ABSTRACT

Title of Thesis:	EXECUTION OF COMPLEX ACTION SEQUENCES UNDER VARIOUS COGNITIVE DEMAND WITH AND WITHOUT HAND BIOMECHANICS ALTERATIONS
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Many previous studies have investigated the effects of compromised limb biomechanics on cognitive-motor performance. However, many have focused on lower rather than upper extremities while disregarding problem-solving tasks achieved under various demands. Additionally, limited efforts have examined performance and mental workload concurrent to the completion of a complex sequential task utilizing upper extremities and particularly when their biomechanics are altered. However, the examination of cognitive-motor performance when upper limb biomechanics are compromised would inform the relationship between cognitive and sensorimotor control processes. This work aims to examine the effects of altered hand biomechanics on performance and mental workload as individuals solve a sequential task under two cognitive demands. In the current work, participants completed the Tower of Hanoi task under both low and high cognitive demand while the hand effector was biomechanically altered or not. Biomechanics alterations were achieved via a brace, in which degrees of freedom and effector sensorimotor

capabilities were substantially diminished. The sequential task performance was examined via Levenshtein Distance (LD), which assesses the optimality of participant sequencing along with sequence completion time, which was subsequently segmented to measure time during which hand movement is being executed or paused, and the number of disk drops. Mental workload and physical demand were assessed via NASA-TLX survey, while visual analog scale surveys evaluated physical as well as cognitive effort and fatigue. Results revealed that compared to the unbraced condition, brace usage led to an increase of the hand motion time along with an elevation of both perceived mental workload as well as cognitive fatigue and effort without affecting the structure of the sequence (i.e., LD) nor the time during which movement was paused. The same findings were obtained in response to an elevation of cognitive task demands with the only difference being that of a deterioration of sequence structure (i.e., increased LD) and an elevation of the time during which movement was paused were also observed. Furthermore, enhanced cognitive task demand under the brace condition led to an elevation of the number of disk drops and perceived physical demand accompanied by an increase of physical effort and fatigue whereas this was not observed for the unbraced conditions. These findings suggest the alteration of the upper-extremity biomechanics, or an elevation of cognitive-task demand resulted in a decrement of performance along with an elevation of the engagement of cognitive-motor processing resources resulting in a greater mental workload and ultimately leading to a decrease of cognitive-motor efficiency. Further, an increase of cognitive task demand leading to greater errors of fine sensorimotor coordination (disk drops) while maintaining the action sequence structure when individuals performed with compromised but not normal limb biomechanics suggest that individuals may have prioritized the completion of the action sequencing at the expense of the accurate motor execution. In turn, these greater sensorimotor errors would have required further

movement regulation leading to an increase of the perceived physical demand, effort and fatigue. This work provides further insight into the understanding of adaptive human behavior and has the potential to inform rehabilitation of individuals with compromised upper-extremity biomechanics.

EXECUTION OF COMPLEX ACTION SEQUENCES UNDER VARIOUS COGNITIVE DEMAND WITH AND WITHOUT HAND BIOMECHANICS ALTERATIONS

By

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I. Introduction

I.a. Mental Workload and performance in individuals with compromised limb biomechanics

Although various definitions of mental or cognitive workload can be identified, one variation proposed is to define this notion through the relationship between the deployment of available processing resources to face a certain level of task demand (Young et al., 2015; Wicken et al., 2008). While a large body of work has examined the relationship between performance and mental workload, this examination has proved to be limited when expanded to include individuals with compromised limb biomechanics (Park & Zahabi, 2022; Berka et al., 2007; Miller et al., 2001; Gentili et al., 2014; Shuggi et al., 2017; Pruziner et al., 2019; Shaw et al., 2019; Shuggi et al., 2018). Typically, sensorimotor processing is relatively automatic in able bodied individuals, thus requiring little deployment of cognitive-motor resources which can be in turn allocated to task performance when faced with a complex problem (Park & Zahabi, 2022). However, sensorimotor processing in compromised populations requires greater use of such processing resources directed toward motor execution, limiting their allocation to other aspects of performance which become more challenging (Morgan et al., 2018). This has previously been shown in populations with compromised lower limb biomechanics during dual task walking and standing paradigms. As a result, lower limb biomechanics alterations have been shown to conditionally decrease performance in cognitive tasks such as the visual Stroop task, word association test, and serial subtraction tasks (Morgan et al., 2018). However, results become negated as participants gain increased familiarity with lower limb biomechanic alterations during a dual task paradigm (Pruziner et al., 2018). Although several studies have examined the effects of lower-limb biomechanics alterations during dual tasking (Pruziner et al. 2018; Shaw et al., 2019). These

studies revealed that individuals with and without lower limb loss displayed somewhat similar gait mechanics as well as cortical dynamics (Pruziner et al. 2018; Shaw et al., 2019). However, as the altered limb was further compromised, walking mechanics and cortical dynamics underlying mental workload were further affected (Pruziner et al. 2018; Shaw et al., 2019).

While limited, some prior efforts have examined mental workload and performance in individuals with lower limb loss, however such a paucity of work is particularly marked for upper-limb control. Previous literature has investigated cognitive workload during the utilization of different prosthetic devices through a variety of differing measurements, including subjective ratings, physiological markers, and eye-tracking measures (Park & Zahabi, 2022; Bradley, 2018; Gonzalez et al., 2012; Khalid, 2014; O'Meara et al., 2019). In particular, it has been suggested that high mental workload negatively affects performance, thus ultimately decreasing overall usability of prosthetic devices, particularly during dual task paradigms and simple action sequences. Additionally, performance reduction has been previously attributed to poor sensory feedback and reduced cognitive capacity as a result of biomechanic alterations (Park & Zahabi, 2022; Bradley, 2018; Gonzalez et al., 2012; Khalid, 2014; O'Meara et al., 2019). Typically, this literature assessing cognitive workload and performance with upper limb biomechanic alterations have been centered around the completion and execution of motor tasks with a focus on movement, which is mainly driven by lower-order motor planning tasks (Park & Zahabi, 2022; Jang et al., 2011; Krakauer et al., 1999). Lower-order motor planning tasks typically involve singular movement actions and are widely utilized within literature, encompassing motions such as reaching, grabbing, or transporting objects (Morasso, 1981; Sergio & Kalaska, 2003; Krakauer et al., 1999; Zahabi et al., 2019; Jang et al., 2011; Park & Zahabi, 2022**)**. For instance, prior studies have examined the effects of altered hand biomechanics during reaching tasks in which participants were instructed

