/arm angle was at a 90-degree angle when resting their prosthesis and left hand on the table with feet flat on the floor.

Training Only Sessions

Sessions S3,S4,S6,S7,S9 and S10 were training only sessions. Sessions at the beginning of the training program typically lasted 50 minutes while sessions later in the program lasted around 30 minutes due to the participants advancing more quickly through the object manipulation portion of the training and completing all tasks of the ADL training before the 20 minute time allotment elapsed. Before the start of training, participants donned their prosthetic devices and device set-up was completed.

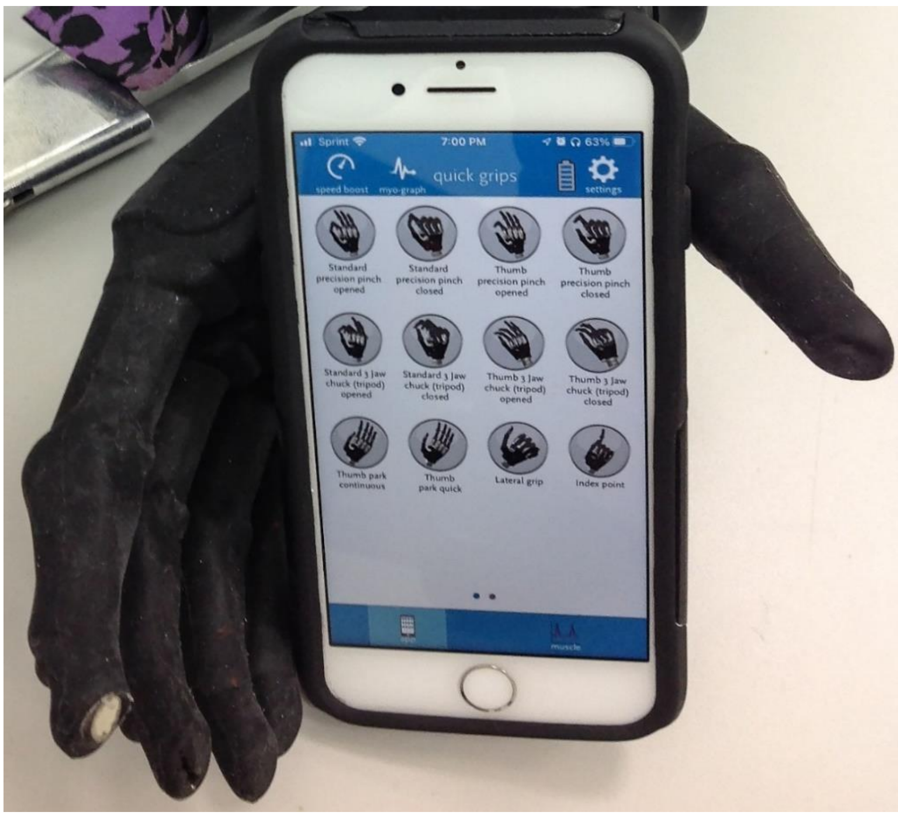


Fig. 1. Biosim™ smartphone application with 12 available grips. Top row(left to right): standard precision pinch opened, standard precision pinch closed, thumb precision grip opened, thumb precision grip closed. Middle row(left to right): standard 3- jaw chuck (tripod) opened, standard 3- jaw chuck (tripod) closed, thumb 3-jaw chuck (tripod) opened, thumb 3-jaw chuck (tripod) closed, Bottom row(left to right): thumb park continuous, thumb park quick(not used), lateral grip, index point. Not pictured: composite grip. This grip was acquired by double-tapping any grip icon.

Object Manipulation

Prosthesis users demonstrated three types of object manipulation strategies (direct grasping, indirect grasping, and fixation) to manipulate a variety of objects. The prosthesis users employed a direct grasp(grasp items directly from surface) and indirect grasp (pick up item from table using intact hand, then use prosthetic hand to grasp item from intact hand) to transport a wood cube, metal can and foam ball. For fixation, both groups used their prosthesis to stabilize a zipper, sweater, and ruler while the intact hand opened and closed the zipper, unbuttoned the sweater buttons, and drew a straight line using the ruler, respectively.

Free Training

Free training permitted five minutes of unstructured time for the participants to use their prosthesis while seated to manipulate a variety of objects (plates, pens, bottles; etc.) using the object manipulation strategies just learned.

ADL Training

Participants then completed 10 activity of daily living (ADL) and instrumental activities of daily living(iADLs) from the validated Activities Measure for Upper Limb Amputees (Resnik, Adams, Otr, et al., 2013) in a 20-minute time window. Knowledge of performance and results feedback were delivered as needed via verbal and physical demonstration mediums throughout training.

For more details of the training protocol, please refer to the Study 1 Protocol in the Appendix.

Training and Assessment Sessions

The participants completed training and assessment segments during the initial training session (S2), sessions 5 (S5) and 8 (S8) and the final training session (S11). Prosthesis users donned their prostheses before EEG and Inertial Measurement Unit (IMU) set-up and completed the prosthesis operational check after EEG and IMU set-up. The participants then completed the BBT and SHAP. Please see the Data Acquisition section for the IMU, BBT, SHAP, NASA-TLX and POLI data capture. Including EEG and kinematic set-up and breakdown, sessions on average took approximately 3.5 hours.

Retention Session

The median days spent in the training program (S2-S11) was 33 days for the BP users and 38 days for the MYO users. At least one week after the completion of training, participants completed the retention session. No training was completed during this session. EEG and IMU set-up were completed first. Prosthesis users donned their prostheses before EEG and Inertial Measurement Unit (IMU) set-up and completed the prosthesis operational check after EEG and IMU set-up. The participants then completed the BBT and SHAP. Please see the Data Acquisition section for the EEG, IMU, BBT and NASA-TLX data acquisition process. Including EEG and kinematic set-up and breakdown, sessions on average took approximately 2.5 hours. The average number of days between the final training session and retention session for the BP and MYO users were 12.4 and 14.7 days, respectively.

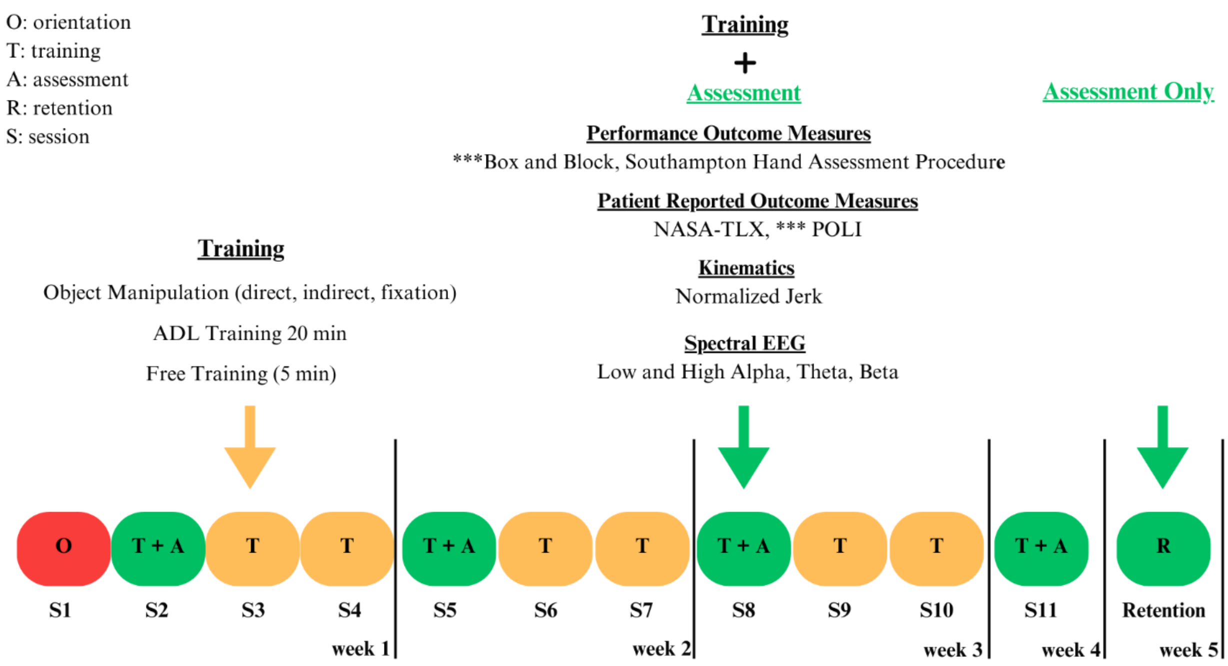


Fig. 2. Training Program. S2 denotes the start of the training program and S11 denotes the end of the training program. The retention session was completed at least one week after the final training session. *** indicates results that are not of primary interest in this study and are reported in other studies.

Experimental Set-Up

A pre-fitted EEG cap was donned on the participant's head and secured using chin and chest straps to reduce unwanted movement artifacts. Electrode lines were gathered and felt material secured the electrode lines in a ponytail using a simple rope knot. The lines were then clipped to the participant's the participant's back. Line bundles that were not included in the ponytail were taped to the participant's back. Gel was applied to each electrode until an impedance below 10 kΩ was achieved. EEG was recorded from 64 active electrode sites (10-20 system) at a 1000 Hz sampling rate using the Brain Vision EEG system (Brain Products GmbH, Germany). The EEG data was online referenced to the left earlobe and offline re-referenced using activity from the right earlobe. and a common ground was employed at the AFz site on the scalp. The horizontal electro-oculographic channel (HEOG) and vertical electro-oculographic channel (VEOG) was recorded by one electrode on the right outer canthus of the eye and one electrode on the superior orbital ridge of the right eye, respectively.

EEG

EEG data was processed using the EEGlab package of Matlab® (The Mathworks Inc., USA) using custom code. Bad channels were identified and interpolated. Data was band-pass filtered with a low cut-off of 0.1 Hz and a high cut-off of 60 Hz with a 48 dB rolloff. Next, independent component analysis (ICA) was employed to remove ocular, muscle, and line noise artifacts. Data was resampled to 500Hz for synchronization with inertial measurement units (IMUs). Using a custom Matlab® script, data was epoched into early (-2 to -1 seconds) and late planning (-1 to 0 seconds) before movement onset. Movement onset was epoched from 0 seconds to the end of the trial which was marked by a manual end of movement execution trigger from the IMU system. Spectral power was calculated across 1-Hz bins and summed across the frequency bandwidths theta (4-7Hz) low-alpha (8-10Hz, high-alpha (11-13 Hz) and beta (14-35 Hz).

IMU

An inertial movement unit (IMU; Xsens™) was placed on the center of the participant's forehead, the right mid- humerus and distal end of the bypass prosthesis to measure kinematic changes of the head, arm, and wrist, respectively at a sampling rate of 100Hz. Data was bandpass filtered with a low cut-off of 0.01 Hz and a high cut-off of 20 Hz with an 80 dB rolloff. Data was up sampled to 500 Hz to synchronize with the EEG data. Normalized jerk was computed from the acceleration data using a custom Matlab® script. Due to the focus of this work to examine differences in upper limb movement smoothness, normalized jerk for the wrist and arm was computed to determine the rate of change in movement acceleration as an index of movement smoothness (Balasubramanian et al., 2015).

BBT, NASA-TLX, POLI

After EEG and IMU set-up, training was completed as outlined in the Training Only Sessions section. For the BBT, participants were required to individually transport as many 2.5cm^3 blocks as possible across a 15.2 cm partition (Desrosiers et al., 1994). The BBT instructions were explained to the participant and the experimenter provided a physical demonstration of a proper block transfer sequence. Participants were allowed to transport 3 blocks prior to their first BBT trial per the BBT instructions. The experimenter then explained the EEG and kinematic data capture sequence. Participants were instructed to remain still with their head facing forward and their left forearm and prosthesis resting on the border of the BBT box. The experimenter verbally confirmed that the participant was ready to begin the data capture. Four seconds prior to the start of each trial, the experimenter asked the question, “Ready?” EEG and IMU recording were started manually. After four seconds elapsed, an audible beep sounded from the computer speaker, and the participant began the trial. A manual trigger was created at the start of the trial in the EEG and IMU recordings. After one minute elapsed, the experimenter stated the word, “Stop.” A manual trigger was created at the end of the trial to mark the end of movement execution in the EEG and IMU recordings. If a block was in transport when the trial was stopped, it was not included in the summation of the total number of blocks transported for the trial. After a two-minute rest break, the second trial was completed. No feedback was provided between or after trials. Scoring was based on the number of blocks transported in one minute. The average number of blocks was computed using scores from both trials for each Training and Assessment session.

After the completion of the 2nd BBT trial, participants completed the NASA-TLX and Prosthesis-Orthosis Load Index (POLI) paper surveys in a counterbalanced order using their non-prosthetic hand to circle tick marks that corresponded with their average perceived workload levels across both trials of the BBT.

SHAP, NASA-TLX, POLI

After EEG and IMU set-up, training was completed as outlined in the Training Only Sessions section. The SHAP is a validated upper limb amputee assessment that includes two broad categories, the abstract object tasks and activities of daily living(Light et al., 2002). The abstract object tasks category required individuals to transport six objects in lightweight and heavyweight forms. The ADL category required individuals to complete 14 ADLs with primary use of the unilateral upper limb.

Participants sat in a chair with back support with their feet flat on the floor with their intact hand and prosthetic terminal device resting on the table with their arms at a 90-degree angle. Due to the extensive time for experimental set-up and SHAP completion, participants were allowed to rest using the back support in between tasks; however, they were instructed to sit upright when completing each task. The SHAP board was positioned eight centimeters in front of the participant. Each task was explained by the experimenter, and the participants were allowed up to one minute to practice this task. No verbal feedback was provided during the practice period.

After one minute had elapsed or the participant stated they were ready, participants were instructed to remain still with their head facing forward and their left forearm and prosthesis resting on the border of the table. The experimenter verbally confirmed again that the participant was ready to begin the data capture. Four seconds prior to the start of each trial, the experimenter asked the question, “Ready?” EEG and IMU recording were started manually. After four seconds elapsed, an audible beep sounded from the computer speaker, and the participant began the trial. A manual trigger was created at the start of the trial in the EEG and IMU recordings. Participants then used their prosthesis to start a timer located in the middle of the SHAP board by pressing a large blue button. Next, they moved the object from the rear slot to the front slot as quickly as possible, and then stopped the timer by pressing the large blue button again to stop the timer. The end of the trial was denoted by the stopping of the timer after the object transport. A manual trigger was sent by the experimenter at the end of the trial to mark the end of movement execution in the EEG and IMU recordings. Per the SHAP instructions, only one attempt was given to complete the task. If an object fell off the board, it was noted as a task failure and the time was not recorded for the task.

After the completion of each category of the SHAP (Table 2), participants completed the NASA-TLX and Prosthesis-Orthosis Load Index (POLI) paper surveys in a counterbalanced order using their non-prosthetic hand to circle tick marks that corresponded with their average perceived workload levels. The surveys were administered after each category to assess differences in perceived mental workload between categories. Chapter 3 addresses some of these between category analyses; however, these analyses are outside the scope of the present study and will be discussed in future work. The SHAP and BBT were completed in a counterbalanced order. Including EEG and kinematic set-up and breakdown, sessions on average took approximately 3 hours.

Table 2. NASA-TLX and POLI Administration Schedule

	NASA-TLX and POLI administration
1.	BBT: After the 2nd trial of the BBT
2.	SHAP: After the abstract light power tasks
3.	SHAP: After the abstract light precision tasks
4.	SHAP: After the abstract heavy power tasks
5.	SHAP: After the abstract heavy precision tasks
6.	SHAP: After ADL power tasks
7.	SHAP: After ADL precision tasks

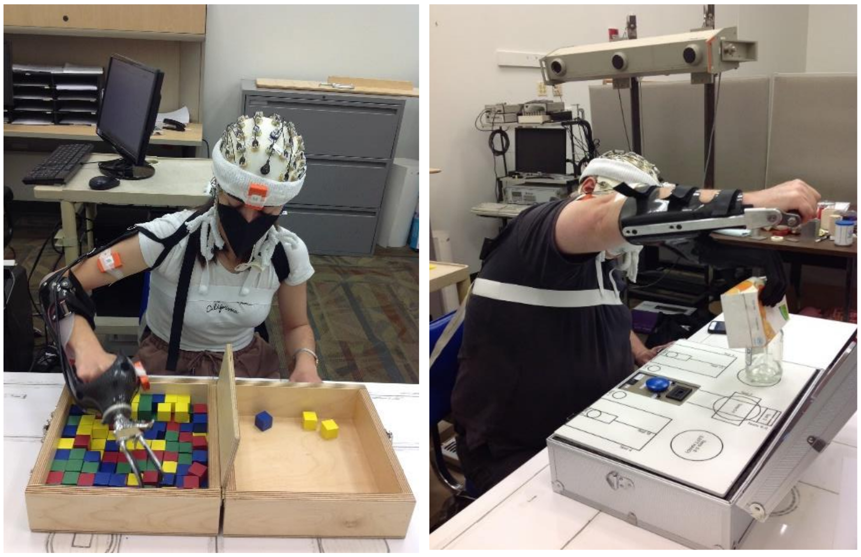


Fig. 3. Images of BP user completing the BBT(left) and MYO user completing the Glass Jug Pouring ADL task of the SHAP.

Data Acquisition

Performance

For the BBT, scoring was based on the number of blocks transported in one minute. Participant completed two trials of the BBT with a two-minute break in between trials to reduce fatigue. The average number of blocks were computed using scores from both trials. For the SHAP, the time required to complete each task was recorded. The times were converted to task scores and then used to compute an overall index of functional score (IOF) per the SHAP instructions (Light et al., 2002).

Questionnaires

Scores on the NASA-TLX and POLI ranged from 0-100 points. Each of the 20 vertical tick-marks represented an increment of 5 points. Circled tick-marks by the prosthesis users were converted to scores for each dimension with lower scores indicated lower workload and higher scores indicated higher workloads Averages for each dimension for the NASA-TLX and POLI were computed. Each dimension score was summed and divided by the total number of dimensions (n = 6) to compute the total workload score.

Kinematics

An inertial movement unit (IMU; Xsens™) was placed on the center of the participant's forehead, the right mid- humerus and distal end of the bypass prosthesis to measure change in the rate of acceleration of the head, arm, and wrist, respectively at a sampling rate of 100Hz. Data was bandpass filtered with a low cut-off of 0.01 Hz and a high cut-off of 20 Hz with an 80 dB rolloff. Data was up sampled to 500 Hz to synchronize with the EEG data. Normalized jerk for the wrist and arm was computed to determine the rate of change in movement acceleration as an index of movement smoothness (Balasubramanian et al., 2015).

Statistical Analysis

Performance and Kinematics

To assess changes in mental workload in context of performance and kinematic changes experienced by the prosthesis users during training, performance, wrist, and arm normalized jerk were assessed using linear mixed effect models with the Prosthesis and Session factors as the fixed effects and the Participants factors as the random effect in a 2 (Prosthesis[BP,MYO] x 3 (Session[S2, S11, Retention] design was employed. To increase clarity of reporting, main effects and interactions between the initial session and final session, and the initial session and retention session are reported to capture the overall effect of prosthetic training.

Internal Consistency

The Omega hierarchal was used to assess internal consistency, since the assumption of tau equivalence is not required, unlike the Cronbach alpha. Additionally, omega hierarchal has been shown to have less bias, have less reports of reliability overestimation and is recommended for multi-dimensional scales when compared to Cronbach alpha (Cheung et al., 2023; Trizano-Hermosilla et al., 2021). POLI scores were averaged across the training + assessment sessions and the retention session to compute the Omega hierarchal. To increase clarity in reporting, a cut-off of 0.7 or higher is acceptable internal consistency.

Responsiveness

Responsiveness of the POLI and the NASA-TLX was measured using an effect size index called the standardized response mean(SRM) to reveal the degree to which each instrument was able to measure changes in mental workload over time. The SRM was calculated for the total workload scores for both questionnaires at the beginning of training (S2) and at the retention session for the BBT and SHAP. To increase clarity in reporting, a SRM > 0.8 indicates large responsiveness, 0.5-0.8 indicates moderate responsiveness, and 0.2-0.5 indicates low responsiveness (Cornett et al., 2020; Devilliers et al., 2014). A positive SRM reflects an increase of the questionnaire scores over time while a negative SRM reflects an attenuation of the questionnaire scores over time.

Criterion Validity with the NASA-TLX

To establish criterion validity of the POLI with the NASA-TLX, linear mixed effect models with the Prosthesis and Session factors as the fixed effects and the Participants factors as the random effect in a 2 (Prosthesis[BP,MYO] x 3 (Session[S2, S11, Retention] design was employed to determine if the NASA-TLX total workload scores significantly predicted the POLI total workload scores for the BBT and SHAP.

Known Group Validity

Linear mixed effect models with the Prosthesis and Session factors as the fixed effects and the Participants factors as the random effect in a 2 (Prosthesis[BP,MYO] x 3 (Session[S2, S11, Retention] design were employed to determine if the dimensions of the POLI and the NASA-TLX were able to discriminate between mental workload between prosthetic groups when completing the BBT and SHAP performance outcome measures. Main effects of Prosthesis and interactions of Prosthesis and Session are reported to capture the survey's ability to distinguish differences between the prosthetic groups in general between the initial and final training sessions and initial retention sessions. Since the purpose of known group validity was to determine differences between experimental groups, Session main effects were not reported. Due to past work revealing better motor performance in BP users when compared to MYO users

(Bouwsema et al., 2008; Resnik et al., 2022) and it being well established that mental workload is inversely related to motor performance (Gentili et al., 2014; Jaquess et al., 2017; Shaw et al., 2018; Shuggi et al., 2019), we predicted the MYO users would experience more mental workload when compared to the BP users.

Construct Validity

Construct validity was assessed using linear mixed effect models with the Prosthesis and Session factors as the fixed effects and the Participants factors as the random effect in a 2 (Prosthesis[BP,MYO] x 3 (Session[S2, S11, Retention] design to determine how well the performance and normalized jerk measures predicted the total workload and dimensions of the POLI.

For performance, normalized jerk, known group validity, criterion validity and construct validity, p-values are reported with a $p < 0.05$ as the threshold to determine statistical significance.

Results

Internal Consistency

The POLI demonstrated good internal consistency as a measure of mental workload for the Box and Block Test ($\omega_{hierarchical} = 0.86$), excellent internal consistency for the SHAP ($\omega_{hierarchical} = 0.96$). The g value, an internal consistency estimate, is reported for each POLI dimension for the BBT and SHAP.

Table 3. Internal consistency for each POLI dimension

Dimension	**BBT(g-values)**	**SHAP(g-values)**
Mental Planning	0.72	0.96
Grasp Demand	0.83	0.95
Positioning Demand	0.80	0.98
Effort	0.68	0.94
Performance	0.50	0.68
Task Complexity	0.68	0.78

Performance and Kinematics

For BBT performance, a main effect was revealed for Session ($F(4, 72) = 23.809$, $p < 0.001$, $\eta p^2 = 0.569$). The post-hoc analysis revealed that when compared to the initial training session, prosthesis users transported more blocks in during the final training session ($p < 0.001$, $d = 1.624$) and the retention session ($p < 0.001$, $d = 1.703$). For BBT wrist movement smoothness, a main effect was revealed for

Prosthesis ($F(1, 82) = 58.921$, $p < 0.001$, $\eta p^2 = 0.418$) such that the MYO users had more wrist movement variability when compared to the BP users. For BBT arm movement smoothness, main effects were revealed for Prosthesis ($F(1, 16) = 32.049$, $p < 0.001$, $\eta p^2 = 0.66$) and Session ($F(4, 61) = 3.699$, $p = 0.009$, $\eta p^2 = 0.193$). These main effects were superseded by a Prosthesis x Session interaction ($F(4, 61) = 2.71$, $p = 0.038$, $\eta p^2 = 0.149$). The post-hoc analysis revealed that the MYO users had more movement variability when compared to the BP users the initial training session ($p < 0.001$, 0.294), the final training session ($p < 0.001$, 0.857) and the retention session ($p = 0.012$, 1.274). In comparison to the initial session, the MYO users experienced more movement variability in the final training session($p = 0.016$, $d = 0.243$; however, this change in movement smoothness did not persist in the retention session.