to perform out and back arm motions, or move a digital cursor to a moving target rotating both clockwise and counterclockwise (Krakauer et al., 1999). These prior works considered a fairly simple motor action with likely little engagement of executive functioning resources and without assessing mental workload (Krakauer et al. 1999). More recently, other efforts have assessed cognitive workload when utilizing a transradial upper-limb prosthesis utilizing a direct control and pattern recognition control electromyography-based control schemes (Zahabi et al., 2019). While the cognitive task employed simulated an activity of daily living, involving clothespin relocation while utilizing differing prosthetic devices, the task did not require the generation of complex action sequences to solve a particular problem. Primary measures assessed with lower-order motor planning tasks have included kinematic analysis of movement utilized to quantify movement efficiency (Krauker et al., 1999). Although informative, this prior body of work focuses on upper-limb prosthesis were often centered around identifying the degree of usability for differing prosthetic devices. Importantly these prior efforts did not investigate mental workload and performance dynamics during the execution of complex action sequences in problem-solving tasks most similar to activities of daily living and which are driven by high-level planning processes.

I.b. High-level planning processes and action sequence generation for problem-solving

The generation of complex action sequences in problem-solving tasks relies heavily on higher-order motor planning processes which are involved in generating action sequences to reach a particular end goal (Weigelt et al., 2009; Shin & Rosenbaum, 2002). As a result, participants employ higher order planning process to execute complex action sequences to solve puzzle tasks such as the well-known Tower of Hanoi (TOH). A few studies employing the TOH have been previously utilized to assess higher order motor planning and mental workload with non-traditional motor mapping (Ceja, 2019; Milla et al., 2019; Hardy et al., 2018; Shaver et al., 2023). For

instance, in a prior fNIRS study in which individuals executed the TOH under a three-dimensional (3D) and two-dimensional (2D) modalities, changes in hemodynamic data within the prefrontal cortex were examined to quantify the prefrontal cortical dynamics underlying mental workload. Oxygenated hemoglobin levels were found to be significantly higher within 3D conditions compared to 2D conditions, likely because of more complex fine sensorimotor processes engaged in the former compared to the latter (Ceja, 2019; Milla et al., 2019). Although this investigation explored the relationship between the cognitive and sensorimotor processes by manipulating task environment and disrupting traditional effector mapping, hand biomechanics were not altered.

A critical neurocognitive component to producing action sequences to complete problem-solving tasks such as the TOH is the executive functioning which includes high-level planning as well as other critical neural functions. Specifically, executive functions are top-down mental processes in which attention, concentration, and cognitive allocation are increased (Diamond, 2013). The TOH task is popular within literature as a complex problem-solving task to assess executive function (Shaver et al., 2023; Humes, 1997; Guevara et al., 2012; Mitani et al., 2022). It was suggested that the three main executive functions were inhibition, working memory, and cognitive flexibility (Diamond, 2013; Lehto et al., 2003; Miyake et al., 2000). Inhibitory control has previously been shown to be essential to complete the TOH puzzle, as counterintuitive moves are needed to complete the task (Zook et al., 2004). Working memory involves the storing and usage of information which is no longer present and plays also a large role in reordering items, and formulating alternative plans of action (Diamond, 2013; Baddeley & Hitch, 1994). Working memory is integral for optimal performance in the TOH task, as spatial memory capacity has been shown to correlate with solution time on the TOH task (Handley et al., 2002). Cognitive flexibility is the ability to alter perspectives from the current reality and requires input from both inhibitory

control and working memory (Diamond, 2013). These main executive functions serve as building blocks for higher-level cognitive functions that are integral to the solution of the TOH, as well as the generation of complex action sequences to solve and decipher complex problems (Diamond, 2013; Hauge et al., 2021).

Importantly, it was suggested that although cognitive processes such as executive functioning would be deployed specifically for both cognitive and motor tasks, they would also, to some extent, be shared by both domains (Leisman et al., 2016; Feolo et al., 2023; Marvel et al., 2019; Gerver et al., 2020; Rushworth et al., 2003). Such a close relationship between high-level (cognitive) and low-level (sensorimotor) mechanisms is supported by previous efforts which suggested that the engagement of each level depends upon the demands related to physical space and the complexity of the motor task (Longo et al., 2022; Stuhr et al., 2018; Anwar et al., 2016; Fine & Hayden, 2021; Funahashi, 2017; Fuster, 2015; Miller & Cohen, 2001). Therefore, the examination of mental workload and performance when individuals solve tasks by generating action sequences when upper limb biomechanics are compromised would allow for further investigations of the relationship between the cognitive and sensorimotor control processes.

While many measures assess the low-level sensorimotor performance (e.g., kinematics), metrics utilized to evaluate the quality of the structure of the sequence generated by individuals and in particular the degree of optimality are more sparse. However, prior studies have proposed to employ the Levenshtein Distance (LD) which is a relatively novel computational approach within the field of cognitive motor performance, to assess complex action sequences performance (Hauge et al., 2021; Ho et al., 2017). The use of LD allows for the comparison of generated action sequences during the TOH task to optimal action sequences used as reference (Hauge et al., 2021; Ho et al., 2017). Thus, LD allows for the assessment of cognitive-motor performance in greater

detail than traditional metrics such as response time and number of moves, by indicating at which points throughout the action sequence moves were added, removed, or switched but also assessing the degree of optimality of the sequence executed (Hauge et al., 2021). Thus, in this work LD will be our primary metric to assess performance when participants execute the TOH task under varying demands.

I.c. Research Aims and Hypothesis

As a result, previous literature has assessed the cognitive-motor performance in individuals with upper (Park & Zahabi, 2022; Jang et al., 2011; Krakauer et al., 1999) and lower (Morgan et al., 2018; Pruziner et al., 2018; Shaw et al., 2019) limb biomechanic alterations often employing during dual task paradigms. However, as far as we know, no study has examined the mental workload and performance dynamics when individuals engage in problem-solving through the generation of complex action sequences under various task demands while upper extremities are biomechanically altered. Moreover, in such a context, these studies implemented a dual task paradigm, however, it would be interesting to examine how cognitive-motor processes underlying mental workload are deployed when facing both sensorimotor and cognitive demand within a single task.