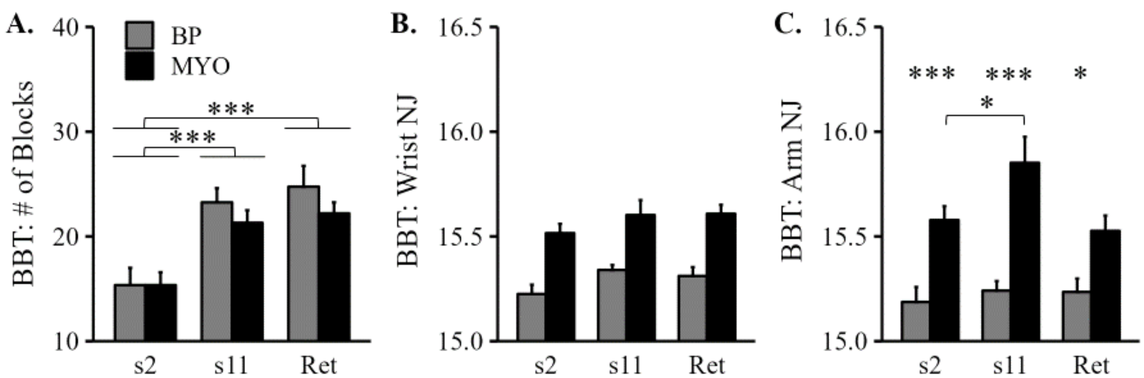


Fig. 2. BBT performance and normalized jerk results across the initial, final and retention training sessions. **A.** # of blocks transported. **B.** The wrist normalized jerk. **C.** The arm normalized jerk. BP - Body-powered. MYO - Myoelectric. * p< 0.05, ** p <- 0.01, *** p < 0.001.

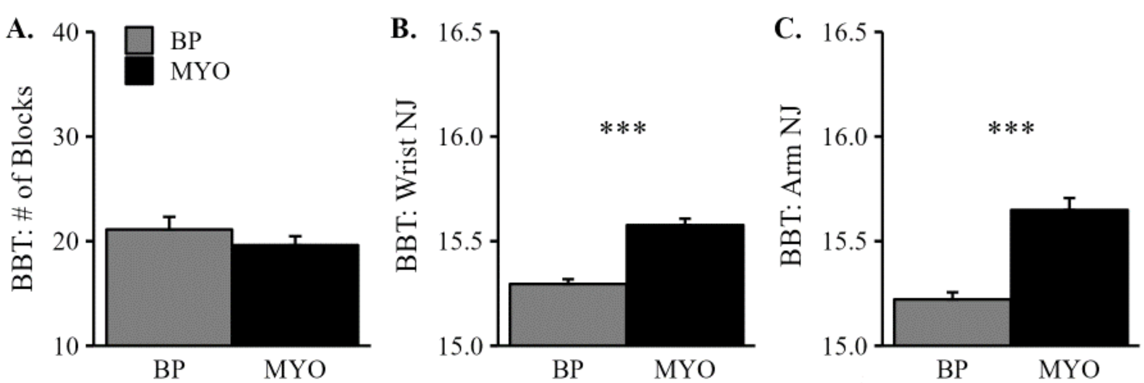


Fig.5. BBT performance and normalized jerk results averaged across training sessions. **A.** # of blocks transported. **B.** The wrist normalized jerk. **C.** The arm normalized jerk. BP - Body-powered. MYO - Myoelectric. * p< 0.05, ** p <- 0.01, *** p < 0.001.

For the SHAP performance, a main effect was revealed for Session(F(4, 54) = 15.091, p < 0.001, ηp^2 = 0.526). The post-hoc analysis revealed that when compared to the initial training session, prosthesis users had higher IOF scores during the final training session (p < 0.001, d = 1.488) and the retention session (p < 0.001, d = 1.500). For the SHAP wrist movement smoothness, a main effect was revealed for Session (F(4, 59) = 23.667, p < 0.001, ηp^2 = 0.616). The post-hoc analysis revealed that when compared to the initial training session, prosthesis users had less wrist movement variability during the final training session (p < 0.001, d = 1.334) and the retention session (p < 0.001, d = 1.558). For the SHAP arm movement smoothness, a main effect was revealed for Prosthesis (F(1,16) = 9.462, p = 0.007, ηp^2 = 0.371). The post-hoc analysis revealed that when compared to the initial training session, prosthesis users had less arm movement variability during the final training session (p < 0.001, d = 1.155) and the retention session (p < 0.001, d = 1.178).

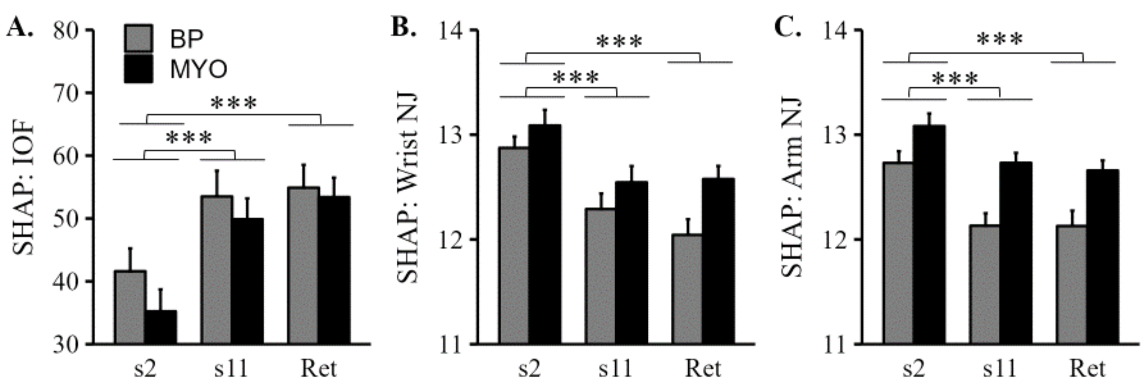


Fig.4. SHAP performance and normalized jerk results across the initial, final and retention training sessions. **A.** # of blocks transported during training. **B.** The wrist normalized jerk. **C.** The arm normalized jerk. BP - Body-powered. MYO - Myoelectric. IOF= Index of Functionality Score. * p< 0.05, ** p <- 0.01, *** p < 0.001.

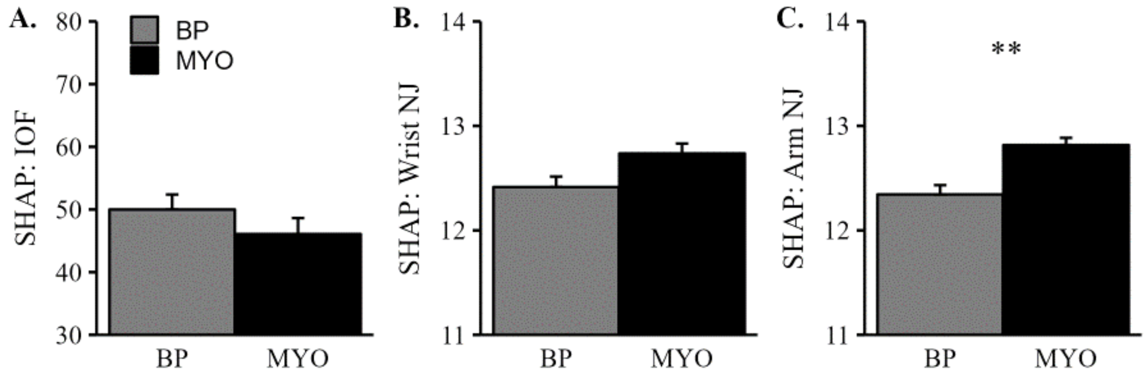


Fig. 6. SHAP performance and normalized jerk results averaged across the initial, final and retention training sessions. **A.** # of blocks transported during training. **B.** The wrist normalized jerk. **C.** The arm normalized jerk. BP - Body-powered. MYO - Myoelectric. IOF= Index of Functionality Score. * p< 0.05, ** p <- 0.01, *** p < 0.001.

Known Group Validity

NASA-TLX Detection of Mental Workload Differences Between Groups During the BBT

The temporal demand was the only NASA-TLX dimension that distinguished differences between the prosthetic groups . A significant Prosthesis x Session interaction was detected F(4, 64) = 2.592, 0.045, ηp^2 = 0.139). However, the post-hoc analysis did not reveal the locus of the interaction.

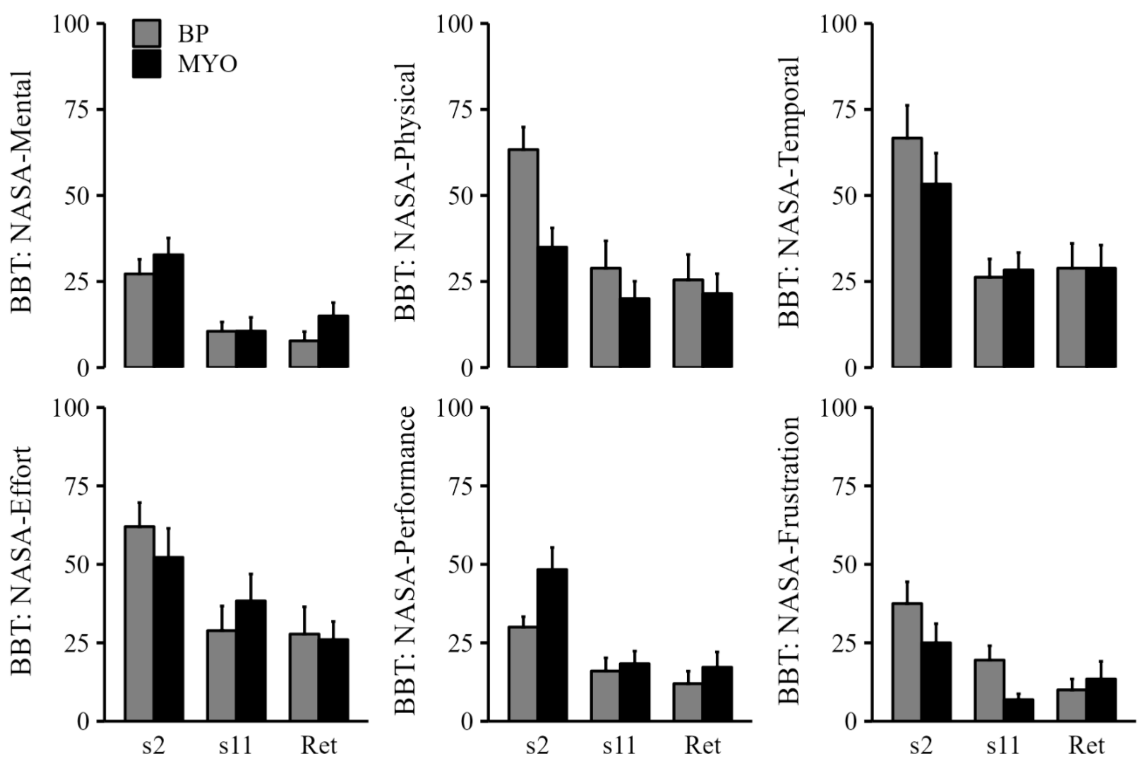


Fig.7 . The results of each dimension of the NASA-TLX to capture mental workload during completion of the BBT during the initial, final and retention training sessions. BP - Body-powered. MYO - Myoelectric. * p< 0.05, ** p <- 0.01, *** p < 0.001.

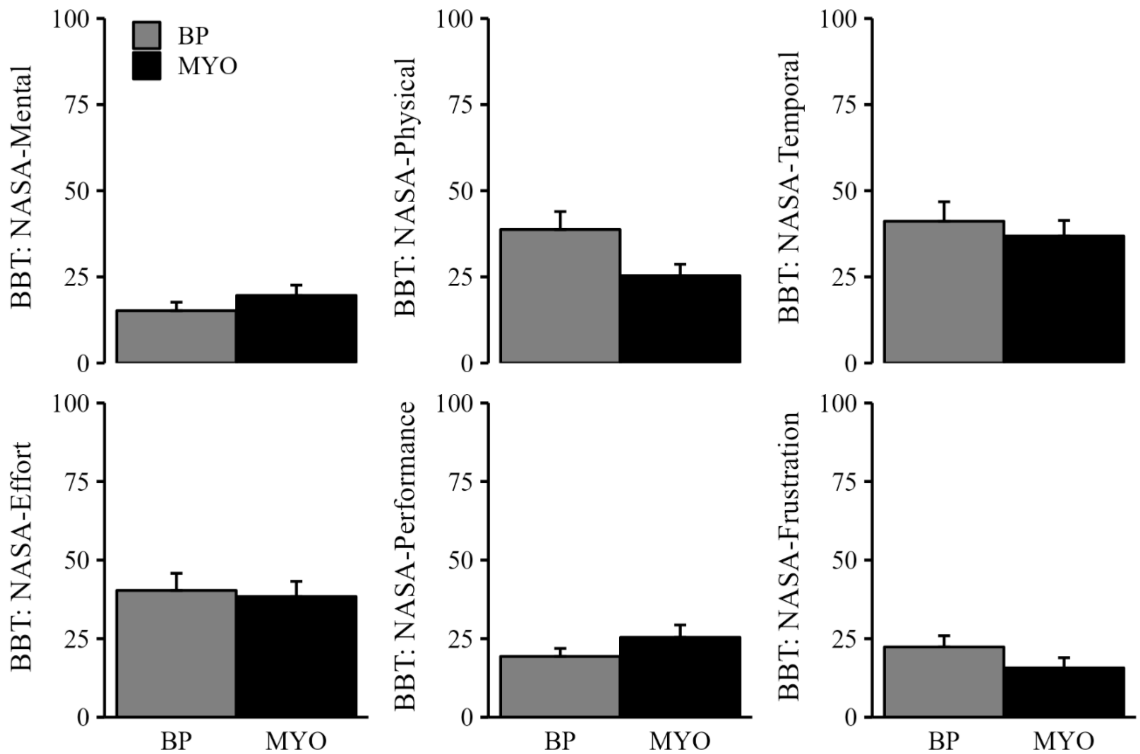


Fig.8. The results of each dimension of the NASA-TLX to capture mental workload during completion of the BBT averaged across the initial, final and retention sessions. . BP - Body-powered. MYO - Myoelectric. * p< 0.05, ** p <- 0.01, *** p < 0.001.

POLI Detection of Mental Workload Differences Between Groups During the BBT

For the mental planning dimension, a significant Prosthesis x Session interaction was detected (F(4, 62.09) = 10.767, p < 0.001, ηp^2 = 0.41). The post-hoc analysis revealed that the MYO users had higher perceived mental planning demands (p = 0.007 , d = 0.466) during session 2 when compared to the BP users.

For the positioning dimension, a significant Prosthesis x Session interaction was detected (F(4, 63.778) = 3.168, p = 0.194, ηp^2 = 0.166). The post-hoc analysis revealed that during the initial session, the BP group perceived more difficulty transporting the blocks with their selected terminal device positioning when compared to the MYO users ($p = 0.024$, $d = 0.335$).

For the performance dimension, a main effect was revealed for Prosthesis ($F(1, 17) = 4.582$, 0.047, $\eta p^2 = 0.209$). This main effect was superseded by a Prosthesis x Session interaction($F(4, 63) =$ 4.235, 0.004, $\eta p^2 = 0.223$). The post-hoc analysis revealed during the initial training session MYO users perceived poorer performance when compared to the BP users ($p < 0.001$, $d = 0.546$).

A significant prosthesis main effect or Prosthesis x Session interaction were not detected for the grasp and release demand, effort, and task complexity dimensions of the POLI during BBT completion.

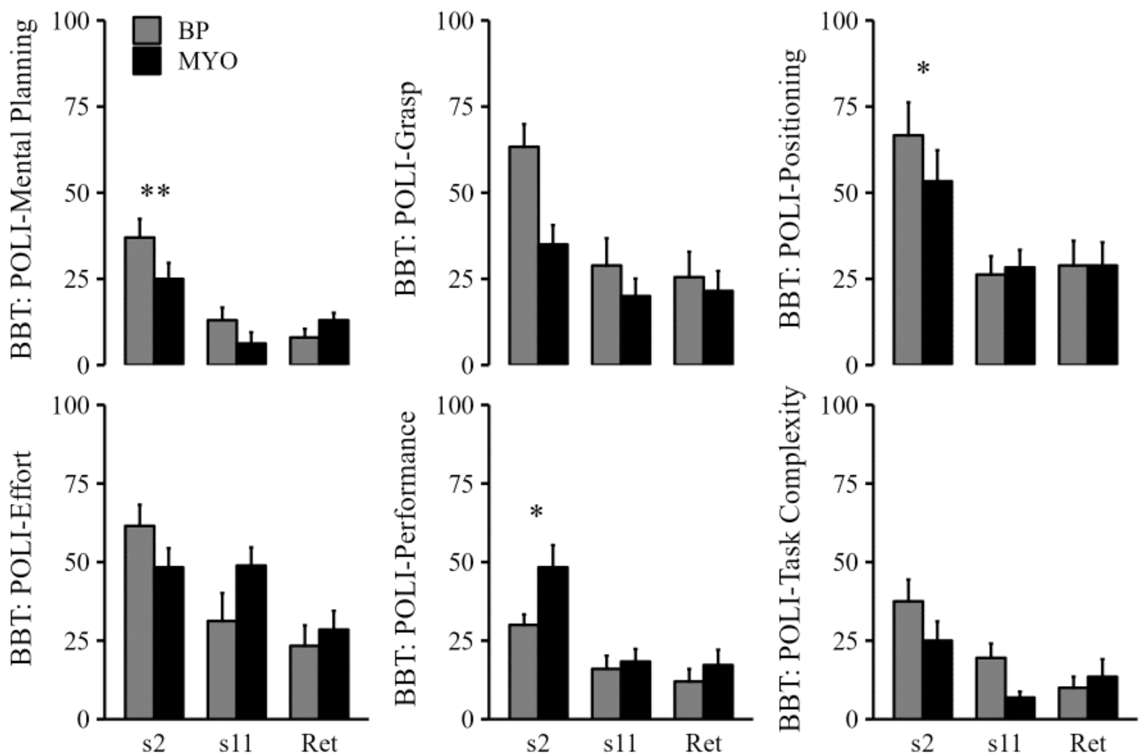


Fig.9. The results of each dimension of the POLI as a measurement of mental workload during completion of the BBT during the initial, final and retention training sessions. BP - Body-powered. MYO - Myoelectric. * p< 0.05, ** p <- 0.01, *** p < 0.001.

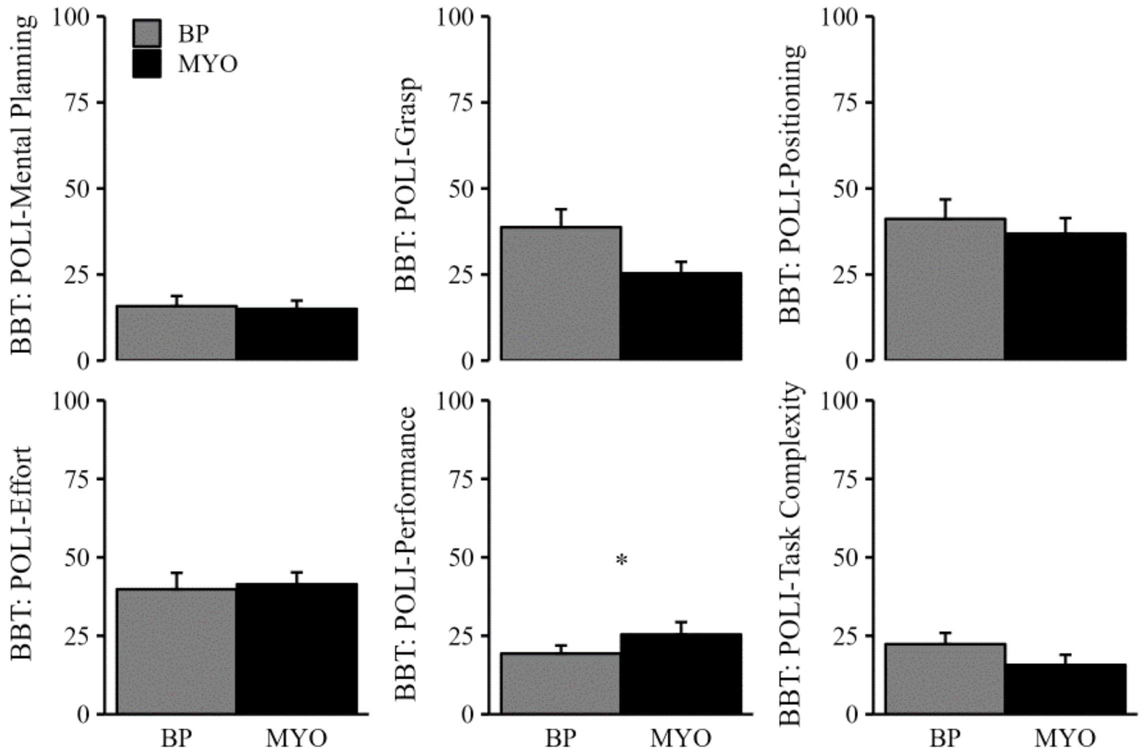


Fig. 10. The results of each dimension of the POLI as a measurement of mental workload during completion of the BBT averaged across the initial, final and retention sessions. . BP - Body-powered. MYO - Myoelectric. * p< 0.05, ** p <- 0.01, *** p < 0.001.

NASA-TLX Detection of Mental Workload Differences Between Groups During the SHAP

For the mental dimension of the NASA-TLX, a significant Prosthesis main effect was revealed (F(1, 16) = 6.834, p = 0.018, ηp^2 = 0.290). This main effect was superseded by a Prosthesis x Session interaction (F(4, 57.08) = 2.591, p = 0.046, ηp^2 = 0.290). The post-hoc analysis revealed that during the initial session, the MYO users perceived higher mental demands when compared to the BP users (p = 0.012, d = 1.552).

For the performance dimension, a significant Prosthesis main effect was revealed such that the MYO users experienced poorer performance when compared to the BP users (F(1, 15) = 7.093, p = 0.0174, ηp^2 = 0.316).

A significant Prosthesis main effect or Prosthesis x Session interaction was not detected for the physical, temporal, effort, or frustration dimension of the NASA-TLX during completion of the SHAP.

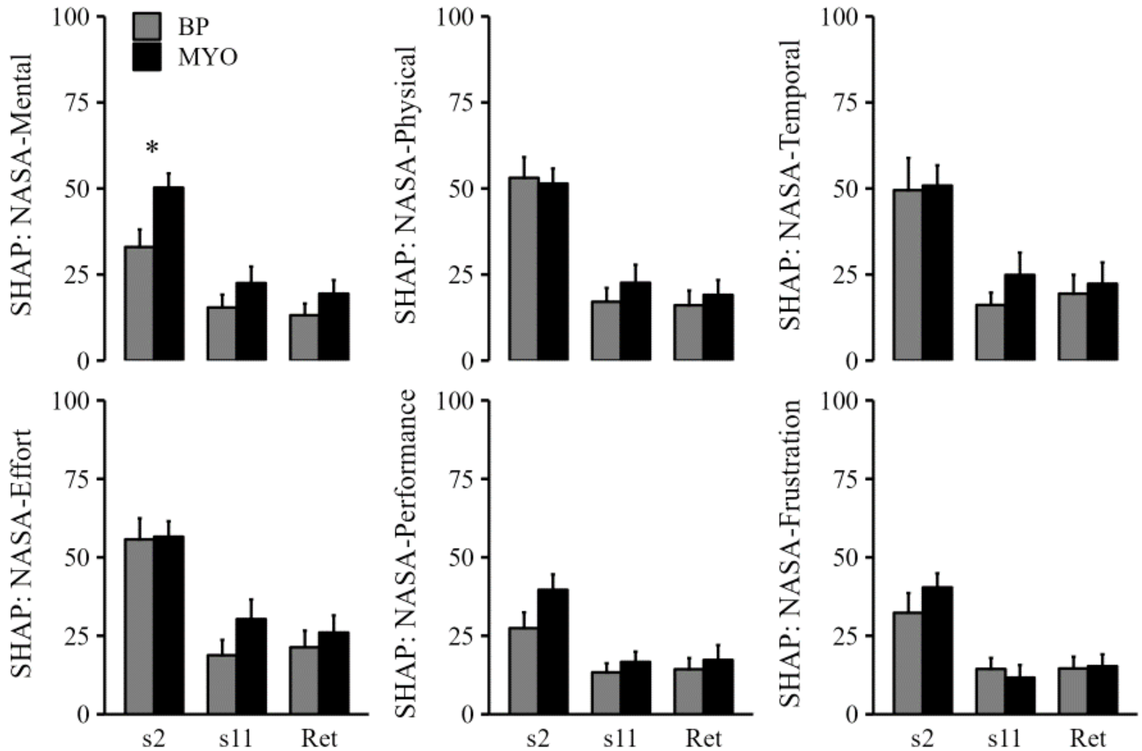


Fig. 11. The results of each dimension of the NASA-TLX as a measurement of mental workload during completion of the SHAP during the initial, final and retention training sessions. BP - Body-powered. MYO - Myoelectric. * p< 0.05, ** p <- 0.01, *** p < 0.001.