Therefore, this study aims to examine the effects of altered hand biomechanics on performance and mental workload as individuals solve a problem-solving task (TOH) under a low and high cognitive demand. From a theoretical standpoint, compromised biomechanics should result in a misalignment between the internal model of the familiar sensorimotor mapping and that used by the actual effector. As such, not only is the neural drive affected, but the quality of the sensorimotor prediction is also degraded, resulting in a greater use of feedback regulation for

movement control (Wolpert et al., 1998). Therefore, it is hypothesized that such misalignment between the internal model of the hand, and actual effector due to hand biomechanics alterations will result in degraded performance along with enhanced mental workload likely driven by greater engagement of executive functioning resources ultimately leading to attenuated cognitive-motor efficiency. In addition, it was also hypothesized that an elevation of the cognitive task demand will also result in decreased performance along with a greater mental workload, with both modulations being indicative of a reduced cognitive-motor efficiency. If executive resources are relatively distinct between cognitive and sensorimotor levels, it is hypothesized that the effects described above resulting from hand biomechanics alterations and enhanced cognitive task demand will mainly occur in a separate manner, otherwise interactions will be observed.

II. Methods

II.a. Participants

Thirty neurotypical participants between the ages of 18-35 with no known neurological deficits were recruited for this study. Inclusion criteria for this study included having little to no prior knowledge of the task employed in this study and limited experience with sequential puzzles and games along with no prior experience with bracing systems for upper-limb. Exclusion criteria included any history of head trauma within the last year, and any current injuries to either the head or below the shoulder. Finally, participants completed the Montreal Cognitive Assessment (MoCA). The MoCA is among the most commonly utilized tools to detect mild cognitive impairment (MCI). Previous literature has indicated the MoCA exam to detect 90% of MCI participants, including 100% sensitivity (Nasreddine et al., 2005). Participants provided written informed consent approved by the Institutional Review Board at The University of Maryland-

College Park. Participants had little to no prior knowledge of the TOH task, and had no previous experience with the brace used, as determined via questionnaire. Participants were recruited from the University of Maryland and surrounding area.

II.b. TOH Task

The TOH task is a complex puzzle used both clinically and in research as a means to measure executive function. The TOH begins with a platform with three pegs attached vertically, equidistant from each other. Three or four disks were stacked upon one another on one peg, in descending diameter, with the largest disk on the bottom (Figure 1A). There are three main rules in the TOH task: i) each disk must be moved one at a time; ii) a larger disk may not be placed upon a smaller disk; and iii) disks cannot be placed upon the table, or in another hand while another disk is being manipulated (Hauge et al., 2018). The TOH increases in complexity dependent on how many disks are provided at the time. The minimum number of moves required to complete the move of a complete tower from Peg 1 to Peg 3 is $h_n = 2^n - 1$ (Palmer, 1996; Hauge et al., 2018). Other common TOH tasks begin with disks dispersed throughout the three pegs, in which $h_d < h_n$ (Hauge et al., 2018). It must be noted that there is a multitude of ways to manipulate the minimum number of moves including; adding and subtracting disks, manipulating the starting state of the disks, and manipulating the number of pegs in which the tower of disks must be built upon (Hauge, 2018; Palmer, 1996; Egan & Greeno, 1974). The TOH disks utilized ranged from thirty millimeters in diameter for the smallest disk to forty millimeters in diameter, fifty millimeters in diameter, and finally sixty millimeters in diameter for the largest disk. Disks were of non-standard shape, differing from the traditional circular shape. Pilot tests determined that a hexagonal shape of disks allowed for the most homogenous motor difficulty for all disks when tasked with moving disks with the brace. Thus, to control for motor difficulty with the disks themselves, a hexagonal shape

was determined to have the most similar motor difficulty between all disks and thus was used in this study. Disks height was standardized, with a height of ten-millimeters. At the base of each peg, a fixed disk was placed to act as an eight-millimeter buffer to make the artificial brace condition feasible. Additionally, the buffer disk was a separate color from all other disks, as a visual reminder that the disk was fixed and thus not part of the task to solve.

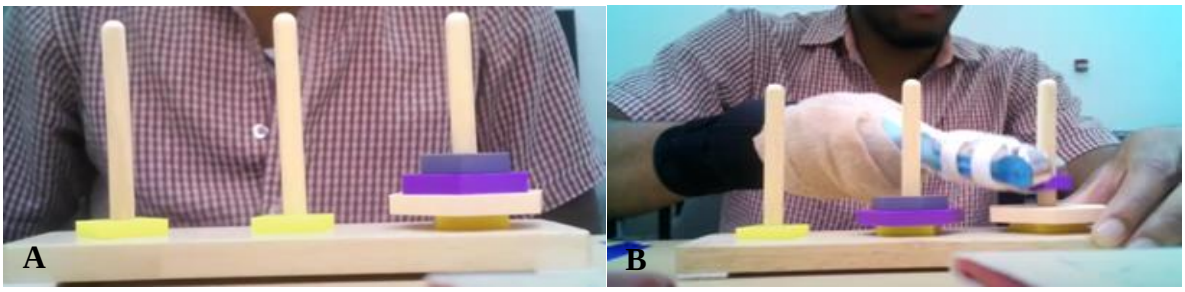


Figure 1: A. An example of the starting condition of the TOH. Participants are tasked with moving the tower one disk at a time, until the tower is rebuilt on the third peg. B. Picture of an individual completing the TOH task while wearing the artificial brace.

II.c. Artificial Brace

An artificial brace was designed to manipulate the controllability of the effector while additionally decreasing sensory information acquired via the index and middle fingers when individuals completed the TOH task. Participants also wore an industrial disposable glove which also contributed to limit sensory information. The artificial brace was constructed with a wrist cock up splint, in an attempt to limit degrees of freedom within the wrist. Finger splints (CVS Health Finger Splint Deluxe Aluminum/Foam) were placed on the index and middle finger of each participant, to limit mobility as well as sensory information. Straps attached to the finger splints were tightened to comfort, however, were still tight enough that the finger splints did not slide off, or begin to tilt with repeated use. Coban wrapping was placed around the remaining fingers, to prevent use of fingers not placed within the brace, and serve as both a visual and physical reminder that fingers not placed within the brace were not allowed to be of use (Figure 1B). Degrees of

freedom were not limited to the degree that finger adduction and abduction was unattainable, however was substantially more difficult.