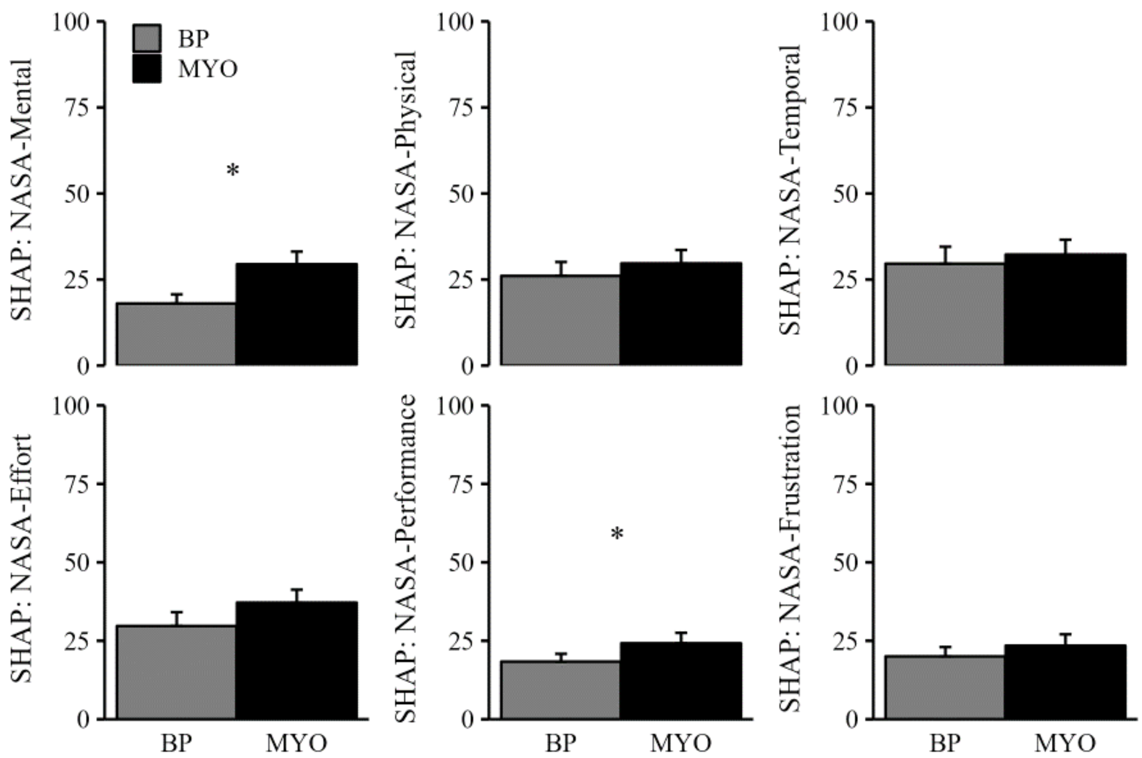


Fig. 12. The results of each dimension of the NASA-TLX as a measurement of mental workload during completion of the SHAP averaged across the initial, final and retention sessions. . BP - Body-powered. MYO - Myoelectric. * p< 0.05, ** p <- 0.01, *** p < 0.001.

POLI Detection of Mental Workload Differences Between Groups During the SHAP

For the mental planning dimension, a significant Prosthesis main effect was revealed (F(1, 15) = 9.043, p = 0.009, ηp^2 = 0.369) such that the MYO users perceived a greater mental planning demand when compared to the BP users.

For the grasp and release dimension. a significant Prosthesis main effect was revealed (F(1, 16) = 4.685, p = 0.045, ηp^2 = 0.222) such that the MYO users perceived more difficulty grasping and releasing objects when compared to the BP users.

For the positioning dimension, a significant Prosthesis main effect was revealed (F(1, 16) = 11.776, p = 0.003, ηp^2 = 0.420) such that the MYO users perceived more demands positioning their terminal device in their preferred position in preparation for object manipulation when compared to the BP users.

For the performance dimension, a significant Prosthesis main effect was revealed (F(1, 16) = 10.146, p = 0.006, ηp^2 = 0.382). This main effect was superseded by a Prosthesis x Session interaction (F(4, 58) = 4.44, p = 0.003, ηp^2 = 0.234). The post-hoc analysis revealed that during the initial session, MYO users perceived poorer performance when compared to the BP users (p < 0.001, d = 1.062).

For the effort dimension, a significant Prosthesis x Session interaction was revealed (F(1, 56) = 3.186, p = 0.020, ηp^2 = 0.183). The post-hoc analysis did not reveal the locus of the interaction.

A significant Prosthesis main effect or Prosthesis x Session interaction was not detected for the task complexity dimension of the POLI.

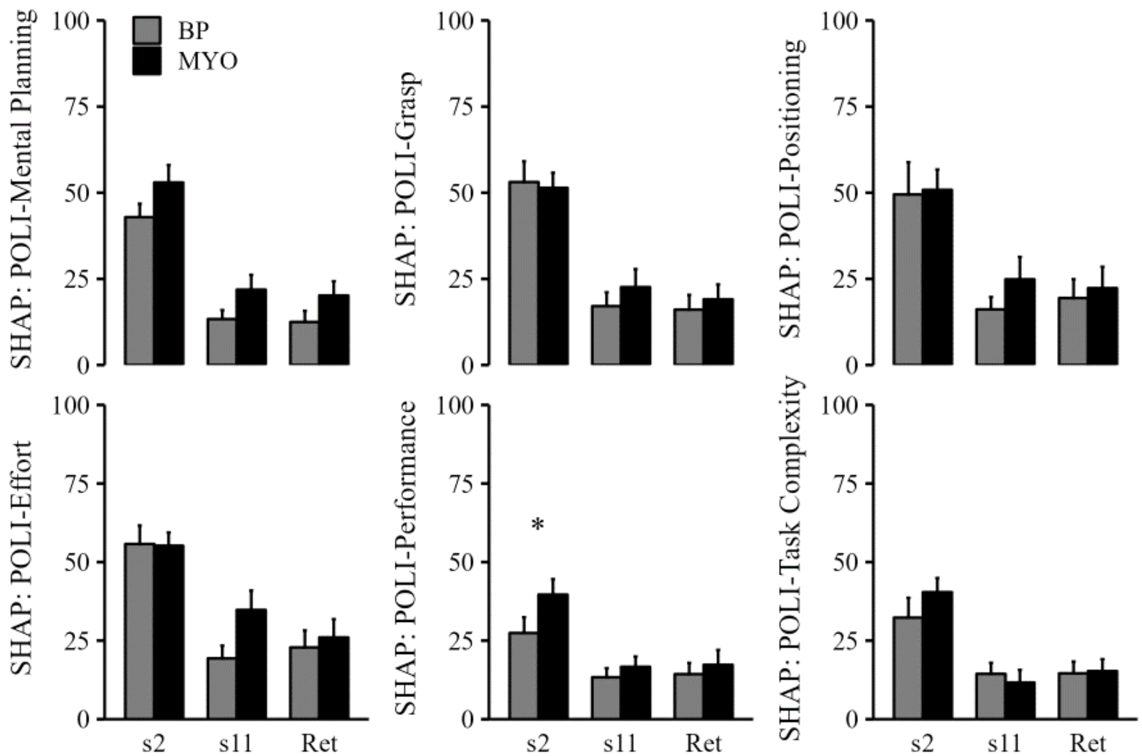


Fig. 13. The results of each dimension of the POLI as a measurement of mental workload during completion of the SHAP during the initial, final and retention training sessions. BP - Body-powered. MYO - Myoelectric. * p< 0.05, ** p <- 0.01, *** p < 0.001.

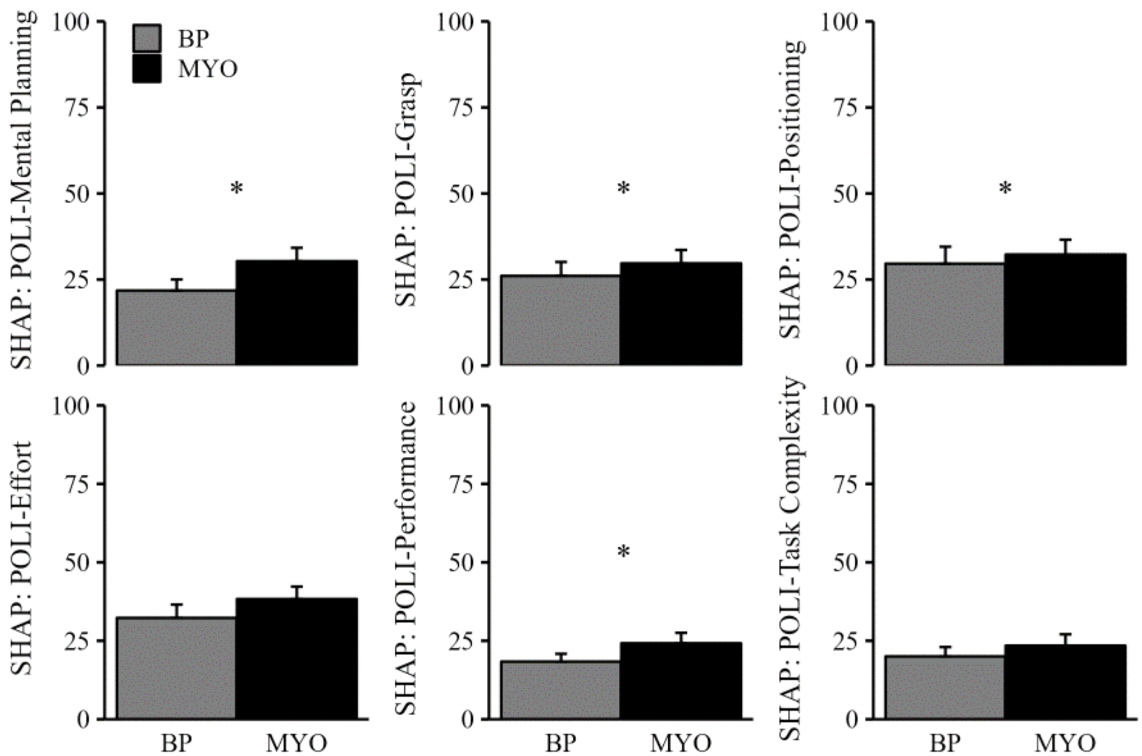


Fig. 14. The results of each dimension of the NASA-TLX as a measurement of mental workload during completion of the SHAP averaged across the initial, final and retention sessions. . BP - Body-powered. MYO - Myoelectric. * $p< 0.05$, ** $p <- 0.01$, *** $p < 0.001$.

Criterion Validity

Criterion Validity Between the NASA-TLX and the POLI During the BBT

The NASA-TLX was a significant predictor of POLI scores ($\beta = 0.700$, SE = 0.466, $t(79) = 15.017$, $p < 0.001$). This result supports the criterion validity of the POLI for the BBT, as higher scores on the NASA-TLX are associated with higher scores on the POLI.

Criterion Validity Between the NASA-TLX and the POLI During the SHAP

The NASA-TLX was a significant predictor of POLI scores, $\beta = 0.88$, SE = 0.043, $t(85) = 20.396$, $p < 0.001$. This result supports the criterion validity of the POLI for the SHAP, as higher scores on the NASA-TLX are associated with higher scores on the POLI.

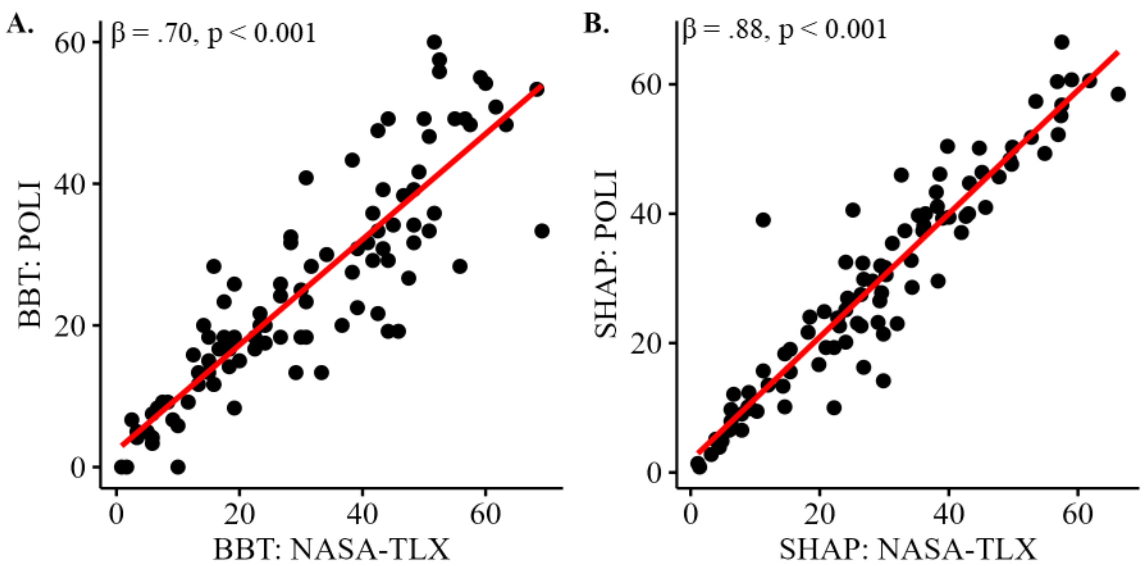


Fig. 15. A. The NASA-TLX total workload as a predictor of the POLI total workload as a measure of criterion validity during completion of the BBT. **B.** The NASA-TLX total workload as a predictor of the POLI total workload as a measure of criterion validity during completion of the SHAP. * p< 0.05, ** p <- 0.01, *** p < 0.001.

Responsiveness

The responsiveness of the POLI to changes in mental workload for the BBT was high, indicating a significant reduction in perceived mental workload over time (SRM = -1.504). The NASA-TLX had a similar level of responsiveness (SRM = -1.239).

The responsiveness of the POLI to changes in mental workload for the SHAP was also high, indicating a significant reduction in perceived mental workload over time (SRM = -1.651). The NASA-TLX had a similar level of responsiveness (SRM = -1.467).

Construct Validity

BBT Motor Performance

The total workload and dimensions of the POLI and the NASA-TLX were not significantly related to the number of blocks transported during the BBT, therefore construct validity could not established for either questionnaire.

BBT Normalized Jerk

The physical dimension of the NASA-TLX shared a significant positive relationship with normalized jerk (β = 18.567, SE = 7.105, t(75) = 2.613, p = 0.011). The positioning dimension of the POLI shared a significant positive relationship with normalized jerk (β = 14.5811, SE = 7.101, t(83) = 2.053, p = 0.043).

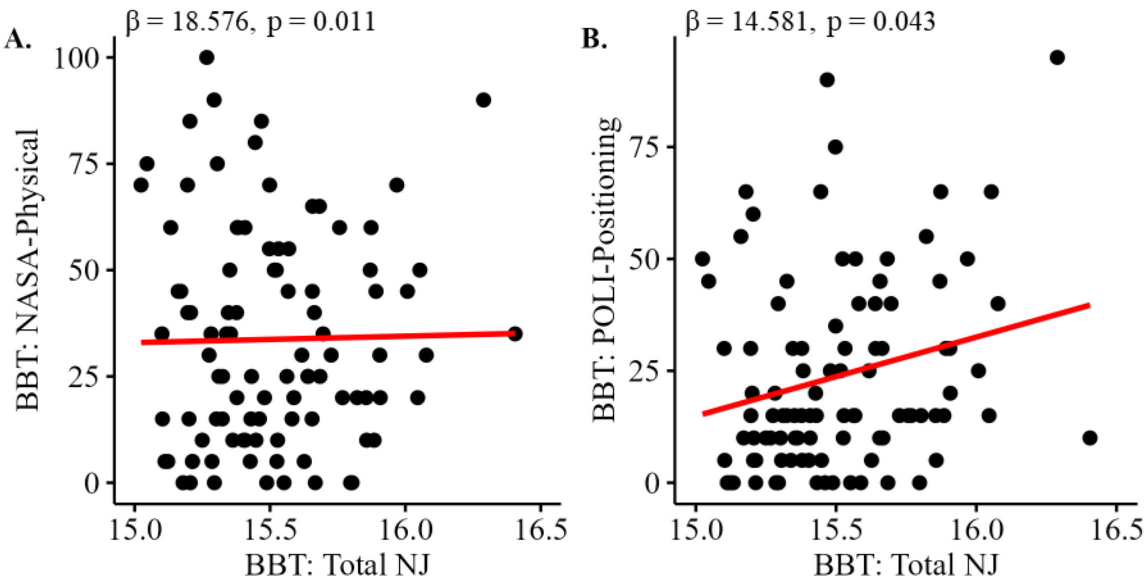


Fig. 16. A. The total normalized jerk(wrist and arm) as a predictor of the NASA-TLX physical dimension as a measure of construct validity during completion of the BBT. **B.** The total normalized jerk (wrist and arm) as a predictor of the POLI positioning dimension as a measure of construct validity during completion of the BBT.

SHAP Motor Performance

The physical dimension of the NASA-TLX shared a significant positive relationship with the index of functionality score (β = 0.342, SE = 0.171, t(85) = 2.002, p = 0.048). No dimensions of the POLI or the total workload were related to the index of functionality score.

SHAP Normalized Jerk

The total workload of the NASA-TLX shared a significant positive relationship with normalized jerk (β = 8.585, SE = 3.428, t(72) = 2.505, p = 0.015). The mental dimension (β = 9.739, SE = 3.641, t(68) = 2.675, p = 0.009) shared a significant positive relationship with normalized jerk. The physical dimension (β = 11.500, SE = 4.193, t(71) = 2.743, p = 0.008) shared a significant positive relationship with normalized jerk. Lastly, the effort dimension (β = 13.357, SE = 4.317, t(72) = 3.094, p = 0.003) shared a significant positive relationship with normalized jerk.

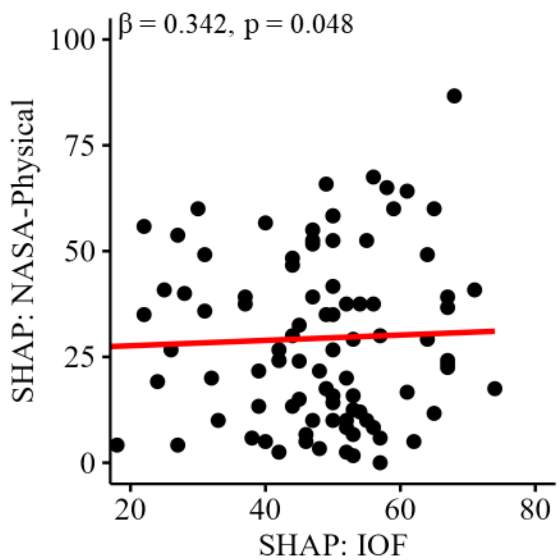


Fig. 17. A. The Index of Functionality scores as a predictor of the NASA-TLX physical dimension as a measure of construct validity during completion of the SHAP.

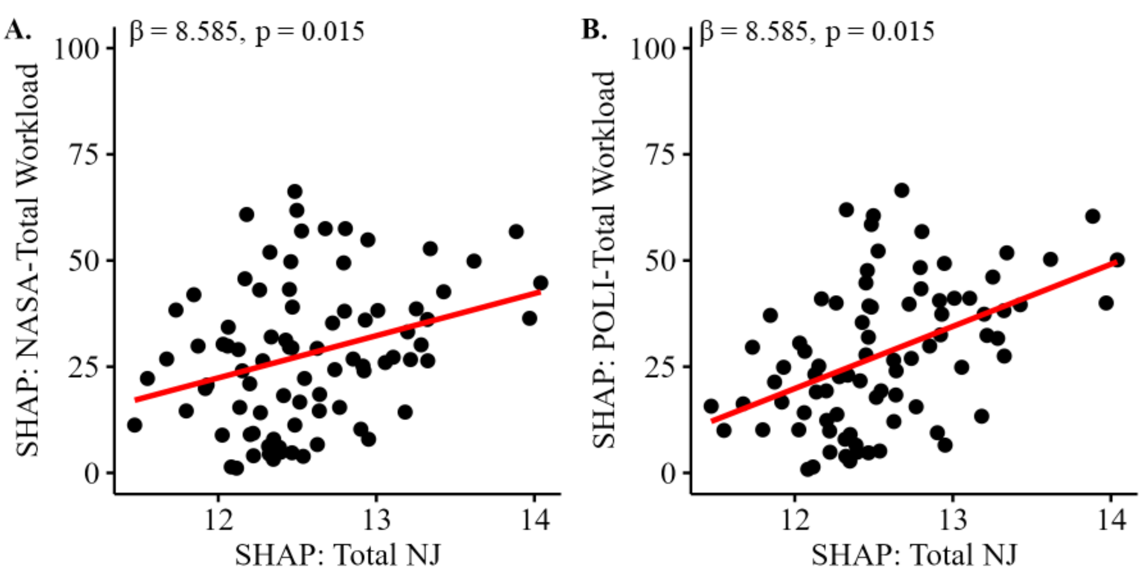


Fig. 18. A. The total normalized jerk(wrist and arm) as a predictor of the NASA-TLX total workload as a measure of construct validity during completion of the SHAP. **B.** The total normalized jerk (wrist and arm) as a predictor of the POLI total workload as a measure of construct validity during completion of the SHAP.

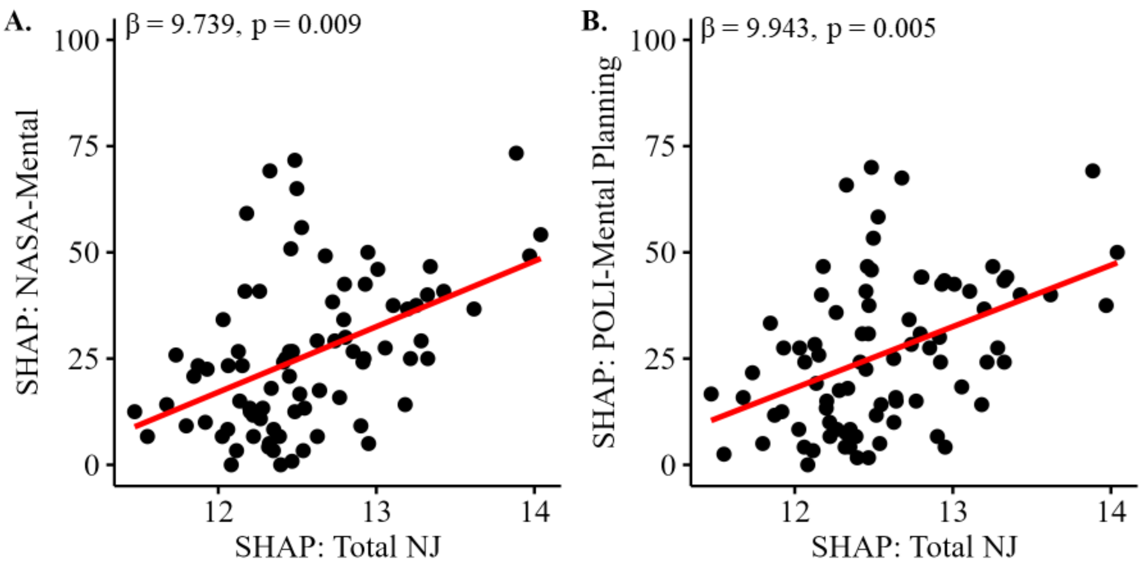


Fig. 19. A. The total normalized jerk(wrist and arm) as a predictor of the NASA-TLX total workload as a measure of construct validity during completion of the SHAP. **B.** The total normalized jerk (wrist and arm) as a predictor of the POLI total workload as a measure of construct validity during completion of the SHAP.

The total workload of the POLI shared a significant positive relationship with normalized jerk (β = 10.927, SE = 3.189, $t(70.79) = 3.426$, $p = 0.001$). The mental planning dimension shared a significant positive relationship with normalized jerk (β = 9.943, SE = 3.290, $t(70) = 2.868$, $p = 0.005$). The grasp and release dimension shared a significant positive relationship with normalized jerk (β = 13.618, SE = 4.151, $t(70) = 3.280$, $p = 0.002$). The positioning dimension shared a significant positive relationship with normalized jerk (β = 12.528, SE = 3.869, $t(63) = 3.238$, $p = 0.005$).

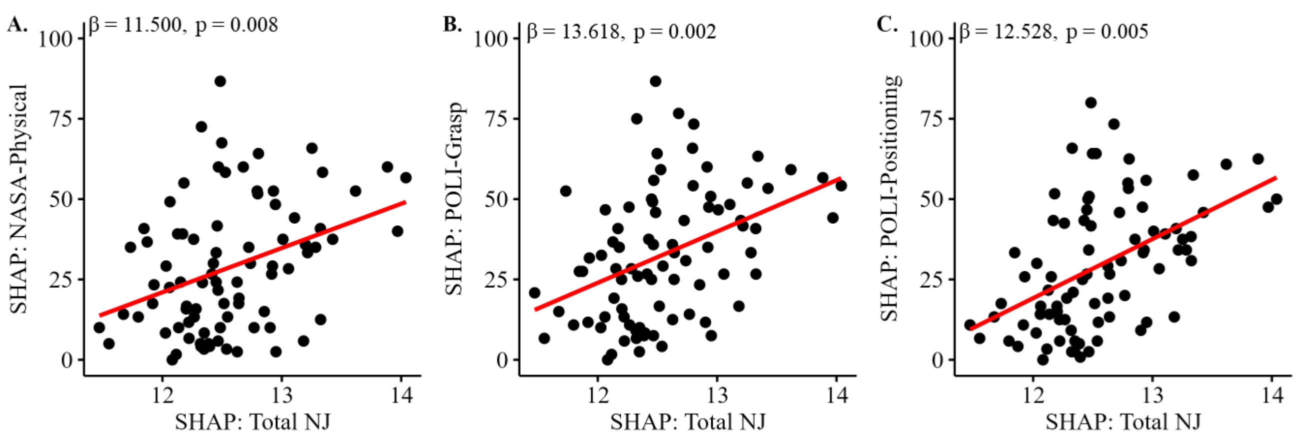


Fig. 20. A. The total normalized jerk(wrist and arm) as a predictor of the NASA-TLX physical dimension as a measure of construct validity during completion of the SHAP. **B.** The total normalized jerk (wrist and arm) as a predictor of the POLI grasp and release dimension as a measure of construct validity during completion of the SHAP. **C.** The total normalized jerk (wrist and arm) as a predictor of the POLI positioning dimension as a measure of construct validity during completion of the SHAP.

The effort dimension shared a significant positive relationship with normalized jerk ($\beta = 12.1360$, SE = 4.327, $t(71) = 2.805$, $p = 0.006$).

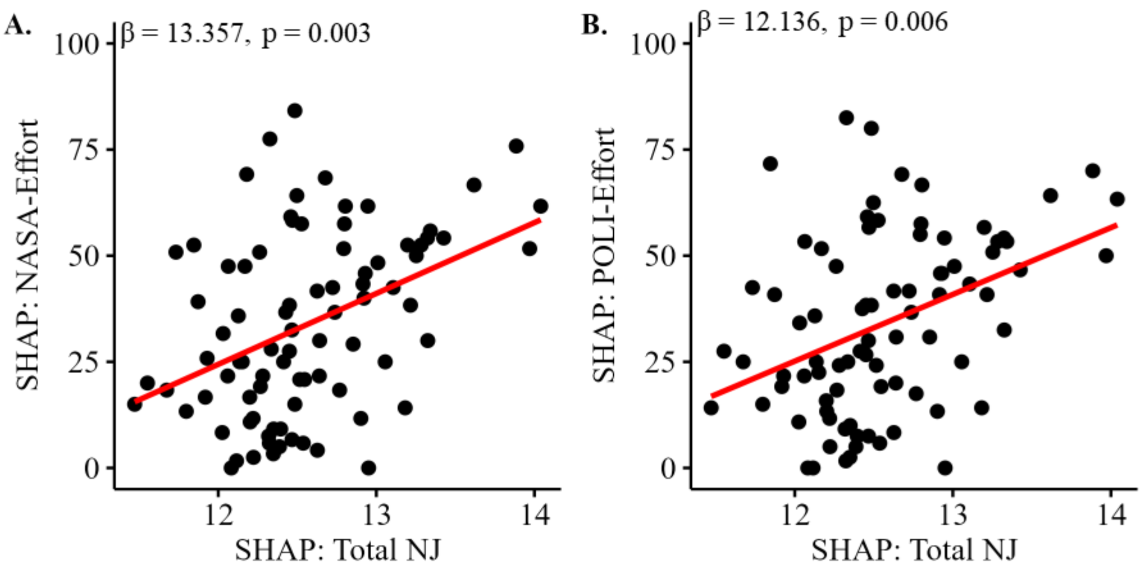


Fig. 21. A. The total normalized jerk (wrist and arm) as a predictor of the NASA-TLX effort dimension as a measure of construct validity during completion of the SHAP. **B.** The total normalized jerk (wrist and arm) as a predictor of the POLI effort dimension as a measure of construct validity during completion of the SHAP.

Discussion

The aim of this study was to develop and assess the POLI as a self-report measure of mental workload for individuals using upper limb prostheses and powered orthoses. As an exercise to capture preliminary validation evidence, the POLI was used to capture differences in mental workload for 20 individuals with intact upper limbs learning to use a BP and MYO bypass prosthesis during a bypass prosthetic training program.

First, internal consistency was established for the POLI during completion of the BBT and SHAP. We were interested in capturing the questionnaires' ability to measure mental workload changes during performance outcome measures that had different task demands. Specifically, the BBT is a measure of dexterity and incorporates repetitious movements to transport as many blocks as possible over a partition. The BBT does not inherently manipulate task demand since upper limb device users are only grasping blocks and not a variety of objects with different shapes. The SHAP also assesses for dexterity but requires users to grasp objects of various shapes and sizes that elicit six different prehensile patterns in the normative population and incorporates basic objects with various shapes and more objects that we encounter in daily living (e.g., jar, coins, buttons). The internal consistency for the POLI as a measure of mental workload during the SHAP was greater when compared to the BBT. This difference in internal consistency could simply reflect the number of times the surveys were administered during the SHAP(for each category for a total of seven times) when compared to the BBT (one time) thus allowing for a richer dataset. Alternatively, this may indicate that the POLI was more reliably capturing various sources of mental workload experienced during the SHAP since manipulation of various types of objects and completion of tasks with varying complexity (abstract objects to ADL-based objects) were required. This may suggest that the POLI may be better suited to consistently measure mental workload in assessments or tasks that require completion of various sub-tasks with varying levels of complexity. When examining the dimensions of the POLI, the performance dimension had the least consistency for measurement of mental workload during the BBT and SHAP. Removal of this dimension and incorporation of a more informative source of mental workload such as visual demand (J. Parr, 2018; J. V.V. Parr et al., 2019; Johnny V.V. Parr et al., 2023) could be considered for future questionnaire iterations. For example, the PROS-TLX revealed moderately strong relationship between conscious processing and visual demands (Johnny V.V. Parr et al., 2023).

When comparing BP and MYO users, no differences in motor performance were observed in either performance outcome measure; however, MYO users demonstrated increased proximal arm movement variability when compared to the BP users during the BBT and SHAP. While the temporal dimension was the only NASA-TLX dimension to detect differences between the prosthetic groups when completing the BBT, the mental planning, positioning, and performance dimensions of the POLI revealed the MYO users perceived greater demands when compared to the BP users. While the mental dimension of the NASA-TLX and the mental planning dimension of the POLI are similar, the mental planning dimension may be more sensitive to updates in motor strategies. This is consistent with the notion that prior kinematic analyses suggests the MYO users demonstrated more proximal arm movement variability, which may represent compensatory movement patterns due to lack of distal degrees of freedom (Bloomer et al., 2020; Carey et al., 2008, 2009). Interestingly, the mental planning dimension was not significantly related to movement smoothness during the BBT, since this dimension may reflect updates related to higher-level cognitive-motor resources that govern changes in movement (e.g., high-level planning, strategies). However, the positioning demand may better reflect the sensorimotor processes such as kinematic adjustments to place the terminal devices of the prostheses in the preferred position to complete a grasp the blocks since this measure detected differences between the prosthetic groups and has a significant inverse relationship with movement smoothness. Regarding the performance dimension of the POLI detecting differences between the prosthetic groups , it is particularly interesting that this dimension, which is also in the NASA-TLX did not reveal differences between the prosthetic groups . This may suggest an order effect occurred such that the performance dimension of the POLI may have been shaped around the preceding survey questions about the physical demands of grasping and releasing the block and positioning their terminal device (Strack, 1992). Due to the preceding contextual information elicited by these more targeted questions about physical and mental demand, prosthesis users, may have attributed a greater weight to the frequency of strategy updates, grasp and release and device positioning challenges, which may have yielded more sensitivity to distinguish performance differences between prosthetic groups . The POLI consistently revealed higher mental workload in MYO users when compared to BP users despite similar motor performances between the two groups while the NASA-TLX was not as sensitive to changes in mental workload between the two groups. This may reflect the POLI's sensitivity to detect varying amounts of cognitive-motor demand generated by different design features of the prostheses. For example, myoelectric devices have been shown to have more control unpredictability due to sensor issues, signal latency issues and sensitivity to agonist and antagonist co-contraction (Alix Chadwell et al., 2016; Rackerby et al., 2022). This unpredictability may have caused elevations in various dimensions of the POLI. Additionally, the Hosmer hook used for the body-powered prosthesis weighs only approx. 0.31lbs while the i-Limb® myoelectric hand weighs approximately 1.16 lbs. The weight of the MYO device may cause more physical demand on the user.

In line with the internal consistency results revealing the POLI's greater reliability to measure mental workload during a multi-faceted measure instead of a unidimensional performance outcome measure such as the BBT, all measures except for the task complexity dimension detected the MYO users experiencing elevated mental workload from various sources during the SHAP. In addition to the task complexity dimension being unable to detect differences between prosthetic groups in either performance outcome measure, it was also unrelated to BBT and SHAP performance and movement smoothness. While this dimension was included based upon the assumption that the interaction of device design and task demands would modulate the perception of task complexity, this dimension does not appear to be related to key constructs in motor performance and may not add additional information, thus may not be considered for inclusion in future iterations of the POLI. All dimensions except for the task complexity dimension of the POLI exhibited known group validity, only the mental and performance dimension of the NASA-TLX detected differences between the prosthetic groups during the SHAP. During the BBT, the mental planning, positioning, and performance dimensions of the POLI detected differences between prosthetic groups, while only the temporal dimension of the NASA-TLX detected differences between the prosthetic groups during the BBT. The enhanced sensitivity of the POLI in comparison to the NASA-TLX likely reflects the language specificity of the POLI to query the participant about upper limb device use.

Contrary to our expectations, there appears to be a very weak correlation between perceived mental workload and motor performance. Both surveys were unrelated to BBT motor performance and only the physical demand of the NASA-TLX was positively related to the SHAP Index of Functionality

Score. However, this relationship was against expectations since it is well established that elevation in physical demand is usually accompanied by a decline in motor performance (Miller et al., 2011; Rietschel et al., 2014; Shuggi et al., 2019).

Instead, elevations in perceived mental workload as noted by the POLI and similarly by the NASA-TLX were more strongly associated with movement smoothness. It is possible that the performance (e.g., number of blocks transported) may be representative of many underlying processes(e.g. movement smoothness, movement efficiency, effort) and the surveys were unable to capture the combined effect of these various underlying processes. Movement smoothness is likely a result of feedback processing for motion regulations and possibly identification of strategies by trial and error (as well as optimization processes from a computational standpoint) and thus more related to mental workload assessment. The physical demand of the NASA-TLX and the positioning demand of the POLI were associated with a decline in movement smoothness for the BBT. For the SHAP, total workload scores of both questionnaires were associated with movement smoothness. The mental, physical and effort dimensions of the NASA-TLX were related to movement smoothness while all dimensions of the POLI except for task complexity were related to movement smoothness. These findings may suggest that the POLI is capturing the cognitive-motor resources that govern movement kinematics underlying motor performance mor effectively than the NASA-TLX. This may suggest that measurement of mental workload may not only inform underlying cognitive-motor resources required for intended task performance outcomes, but also serve as an indirect, inverse measure of movement smoothness. This is consistent with the notion that a misalignment between the predicted movement target and actual movement target(e.g., grasping an object) has been evidenced to increase feedforward control from the central executive system for error correction, which consumes more cognitive-motor resources when compared to less cortical influence on the movement end effector that exists in tasks with less cognitive-motor demands(Gentili et al., 2015; Lum et al., 2014). Both surveys may detect the changes of feedforward control thus exhibiting an inverse relationship with movement smoothness. This is of significance since movement quality is not frequently examined quantitatively in clinical rehabilitation due to barriers such as equipment cost, operations competency, and data interpretation. While some measures provide a qualitative assessment of movement quality (Wang et al., 2018), these measures may fail to capture an accurate representation. Therefore, implementation of patient reported outcome measures that capture sources of mental workload, may help the clinician identify and address upper limb device design inefficiencies and task demands that elevate mental workload and degrade movement quality and overall motor performance.

Conclusion, Limitations, and Future Directions

We achieved our aim of successfully assessing preliminary validity and reliability of the self-report mental workload measure, the POLI. To demonstrate criterion validity with the NASA-TLX, we revealed significant positive correlations between the POLI and the NASA-TLX during completion of the BBT and SHAP performance outcome measures. For both surveys, similar correlations with performance and movement smoothness were noted with stronger positive correlations existing for both surveys when correlated with normalized jerk as a measure of movement smoothness. To strengthen the POLI's validity, we also demonstrated that POLI was more sensitive in detecting differences between prosthetic types when compared to the NASA-TLX. Specifically, three dimensions of the POLI detected differences between prosthetic groups compared to only one dimension of the NASA-TLX during completion of the BBT. Five dimensions of the POLI detected differences between prosthetic groups compared to only two dimensions of the NASA-TLX during completion of the SHAP. Additionally, we demonstrated that the POLI had similar responsiveness to changes in mental workload and relationships with related constructs such as motor performance and movement quality when compared to the NASA-TLX.

While the findings of this preliminary validation are hopeful, there are several limitations. First, we did not utilize the Delphi Method to consult a panel of experts in prosthesis and orthosis rehabilitation to facilitate the iterative developmental process of the POLI. Incorporating feedback from clinical experts or patients who use upper limb prostheses or orthoses may have resulted in a questionnaire that better reflects the sources of mental workload associated with upper limb device use. Secondly, the POLI was administered to individuals with intact upper limbs learning to use a bypass upper limb prosthesis. While there has been documented similarities between the kinematics of clinical upper limb prosthesis users and bypass users (Bloomer et al., 2020; Carey et al., 2008; H. E. Williams et al., 2021), it is not clear if bypass users have similar cognitive-motor resource recruitment as an individual with an upper limb amputation and altered peripheral sensorimotor function that may elicit cortical changes. While this is a significant limitation of this work, this effort extends prior work that developed and assessed preliminary validity of the Prosthesis Task Load Index (PROS-TLX) by administering the POLI to capture mental workload during two standardized and validated performance outcome measures. While the PROS-TLX was administered to myoelectric bypass users at a single timepoint, we assessed the POLI in myoelectric and body-powered prosthesis bypass users which may have resulted in more generalizable results that reflects the current population of prosthesis users BP and MYO devices (Resnik et al., 2019). Additionally, we assessed preliminary longitudinal reliability and validity of the POLI across multiple timepoints thus informing the measure's ability to detect mental workload over time, which is critical for multi-week rehabilitation programs. This is of significance since there is an interest from insurance and regulatory agencies for clinicians to reliably capture markers of performance and functional status of patients in order to justify healthcare services (Hanmer et al., 2022). Thirdly, while aim of this study was to develop a self-report mental workload questionnaire for upper limb prosthesis and orthosis users, we only administered the questionnaire to prosthesis users. While mental workload is increasingly being explored in upper limb prosthesis research and may be associated with an increase in technological advancement (Pasquina et al., 2015; Rackerby et al., 2022), this construct has been less explored in powered orthoses such as exoskeletons (Marchand et al., 2021). Future validation efforts of the POLI will need to be completed with clinical prosthesis and orthosis users to translate the POLI into a PROM that can be deployed into the clinical space.

References

Balasubramanian, S., Melendez-Calderon, A., Roby-Brami, A., & Burdet, E. (2015). On the analysis of movement smoothness. *Journal of NeuroEngineering and Rehabilitation*, *12*(1), 1–11. https://doi.org/10.1186/s12984-015-0090-9

Bloomer, C., Wang, S., & Kontson, K. (2020). Kinematic analysis of motor learning in upper limb body-powered bypass prosthesis training. *PLoS ONE*, *15*(1), 1–16. https://doi.org/10.1371/journal.pone.0226563

Bloomer, C., Wang, S., & Kontson, K. L. (2018). Creating a standardized , quantitative training protocol for upper limb bypass prostheses. *Physical Medicine and Rehabilitation Research*.

Bouwsema, H., Van Der Sluis, C. K., & Bongers, R. M. (2008). *The Role of Order of Practice in Learning to Handle an Upper-Limb Prosthesis*. https://doi.org/10.1016/j.apmr.2007.12.046

Butkus, J., Dennison, C., Orr, A., & Laurent, M. St. (2014). Occupational Therapy with the Military Upper Extremity Amputee: Advances and Research Implications. *Current Physical Medicine and Rehabilitation Reports*, *2*(4), 255–262. https://doi.org/10.1007/s40141-014-0065-y

Carey, S. L., Dubey, R. V., Bauer, G. S., & Highsmith, M. J. (2009). Kinematic comparison of myoelectric and body powered prostheses while performing common activities. *Prosthetics and Orthotics International*, *33*(2), 179–186. https://doi.org/10.1080/03093640802613229

Carey, S. L., Jason Highsmith, M., Maitland, M. E., & Dubey, R. V. (2008). Compensatory movements of transradial prosthesis users during common tasks. *Clinical Biomechanics*, *23*(9), 1128–1135. https://doi.org/10.1016/j.clinbiomech.2008.05.008

Chadwell, A., Kenney, L., Thies, S., Galpin, A., & Head, J. (2016). The reality of myoelectric prostheses: Understanding what makes these devices difficult for some users to control. *Frontiers in Neurorobotics*, *10*(AUG), 1–21. https://doi.org/10.3389/fnbot.2016.00007

Cheung, G. W., Cooper, H. D., Rebecca, T., & Wang, L. C. (2023). Reporting reliability , convergent and discriminant and best - practice recommendations. In *Asia Pacific Journal of Management* (Vol. 3, Issue 0123456789). Springer US. https://doi.org/10.1007/s10490-023-09871-y

Churruca, K., Pomare, C., Ellis, L. A., Long, J. C., Henderson, S. B., Murphy, L. E. D., Leahy, C. J., & Braithwaite, J. (2021). Patient-reported outcome measures (PROMs): A review of generic and condition-specific measures and a discussion of trends and issues. *Health Expectations*, *24*(4), 1015–1024. https://doi.org/10.1111/hex.13254

Coles, T. M., Hernandez, A. F., Reeve, B. B., Cook, K., Edwards, M. C., Boutin, M., Bush, E., Degboe, A., Roessig, L., Rudolph, A., McNulty, P., Patel, N., Kay-Mugford, T., Vernon, M., Woloschak, M., Buchele, G., Spertus, J. A., Roe, M. T., Bury, D., & Weinfurt, K. (2021). Enabling patient-reported outcome measures in clinical trials, exemplified by cardiovascular trials. *Health and Quality of Life Outcomes*, *19*(1), 1–7. https://doi.org/10.1186/s12955-021-01800-1

Cornett, K. M. D., Menezes, M. P., Bray, P., Shy, R. R., Moroni, I., Pagliano, E., Pareyson, D., Estilow, T., Yum, S. W., Bhandari, T., Muntoni, F., Laura, M., Reilly, M. M., Finkel, R. S., Eichinger, K. J., Herrmann, D. N., Shy, M. E., & Burns, J. (2020). Refining clinical trial inclusion criteria to optimize the standardized response mean of the CMTPedS. *Annals of Clinical and Translational Neurology*, *7*(9), 1713–1715. https://doi.org/10.1002/acn3.51145

Desrosiers, J., Bravo, G., Hébert, R., Dutil, É., & Mercier, L. (1994). Validation of the Box and Block Test as a measure of dexterity of elderly people: Reliability, validity, and norms studies. *Archives of Physical Medicine and Rehabilitation*, *75*(7), 751–755. https://doi.org/10.5555/uri:pii:0003999394901309

Devilliers, H., Amoura, Z., Besancenot, J. F., Bonnotte, B., Pasquali, J. L., Wahl, D., Maurier, F., Kaminsky, P., Pennaforte, J. L., Magy-Bertrand, N., Arnaud, L., Binquet, C., Guillemin, F., & Bonithon-Kopp, C. (2014). Responsiveness of the 36-item short form health survey and the lupus quality of life questionnaire in SLE. *Rheumatology (United Kingdom)*, *54*(5), 940–949. https://doi.org/10.1093/rheumatology/keu410

El Hayek, M., Lobo Jofili Lopes, J. L. M., Lelaurin, J. H., Gregory, M. E., Abi Nehme, A. M., McCall-Junkin, P., Au, K. L. K., Okun, M. S., & Salloum, R. G. (2023). Type, Timing, Frequency, and

Durability of Outcome of Physical Therapy for Parkinson Disease: A Systematic Review and Meta-Analysis. *JAMA Network Open*, *6*(7), E2324860. https://doi.org/10.1001/jamanetworkopen.2023.24860

Gentili, R. J., Bradberry, T. J., Oh, H., Costanzo, M. E., Kerick, S. E., Contreras-Vidal, J. L., & Hatfield, B. D. (2015). Evolution of cerebral cortico-cortical communication during visuomotor adaptation to a cognitive-motor executive challenge. *Biological Psychology*, *105*, 51–65. https://doi.org/10.1016/j.biopsycho.2014.12.003

Gentili, R. J., Rietschel, J. C., Jaquess, K. J., Lo, L. C., Prevost, M., Miller, M. W., Mohler, J. M., Oh, H., Tan, Y. Y. ing, & Hatfield, B. D. (2014). Brain biomarkers based assessment of cognitive workload in pilots under various task demands. *Conference Proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference*, *2014*, 5860–5863. https://doi.org/10.1109/EMBC.2014.6944961

Gull, M. A., Bai, S., & Bak, T. (2020). A review on design of upper limb exoskeletons. *Robotics*, *9*(1), 1–35. https://doi.org/10.3390/robotics9010016

Hanmer, J., Cizik, A. M., Gulek, B. G., & Mccracken, P. (2022). *A Scoping Review of US Insurers '* (Vol. 28, Issue June). https://doi.org/10.37765/ajmc.2022.89162

Heitz, R. P. (2014). The speed-accuracy tradeoff: History, physiology, methodology, and behavior. *Frontiers in Neuroscience*, *8*(8 JUN), 1–19. https://doi.org/10.3389/fnins.2014.00150

Jaquess, K. J., Gentili, R. J., Lo, L. C., Oh, H., Zhang, J., Rietschel, J. C., Miller, M. W., Tan, Y. Y., & Hatfield, B. D. (2017). Empirical evidence for the relationship between cognitive workload and attentional reserve. *International Journal of Psychophysiology*, *121*(February), 46–55. https://doi.org/10.1016/j.ijpsycho.2017.09.007

Kim, H., Her, J., Ko, J., Park, D. S., Woo, J. H., You, Y., & Choi, Y. (2012). Reliability, concurrent validity, and responsiveness of the fugl-meyer assessment (FMA) for hemiplegic patients. *Journal of Physical Therapy Science*, *24*(9), 893–899. https://doi.org/10.1589/jpts.24.893

Kimberley, T. J. ., & Lewis, S. M. (2007). Neuroimaging in Rehabilitation. *Physical Therapy*, *87*(6), 704–718.