II.d. Testing Protocol

First, the TOH was introduced to the participants who were instructed to manipulate the TOH environment for two thirty second familiarization trials, one with the artificial brace, and one without. Familiarization order was randomized. Participants were additionally informed that they were allowed to stabilize the TOH platform with their off hand, but must use their primary hand when moving the disks. During the familiarization phase, participants were encouraged to ask as many questions as they wished about the task environment. Additionally, participants were not directed on any method of using the artificial brace. TOH rules were not explained to the participants, and task goals were not given for the familiarization phase, participants were only instructed to move the disks in any direction or orientation they wished. Following the familiarization phase, a prompt was read to participants explaining the three main rules of the TOH task. Participants were allowed to ask questions to gain clarity on the task at hand. Then, participants were to complete the TOH task tasked by moving the tower of disks from Peg 1 to Peg 3 in as few moves as possible and as fast as possible under a low (3 disks) and high (4D) cognitive demand with and without the brace. Thus, after a verbally delivered "Go" signal, participants begin one of four experimental conditions, three disc no brace (3NB), three disk braced (3B), four disk no brace (4NB), and four disk braced (4B). Trial order was counterbalanced for each participant. Each experimental condition was completed five times, forming a grand total of twenty trials for the entire experiment. To prevent fatigue, participants were allowed to take breaks at any point between trials if they deem it necessary. A digital camera was used to record participant action sequences for subsequent analysis. Each trial had a time limit of 240 seconds.

Participants were corrected if any of the three major TOH rules were broken. If a rule was broken and the disk was placed, a rule break penalty was recorded. If participants dropped a disk onto the table, they were instructed to pick up the disk in any way they could with their dominant hand, and continue the trial. If participants accidentally moved two disks at once, they were instructed to return one disk to the previous peg, and subsequently continue to solve the task. If a participant dropped the disk onto the stabilizing hand, the hand effectively serves as the "desk" in the way that participants can continue the trial and pick up the disk. However, the participant was not to move the stabilizing hand until the disk is placed on a peg, to avoid any unfair advantages it may give. If participants dropped a disk onto the floor, they were instructed not to pick up the disk, and the trial was immediately terminated. The researcher then picked up the disk, and had the participant restart the same trial. At the end of each trial with the artificial brace, participants were then given an opportunity to have the researcher adjust the brace if it felt too tight or loose. After each block of five trials, NASA-TLX and VAS surveys were administered. Participants totally completed twenty trials of experimental conditions and answered four NASA-TLX, and four groups of VAS surveys.

II.e. Cognitive-Motor Performance Measurement

First, performance data was measured by computing the LD which assesses the distance between two sequences, and the number of alterations needed for one sequence to completely match the other (Hauge, 2021). The optimal action sequence was determined by the action sequence which requires the minimum number of moves to complete the TOH task which was of 7 and 15 moves for the low and high cognitive demand, respectively. Participant action sequence was derived via video recorder during the time of task. LD was then derived by comparing the optimal action sequence to that which was generated from the participant, with higher LD values

indicating that the participant was farther away from the optimal action sequence, and zero indicating that the participant achieved optimality. Additionally, G-SCT, C-SCT, and M-SCT were derived via video recording. M-SCT was derived by subtracting the time that participants were actively moving disks from the G-SCT, resulting in C-SCT, in which participant decision making may occur. The NASA-TLX was administered at the end of each block of trials. Previous literature has examined and observed excellent reliability of the NASA-TLX when determining cognitive workload (Devos et al., 2020; Hart & Staveland, 1988). Previous literature has also shown support for the validity of the NASA-TLX (Hoonakker et al., 2011). NASA-TLX surveys are a six-question survey to assess mental demand (MD), physical demand (PD), temporal demand (TD), performance (PER), frustration (FR), and effort (EF). The NASA-TLX consists of twenty-one tick marks for each question, each worth a score of five. Thus, a score from 0-100 is derived for each question. If a participant indicated between tick marks, scores were rounded down to the closest marking. Perceived mental workload of the task was derived specifically from the MD dimension, as mental workload appears to be most related to this dimension (Akizuki et al., 2015; Shuggi et al., 2017, 2018; Shaw et al., 2019). PD was also determined via NASA-TLX questionnaire. In addition to the NASA-TLX, participants completed four VAS surveys in which participants were asked to give their subjective ratings on their physical effort (VAS-PE), cognitive effort (VAS-CE), physical fatigue (VAS-PF), and cognitive fatigue (VAS-CF). Participants were asked to draw a vertical line across a ten-centimeter horizontal line, with each end of the spectrum indicating that participants had subjective ratings that were “Extremely low”, or “Extremely high”, respectively. VAS scores were determined by how many millimeters the participants vertical line crossed the horizontal line from the “Extremely low” side. To assess VAS-PE, participants were asked the following question; “The *physical effort* to complete this task was”. VAS-CE was assessed via the

question, “The *cognitive effort* to complete this task was”. For VAS-PF and VAS-CF metrics, participants were asked the following questions; “How *physically* fatigued do you feel after the last trial?” and, “How *mentally* fatigued do you feel after the last trial?” Each VAS scale was given independently, as to prevent participants from being able to see any of their previous scores. Visual Analog Scales have been shown to demonstrate good reliability and were administered with the NASA-TLX at the conclusion of each experimental condition (Boonstra et al., 2008; Begum & Hossain, 2019; Folstein & Luria, 1973). Whenever the normality was violated, the data were log-transformed to approximate a normal distribution before statistical analysis.

II.f. Statistical Analysis

The effects of the brace and cognitive task demand were examined using a 2 HAND [No brace, Brace] x 2 COGNITIVE DEMAND [Low, High] repeated measures ANOVA. When needed, post-hoc analyses were executed via Tukey’s HSD test. The p-values were reported using the corrected degrees of freedom. Partial eta squared (η_p^2) and Cohen’s d effect sizes were reported when necessary. All criterion alpha levels were set to $p < 0.050$. An a priori power analysis indicated that a minimum number of 20 participants was needed in this study to detect a slightly above moderate effect ($f = 0.27$) with a power of 0.80 and a significance threshold of 0.05 (Cohen, 1988).