Light, C. M., Chappell, P. H., & Kyberd, P. J. (2002). Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity. *Archives of Physical Medicine and Rehabilitation*, *83*(6), 776–783. https://doi.org/10.1053/apmr.2002.32737

Lum, P. S., Black, I., Holley, R. J., Barth, J., & Dromerick, A. W. (2014). Internal models of upper limb prosthesis users when grasping and lifting a fragile object with their prosthetic limb. *Experimental Brain Research*, *232*(12), 3785–3795. https://doi.org/10.1007/s00221-014-4071-1

Marchand, C., De Graaf, J. B., & Jarrassé, N. (2021). Measuring mental workload in assistive wearable devices: a review. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 1–15. https://doi.org/10.1186/s12984-021-00953-w

Mathiowetz, V., & Weber, K. (1985). Adult Norms for the Box and Block. *The American Journal of Ocupational Therapy*, *39*(6), 387–391.

Miller, M. W., Rietschel, J. C., Mcdonald, C. G., & Hatfield, B. D. (2011). A novel approach to the physiological measurement of mental workload. *International Journal of Psychophysiology*, *80*, 75–78. https://doi.org/10.1016/j.ijpsycho.2011.02.003

Mou, D., Mjaset, C., Sokas, C. M., Virji, A., Bokhour, B., Heng, M., Sisodia, R. C., Pusic, A. L., & Rosenthal, M. B. (2022). Impetus of US hospital leaders to invest in patient-reported outcome measures (PROMs): a qualitative study. *BMJ Open*, *12*(7). https://doi.org/10.1136/bmjopen-2022-061761

Parr, J. (2018). *Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand*. *50*(4).

Parr, J. V.V., Vine, S. J., Wilson, M. R., Harrison, N. R., & Wood, G. (2019). Visual attention, EEG alpha power and T7-Fz connectivity are implicated in prosthetic hand control and can be optimized through gaze training. *Journal of NeuroEngineering and Rehabilitation*, *16*(1), 1–20. https://doi.org/10.1186/s12984-019-0524-x

Parr, Johnny V.V., Galpin, A., Uiga, L., Marshall, B., Wright, D. J., Franklin, Z. C., & Wood, G. (2023). A tool for measuring mental workload during prosthesis use: The Prosthesis Task Load Index (PROS-TLX). *PLoS ONE*, *18*(5 MAY), 1–15. https://doi.org/10.1371/journal.pone.0285382

Pasquina, P. F., Perry, B. N., Miller, M. E., Ling, G. S. F., & Tsao, J. W. (2015). Recent Advances in Bioelectric Protheses. *Neurology Clinical Practice*, 164–170.

Pauzié, A. (2008). A method to assess the driver mental workload: The driving activity load index (DALI). *IET Intelligent Transport Systems*, *2*(4), 315–322. https://doi.org/10.1049/iet-its:20080023

Rackerby, R., Lukosch, S., & Munro, D. (2022). Understanding and Measuring the Cognitive Load of Amputees for Rehabilitation and Prosthesis Development. *Archives of Rehabilitation Research and Clinical Translation*, *4*(3), 100216. https://doi.org/10.1016/j.arrct.2022.100216

Resnik, L., Adams, L., Otr, L., Borgia, M., Delikat, J., Otr, L., Disla, R., Ebner, C., Walters, L. S., & Otr, L. (2013). Development and Evaluation of the Activities Measure for Upper Limb Amputees. *Archives of Physical Medicine and Rehabilitation*, *94*(3), 488-494.e4. https://doi.org/10.1016/j.apmr.2012.10.004

Resnik, L., Borgia, M., Cancio, J., Heckman, J., Highsmith, J., Levy, C., Phillips, S., & Webster, J. (2022). Dexterity, activity performance, disability, quality of life, and independence in upper limb Veteran prosthesis users: a normative study. *Disability and Rehabilitation*, *44*(11), 2470–2481. https://doi.org/10.1080/09638288.2020.1829106

Resnik, L., Ekerholm, S., Borgia, M., & Clark, M. A. (2019). A national study of Veterans with major upper limb amputation: Survey methods, participants, and summary findings. *PLoS ONE*, *14*(3), 1–24. https://doi.org/10.1371/journal.pone.0213578

Rietschel, J. C., McDonald, C. G., Goodman, R. N., Miller, M. W., Jones-Lush, L. M., Wittenberg, G. F., & Hatfield, B. D. (2014). Psychophysiological support of increasing attentional reserve during the development of a motor skill. *Biological Psychology*, *103*, 349–356. https://doi.org/10.1016/j.biopsycho.2014.10.008

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili,

R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological Psychology*. https://doi.org/10.1016/j.biopsycho.2018.01.009

Shuggi, I. M., Oh, H., Wu, H., Ayoub, M. J., Moreno, A., Shaw, E. P., Shewokis, P. A., & Gentili, R. J. (2019). Motor Performance, Mental Workload and Self-Efficacy Dynamics during Learning of Reaching Movements throughout Multiple Practice Sessions. *Neuroscience*, *423*, 232–248. https://doi.org/10.1016/j.neuroscience.2019.07.001

Soufineyestani, M., Dowling, D., & Khan, A. (2020). Electroencephalography (EEG) technology applications and available devices. *Applied Sciences (Switzerland)*, *10*(21), 1–23. https://doi.org/10.3390/app10217453

Stokes, E. K., & O'Neill, D. (2008). Use of Outcome Measures in Physiotherapy Practice in Ireland from 1998 to 2003 and Comparison to Canadian Trends. *Physiotherapy Canada*, *60*(2), 109–116. https://doi.org/10.3138/physio.60.2.109

Strack, F. (1992). *"Order Effects" in Survey Research: Activation and Information Functions of Preceding Questions BT - Context Effects in Social and Psychological Research* (N. Schwarz & S. Sudman (eds.); pp. 23–34). Springer New York. https://doi.org/10.1007/978-1-4612-2848-6_3

Trizano-Hermosilla, I., Gálvez-Nieto, J. L., Alvarado, J. M., Saiz, J. L., & Salvo-Garrido, S. (2021). Reliability Estimation in Multidimensional Scales: Comparing the Bias of Six Estimators in Measures With a Bifactor Structure. *Frontiers in Psychology*, *12*(June), 1–7. https://doi.org/10.3389/fpsyg.2021.508287

Wang, S., Hsu, C. J., Trent, L., Ryan, T., Kearns, N. T., Civillico, E. F., & Kontson, K. L. (2018). Evaluation of Performance-Based Outcome Measures for the Upper Limb : A Comprehensive Narrative Review. *PM&R*, *10*(9), 951-962.e3. https://doi.org/10.1016/j.pmrj.2018.02.008

Williams, H. E., Chapman, C. S., Pilarski, P. M., Vette, A. H., & Hebert, J. S. (2021). Myoelectric prosthesis users and non-disabled individuals wearing a simulated prosthesis exhibit similar compensatory movement strategies. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 1–15.

https://doi.org/10.1186/s12984-021-00855-x

Wilson, M. R., Poolton, J. M., Malhotra, N., Ngo, K., Bright, E., & Masters, R. S. W. (2011). Development and validation of a surgical workload measure: The surgery task load index (SURG-TLX). *World Journal of Surgery*, *35*(9), 1961–1969. https://doi.org/10.1007/s00268-011-1141-4

Zidarov, D., & Poissant, L. (2014). Exploring Factors in the Systematic Use of Outcome Measures: A Multi-Disciplinary Rehabilitation Team Perspective. *Open Journal of Therapy and Rehabilitation*, *02*(02), 86–96. https://doi.org/10.4236/ojtr.2014.22013

Chapter 6: General Conclusion

This corpus of research investigated the underlying cortical dynamics of motor learning and mental workload in individuals with intact upper limbs who learned to use either a body-powered or myoelectric bypass prothesis during a standardized upper limb bypass prosthetic training program. First, we sought to examine how prosthesis learners acquire dexterity skills required to grasp same shaped objects using the standardized Box and Block Test (BBT). Study 1 presented empirical evidence that as a result of training, prosthesis users enhanced motor performance and refined movement smoothness. The spectral electroencephalography (EEG) analysis revealed divergent cortical activation patterns between the two prosthesis groups despite similar improvements in motor performance and movement smoothness. Specifically, the MYO users engaged more task-relevant cognitive-motor and sensorimotor processes to obtain a similar BBT performance to that of the BP users. This evidence suggests that BP users better encoded the internal models of their device and produced greater cognitive-motor efficiency when compared to the MYO users when grasping objects of the same shape. However, although the training considering here lasted several weeks, it seemed that longer training would have been beneficial to further refine the cortical dynamics in particular for the MYO users.

Study 2 expanded the scope of Study 1 by examining differences in cortical dynamics as prosthesis users grasped objects of various shapes and sizes that typically required either a power or precision grip as a part of the Southampton Hand Assessment Procedure (SHAP). In line with the first study, in response to training, the BP users exhibited stronger characteristics of cognitive-motor efficiency(refinement of cognitive-motor processing accompanied by enhanced performance and refined kinematics when compared to the MYO users, who engaged greater cognitive-motor processing as a result of training to achieve similar levels of cognitive-motor performance. However, while these differences in cognitive-motor efficiency was observed, both groups produced greater sensorimotor processes as a result of training which indicates prosthesis users are still learning to deploy efficient sensorimotor resources in response to task demands. When examining neural correlates of grip type, MYO users produced greater high-alpha power during the precision grip tasks when compared to the power grip tasks. This may reflect the engagement of inhibitory processes to reduce unintended terminal device actions potentially due to a limited capability to produce agonist muscle contractions without muscular co-contraction interference. On the contrary, BP users deployed fewer visual resources during the power grip tasks when compared to the precision grip tasks and when compared to the MYO users which may indicate a slight advantage in cognitive-motor efficiency for power grip tasks for the BP users, relative to the MYO users.

The collective findings of Study 1 and 2 suggest that BP users may be emerging from the cognitive stage of motor learning where the internal model of the device was progressively encoded while MYO users may be engaged at an earlier cognitive stage, which is a more resource intensive motor learning state where the encoding of the internal model is still very limited.

Study 3 built on the foundation of the first two studies by extending mental workload and cognitive-motor performance assessment to more ecologically valid activities. The goal of this work was to inform how prosthesis users and a normative sample complete a novel performance outcome measure, the Household Item Transport Test by performing complex daily activities. These activities were completed in a non-contextual condition that needed minimal instruction and a contextual condition that required participants to follow more complex instructions that simulated executive function demands in real world environments. As expected, contextual demands generally resulted in slower activity completion times, reduction in movement smoothness and elevation of perceived mental and physical demands in all groups. In response to contextual demands, the CTRL group revealed patterns of cortical inhibition and the recruitment of fewer working memory, attentional and error monitoring resources while the cortical dynamics for the BP and MYO users. When comparing the experimental groups, the CTRL group produced significantly enhanced performance, kinematics, and reductions in perceived workload when compared to prosthesis users. However, in contrast to our expectations, the CTRL group consistently produced greater cognitive-motor (lower low-alpha, high-alpha) and sensorimotor (lower beta) processes with less engagement of working memory, attentional and error monitoring resources (lower theta) when compared to prosthesis users.

In the context of an internal model framework, these findings may suggest that learning to use an upper limb prosthesis significantly disrupts the pre-existing motor repertoire and requires a new internal model of the sensorimotor mapping used to control the prosthetic device. Under such a condition, this may explain the impoverished ability of the prosthesis users to engage the necessary cortical resources in response to the varying cognitive-motor demands of an activity when compared to a normative sample who can recruit a robust and accurate internal model of their upper extremity to execute the same activities.

This framework also informs our first two studies which may suggest that the cognitive-motor efficiency observed in the BP users when compared to the MYO users may reflect a more defined and encoded internal model of the body-powered prosthesis.

Finally, Study 4 addressed the lack of patient reported outcome measures (PROMs) that assess mental workload in the clinical rehabilitation space. The development of the Prosthesis-Orthosis Load Index (POLI) is outlined in this work. The administration of the POLI to capture mental workload during completion of the BBT and SHAP revealed good and excellent internal consistency for the BBT and SHAP, respectively. Strong correlations between the POLI and the self-report mental workload standard, the National Aeronautics Space Administration Task Load Index (NASA-TLX) were revealed thus suggesting good criterion validity. Additionally, the POLI was more sensitive to differences in perceived workload between the prosthetic groups when compared to the NASA-TLX. These results show promise for the POLI; however, more research is warranted to assess the utility of the measure in clinical populations.

While the aforementioned research line is informative for basic cognitive-motor neuroscience and kinesiology, these efforts must be conducted in a clinical context before these findings can be generalized to clinical populations. However, this work presented spectral EEG as a tool that can provide deeper, cortical insights into cognitive-motor performance when compared to only using traditional clinical rehabilitation measures such as performance outcome measures and self-report measures. Additionally, to address the lack of mental workload assessment in the rehabilitation field, this dissertation introduced two novel measures (the performance outcome measure, the HITT, and the mental workload self- report measure, the POLI) that have preliminarily demonstrated an effective ability to extract insights on mental workload and cognitive-motor performance.

Appendix

NASA-TLX Survey

NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

ID	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

POLI Survey

Prosthesis-Orthosis Load Index (POLI)

Adapted from Hart and Staveland's NASA Task Load Index (TLX)

ID	Task	Date

Mental Planning Demand

How hard was it to develop the most effective strategy to complete the task?

Very Low — Very High

Grasp and Release Demand

How difficult was it to grasp and release during the task?

Very Low — Very High

Positioning Demand

How difficult was it to position your device in preparation for grasping?

Very Low — Very High

Performance

How successful were you in accomplishing what you were asked to do?

Perfect Failure

Effort

How much effort did you use during the task?

Very Low Very High

Task Complexity

How complex was the task?

Very Low Very High

NASA-TLX and POLI Dimension Long Descriptions

NASA-TLX Definitions

Title	Endpoints	Descriptions
MENTAL DEMAND	*Low/High*	How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching; etc.) Was the task easy or demanding? Simple or complex? Exacting or forgiving?
PHYSICAL DEMAND	*Low/High*	How much physical activity was required (e.g. pushing, pulling, turning, controlling, activating; etc.) Was the task easy or demanding, slow or brisk? Slack or strenuous? Restful or laborious?
TEMPORAL DEMAND	*Low/High*	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
PERFORMANCE	*Good/Poor*	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
EFFORT	*Low/High*	How hard did you have to work (mentally and physically) to accomplish your level of performance?
FRUSTRATION	*Low/High*	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?

Prosthetic Training Protocol

Myoelectric Bypass Prosthesis Set-Up

A general overview of the device, its functionality, and its controls should be given. While the Arm should be turned off for this portion, it should still be available and used to point out each component and to demonstrate some of the wrist movements. The subject should be allowed to pick up the device now to gain a sense of its weight and shape.

> *"This is the Touch Bionics radial configuration i-limb ultra. It is an upper extremity prosthesis that features a rotatable wrist, a movable thumb, and a variety of grips. The hand can be opened and closed by myoelectric signals read from the users arm via these electrodes. By flexing the corresponding muscle, the hand can either be opened or closed. In this case we'll be using the forearm muscles. The extensors, flexed by wrist extension, will correspond to open, the flexors will correspond to close."*

Electrodes: Discuss the electrodes

> *"Myoelectric control uses electrodes to record electrical muscle signals (myoelectric) to control the prosthesis. Electrodes need to be carefully positioned to optimize these signals. Movement of these electrodes during the use or accumulation of sweat beneath them can disrupt the signal. If the i-limb becomes harder to operate and you suspect the electrode, please let us*

[Show the electrodes]

Wrist Prepositioning: Discuss the ability to rotate the wrist and its importance.

> *"The wrist can be rotated using the opposite hand. Known as prepositioning, a user can rotate the wrist to a desired position before attempting a task. This strategy is highly recommended and can be helpful in accomplishing a task and doing so comfortably."*

[Demonstrate rotating the wrist.]

Manual Rotation of the Thumb: Discuss the ability to rotate the thumb and its importance.

> *"The thumb can be rotated using the opposite hand. This allows users to adjust the grip of the hand. Like the wrist, users are highly recommended to consider the thumbs position and adjust it accordingly prior to attempting a*

[Demonstrate rotating the thumb]

Stall out and Compliant Grip: Discuss stalling the fingers and the compliant grip.

> *"The fingers of the i-limb will stall (or stop) when they reach resistance or pressure is put against them. This allows the hand to conform to objects of various shapes, known as a compliant grip. It also allows the user to modify the grip by stalling a digit themselves. While users should be careful not to pinch themselves, the fingers' ability to stall will prevent the fingers from*

[Demonstrate stalling the fingers]

i-Touch: Discuss the I touch grip selection.

> *"Grips are selected via the Biosim™ app on this Itouch. Pressing a grip type will select that grip when the hand is open. Pressing that grip again will return the hand to the standard grip."*

[Demonstrate stalling the fingers]

Standard Hand Mode/ Composite Grip: Describe standard hand mode.

> *"In standard hand mode all fingers and the thumb are active and will open and close."*

[Demonstrate standard hand mode.]

Precision Pinch: Describe the precision pinch grip.

> *"The precision pinch grip closes the index finger, opposing the thumb, while the middle, ring, and pinky fingers remain still. This grip is recommended for picking up smaller items."*

[Demonstrate the precision pinch grip.]

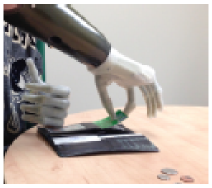
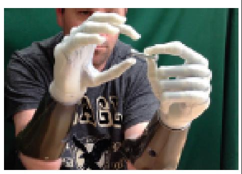
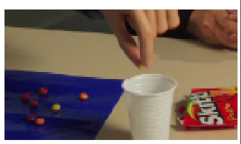
Tripod Grip: Describe the tripod grip.

> *"The tripod grip closes the index and middle finger, opposing the thumb, while the ring and pinky fingers remain still. This grip is recommended for slightly larger objects for greater stability."*

[Demonstrate the tripod grip]

Grip Types: Describe open, close, standard, and thumb options for the previous grips.

> *"Within these two grips are four different categories. Open, closed, standard, and thumb. In the open version of each grip the still fingers (middle, ring, and pinky in precision pinch and ring and pinky in tripod grip) are opened. In the closed version of each grip the still fingers are closed. In the standard version of each grip the thumb moves in addition to the active fingers (index finger in precision pinch, index finger and ring finger in tripod grip). In the thumb version of each grip the thumb does not move, only the active fingers of that*

Feature	Picture Example	Description	Use	Task Examples
 Standard Precision Pinch Open		Middle, ring and little fingers remain open while the index finger and thumb open and close together to provide grip.	Allows for a wider space opening to pinch larger objects. Positions the other three fingers out of the way to avoid interference with tasks.	1. Returning cards or money to wallet 2. Picking up napkins 3. Folding laundry
 Thumb Precision Pinch Open		Middle, ring and little fingers remain open. Thumb automatically moves to a partially closed position. Only index finger will move to provide grip against the fixed thumb.	Accuracy is improved when picking up an object by allowing you to place the thumb against the object to be pinched. Only the index finger moves to grasp the object. Ideal for repetitive tasks.	1. Pick up pencil or slim, long objects 2. Thread needle 3. Sort/Pick up medications
 Standard Precision Pinch Closed		Middle, ring and little fingers remain closed. Both index finger and thumb open and close together to provide grip.	Allows for a wider web space opening to pinch larger objects. Allows better visual access to objects when the working surface is not at eye level. Positions the other three fingers so as not to block the user's view of the task.	1. Retrieve small object from shelf over head 2. Pick up small object from floor
 Thumb Precision Pinch Closed		Middle, ring and little fingers remain closed. Thumb automatically moves to a partially closed position. Only index finger will move to provide grip against the fixed thumb.	Can improve accuracy for picking up an object by allowing you to place the thumb against the object to be pinched and only the index finger moves to grasp the object. Ideal for repetitive tasks.	1. Pick up and open sugar packet from a coffee stand 2. Pick up coins 3. Alternative way to tie shoes (also see "lateral grip")

Feature	Picture Example	Description	Use	Task Examples
 Standard 3 Jaw Chuck (Tripod) Open		Ring and little fingers remain open. Thumb, index and middle fingers actively open and close to provide grip.	Allows for larger objects to be grasped using the tripod pinch. Can also improve positioning. May also decrease compensation at shoulder for tasks where closed digits get in the way of the pinch.	1. Preparing food with ring and little finger clear, such as slicing cucumber or carrot 2. Holding cell phone (would manually rotate thumb laterally based on size of phone or setup custom grip)
 Thumb 3 Jaw Chuck (Tripod) Open		Ring and little fingers remain open. Thumb automatically moves to a partially closed position. Only index and middle fingers will move to provide grip against the fixed thumb.	For smaller motion, but increased accuracy. Tripod grip allows for greater stability with larger or round objects in comparision to Precision Pinch. May also decrease elbow compensation when seated.	1. Grab spices from cupboard 2. Open bag of chips
 Standard 3 Jaw Chuck (Tripod) Closed		Ring and little fingers remain closed. Thumb, index and middle fingers actively open and close together to provide grip.	Allows for a wider space opening tio pinch larger objects. Tripod grip allows greater stability for larger or round objects in comparision to precision pinch.	1. Open bag of chips 2. Pull up socks
 Thumb 3 Jaw Chuck (Tripod) Closed		Ring and little fingers automatically close and switch off. Thumb automatically moves to a partially closed position. Only index and middle fingers will move to provide grip against the fixed thumb.	Can improve stability and control grasping larger objects. With thumb in a static position, your ability to align an object can improve particularly on small objects. Can also decrease elbow compensation when seated.	1. Repetitive factory type work moving pieces 2. Grasp pen for writing 3. Laundry 4. Pack bag

Additional Grips: Describe the additional grips.

> *"Additional grips include thumb park continuous. In this grip all four fingers remain in an open position, while the thumb is active. The lateral grip is also an additional grip. In this grip all four fingers remain in a closed position, while the thumb is active. The thumb is expected in the lateral position in this grip and can be rotated accordingly. Index point is the final additional grip.*

> *while the thumb, middle, ring, and pinky fingers remain closed. No fingers are active in this grip. "*

[Demonstrate each grip and show the following table.]

Feature	Picture Example	Description	Use	Task Examples
 Thumb Park Continuous		Thumb rotates to palmar adduction and the other four fingers remain fully open. Only the thumb moves open and closed.	For longer dressing period that will require more than the 1.5 seconds of thumb park quick or grasping light weight flat objects. Can also use stalling out digits to complete, putting pressure against index to little and closing thumb in to hand.	1. Put on jacket 2. Grasp flat objects, such as a book or a tablet computer or clipboard 3. Opening letters or sorting paperwork.
 Thumb Park Quick		Thumb rotates to palmar adduction and the other four digits remain fully open. Only the thumb moves open and closed for 1.5 seconds of run time. In contrast to Thumb Park Continuous, this feature returns to the Standard Hand Mode after the open signal is sent.	Dressing or putting on a coat. You can achieve this position by using the stall out capability of digits against a table if you do not want to program.	1. Put on jacket or shirt
 Lateral Grip		Thumb automatically rotates into lateral position and partially closes. All four fingers fully close and switch off. Only thumb will move.	Holding onto plate, papers, CD or other flat objects. Improved stability with use of the side of the index finger. See additional images on page 10.	1. Hold plate while serving food 2. Hold clipboard 3. Get card from ATM 5. Open ziplock bag 6. Tie Shoe Laces 7. Hold a utensil
 Index Point		Thumb automatically rotates into lateral position and fully closes. Thumb switches off. Middle, ring and little fingers fully close and switch off. Index finger remains open and active	Used for pushing buttons, typing on computer, or simply pointing. Can be achieved with stall out.	1. Keyboarding (pressing shift key, CTRL, ALT, DEL, general typing) 2. Push Button for elevator

Componentry Quiz: Quiz the subject on the componentry information.

"What muscle and movement are used to open the

hand?" "What muscle and movement are used to close

the hand?"

"What component measures the signals needed to control the

hand?" "Demonstrate wrist rotation."

"Demonstrate thumb rotation."

"What does it mean to stall a finger or to have a compliant

grip?" "How are grips selected?"

"What fingers move in standard hand mode?"

"What does the precision pinch grip look like? Demonstrate both the open and closed versions."

"What does the tripod grip look like? Demonstrate both the open and closed versions."

"What is the difference between a standard grip and a thumb

grip?" "What are the additional grips? Demonstrate them."

Body-Powered Bypass Prosthesis Set-Up

Componentry Training

Introduce the major components of the prosthesis, namely the harness, the control cable, the wrist unit, and the terminal device (TD) while pointing out each on the bypass to the participant. Describe the control cable's ability to voluntarily open the TD against passive closure due to the rubber bands. All participants will use the prosthesis with two rubber bands.

Have the bypass prosthesis, with the control cable detached, on the table.

> *"The body-powered bypass prosthesis consists of four major components. The harness, which will fit over your shoulders and back, the wrist unit, which will fit over your forearm, the TD which will function in place of your hand, and the control cable, which will connect the harness to the TD such that certain movements will open and close the TD. The rubber band on the TD will then cause passive closure."*
>
> *"Taking a closer look at the TD we note this lever here, often referred to as the thumb, it can be a useful additional point of contact during tasks. Additionally, we can see where the rubber grip extends along the hook, the notch in the grip right at the corner, and how the hooks move and align in relation to one another. Keeping these aspects in mind will help you to use the prosthesis as efficiently as possible."*

[Point out each component as you discuss. Pull on the control cable to demonstrate voluntary opening of the TD.]

Demonstrate and discuss the ability to pre-position/rotate the TD by pressing the lever and then pushing the TD to seat it again. Stress the importance of this in maximizing prosthesis functionality.

> *"The TD can be rotated by pressing this lever to release and then pushing the TD in to seat again, indicated by the click you hear. This feature is important to consider due to the inability to rotate the wrist unit. Therefore, prior to starting a task, time should be taken to think through the necessary grip and to*

[Demonstrate the ability to rotate and seat the TD.]

Body Control Motions

The prosthesis is controlled through two main body control motions, shoulder flexion/extension and scapular protraction. Describe and demonstrate each motion and have the participant mirror your motions. Stress the importance of thinking and selecting from these control motions prior to performing a task.

> *"The TD can be opened through specific body control motions. Shoulder flexion/extension and scapular protraction, which can be performed in 3 ways: Bypass side, sound side, or biscapular side. It is important to think through these control motions and select a strategy before performing a task."*

[Demonstrate each movement as you discuss it and have the participant mirror your motions.]

Give the participant additional time to try each motion on their own and offer to make any adjustments to the harness now.

Initial Session

A general assessment of prosthesis control, prior to task training, will be performed to ensure participants have an adequate understanding of the prosthesis in order to communicate effectively and to use the prosthesis safely.

> *"Before moving on to work with actual objects and grasping we need to go through a quick assessment to ensure you understand how to properly use the*

Have the participant demonstrate body control motions, adjustment and seating of the TD, various ranges of TD opening and closing, and various heights of wrist unit during opening and closing. This assessment is not designed to be restrictive, if the participant answers incorrectly prompt them with an explanation and quick demonstration and ask them to repeat.

> *"Open and close the TD using shoulder flexion/extension." "Open and close the TD using bypass side scapular protraction" "Open and close the TD using sound side scapular protraction." "Open and close the TD using bi-scapular protraction."*
>
> *"Adjust the TD orientation and reseat it."*
>
> *"Using any body control motion you like open the TD fully… open the TD half-way."*

[Engage participant and adjust any straps as needed. Observe when the TD begins opening through the body control motion and ensure harness fit allows proper activation.]

Participants must demonstrate mastery of these skills prior to moving on to task training. Continue coaching and repeating this assessment as necessary until the participant completes it satisfactorily. Again, offer to make any adjustments to the prosthesis now.

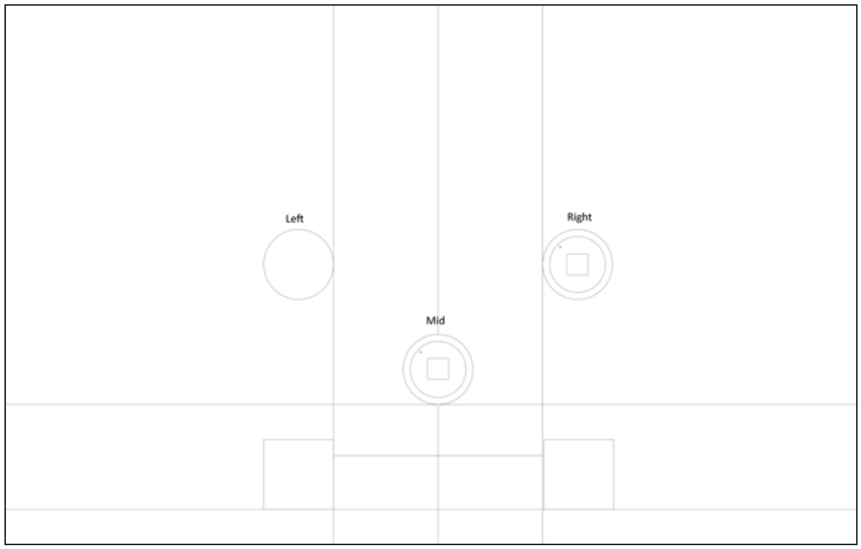
Task Training

The participant will perform 3 forms of basic object manipulation tasks. Indirect grasping (IG) and direct grasping (DG) tasks will follow the same procedure for each trial but will utilize 3 different objects: a wooden block, a foam ball, and a metal can. Fixation tasks will involve 3 unique tasks. These tasks will be performed seated.

In blocked order sessions all 4 trials for an object/task will be completed before moving on to the next object/task. In the random order sessions objects/tasks will be randomized and only 2 trials will be performed for each object/task combination.

Tasks will be performed on a tabletop with standardized dimensions and site locations for hands and objects. The template is designed to cover a 122 x 77 cm tabletop. The far horizontal line (the JHFT line) marks 20 cm from the near edge of the table; the vertical line marks the midline of the table. Each circle is 10 cm in diameter. The left and right circles' centers are both 40 cm from the near edge of the table and 20 cm from midline. The mid circle's center is 25 cm from the near edge of the table. The squares (home) are aligned vertically with the left and right circles, are centered 10 cm from the near edge of the table and are 10 x 10 cm. The short horizontal line between the home squares (the BBT line) is 5 inches from the near edge of the table.

Outlines of the 3 x 3 cm block and 8 cm diameter can used in training can be found in the mid and right circles. These can be used as an additional challenge for participants by prompting them to release the object within the shape in either grasping task.



The table template is used to guide the tasks. Locations labelled on the template are referred to as right circle, left circle, and mid circle in the task instructions. Midline refers to the vertical line centered in the template. Home refers to the 2 squares. The JHFT line refers to the far horizontal line. The BBT line refers to the horizontal line between the home squares.

Have a wooden block, foam ball, and metal can nearby. The table should be clear except for the template. The participant should be seated with their midline aligned with the vertical line on the table template.

> *"Now we'll move on to object manipulation tasks. Each grasping task will be performed 4 times each for 3 different objects. The grasping tasks are either IG, in which the object is placed into the TD with the free hand, or direct grasping, in which the object is picked up directly with the TD. Each of the 3 fixation tasks will be completed 4 times. The fixation tasks involve completing a task with your free hand while using the TD to stabilize, or fixate, the object. These tasks will not be timed and are for training purposes only, therefore we encourage you to take your time and discuss each task."*

For the 1st trial of each object/task prompt the participant to explain the grip strategy and body control motion that they plan to use prior to starting the task.

> *"Before beginning the task I want you to plan your strategy and explain it to me. Be sure to include TD orientation, how the object will be situated in the grip, and body control motions for both grasp and release."*

Before the 2nd trial, prompt the participant to describe any difficulties they found during the 1st trial and any changes they plan to make in their second attempt.

> *"What difficulties did you find with the task and with your particular strategy? How do you plan on performing the task differently this time?"*

Before the 3rd trial offer any coaching on strategy if appropriate. Finally, before and after the 4th trial offer feedback on what worked in their strategies and what can be improved.

[Prompts for the 3rd and 4th trials will be based on the participants' unique performance and can't be standardized. Suggestions commonly focus on TD orientation, isolation of body control motions during tasks, use of compensatory movements, etc.]

IG tasks involve placing an object into the grip of the TD using the free hand. The object will begin in the left circle, be grasped by the left hand, transferred to the TD in midair at the midline, and be released in the right circle. Both hands will start at home.

Place one of the objects in the left circle.

> *"First, we'll do the IG tasks. A series of objects will be placed on the table in front of you in the left circle and you will move them to the right circle as labeled on the table. In this task your hands will start at home, you will grasp the object in your left hand from the left circle. You will transfer the object to your TD at the midline in midair. You will then place that object in the right circle and release it using only the TD."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial.]

DG tasks involve picking up and moving an object solely with the TD. The object will begin in the right circle, be grasped by the TD, and released in the mid circle. Both hands will start at home.

Place one of the objects in the right circle.

> *"Now we'll move to DG tasks. A series of objects will be placed on the table in front of you in the right circle and you will move them to the mid circle as labeled on the table. In this task your hands will start at home, you will grasp the object with your TD from the right circle. You will then place that object in the mid circle and release it using only the TD."*

[Demonstrate the procedure yourself while explaining the task to the participant. Reset the object following your demonstration and after each trial. Deliver the appropriate prompt for each trial]

Fixation tasks involve performing a task with the free hand while the TD acts as a stabilizer. The objects are centered over the mid circle.

RULER TASK

Participants will fixate (or hold steady) a ruler between two dots drawn on a piece of paper 20 cm apart with the TD. Using their free hand and the ruler they'll draw a straight line between the two dots. The participants can use their free hand to move the ruler but must use the prosthesis to fixate the ruler while drawing. Both hands will begin at home.

The piece of paper should be centered over the mid circle with the ruler situated along the two dots drawn 20 cm apart. The pen should start in the left circle.

> *"Now we'll move to FIX tasks. In this task you will use the TD to fixate, or stabilize, the ruler between the two dots on the paper in front of you. You will use your left hand to draw a straight line between the dots. Your hands will start at home, you will grasp the pen from the left circle, you will draw a*

> *using the ruler, you will fixate the ruler with the TD, and then you will release the pen in the left circle."*

[Demonstrate the procedure yourself while explaining the task to the participant. Reset the object following your demonstration and after each trial. Deliver the appropriate prompt for each trial]

ZIPPER TASK

In the second task participants will fixate a piece of cloth with a zipper using the TD. Using their left hand, they'll open and close the zipper. Both hands will begin at home.

The zipper should be centered over the mid circle. The zipper should be fully zipped.

> *"In this task you will use the TD to fixate the cloth in front of you. You will use your left hand to unzip the zipper fully and then zip the zipper closed."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial]

BUTTON TASK

In the third task the participant will fixate a piece of cloth with four buttons with the TD. Using the free hand, they'll unbutton each button. Both hands will begin at home.

The button board should be centered at the mid site with the buttons aligned horizontally.

> *"In this task you will use the TD to fixate the board in front of you. You will use your left hand to grasp the cloth and unbutton each button. "*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial]

Free Training

Allow the participant 5 minutes to use the prosthesis as they wish. Encourage them to interact with the objects laid out on the table. Participants will remain seated, with the table at the sitting height, for 5 minutes.

Table full of free training materials for use by the participant

Activities of Daily Living

12 ADLs have been chosen to provide additional training. Participants should be encouraged to discuss strategies with the research assistant. Each ADL will be performed twice while seated. In the blocked order sessions, the unilateral tasks and then the bilateral tasks will be performed in the order they appear below. In the random order sessions, the task trials will be randomized. ADL training will last for 20 minutes, independent of the number of tasks performed within that time, to give the participant and the research assistant flexibility in training. Only the prosthesis should be used in unilateral tasks unless otherwise stated. The prosthesis and free hand can both be used in bilateral tasks.

The table should be cleared except for the table template. The ADL materials should be nearby and ready for use.

> *"Now we're going to work through some activities of daily living, or ADLs, these tasks are based on real-life tasks and require combinations of movements and more complex strategies. We encourage you to discuss movement strategies with us prior to starting a task and to actively think through your*

For the 1st trial of each object/task prompt the participant to explain the grip strategy and body control motion that they plan to use prior to starting the task.

> *"Before beginning the task I want you to plan your strategy and explain it to me. Be sure to include TD orientation, how the object will be situated in the grip, and body control motions for both grasp and release."*

Before the 2nd trial, prompt the participant to describe any difficulties they found during the 1st trial and any changes they plan to make in their second attempt.

> *"What difficulties did you find with the task and with your particular strategy? How do you plan on performing the task differently this time?"*

Before moving on to the next task give feedback on their strategy, what worked and what didn't, and anything they may have done differently.

[Feedback following the 2nd trial will be based on the participants' unique performance and can't be standardized. Suggestions commonly focus on TD orientation, isolation of body control motions during tasks, use of compensatory movements, etc.]

Unilateral Tasks

BRUSH HAIR

Instruct the participant to grasp the brush, bring the brush to their head, brush their hair, or perform a brushing motion, and release the brush from grasp.

The comb should be aligned horizontally and centered in the mid circle. The participant should be standing with both hands at home.

> *"Please take this brush and, while grasping it, run it through your hair (or over the top of their head if bald). Then put the brush down in the mid circle. Try to use only your prosthesis to do this task."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

DRINK FROM A CUP

Instruct the participant to pick up the cup from the table, bring the cup to their mouth, tilt the cup, and simulate drinking, return the cup to the table in the mid circle, and release their grip on the cup.

The cup should be centered in the mid circle. The participant should be standing with both hands at home.

> *"Pick up this paper cup from the table, bring it all the way to your mouth, and pretend to drink from it. Then put the cup back on the table in the mid circle. Try to use only your prosthesis to do this task."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

Use a Fork

Instruct the participant to grasp the fork, use the fork to stab the plasticine, bring the fork and plasticine all the way to the mouth as if taking a bite of food, move the fork away from their mouth and return it to the mid circle, and release their grip on the fork.

The fork should be aligned vertically and centered in the mid circle. The plasticine should be shaped into a ball and centered in the left circle. The participant should be sitting with both hands at home.

> *"Please grasp this fork, stab the plasticine, and bring it to your mouth as if you were going to take a bite of food from it. Then put the fork back on the table in the mid circle. Try to use only your prosthesis to do this task."*

Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

Use a Spoon

Instruct the participant to grasp the spoon, use the spoon to scoop bean(s) from the bowl, bring the spoon and bean(s) all the way to their mouth as if taking a bite of food, move the spoon away from their mouth, deposit the bean(s) in the bowl, return the spoon to the mid circle, and release their grip on the spoon.

The spoon should be aligned vertically and centered in the mid circle. The bowl of beans should be centered in the right circle. The participant should be sitting with both hands at home.

> *"Please grasp this spoon with your prosthesis, use it to scoop a bean(s) from the bowl, and bring the spoon and bean(s) to your mouth as if you were going to take a bite from it. Then put the bean(s) back in the bowl and the spoon back on the table in the mid circle. Be sure to use your prosthesis while doing this."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

POUR FROM A CAN

Instruct the participant to pick up the can, pour the contents into the cup, set the can down on the table, and release the can.

The can should be filled with 100 mL of water and centered in the mid circle, with the tab open and pointing to the far edge of the table. The cup should be centered in the left circle. The participant should be sitting with both hands at home.

> *"Please pick up the soda can from the table. Then pour the water from the can into the cup, making sure not to spill any water. When finished set the can down on the table upright in the mid circle. Be sure to use your prosthesis."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

WRITE LEGIBLY

Instruct the participant to grasp the pen, write the word "LETTER," set the pen down on the table in the mid circle, and release their grip.

The paper should be aligned vertically, centered over the mid circle. The pen should be aligned vertically with the tip towards the participant, centered over the right circle. The pen should be 'clicked' closed. The participant should be sitting with both hands at home.

> *"Please grasp this pen with your prosthesis, click it open, and write the word "LETTER" on the blank sheet of paper on the table. Then set the pen down on the table in the right circle. Try to use only your prosthesis to do this task. You may use your left hand to stabilize the paper."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

Bilateral Tasks

ZIP VEST

Instruct the participant to don the vest, initiate the zipper, pull the zipper up at least two thirds of the way, and then unzip the zipper.

The vest should be laid with the collar towards the far edge of the table, unzipped with the front facing upwards, centered over the mid circle. The participant should be standing with both hands at home.

> *"Please put this vest on (therapist may help don vest), start the zipper, and pull it at least two-thirds of the way up. Then unzip the zipper. Be sure to use your prosthesis while doing this."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

TIE SHOELACES

Instruct the participant to grasp a lace with each hand, crisscross the laces, make loops, pull the bow tight, and release their grasp on the laces.

The shoe should be positioned with the toe closest to the far edge of the table, centered over the mid circle. The participant should be standing with both hands at home.

> *"Please take this shoe and tie the laces. Grasp a lace in each hand, crisscross the laces, making loops, and tie the bow tight. Be sure to use your prosthesis while doing this."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

FOLD A BATH TOWEL

Instruct the participant to grasp the ends of the towel, lift the towel off the table, bring the ends together to fold twice in two different directions, and release their grasp on the towel.

The towel should be centered over the mid circle. The participant should be standing with both hands at home.

> *"Please grasp the ends of this bath towel and hold the towel off the table, then bring the ends of the towel together to fold it twice in two different directions. Place the folded towel back on the table. Be sure to use your prosthesis while*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

OPEN AN ENVELOPE

Instruct the participant to grasp the envelope in the TD, use a pen break the top seal of the envelope, open the envelope, remove the paper within the envelope, place the envelope and contents over the mid circle and the pen in the left circle, and release the envelope, its contents, and the pen.

The envelope should be centered over the mid circle. The pen should be oriented vertically, tip pointing down, centered in the left circle. The participant should be sitting with both hands at home.

> *"Please secure this envelope and, using a pen, break the seal on it. Then open the envelope, remove it contents, and place both on the table over the mid circle. Return the pen to the left circle. Be sure to use your prosthesis while*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

TAPE MEASURE

Instruct the participant to grasp the tape measure, extend the tape to measure between the mid circle and the right circle, withdraw the tape, place the tape measure over the mid circle, and release their grip.

The tape measure should be centered in the left circle, with the tape withdrawn and oriented on the right. The participant should be sitting with both hands at home.

> *"Please grasp the tape measure and measure the distance between the boundaries of the mid circle and the right circle. Then withdraw the tape and place it in the mid circle. Be sure to use your prosthesis while doing this."*

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task.]

OPEN A BAG

Instruct the participant to grasp the Ziploc bag, open the bag in the air (without fixating against the table), grasp the pen, place the pen in the Ziploc bag, seal the bag, place the bag in the mid circle, and release their grip.

The Ziploc bag should be centered over the mid circle. The pen should be aligned horizontally, centered in the left circle. The participant should be standing with both hands at home.

“Please grasp the Ziploc bag and, holding it off the table, grasp the pen and place it in the bag. Then seal the bag and place it back on the table over the mid circle. Be sure to use your prosthesis while doing this.”

[Demonstrate the procedure yourself while explaining the task to the participant. Deliver the appropriate prompt for each trial. Reset the task. Don’t allow the participant to fixate the bag or pen against their body.]

Bibliography

Akizuki, K., & Ohashi, Y. (2015). Measurement of functional task difficulty during motor learning: What level of difficulty corresponds to the optimal challenge point? *Human Movement Science*, *43*, 107–117. https://doi.org/10.1016/j.humov.2015.07.007

Alexander, W. H., & Brown, J. W. (2019). The Role of the Anterior Cingulate Cortex in Prediction Error and Signaling Surprise. *Topics in Cognitive Science*, *11*(1), 119–135. https://doi.org/10.1111/tops.12307

Arrighi, P., Bonfiglio, L., Minichilli, F., Cantore, N., Carboncini, M. C., Piccotti, E., Rossi, B., & Andre, P. (2016). EEG theta dynamics within frontal and parietal cortices for error processing during reaching movements in a prism adaptation study altering visuo-motor predictive planning. *PLoS ONE*, *11*(3), 1–27. https://doi.org/10.1371/journal.pone.0150265

Babiloni, C., Del Percio, C., Iacoboni, M., Infarinato, F., Lizio, R., Marzano, N., Crespi, G., Dassù, F., Pirritano, M., Gallamini, M., & Eusebi, F. (2008). Golf putt outcomes are predicted by sensorimotor cerebral EEG rhythms. *Journal of Physiology*, *586*(1), 131–139. https://doi.org/10.1113/jphysiol.2007.141630

Babulal, G. M., Foster, E. R., & Wolf, T. J. (2017). *Therapy Practice : Practical Application of Transfer Principles*. *11*(1), 19–25. https://doi.org/10.11596/asiajot.11.19.Facilitating

Balasubramanian, S., Melendez-Calderon, A., Roby-Brami, A., & Burdet, E. (2015). On the analysis of movement smoothness. *Journal of NeuroEngineering and Rehabilitation*, *12*(1), 1–11. https://doi.org/10.1186/s12984-015-0090-9

Baumeister, J., Reinecke, K., Liesen, H., & Weiss, M. (2008). Cortical activity of skilled performance in a complex sports related motor task. *European Journal of Applied Physiology*, *104*(4), 625–631. https://doi.org/10.1007/s00421-008-0811-x

Beck, M. M., Spedden, M. E., Dietz, M. J., Karabanov, A. N., Christensen, M. S., & Lundbye-Jensen, J. (2021). Cortical signatures of precision grip force control in children, adolescents, and adults. *ELife*, *10*, 1–22. https://doi.org/10.7554/eLife.61018

Biddiss, E., & Chau, T. (2007). Upper limb prosthesis use and abandonment: A survey of the last 25 years. *Prosthetics and Orthotics International*, *31*(3), 236–257. https://doi.org/10.1080/03093640600994581

Blakemore, S. J., & Sirigu, A. (2003). Action prediction in the cerebellum and in the parietal lobe. *Experimental Brain Research*, *153*(2), 239–245. https://doi.org/10.1007/s00221-003-1597-z

Bloomer, C., & Kontson, K. L. (2020). Comparison of DEKA Arm and Body-Powered Upper Limb Prosthesis Joint Kinematics. *Archives of Rehabilitation Research and Clinical Translation*, *2*(3), 100057. https://doi.org/10.1016/j.arrct.2020.100057

Bloomer, C., Wang, S., & Kontson, K. (2020). Kinematic analysis of motor learning in upper limb body-powered bypass prosthesis training. *PLoS ONE*, *15*(1), 1–16. https://doi.org/10.1371/journal.pone.0226563

Bloomer, C., Wang, S., & Kontson, K. L. (2018). Creating a standardized , quantitative training protocol for upper limb bypass prostheses. *Physical Medicine and Rehabilitation Research*.

Boop, C., Cahill, S. M., Davis, C., Dorsey, J., Gibbs, V., Herr, B., Kearney, K., Liz Griffin Lannigan, E., Metzger, L., Miller, J., Owens, A., Rives, K., Synovec, C., Winistorfer, W. L., & Lieberman, D. (2020). Occupational therapy practice framework: Domain and process fourth edition. In *American Journal of Occupational Therapy* (Vol. 74, Issue August). https://doi.org/10.5014/ajot.2020.74S2001

Boser, Q. A. (2019). *Characterizing the Visuomotor Behaviour of Upper Limb Body-Powered Prosthesis Users*. University of Alberta.