III. Results

III.a.Performance Metrics

The statistical analysis revealed brace did not significantly affect the LD ($p = .924$) (Figure 2A). As expected, a main COGNITIVE DEMAND effect for the LD was detected such as it

increased as the cognitive task demand became elevated for both brace condition ($F(1,28) = 87.812$, $p = .001$, $\eta_P^2 = .758$) (Figure 2A). A main effect of COGNITIVE DEMAND for C-SCT was identified such that this metric was greater for the high relative to the low cognitive task demand irrespective of bracing condition ($F(1,28) = 17\ 7.467$, $p = .001$, $\eta_P^2 = .864$) (Figure 2B). For M-SCT a main effect of HAND ($F(1,28) = 310.322$, $p = .001$, $\eta_P^2 = .917$) was observed such that M-SCT was greater for the brace compared to the no brace condition (Figure 2C). Also, independently of bracing condition, a main COGNITIVE DEMAND effect was identified such that M-SCT became elevated as cognitive difficulty increased ($F(1,28) = 240.520$, $p = .001$, $\eta_P^2 = .896$) (Figure 2C). A main effect for HAND ($F(1,28) = 141.295$, $p = .001$, $\eta_P^2 = .835$) and of COGNITIVE DEMAND ($F(1,28) = 69.277$, $p = .001$, $\eta_P^2 = .712$) were identified. However, these effects were superseded by a HAND x COGNITIVE DEMAND interaction effect ($F(1,28) = 36.680$, $p = .001$, $\eta P2 = .567$) (Figure 2D). Post-hoc analysis revealed that the number of drops increased from the low to high cognitive demand under the brace conditions ($p < 0.001$; $d = 1.117$) whereas this was not observed in absence of brace ($p < 0.224$). In addition, the number of drops were greater for the braced compared to the unbraced condition for both the low ($p < 0.001$; $d = 1.630$) and high ($p < 0.001$; $d = 1.632$) cognitive demand.

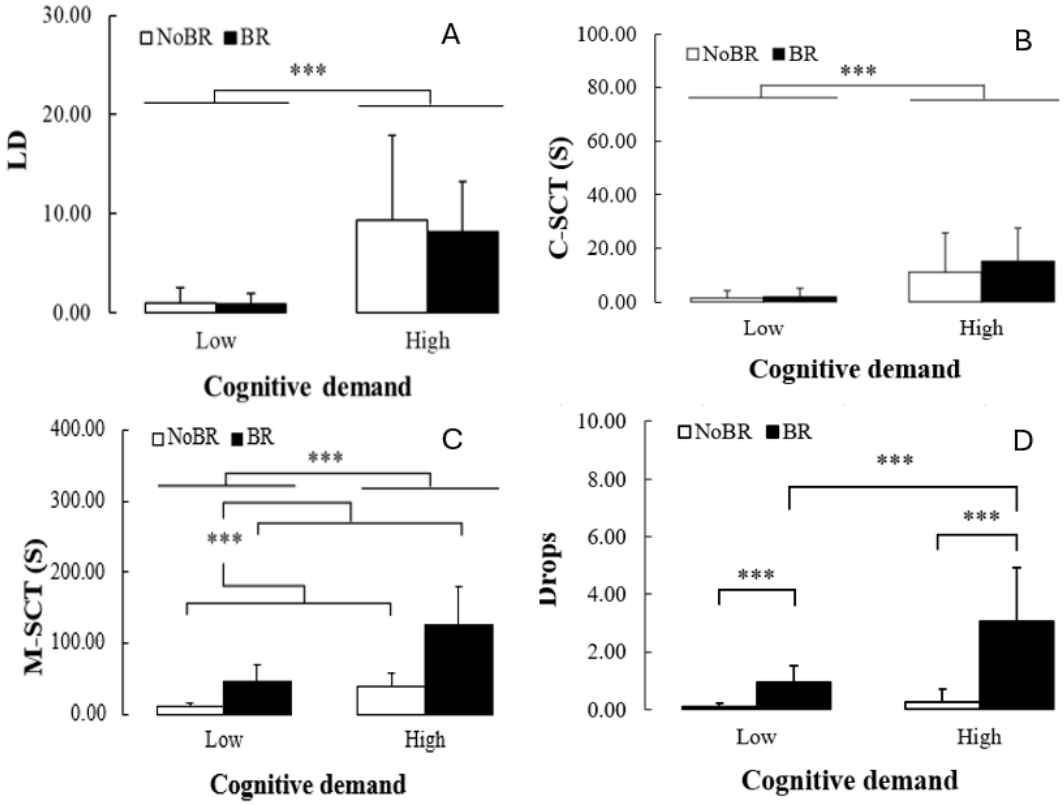


Figure 2. Performance measured by the LD (top left panel, 2A), C-SCT (top right panel 2B), M-SCT (bottom right panel 2C), and Drops (bottom left panel 2D) during the execution of the ToH under a low and high cognitive demand with (black bars) and without (white bars) brace. ***: $p<0.05$.

III.b. Perceived mental and physical demand

A main effect of HAND ($F(1,28) = 28.788$, $p = .001$, $\eta_P^2 = .507$) and of COGNITVE DEMAND ($F(1,28) = 39.244$, $p = .001$, $\eta_P^2 = .584$) was observed for MD such that this score was larger for the brace vs. no-brace condition and as cognitive demand increased (Figure 3A). Additionally, a main effect of HAND ($F(1,29) = 118.427$, $p = .001$, $\eta_P^2 = .803$) and of COGNITVE DEMAND ($F(1,29) = 14.102$, $p = .001$, $\eta_P^2 = .327$) was detected for PD. However, these were superseded by a significant HAND x COGNITVE DEMAND interaction effect ($F(1,28) = 7.232$, $p = .012$, $\eta_P^2 = .200$) (Figure 3B). Post-hoc analysis revealed that PD increased from the low to high cognitive demand under the brace conditions ($p < 0.001$; $d = 2.326$) whereas this was not observed in absence of brace ($p < 0.675$). In addition, the PD were greater for the braced compared

to the unbraced condition for both the low ($p < 0.001$; $d = 1.458$) and high ($p < 0.001$; $d = 2.326$) cognitive demand.