Bouwsema, H., Van Der Sluis, C. K., & Bongers, R. M. (2008). *The Role of Order of Practice in Learning to Handle an Upper-Limb Prosthesis*. https://doi.org/10.1016/j.apmr.2007.12.046

Bouwsema, H., Van Der Sluis, C. K., & Bongers, R. M. (2014a). Changes in performance over time while learning to use a myoelectric prosthesis. In *Journal of NeuroEngineering and Rehabilitation* (Vol. 11). https://doi.org/10.1186/1743-0003-11-16

Bouwsema, H., Van Der Sluis, C. K., & Bongers, R. M. (2014b). Changes in performance over time while learning to use a myoelectric prosthesis. *Journal of NeuroEngineering and Rehabilitation*.

https://doi.org/10.1186/1743-0003-11-16

Brinkman, L., Stolk, A., Dijkerman, H. C., de Lange, F. P., & Toni, I. (2014). Distinct Roles for Alpha- and Beta-Band Oscillations during Mental Simulation of Goal-Directed Actions. *Journal of Neuroscience*, *34*(44), 14783–14792. https://doi.org/10.1523/JNEUROSCI.2039-14.2014

Brinkman, L., Stolk, A., Marshall, T. R., Esterer, S., Sharp, P., Dijkerman, H. C., de Lange, F. P., & Toni, I. (2016). Independent causal contributions of Alpha- and Beta-band oscillations during movement selection. *Journal of Neuroscience*, *36*(33), 8726–8733. https://doi.org/10.1523/JNEUROSCI.0868-16.2016

Brown, J. D., Paek, A., Syed, M., O'Malley, M. K., Shewokis, P. A., Contreras-Vidal, J. L., Davis, A. J., & Gillespie, R. B. (2015). An exploration of grip force regulation with a low-impedance myoelectric prosthesis featuring referred haptic feedback. *Journal of NeuroEngineering and Rehabilitation*, *12*(1), 1–17. https://doi.org/10.1186/s12984-015-0098-1

Butkus, J., Dennison, C., Orr, A., & Laurent, M. St. (2014). Occupational Therapy with the Military Upper Extremity Amputee: Advances and Research Implications. *Current Physical Medicine and Rehabilitation Reports*, *2*(4), 255–262. https://doi.org/10.1007/s40141-014-0065-y

Carey, S. L., Dubey, R. V., Bauer, G. S., & Highsmith, M. J. (2009). Kinematic comparison of myoelectric and body powered prostheses while performing common activities. *Prosthetics and Orthotics International*, *33*(2), 179–186. https://doi.org/10.1080/03093640802613229

Carey, S. L., Jason Highsmith, M., Maitland, M. E., & Dubey, R. V. (2008). Compensatory movements of transradial prosthesis users during common tasks. *Clinical Biomechanics*, *23*(9), 1128–1135. https://doi.org/10.1016/j.clinbiomech.2008.05.008

Carey, S. L., Lura, D. J., & Highsmith, M. J. (2015a). *Differences in myoelectric and body- powered upper-limb prostheses: Systematic literature review*. *52*(3), 247–262.

Carey, S. L., Lura, D. J., & Highsmith, M. J. (2015b). *Differences in myoelectric and body-powered upper-limb prostheses: Systematic literature review*. *52*(3), 247–262. https://doi.org/10.1682/JRRD.2014.08.0192

Casadio, M., Ranganathan, R., & Mussa-Ivaldi, F. A. (2012). The body-machine interface: A new perspective on an old theme. *Journal of Motor Behavior*, *44*(6), 419–433. https://doi.org/10.1080/00222895.2012.700968

Cavanagh, J. F., Figueroa, C. M., Cohen, M. X., & Frank, M. J. (2012). Frontal theta reflects uncertainty and unexpectedness during exploration and exploitation. *Cerebral Cortex*, *22*(11), 2575–2586. https://doi.org/10.1093/cercor/bhr332

Chadwell, A., Kenney, L., Thies, S., Head, J., Galpin, A., & Baker, R. (2021). Addressing unpredictability may be the key to improving performance with current clinically prescribed myoelectric prostheses. *Scientific Reports*, *11*(1), 1–15. https://doi.org/10.1038/s41598-021-82764-6

Chadwell, Alix, Kenney, L., Thies, S., Galpin, A., & Head, J. (2016a). The reality of myoelectric prostheses: Understanding what makes these devices difficult for some users to control. *Frontiers in Neurorobotics*, *10*(AUG), 1–21. https://doi.org/10.3389/fnbot.2016.00007

Chadwell, Alix, Kenney, L., Thies, S., Galpin, A., & Head, J. (2016b). The reality of myoelectric prostheses: Understanding what makes these devices difficult for some users to control. *Frontiers in Neurorobotics*, *10*(AUG), 1–21. https://doi.org/10.3389/fnbot.2016.00007

Chen, A., Yao, J., Kuiken, T., & Dewald, J. P. A. (2013). Cortical motor activity and reorganization following upper-limb amputation and subsequent targeted reinnervation. *NeuroImage: Clinical*, *3*, 498–506. https://doi.org/10.1016/j.nicl.2013.10.001

Cheung, G. W., Cooper, H. D., Rebecca, T., & Wang, L. C. (2023). Reporting reliability , convergent and discriminant and best - practice recommendations. In *Asia Pacific Journal of Management* (Vol. 3, Issue 0123456789). Springer US. https://doi.org/10.1007/s10490-023-09871-y

Churruca, K., Pomare, C., Ellis, L. A., Long, J. C., Henderson, S. B., Murphy, L. E. D., Leahy, C. J., & Braithwaite, J. (2021). Patient-reported outcome measures (PROMs): A review of generic and condition-specific measures and a discussion of trends and issues. *Health Expectations*, *24*(4), 1015–1024. https://doi.org/10.1111/hex.13254

Coles, T. M., Hernandez, A. F., Reeve, B. B., Cook, K., Edwards, M. C., Boutin, M., Bush, E., Degboe, A., Roessig, L., Rudolph, A., McNulty, P., Patel, N., Kay-Mugford, T., Vernon, M., Woloschak, M., Buchele, G., Spertus, J. A., Roe, M. T., Bury, D., & Weinfurt, K. (2021). Enabling patient-reported outcome measures in clinical trials, exemplified by cardiovascular trials. *Health and Quality of Life Outcomes*, *19*(1), 1–7. https://doi.org/10.1186/s12955-021-01800-1

Cook, R. D. (1977). Detection of Influential Observation in Linear Regression. *Technometrics*, *19*(1), 15–18. https://doi.org/10.2307/1268249

Cornett, K. M. D., Menezes, M. P., Bray, P., Shy, R. R., Moroni, I., Pagliano, E., Pareyson, D., Estilow, T., Yum, S. W., Bhandari, T., Muntoni, F., Laura, M., Reilly, M. M., Finkel, R. S., Eichinger, K. J., Herrmann, D. N., Shy, M. E., & Burns, J. (2020). Refining clinical trial inclusion criteria to optimize the standardized response mean of the CMTPedS. *Annals of Clinical and Translational Neurology*, *7*(9), 1713–1715. https://doi.org/10.1002/acn3.51145

Cross-Villasana, F., Gröpel, P., Ehrlenspiel, F., & Beckmann, J. (2018). Central theta amplitude as a negative correlate of performance proficiency in a dynamic visuospatial task. *Biological Psychology*, *132*(April 2017), 37–44. https://doi.org/10.1016/j.biopsycho.2017.10.009

Davis Sears, E., & Chung, K. C. (2010). Validity and Responsiveness of the Jebsen-Taylor Hand Function Test. *Journal of Hand Surgery*, *35*(1), 30–37. https://doi.org/10.1016/j.jhsa.2009.09.008

Deeny, S., Chicoine, C., Hargrove, L., Parrish, T., & Jayaraman, A. (2014). A Simple ERP Method for Quantitative Analysis of Cognitive Workload in Myoelectric Prosthesis Control and Human-Machine Interaction. *PLoS ONE*, *9*(11), e112091. https://doi.org/10.1371/JOURNAL.PONE.0112091

Desmurget, M., & Grafton, S. (2000). Forward modeling allows feedback control for fast reaching movements. *Trends in Cognitive Sciences*, *4*(11), 423–431. https://doi.org/10.1016/S1364-6613(00)01537-0

Desrosiers, J., Bravo, G., Hébert, R., Dutil, É., & Mercier, L. (1994). Validation of the Box and Block Test as a measure of dexterity of elderly people: Reliability, validity, and norms studies. *Archives of Physical Medicine and Rehabilitation*, *75*(7), 751–755. https://doi.org/10.5555/uri:pii:0003999394901309

Devilliers, H., Amoura, Z., Besancenot, J. F., Bonnotte, B., Pasquali, J. L., Wahl, D., Maurier, F., Kaminsky, P., Pennaforte, J. L., Magy-Bertrand, N., Arnaud, L., Binquet, C., Guillemin, F., & Bonithon-Kopp, C. (2014). Responsiveness of the 36-item short form health survey and the lupus quality of life questionnaire in SLE. *Rheumatology (United Kingdom)*, *54*(5), 940–949. https://doi.org/10.1093/rheumatology/keu410

Dufour, B., Thénault, F., & Bernier, P. M. (2018). Theta-band EEG Activity over Sensorimotor Regions is Modulated by Expected Visual Reafferent Feedback During Reach Planning. *Neuroscience*, *385*, 47–58. https://doi.org/10.1016/j.neuroscience.2018.06.005

Ehrsson, H. H., Fagergren, A., Jonsson, T., Westling, G., Johansson, R. S., & Forssberg, H. (2000). Cortical activity in precision- versus power-grip tasks: An fMRI study. *Journal of Neurophysiology*, *83*(1), 528–536. https://doi.org/10.1152/jn.2000.83.1.528

El Hayek, M., Lobo Jofili Lopes, J. L. M., Lelaurin, J. H., Gregory, M. E., Abi Nehme, A. M., McCall-Junkin, P., Au, K. L. K., Okun, M. S., & Salloum, R. G. (2023). Type, Timing, Frequency, and Durability of Outcome of Physical Therapy for Parkinson Disease: A Systematic Review and Meta-Analysis. *JAMA Network Open*, *6*(7), E2324860. https://doi.org/10.1001/jamanetworkopen.2023.24860

Espenhahn, S., van Wijk, B. C. M., Rossiter, H. E., de Berker, A. O., Redman, N. D., Rondina, J., Diedrichsen, J., & Ward, N. S. (2019). Cortical beta oscillations are associated with motor performance following visuomotor learning. *NeuroImage*, *195*(April), 340–353. https://doi.org/10.1016/j.neuroimage.2019.03.079

Fallahi, M., Motamedzade, M., Heidarimoghadam, R., Soltanian, A. R., & Miyake, S. (2016). Assessment of operators' mental workload using physiological andsubjective measures in cement, city traffic and power plant controlcenters. *Health Promotion Perspectives*, *6*(2), 96–103. https://doi.org/10.15171/hpp.2016.17

Feix, T., Romero, J., Schmiedmayer, H.-B., Dollar, A. M., & Kragic, D. (2016). The GRASP Taxonomy of Human Grasp Types. *IEEE Transactions on Human-Machine Systems*, *46*(1), 66–77. https://doi.org/10.1109/THMS.2015.2470657

Fellner, M., Volberg, G., Hanslmayr, S., Wimber, M., Goldhacker, M., & Mark, W. (2016). *Spatial Mnemonic*

Encoding : Theta Power Decreases and Medial Temporal Lobe BOLD Increases Co-Occur during the Usage of the Method of Loci. *3*(December), 1–16.

Fernani, D. C. G. L., Prado, M. T. A., da Silva, T. D., Massetti, T., de Abreu, L. C., Magalhães, F. H., Dawes, H., & de Mello Monteiro, C. B. (2017). Evaluation of speed-accuracy trade-off in a computer task in individuals with cerebral palsy: A cross-sectional study. *BMC Neurology*, *17*(1), 1–9. https://doi.org/10.1186/s12883-017-0920-4

Feys, P., Lamers, I., Francis, G., Benedict, R., Phillips, G., Larocca, N., Hudson, L. D., & Rudick, R. (2017). The Nine-Hole Peg Test as a manual dexterity performance measure for multiple sclerosis. *Multiple Sclerosis Journal*, *23*(5), 711–720. https://doi.org/10.1177/https

Fitts, P. M., & Posner, M. I. (1967). Human performance. In *Human performance*. Brooks/Cole.

Franklin, D. W., & Wolpert, D. M. (2011). Computational mechanisms of sensorimotor control. *Neuron*, *72*(3), 425–442. https://doi.org/10.1016/j.neuron.2011.10.006

Garde, A. H., Laursen, B., Jørgensen, A. H., & Jensen, B. R. (2002). Effects of mental and physical demands on heart rate variability during computer work. *European Journal of Applied Physiology*, *87*(4–5), 456–461. https://doi.org/10.1007/s00421-002-0656-7

Geevasinga, N., Menon, P., Kiernan, M. C., & Vucic, S. (2014). Motor cortical function and the precision grip. *Physiological Reports*, *2*(12), 1–10. https://doi.org/10.14814/phy2.12120

Gentili, R. J., Bradberry, T. J., Oh, H., Costanzo, M. E., Kerick, S. E., Contreras-Vidal, J. L., & Hatfield, B. D. (2015). Evolution of cerebral cortico-cortical communication during visuomotor adaptation to a cognitive-motor executive challenge. *Biological Psychology*, *105*, 51–65. https://doi.org/10.1016/j.biopsycho.2014.12.003

Gentili, R. J., Bradberry, T. J., Oh, H., Hatfield, B. D., & Contreras Vidal, J. L. (2011). Cerebral cortical dynamics during visuomotor transformation: Adaptation to a cognitive-motor executive challenge. *Psychophysiology*, *48*(6), 813–824. https://doi.org/10.1111/j.1469-8986.2010.01143.x

Gentili, R. J., Jaquess, K. J., Shuggi, I. M., Shaw, E. P., Oh, H., Lo, L. C., Tan, Y. Y., Domingues, C. A., Blanco, J. A., Rietschel, J. C., Miller, M. W., & Hatfield, B. D. (2018). Combined assessment of attentional reserve and cognitive-motor effort under various levels of challenge with a dry EEG system. *Psychophysiology*, *55*(6), 1–17. https://doi.org/10.1111/psyp.13059

Gentili, R. J., Rietschel, J. C., Jaquess, K. J., Lo, L. C., Prevost, M., Miller, M. W., Mohler, J. M., Oh, H., Tan, Y. Y. ing, & Hatfield, B. D. (2014). Brain biomarkers based assessment of cognitive workload in pilots under various task demands. *Conference Proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference*, *2014*, 5860–5863. https://doi.org/10.1109/EMBC.2014.6944961

Gevins, a, & Smith, M. E. (2000). Neurophysiological measures of working memory and individual differences in cognitive ability and cognitive style. *Cerebral Cortex (New York, N.Y. : 1991)*, *10*(9), 829–839. https://doi.org/10.1093/cercor/10.9.829

Gevins, A, & Smith, M. E. (2003). Neurophysiological measures of cognitive workload during human-computer interaction. *Theoretical Issues in Ergonomic Science*, *4*, 113–131. https://doi.org/10.1080/14639220210159717

Gevins, Alan, Smith, M. E., McEvoy, L., & Yu, D. (1997). High-resolution EEG mapping of cortical activation related to working memory: Effects of task difficulty, type of processing, and practice. *Cerebral Cortex*, *7*(4), 374–385. https://doi.org/10.1093/cercor/7.4.374

Gonzalez, J., Soma, H., Sekine, M., & Yu, W. (2012). Psycho-physiological assessment of a prosthetic hand sensory feedback system based on an auditory display: A preliminary study. *Journal of NeuroEngineering and Rehabilitation*, *9*(1), 1–14. https://doi.org/10.1186/1743-0003-9-33

Gull, M. A., Bai, S., & Bak, T. (2020). A review on design of upper limb exoskeletons. *Robotics*, *9*(1), 1–35. https://doi.org/10.3390/robotics9010016

H. Yan, J., Hinrichs, R., Gregory Payne, V., & Thomas, J. (2000). Normalized Jerk: A Measure to Capture Developmental Characteristics of Young Girls' Overarm Throwing. *Journal of Applied Biomechanics*, *16*, 196–203. https://doi.org/10.1123/jab.16.2.196

Hanmer, J., Cizik, A. M., Gulek, B. G., & Mccracken, P. (2022). *A Scoping Review of US Insurers '* (Vol. 28, Issue June). https://doi.org/10.37765/ajmc.2022.89162

Harper, J., Malone, S. M., & Iacono, W. G. (2017). Theta- and delta-band EEG network dynamics during a novelty oddball task. *Psychophysiology*, *54*(11), 1590–1605. https://doi.org/10.1111/psyp.12906

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. *Nature*, *394*(6695), 780–784. https://doi.org/10.1038/29528

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. *Advances in Psychology*, *52*, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9

Hatfield, B. D., Haufler, A. J., Hung, T.-M., & Spalding, T. W. (2004a). Electroencephalographic studies of skilled psychomotor performance. LK - https://umaryland.on.worldcat.org/oclc/110223290. *Journal of Clinical Neurophysiology : Official Publication of the American Electroencephalographic Society TA - TT -*, *21*(3), 144–156.

Hatfield, B. D., Haufler, A. J., Hung, T.-M., & Spalding, T. W. (2004b). Electroencephalographic Studies of Skilled Psychomotor Performance. *Journal of Clinical Neurophysiology*, *21*(3).

Hauge, T. C., Katz, G. E., Davis, G. P., Jaquess, K. J., Reinhard, M. J., Costanzo, M. E., Reggia, J. A., & Gentili, R. J. (2020). A novel application of levenshtein distance for assessment of high-level motor planning underlying performance during learning of complex motor sequences. *Journal of Motor Learning and Development*, *8*(1), 67–86. https://doi.org/10.1123/jmld.2018-0060

Haverkate, L., Smit, G., & Plettenburg, Di. H. (2016). Assessment of body-powered upper limb prostheses by able-bodied subjects, using the Box and Blocks Test and the Nine-Hole Peg Test. *Prosthetics and Orthotics International*, *40*(1), 109–116. https://doi.org/10.1177/0309364614554030

Heitz, R. P. (2014). The speed-accuracy tradeoff: History, physiology, methodology, and behavior. *Frontiers in Neuroscience*, *8*(8 JUN), 1–19. https://doi.org/10.3389/fnins.2014.00150

Heitz, R. P., & Schall, J. D. (2012). Neural Mechanisms of Speed-Accuracy Tradeoff. *Neuron*, *76*(3), 616–628.

https://doi.org/10.1016/j.neuron.2012.08.030

Huang, M. E., Levy, C. E., & Webster, J. B. (2001). Acquired limb deficiencies. 3. Prosthetic components, prescriptions, and indications. *Archives of Physical Medicine and Rehabilitation*, *82*(3B), 0s17-0s24. https://doi.org/10.1053/apmr.2001.22226

Huinink, L. H. B., Bouwsema, H., Plettenburg, D. H., Van Der Sluis, C. K., & Bongers, R. M. (2016). *Learning to use a body-powered prosthesis: changes in functionality and kinematics*. https://doi.org/10.1186/s12984-016-0197-7

Iturrate, Inaki, Chavarriaga, R., Pereira, M., & Zhang, H. (2018). Human EEG reveals distinct neural correlates of power and precision grasping types. *NeuroImage*, *July*. https://doi.org/10.1016/j.neuroimage.2018.07.055

Iturrate, Iñaki, Chavarriaga, R., Pereira, M., Zhang, H., Corbet, T., Leeb, R., & Millán, J. del R. (2018). Human EEG reveals distinct neural correlates of power and precision grasping types. *NeuroImage*, *181*(July), 635–644. https://doi.org/10.1016/j.neuroimage.2018.07.055

Jaquess, K. J., Gentili, R. J., Lo, L. C., Oh, H., Zhang, J., Rietschel, J. C., Miller, M. W., Tan, Y. Y., & Hatfield, B. D. (2017). Empirical evidence for the relationship between cognitive workload and attentional reserve. *International Journal of Psychophysiology*, *121*(February), 46–55. https://doi.org/10.1016/j.ijpsycho.2017.09.007

Jaquess, K. J., Lo, L. C., Oh, H., Lu, C., Ginsberg, A., Tan, Y. Y., Lohse, K. R., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Changes in Mental Workload and Motor Performance Throughout Multiple Practice Sessions Under Various Levels of Task Difficulty. *Neuroscience*, *393*, 305–318. https://doi.org/10.1016/j.neuroscience.2018.09.019

Kahneman, D. (1974). Attention and Effort. In *Radiobiologiya* (Vol. 14, Issue 6). https://doi.org/10.2307/1421603

Kantowitz, B. H. (1998). Attention and Mental Workload. *Proceedings of the IEA 2000/HFES 2000 Congress*, 456–459.

Kao, S. C., Huang, C. J., & Hung, T. M. (2013). Frontal midline theta is a specific indicator of optimal attentional engagement during skilled putting performance. *Journal of Sport and Exercise Psychology*, *35*(5), 470–478. https://doi.org/10.1123/jsep.35.5.470

Kardos, Z., Tóth, B., Boha, R., File, B., & Molnár, M. (2014). Age-related changes of frontal-midline theta is predictive of efficient memory maintenance. *Neuroscience*, *273*, 152–162. https://doi.org/10.1016/j.neuroscience.2014.04.071

Kieliba, P., Clode, D., Maimon-Mor, R. O., & Makin, T. R. (2021). Robotic hand augmentation drives changes in neural body representation. *Science Robotics*, *6*(54), 1–14. https://doi.org/10.1126/scirobotics.abd7935

Kim, H., Her, J., Ko, J., Park, D. S., Woo, J. H., You, Y., & Choi, Y. (2012). Reliability, concurrent validity, and responsiveness of the fugl-meyer assessment (FMA) for hemiplegic patients. *Journal of Physical Therapy Science*, *24*(9), 893–899. https://doi.org/10.1589/jpts.24.893

Kim, J. Y., & Ji, Y. G. (2013). *A Comparison of Subjective Mental Workload Measures in Driving Contexts*. *32*(2), 167–177.

Kim, K., Colgate, J. E., Santos-Munné, J. J., Makhlin, A., & Peshkin, M. A. (2010). On the design of miniature haptic devices for upper extremity prosthetics. *IEEE/ASME Transactions on Mechatronics*, *15*(1), 27–39. https://doi.org/10.1109/TMECH.2009.2013944

Kimberley, T. J. ., & Lewis, S. M. (2007). Neuroimaging in Rehabilitation. *Physical Therapy*, *87*(6), 704–718.

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in Cognitive Sciences*, *16*(12), 606–617. https://doi.org/10.1016/j.tics.2012.10.007

Krakauer, J. W., Mazzoni, P., Ghazizadeh, A., Ravindran, R., & Shadmehr, R. (2006). Generalization of motor learning depends on the history of prior action. *PLoS Biology*, *4*(10), 1798–1808. https://doi.org/10.1371/journal.pbio.0040316

Krauth, R., Schwertner, J., Vogt, S., Lindquist, S., Sailer, M., Sickert, A., Lamprecht, J., Perdikis, S., Corbet, T., Del Millán, J. R., Hinrichs, H., Heinze, H. J., & Sweeney-Reed, C. M. (2019). Cortico-muscular coherence is reduced acutely post-stroke and increases bilaterally during motor recovery: A pilot study.

Frontiers in Neurology, *10*(FEB). https://doi.org/10.3389/fneur.2019.00126

Landsmeer, J. M. (1962). Power grip and precision handling. *Annals of the Rheumatic Diseases*, *21*, 164–170. https://doi.org/10.1136/ard.21.2.164

Langer, N., Hänggi, J., Müller, N. A., Simmen, H. P., & Jäncke, L. (2012). Effects of limb immobilization on brain plasticity. *Neurology*, *78*(3), 182 LP – 188. https://doi.org/10.1212/WNL.0b013e31823fcd9c

Lawson, D. H., Lee, S., Zhao, F., Tarhini, A. A., Margolin, K. A., Ernstoff, M. S., Atkins, M. B., Cohen, G. I., Whiteside, T. L., Butterfield, L. H., Kirkwood, J. M., MA Gillentine, LN Berry, RP Goin-Kochel, MA Ali, J Ge, D Guffey, JA Rosenfeld, V Hannig, P Bader, M Proud, M Shinawi, BH Graham1, A Lin, SR Lalani, J Reynolds, M Chen, T Grebe, CG Minard, P Stankiewicz, AL Beaudet, and C., Schaaf, Van Willigen, W. W., Bloemendal, M., Gerritsen, W. R., Schreibelt, G., de Vries, I. J. M., Bol, K. F., … 口田圭吾. (2016). This is to certify that. *Journal of Clinical Oncology*, *1*(1), 97680. https://doi.org/10.1016/j.jconrel.2012.07.004.Enhanced

Light, C. M., Chappell, P. H., & Kyberd, P. J. (2002). Establishing a standardized clinical assessment tool of pathologic and prosthetic hand function: Normative data, reliability, and validity. *Archives of Physical Medicine and Rehabilitation*, *83*(6), 776–783. https://doi.org/10.1053/apmr.2002.32737

Long, C. I. I., Conrad, P. W., Hall, E. A., & Furler, S. L. (1970). Intrinsic-Extrinsic Muscle Control of the Hand in Power Grip and Precision Handling: AN ELECTROMYOGRAPHIC STUDY LK - https://umaryland.on.worldcat.org/oclc/7008000999. *The Journal of Bone & Joint Surgery TA - TT -*, *52*(5), 853–867.