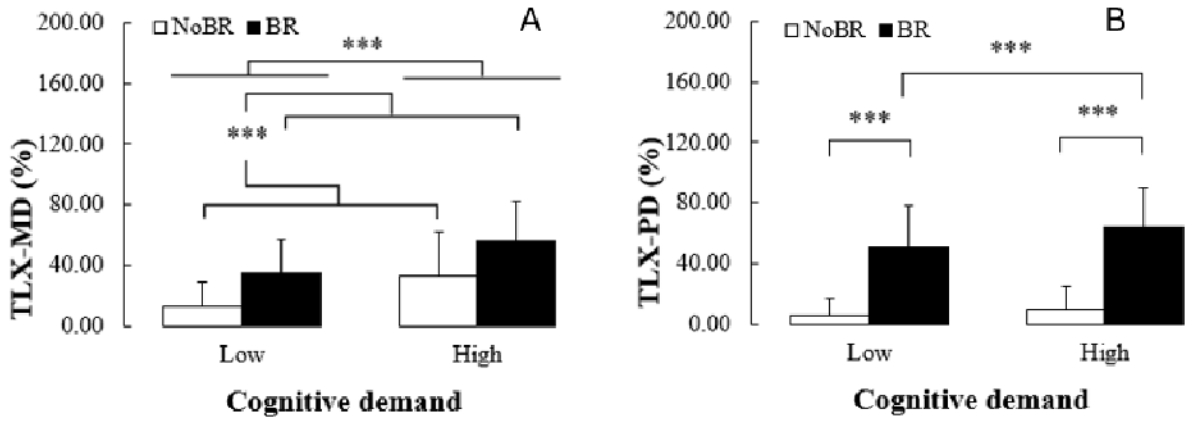


Figure 3. Participant subjective ratings measured by TLX-MD (top left panel, 3A) and TLX-PD (top right panel, 3B) during the execution of the ToH under a low and high cognitive demand with (black bars) and without (white bars) brace. ***: $p<0.05$.

III.c. Perceived mental and physical effort and fatigue

A main effect of VAS-CE was detected ($F(1,28) = 19.429$, $p = 0.001$, $\eta_P^2 = .410$) such that it was greater for the brace relative to the no-brace condition (Figure 4a). Additionally, A main COGNITIVE DEMAND effect was detected ($F(1,28) = 55.401$, $p = .001$, $\eta_P^2 = .664$) for VAS-CE such that independently of brace condition, it increased the perceived cognitive effort from the low to high cognitive task demand (Figure 4A). For the VAS-PE, a main effect of HAND ($F(1,28) = 127.992$, $p = .001$, $\eta_P^2 = .821$) and of COGNITVE DEMAND ($F(1,28) = 22.315$, $p = .001$, $\eta_P^2 = .444$) were identified. However, these were superseded by a HAND x COGNITVE DEMAND interaction ($F(1,28) = 8.864$, $p = .006$, $\eta_P^2 = .240$). Post-hoc analysis revealed that the VAS-PE increased from the low to high cognitive demand under the brace conditions ($p < 0.001$; $d = 2.471$) whereas this was not observed in absence of brace ($p < 0.434$). In addition, the VAS-PE were

greater for the braced compared to the unbraced condition for both the low ($p < 0.001$; $d = 1.466$) and high ($p < 0.001$; $d = 2.12$) cognitive demand.

A main HAND effect ($F(1,26) = 37.282$, $p = .001$, $\eta_P^2 = .589$) was detected for the VAS-CF such that it was larger for the brace vs. no brace condition regardless of cognitive demand (Figure 4b). A main COGNITIVE DEMAND effect was also identified for VAS-CF such that it became elevated as cognitive condition increased independently of bracing condition ($F(1,26) = 23.682$, $p = .001$, $\eta_P^2 = .477$) (Figure 4C).