Lu, Y., Bilaloglu, S., Aluru, V., & Raghavan, P. (2015). Quantifying feed forward control: A linear scaling model for fingertip forces and object weight. *Journal of Neurophysiology*, *114*(1), 411–418. https://doi.org/10.1152/jn.00065.2015

Lum, P. S., Black, I., Holley, R. J., Barth, J., & Dromerick, A. W. (2014a). Internal models of upper limb prosthesis users when grasping and lifting a fragile object with their prosthetic limb. *Experimental Brain Research*, *232*(12), 3785–3795. https://doi.org/10.1007/s00221-014-4071-1

Lum, P. S., Black, I., Holley, R. J., Barth, J., & Dromerick, A. W. (2014b). Internal models of upper limb prosthesis users when grasping and lifting a fragile object with their prosthetic limb. *Experimental Brain Research*, *232*(12), 3785–3795. https://doi.org/10.1007/s00221-014-4071-1

Marchand, C., De Graaf, J. B., & Jarrassé, N. (2021). Measuring mental workload in assistive wearable devices: a review. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 1–15. https://doi.org/10.1186/s12984-021-00953-w

Margraf, L., Krause, D., & Weigelt, M. (2023). Frontal theta reveals further information about neural valence-dependent processing of augmented feedback in extensive motor practice—A secondary analysis. *European Journal of Neuroscience*, *57*(8), 1297–1316. https://doi.org/10.1111/ejn.15951

Mathiowetz, V., & Weber, K. (1985). Adult Norms for the Box and Block. *The American Journal of Ocupational Therapy*, *39*(6), 387–391.

Meissner, S. N., Krause, V., Südmeyer, M., Hartmann, C. J., & Pollok, B. (2018). The significance of brain oscillations in motor sequence learning: Insights from Parkinson's disease. *NeuroImage: Clinical*, *20*(August), 448–457. https://doi.org/10.1016/j.nicl.2018.08.009

Miller, M. W., Rietschel, J. C., Mcdonald, C. G., & Hatfield, B. D. (2011). A novel approach to the physiological measurement of mental workload. *International Journal of Psychophysiology*, *80*, 75–78. https://doi.org/10.1016/j.ijpsycho.2011.02.003

Morehead, R. J., Taylor, J. A., Parvin, D. E., & Ivry, R. B. (2017). Characteristics of Implicit Sensorimotor Adaptation Revealed by Task-irrelevant Clamped Feedback. *Journal of Cognitive Neuroscience*, *29*(6), 139. https://doi.org/10.1162/jocn

Mou, D., Mjaset, C., Sokas, C. M., Virji, A., Bokhour, B., Heng, M., Sisodia, R. C., Pusic, A. L., & Rosenthal, M. B. (2022). Impetus of US hospital leaders to invest in patient-reported outcome measures (PROMs): a qualitative study. *BMJ Open*, *12*(7). https://doi.org/10.1136/bmjopen-2022-061761

Murphy, M. A., Resteghini, C., Feys, P., & Lamers, I. (2015). An overview of systematic reviews on upper extremity outcome measures after stroke. *BMC Neurology*, *15*(1). https://doi.org/10.1186/s12883-015-

0292-6

Naufel, S., Knaack, G. L., Miranda, R., Best, T. K., Fitzpatrick, K., Emondi, A. A., Van Gieson, E., & McClure-Begley, T. (2020). DARPA investment in peripheral nerve interfaces for prosthetics, prescriptions, and plasticity. *Journal of Neuroscience Methods*, *332*(November 2019), 108539. https://doi.org/10.1016/j.jneumeth.2019.108539

Nelson, A. B., Moisello, C., Lin, J., Panday, P., Ricci, S., Canessa, A., Di Rocco, A., Quartarone, A., Frazzitta, G., Isaias, I. U., Tononi, G., Cirelli, C., & Ghilardi, M. F. (2017). Beta oscillatory changes and retention of motor skills during practice in healthy subjects and in patients with Parkinson's disease. *Frontiers in Human Neuroscience*, *11*(March), 1–12. https://doi.org/10.3389/fnhum.2017.00104

Neuper, C., & Pfurtscheller, G. (2001). Event-related dynamics of cortical rhythms: Frequency-specific features and functional correlates. *International Journal of Psychophysiology*, *43*(1), 41–58. https://doi.org/10.1016/S0167-8760(01)00178-7

Niziolek, C. A., Nagarajan, S. S., & Houde, J. F. (2013). What Does Motor Efference Copy Represent? Evidence from Speech Production. *Journal of Neuroscience*, *33*(41), 16110–16116. https://doi.org/10.1523/JNEUROSCI.2137-13.2013

Noble, J. W., Eng, J. J., & Boyd, L. A. (2014). Bilateral motor tasks involve more brain regions and higher neural activation than unilateral tasks: An fMRI study. *Experimental Brain Research*, *232*(9), 2785–2795. https://doi.org/10.1007/s00221-014-3963-4

Park, J., & Zahabi, M. (2022). Cognitive Workload Assessment of Prosthetic Devices: A Review of Literature and Meta-Analysis. *IEEE Transactions on Human-Machine Systems*. https://doi.org/10.1109/THMS.2022.3143998

Parr, J. (2018). *Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand*. *50*(4).

Parr, J. V.V., Vine, S. J., Wilson, M. R., Harrison, N. R., & Wood, G. (2019). Visual attention, EEG alpha power and T7-Fz connectivity are implicated in prosthetic hand control and can be optimized through gaze training. *Journal of NeuroEngineering and Rehabilitation*, *16*(1), 1–20. https://doi.org/10.1186/s12984-019-0524-x

Parr, J., Vic, J., & Parr, V. (2020). *Evaluating and alleviating the cognitive burden associated with myoelectric prosthetic hand control Evaluating and alleviating the cognitive burden associated with myoelectric prosthetic hand control A thesis submitted in partial fulfilment of the require*. *January*. https://doi.org/10.13140/RG.2.2.26474.47048

Parr, Johnny V.V., Gallicchio, G., Harrison, N. R., Johnen, A. K., & Wood, G. (2020). All talk? Challenging the use of left-temporal EEG alpha oscillations as valid measures of verbal processing and conscious motor control. *Biological Psychology*, *155*(May), 107943. https://doi.org/10.1016/j.biopsycho.2020.107943

Parr, Johnny V.V., Galpin, A., Uiga, L., Marshall, B., Wright, D. J., Franklin, Z. C., & Wood, G. (2023). A tool for measuring mental workload during prosthesis use: The Prosthesis Task Load Index (PROS-TLX). *PLoS ONE*, *18*(5 MAY), 1–15. https://doi.org/10.1371/journal.pone.0285382

Parr, J. V. V, Vine, S. J., Harrison, N. R., & Wood, G. (2018). Examining the Spatiotemporal Disruption to Gaze When Using a Myoelectric Prosthetic Hand. *Journal of Motor Behavior*, *50*(4), 416–425. http://10.0.4.56/00222895.2017.1363703

Pasquina, P. F., Perry, B. N., Miller, M. E., Ling, G. S. F., & Tsao, J. W. (2015). Recent Advances in Bioelectric Protheses. *Neurology Clinical Practice*, 164–170.

Pauzié, A. (2008). A method to assess the driver mental workload: The driving activity load index (DALI). *IET Intelligent Transport Systems*, *2*(4), 315–322. https://doi.org/10.1049/iet-its:20080023

Perfetti, B., Moisello, C., Landsness, E. C., Kvint, S., Lanzafame, S., Onofrj, M., Di Rocco, A., Tononi, G., & Ghilardi, M. F. (2011). Modulation of Gamma and Theta Spectral Amplitude and Phase Synchronization Is Associated with the Development of Visuo-Motor Learning. *Journal of Neuroscience*, *31*(41), 14810–14819. https://doi.org/10.1523/JNEUROSCI.1319-11.2011

Pfurtscheller, G., Stancák, A., & Neuper, C. (1996). Event-related synchronization (ERS) in the alpha band -

An electrophysiological correlate of cortical idling: A review. *International Journal of Psychophysiology*, *24*(1–2), 39–46. https://doi.org/10.1016/S0167-8760(96)00066-9

Po, D. K. (2020). Similarity Based Information Retrieval Using Levenshtein Distance Algorithm. *International Journal of Advances in Scientific Research and Engineering*, *06*(04), 06–10. https://doi.org/10.31695/ijasre.2020.33780

Pruziner, A. L., Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Miller, M. W., Wolf, E. J., Hatfield, B. D., Dearth, C. L., & Gentili, R. J. (2019). Biomechanical and neurocognitive performance outcomes of walking with transtibial limb loss while challenged by a concurrent task. *Experimental Brain Research*, *237*(2), 477–491. https://doi.org/10.1007/s00221-018-5419-8

Rackerby, R., Lukosch, S., & Munro, D. (2022). Understanding and Measuring the Cognitive Load of Amputees for Rehabilitation and Prosthesis Development. *Archives of Rehabilitation Research and Clinical Translation*, *4*(3), 100216. https://doi.org/10.1016/j.arrct.2022.100216

Resnik, L., Adams, L., Borgia, M., Delikat, J., Disla, R., Ebner, C., & Walters, L. S. (2013). Development and Evaluation of the Activities Measure for Upper Limb Amputees. *Archives of Physical Medicine and Rehabilitation*, *94*, 488–494. https://doi.org/10.1016/j.apmr.2012.10.004

Resnik, L., Adams, L., Otr, L., Borgia, M., Delikat, J., Otr, L., Disla, R., Ebner, C., Walters, L. S., & Otr, L. (2013). Development and Evaluation of the Activities Measure for Upper Limb Amputees. *Archives of Physical Medicine and Rehabilitation*, *94*(3), 488-494.e4. https://doi.org/10.1016/j.apmr.2012.10.004

Resnik, L., Borgia, M., Cancio, J., Heckman, J., Highsmith, J., Levy, C., Phillips, S., & Webster, J. (2022). Dexterity, activity performance, disability, quality of life, and independence in upper limb Veteran prosthesis users: a normative study. *Disability and Rehabilitation*, *44*(11), 2470–2481. https://doi.org/10.1080/09638288.2020.1829106

Resnik, L., Ekerholm, S., Borgia, M., & Clark, M. A. (2019). A national study of Veterans with major upper limb amputation: Survey methods, participants, and summary findings. *PLoS ONE*, *14*(3), 1–24. https://doi.org/10.1371/journal.pone.0213578

Rietschel, J. C., McDonald, C. G., Goodman, R. N., Miller, M. W., Jones-Lush, L. M., Wittenberg, G. F., & Hatfield, B. D. (2014). Psychophysiological support of increasing attentional reserve during the development of a motor skill. *Biological Psychology*, *103*, 349–356. https://doi.org/10.1016/j.biopsycho.2014.10.008

Rietschel, J. C., Miller, M. W., Gentili, R. J., Goodman, R. N., McDonald, C. G., & Hatfield, B. D. (2012). Cerebral-cortical networking and activation increase as a function of cognitive-motor task difficulty. *Biological Psychology*, *90*(2), 127–133. https://doi.org/10.1016/j.biopsycho.2012.02.022

Salminger, S., Stino, H., Pichler, L. H., Gstoettner, C., Sturma, A., Mayer, J. A., Szivak, M., & Aszmann, O. C. (2022). Current rates of prosthetic usage in upper-limb amputees–have innovations had an impact on device acceptance? *Disability and Rehabilitation*, *44*(14), 3708–3713. https://doi.org/10.1080/09638288.2020.1866684

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological Psychology*. https://doi.org/10.1016/j.biopsycho.2018.01.009

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Wolf, E. J., Dearth, C. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2019). *A Comparison of Mental Workload in Individuals with Transtibial and Transfemoral Lower Limb Loss during Dual-Task Walking under Varying Demand*. 1–13. https://doi.org/10.1017/S1355617719000602

Shim, J., Kim, H., Lee, S., Park, M., & Lee, M. (2011). Comparison of hand power and muscle activation during power grip and pinch grip. *Journal of Physical Therapy Science*, *23*(3), 459–461. https://doi.org/10.1589/jpts.23.459

Shuggi, I. M., Oh, H., Shewokis, P. A., & Gentili, R. J. (2017). Mental workload and motor performance dynamics during practice of reaching movements under various levels of task difficulty. *Neuroscience*. https://doi.org/10.1016/j.neuroscience.2017.07.048

Shuggi, I. M., Oh, H., Wu, H., Ayoub, M. J., Moreno, A., Shaw, E. P., Shewokis, P. A., & Gentili, R. J. (2019). Motor Performance, Mental Workload and Self-Efficacy Dynamics during Learning of Reaching Movements throughout Multiple Practice Sessions. *Neuroscience*, *423*, 232–248. https://doi.org/10.1016/j.neuroscience.2019.07.001

Shuggi, I. M., Shewokis, P. A., Herrmann, J. W., & Gentili, R. J. (2018). Changes in motor performance and mental workload during practice of reaching movements: a team dynamics perspective. *Experimental Brain Research*. https://doi.org/10.1007/s00221-017-5136-8

Soufineyestani, M., Dowling, D., & Khan, A. (2020). Electroencephalography (EEG) technology applications and available devices. *Applied Sciences (Switzerland)*, *10*(21), 1–23. https://doi.org/10.3390/app10217453

Stokes, E. K., & O'Neill, D. (2008). Use of Outcome Measures in Physiotherapy Practice in Ireland from 1998 to 2003 and Comparison to Canadian Trends. *Physiotherapy Canada*, *60*(2), 109–116. https://doi.org/10.3138/physio.60.2.109

Strack, F. (1992). *"Order Effects" in Survey Research: Activation and Information Functions of Preceding Questions BT - Context Effects in Social and Psychological Research* (N. Schwarz & S. Sudman (eds.); pp. 23–34). Springer New York. https://doi.org/10.1007/978-1-4612-2848-6_3

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285. https://doi.org/10.1016/0364-0213(88)90023-7

Sweller, J. (2010). Element interactivity and intrinsic, extraneous, and germane cognitive load. *Educational Psychology Review*, *22*(2), 123–138. https://doi.org/10.1007/s10648-010-9128-5

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive Load Theory*. https://doi.org/10.1007/978-1-4419-8126-4

Takasawa, M., Oku, N., Osaki, Y., Kinoshita, H., Imaizumi, M., Yoshikawa, T., Kimura, Y., Kajimoto, K., Sasagaki, M., Kitagawa, K., Hori, M., & Hatazawa, J. (2003). Cerebral and Cerebellar Activation in Power and Precision Grip Movements: An H215O Positron Emission Tomography Study. *Journal of Cerebral Blood Flow and Metabolism*, *23*(11), 1378–1382.

https://doi.org/10.1097/01.WCB.0000091258.83091.C2

Tan, H., Wade, C., & Brown, P. (2016). Post-movement beta activity in sensorimotor cortex indexes confidence in the estimations from internal models. *Journal of Neuroscience*, *36*(5), 1516–1528. https://doi.org/10.1523/JNEUROSCI.3204-15.2016

Tatti, E., Ferraioli, F., Peter, J., Alalade, T., Nelson, A. B., Ricci, S., Quartarone, A., & Ghilardi, M. F. (2021). Frontal increase of beta modulation during the practice of a motor task is enhanced by visuomotor learning. *Scientific Reports*, *11*(1), 1–14. https://doi.org/10.1038/s41598-021-97004-0

Tazoe, T., & Perez, M. A. (2017). Cortical and reticular contributions to human precision and power grip. *The Journal of Physiology*, *595*(8), 2715–2730. https://doi.org/10.1113/JP273679

Tennent, D. J., Wenke, J. C., Rivera, J. C., & Krueger, C. A. (2014). Characterisation and outcomes of upper extremity amputations §. *Injury*, *45*(6), 965–969. https://doi.org/10.1016/j.injury.2014.02.009

Teodoro, T., Meppelink, A. M., Little, S., Grant, R., Nielsen, G., Macerollo, A., Pareés, I., & Edwards, M. J. (2018). Abnormal beta power is a hallmark of explicit movement control in functional movement disorders. *Neurology*, *90*(3), e247–e243. https://doi.org/10.1212/WNL.0000000000004830

Tombini, M., Zappasodi, F., Zollo, L., Pellegrino, G., Cavallo, G., Tecchio, F., Guglielmelli, E., & Rossini, P. M. (2009). Brain activity preceding a 2D manual catching task. *NeuroImage*, *47*(4), 1735–1746. https://doi.org/10.1016/j.neuroimage.2009.04.046

Trizano-Hermosilla, I., Gálvez-Nieto, J. L., Alvarado, J. M., Saiz, J. L., & Salvo-Garrido, S. (2021). Reliability Estimation in Multidimensional Scales: Comparing the Bias of Six Estimators in Measures With a Bifactor Structure. *Frontiers in Psychology*, *12*(June), 1–7. https://doi.org/10.3389/fpsyg.2021.508287

Uellendahl, J. (2017). Myoelectric versus Body-Powered Upper-Limb Prostheses: A Clinical Perspective. *JPO Journal of Prosthetics and Orthotics*, *29*(4S), P25–P29. https://doi.org/10.1097/jpo.0000000000000151

van der Cruijsen, J., Manoochehri, M., Jonker, Z. D., Andrinopoulou, E. R., Frens, M. A., Ribbers, G. M., Schouten, A. C., & Selles, R. W. (2021). Theta but not beta power is positively associated with better explicit motor task learning. *NeuroImage*, *240*(July), 118373.

https://doi.org/10.1016/j.neuroimage.2021.118373

Van Ede, F., De Lange, F., Jensen, O., & Maris, E. (2011). Orienting attention to an upcoming tactile event involves a spatially and temporally specific modulation of sensorimotor alpha- and beta-band oscillations. *Journal of Neuroscience*, *31*(6), 2016–2024. https://doi.org/10.1523/JNEUROSCI.5630-10.2011

van Ede, F., & Maris, E. (2013). Somatosensory demands modulate muscular beta oscillations, independent of motor demands. *Journal of Neuroscience*, *33*(26), 10849–10857. https://doi.org/10.1523/JNEUROSCI.5629-12.2013

van Ede, F., Winner, T., & Maris, E. (2015). Touch automatically upregulates motor readiness in humans. *Journal of Neurophysiology*, *114*(6), 3121–3130. https://doi.org/10.1152/jn.00504.2015

Van Merriënboer, J. J. G., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. In *Educational Psychology Review* (Vol. 17, Issue 2). https://doi.org/10.1007/s10648-005-3951-0

Wang, S., Hsu, C. J., Trent, L., Ryan, T., Kearns, N. T., Civillico, E. F., & Kontson, K. L. (2018). Evaluation of Performance-Based Outcome Measures for the Upper Limb : A Comprehensive Narrative Review. *PM&R*, *10*(9), 951-962.e3. https://doi.org/10.1016/j.pmrj.2018.02.008

Whelan, R. R. (2007). Neuroimaging of cognitive load in instructional multimedia. *Educational Research Review*, *2*(1), 1–12. https://doi.org/10.1016/j.edurev.2006.11.001

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, *3*(2), 159–177. http://www.ingentaconnect.com/content/tandf/ttie/2002/00000003/00000002/art00005

Wickens, C. D. (2008). Multiple Resources and Mental Workload. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394.

Wickens, C. D. (2015). *the I Ct O R Ia N I S Io N*. *Figure 1*, 1395–1399.

Williams, H. E., Chapman, C. S., Pilarski, P. M., Vette, A. H., & Hebert, J. S. (2019). Gaze and Movement Assessment (GaMA): Inter-site validation of a visuomotor upper limb functional protocol. *PLoS ONE*, *14*(12), 1–20. https://doi.org/10.1371/journal.pone.0219333

Williams, H. E., Chapman, C. S., Pilarski, P. M., Vette, A. H., & Hebert, J. S. (2021). Myoelectric prosthesis users and non-disabled individuals wearing a simulated prosthesis exhibit similar compensatory movement strategies. *Journal of NeuroEngineering and Rehabilitation*, *18*(1), 1–15. https://doi.org/10.1186/s12984-021-00855-x

Williams, T. W. (2011). Progress on stabilizing and controlling powered upper-limb prostheses. *Journal of Rehabilitation Research and Development*, *48*(6), ix–xix. http://www.ncbi.nlm.nih.gov/pubmed/21938646

Wilson, A. W., Blustein, D. H., & Sensinger, J. W. (2017). A third arm - Design of a bypass prosthesis enabling incorporation. *IEEE International Conference on Rehabilitation Robotics*, 1381–1386. https://doi.org/10.1109/ICORR.2017.8009441

Wilson, M. R., Poolton, J. M., Malhotra, N., Ngo, K., Bright, E., & Masters, R. S. W. (2011). Development and validation of a surgical workload measure: The surgery task load index (SURG-TLX). *World Journal of Surgery*, *35*(9), 1961–1969. https://doi.org/10.1007/s00268-011-1141-4

Wolpert, D. M., & Miall, R. C. (1996). Forward Models for Physiological Motor Control. *Neural Networks*, *9*(8), 1265–1279.

Wong, J. D., Cluff, T., & Kuo, A. D. (2021). The energetic basis for smooth human arm movements. *ELife*, *10*, 1–17. https://doi.org/10.7554/eLife.68013

Wong, S. W. H., Chan, R. H. M., & Mak, J. N. (2014). Spectral modulation of frontal EEG during motor skill acquisition: A mobile EEG study. *International Journal of Psychophysiology*, *91*(1), 16–21. https://doi.org/10.1016/j.ijpsycho.2013.09.004

Yu, Z., Guindani, M., Grieco, S. F., Chen, L., Holmes, T. C., & Xu, X. (2022). Beyond t test and ANOVA: applications of mixed-effects models for more rigorous statistical analysis in neuroscience research. *Neuron*, *110*(1), 21–35. https://doi.org/10.1016/j.neuron.2021.10.030

Zaepffel, M., Trachel, R., Kilavik, B. E., & Brochier, T. (2013). Modulations of EEG Beta Power during Planning and Execution of Grasping Movements. *PLoS ONE*, *8*(3).

https://doi.org/10.1371/journal.pone.0060060

Zahabi, M., White, M. M., Zhang, W., Winslow, A. T., Zhang, F., Huang, H., & Kaber, D. B. (2019). Application of Cognitive Task Performance Modeling for Assessing Usability of Transradial Prostheses. *IEEE Transactions on Human-Machine Systems*, *49*(4), 381–387. https://doi.org/10.1109/THMS.2019.2903188

Zhang, J. Y., Liu, S. L., Feng, Q. M., Gao, J. Q., & Zhang, Q. (2017). Correlative Evaluation of Mental and Physical Workload of Laparoscopic Surgeons Based on Surface Electromyography and Eye-tracking Signals. *Scientific Reports*, *7*(1), 1–7. https://doi.org/10.1038/s41598-017-11584-4

Zhang, W., White, M., Zahabi, M., Winslow, A. T., Zhang, F., Huang, H., & Kaber, D. (2017). Cognitive workload in conventional direct control vs. pattern recognition control of an upper-limb prosthesis. *2016 IEEE International Conference on Systems, Man, and Cybernetics, SMC 2016 - Conference Proceedings*, 2335–2340. https://doi.org/10.1109/SMC.2016.7844587

Zheng, B., Cassera, M. A., Martinec, D. V., Spaun, G. O., & Swanström, L. L. (2010). Measuring mental workload during the performance of advanced laparoscopic tasks. *Surgical Endoscopy*, *24*(1), 45–50. https://doi.org/10.1007/s00464-009-0522-3

Zidarov, D., & Poissant, L. (2014). Exploring Factors in the Systematic Use of Outcome Measures: A Multi-Disciplinary Rehabilitation Team Perspective. *Open Journal of Therapy and Rehabilitation*, *02*(02), 86–96. https://doi.org/10.4236/ojtr.2014.22013

Ziegler-Graham, K., MacKenzie, E. J., Ephraim, P. L., Travison, T. G., & Brookmeyer, R. (2008). Estimating the Prevalence of Limb Loss in the United States: 2005 to 2050. *Archives of Physical Medicine and Rehabilitation*, *89*(3), 422–429. https://doi.org/10.1016/j.apmr.2007.11.005