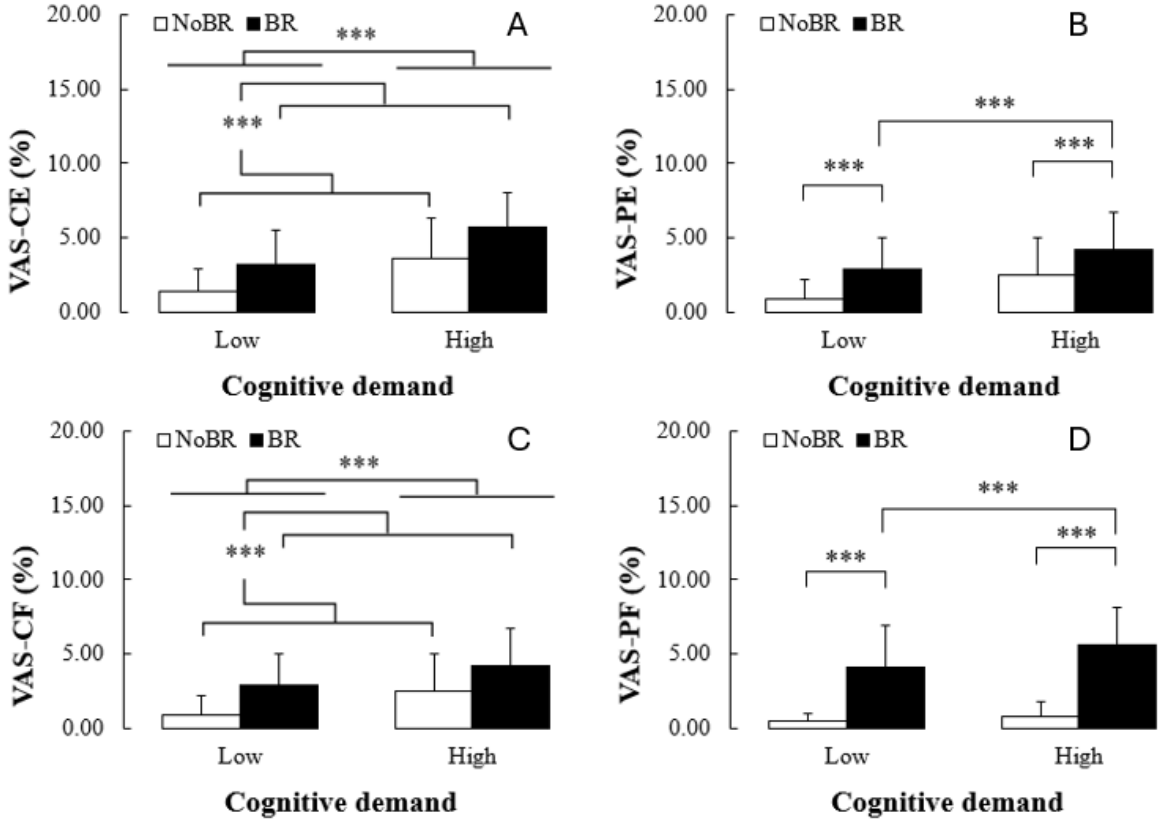


Figure 4. Visual analog scales measured by VAS-CE (top left panel, 4A), VAS-PE (top right panel, 4B), VAS-CF (bottom left panel, 4C) as well as VAS-PF (bottom right panel, 4D) during the execution of the ToH under a low and high cognitive demand with (black bars) and without (white bars) brace. ***: $p<0.05$.

For VAS-PF, a main effect of HAND ($F(1,27) = 78.466$, $p = .001$, $\eta_P^2 = .744$) and of COGNITIVE DEMAND ($F(1,27) = 17.875$, $p = .001$, $\eta_P^2 = .398$) were observed. However, these

main effects were superseded by a significant HAND x COGNITIVE DEMAND interaction effect ($F(1,27) = 6.773$, $p = .015$, $\eta_p^2 = .201$) (Figure 4D). Post-hoc analysis revealed that the VAS-PF increased from the low to high cognitive demand under the brace conditions ($p < 0.001$; $d = 1.924$) whereas this was not observed in absence of brace ($p < 0.776$). In addition, the VAS-PF were greater for the braced compared to the unbraced condition for both the low ($p < 0.001$; $d = .977$) and high ($p < 0.001$; $d = 2.245$) cognitive demand.

IV. Discussion

IV.a. Effect of the altered biomechanics on cognitive-motor performance

Overall, the results revealed that when the hand biomechanics were compromised the motor time (M-SCT) to complete the sequence increased along with an elevation of mental workload, cognitive effort and fatigue although the sequence structure (LD) and the time for cognitive processing during task execution (C-SCT) remained unchanged. As expected, an elevation of the motor time when hand biomechanics were compromised was likely due to the need for further movement regulation using feedback control to manipulate the disk (e.g., disk grasping from the peg and/or the table itself when dropped). Interestingly, no change in sequence structure and time for decision and replanning while completing the task were observed. In other words, while the participants increased their time for motor control, they did not utilize any extra time when preparing for the next action while completing the sequence producing a similar sequence structure regardless of if hand biomechanics were compromised or not. These performance characteristics were also accompanied by an elevation of the perceived mental workload (Akizuki et al., 2015; Shaw et al., 2019; Pruziner et al., 2019). A possible explanation would be when hand biomechanics

are altered, this creates a misalignment between the internal model embedding the hand sensorimotor mapping and the actual effector resulting in a greater movement regulation for fine motor control leading to further engagement of executive processing resources to displace the disks appropriately (Corti et al., 2017; Becker et al., 2014; Kirby et al., 2008; Gonzalez et al., 2014; Casadio et al., 2012; Mussa-Ivaldi et al., 2013; Gentili et al., 2011, 2013, 2015). This possible mechanism is also supported by an increase in the perceived cognitive effort and fatigue when upper-extremity biomechanics are altered compared to the conditions where individuals used their normal hand. Therefore, compared to the normal condition, the altered biomechanics would have resulted in a decrease of motor performance while maintaining the same level of sequence structure along with a greater recruitment of neural processes ultimately resulting in an attenuation of cognitive-motor efficiency and enhanced cognitive fatigue (Lorist et al., 2002, 2000; Smith et al., 2019; Shin et al., 2019). This is consistent with the notion that a prolonged decrease in neural efficiency has been linked to increased fatigue ratings within past literature (Kok, 2022; Nelson et al., 2020; Qi, 2019**)**.

IV.b. Effect of the cognitive task demand on cognitive-motor performance

Enhanced cognitive task demand resulted in a decrement of the quality of the sequence structure (i.e., greater LD) and an elevation of the motor (M-SCT) and cognitive (C-SCT) time to complete the task along with an elevation of mental workload, cognitive effort and fatigue. As the cognitive task demands increased, sequence structure was further degraded as it became less optimal. This was accompanied by an elevation of the motor and cognitive time, which can be attributed to the increased number of moves needed to complete longer, more complex sequences, as well as the need for greater pauses for decision-making and re-planning to execute the sequence, respectively. It must be noted that it could be argued that a possible contributing factor to the increase of M-

SCT may be attributed to the increased difficulty of disk grasping with the brace due to the dimensions of the extra small disk added on the top of the tower in the high cognitive demand condition, however pilot testing revealed that our customized tower did not lead to such a degradation of performance. These results are in agreement with those from prior TOH studies which revealed that performance decreased as the TOH difficulty increased (Humes et al., 1997; Welsh and Huizinga, 2001, 2005). Additionally, these changes of performance were accompanied by a greater mental workload reflecting enhanced recruitment of cognitive-motor processes (e.g., inhibitory control, attention, working memory) to complete the TOH task when cognitive demand increased (Kok, 2022; Nelson et al., 2020; Qi, 2019; Adams, 2003; Zook et al., 2004; Handley et al., 2002; Diamond, 2013; Hauge et al., 2021**)**. This elevation of mental workload as the cognitive task demand increased is also consistent with the elevation of the self-reported elevation of cognitive effort and fatigue. These findings agree with those from previous TOH investigation which revealed that greater mental workload was deployed when individuals completed the TOH task under a higher level of challenge (Hardy et al., 2018; Milla et al., 2019; Shaver et al., 2023). Altogether, these findings suggest that as cognitive task demand increases, a greater neural resource recruitment would occur to attempt to maintain or limit performance degradation leading thus to an attenuation of cognitive-motor efficiency ultimately leading to enhanced cognitive effort and fatigue. This is consistent with the idea that as neural resources are recruited for longer periods of time, this metabolically expensive process has been linked to self-reported levels of fatigue (Kok, 2022; Nelson et al., 2020; Qi, 2019**)**.

IV.c. Relationship between the cognitive and sensorimotor processes

Another finding from this study was that the number of disk drops, the perceived physical demand, physical effort and fatigue significantly increased from the low to high cognitive task demand when hand biomechanics were compromised whereas this was not observed when the effector was unaltered. In addition, the biomechanic alteration led to a greater number of disk drops, a higher perceived physical demand, physical effort, and fatigue relative to the normal hand under both levels of cognitive demand. These results could be explained by several potential mechanisms. A first possibility could be that the greater cognitive task demand condition added an additional disk to the top of the tower which would have driven the changes in number of disk drops. However, as mentioned before, the sole manipulation of the three or four customized disks (i.e., without solving the TOH puzzle) used here were tested in a pilot study and did not change task performance nor mental workload. Another potential mechanism would be that an elevation of cognitive task demand resulted in the need to execute longer, more complex sequences involving a larger number of actions. Mechanically, a larger number of actions would have resulted in a greater likelihood of dropping the disks when displacing them with altered hand biomechanics compared to when the hand is unaltered. To test this possibility, the number of disk drops per action was computed for the low and high cognitive demand with and without brace. The same ANOVA model as previously used for the other metrics of this study was applied. The findings indicated only a main HAND effect such that the number of drops per action was greater when the upper-limb biomechanics were compromised relative to the condition where the effector was fully functional ($F(1,29) = 95.492$, $p < 0.001$, $\eta_P^2 = .767$). Thus, it appears that a greater number of actions under the high cognitive demand would have driven the increase of the disk drops. In turn, this would have resulted in a greater amount of motion and feedback control to pick them up again

leading to higher perceived physical demand, effort and fatigue. However, another potential additional mechanism related to the notion that, to some degree, executive functions are shared between high level cognitive processing and low-level sensorimotor control may also be considered (Feola et al., 2023; Gerver et al., 2020; Rushworth et al., 2003). As discussed earlier, an elevation of cognitive demand would require an increase of the recruitment of executive control resources to solve the puzzle task (Hardy et al., 2018; Ceja, 2019; Milla et al., 2019; Shaver et al., 2022). When individuals performed the task under enhanced cognitive demand with their fully functional effector, only a limited recruitment of executive functioning would be needed since the hand internal model is an accurate representation of the actual effector. However, when the hand is biomechanically compromised, the misalignment of the internal model of the hand sensorimotor mapping with the actual effector would require further engagement of the executive control. In such a context, it is likely that in this condition, resources needed to maintain cognitive and motor performance were in competition within the same resource pool (Pashler, 1994; Kahneman, 1973; Wickens 1980; Musslick & Cohen, 2021; Basil, 2012; Wickens, 1980). Thus, executive functions would, to some extent, be shared to implement fine digit motor control and more cognitive tasks such as here complete an action sequence. Keeping this in mind, it is conceivable that, when biomechanics are altered, some of the shared executive resources will have to be allocated either to complete the sequence or to sensorimotor control. Since compared to normal hand functions, altered hand biomechanics led to a severe degradation of fine sensorimotor control whereas the quality of the sequence structure was maintained, these results may suggest that individuals may have prioritized allocation of executive control to preserve the sequence structure (LD, C-SCT) at the expense of sensorimotor control.

IV.d. Applications

Applications for this line of research are interdisciplinary in nature. Compromised biomechanics systems are typically the result of disease or traumatic injury (Adams, 2020; Park & Zahabi, 2022). Further understanding of the effect of biomechanics alterations on cognitive-motor performance and mental workload, as well as the degree in which executive functions are shared allow for development within the field of not only prosthetics and acute adaptation, but also within the fields of neurorobotics. Currently within the field of neurorobotics, the sensorimotor and cognitive control systems are separated in a very hierarchical manner. Developments within this line of research will better aid the development of robotic systems which can be optimized to mimic human behavior. Current limitations within human-robot dyadic training include the unlimited capability of robotic systems to instantaneously learn action sequences or movement patterns. Thus, a better understanding of how the high- and low-level cognitive-motor systems interact will allow for a better mimicry of adaptive human learning and performance.

V. Conclusion, Limitations and Future Works

These findings suggest that the alteration of upper-extremity biomechanics, or subsequent elevation of cognitive-task demand results in a decrement of performance accompanied with greater mental workload and decreased cognitive-motor efficiency which is consistent with previous relevant literature (Park & Zahabi, 2022; Berka et al., 2007; Miller et al., 2001; Gentili et al., 2014; Pruziner et al., 2018; Shaw et al, 2019; Shuggi et al., 2017; Shuggi et al., 2018). The maintenance of sequence structure accompanied by a degradation of the sensorimotor performance when participants performed the task with altered biomechanics which was particularly pronounced under an elevated cognitive demand may indicate participants prioritized the executive

resource allocation to maintain cognitive task performance at the expense of the sensorimotor control. Accompanying degraded motor performance, further movement regulation likely led to increased perception of physical demand, effort, and fatigue.

However, it is possible that executive function task switching between cognitive and motor functions occurred. If task-switching did indeed occur, it is likely that motor performance would have stagnated, allowing for C-SCT to have possibly increased, as C-SCT can serve as a refocusing, or transitory state during task switching. It is possible that task switching occurred at a speed in which observable effects were not noticeable. As a result, additional studies are required for definitive analysis regarding potential task switching.

While informative, this study had several limitations. First, this work did not include electroencephalography (EEG) nor inertial movement sensors (IMUs). The inclusion of EEG would allow for the analysis of regional and inter-regional cortical dynamics during task execution, allowing for a more detailed understanding of allocation of the neurocognitive processes under different experimental conditions. The inclusion of IMUs will allow for the analysis of kinematic measures including velocity, acceleration, and jerk to inform motion control regulation. The combination of additional measures derived from EEG and IMUs would allow for a more comprehensive analysis of participant performance. Future work should also place a greater emphasis on the analysis of C-SCT states, with potential triggers initiating at the grasping of a disk, and concluding at the placement of said disk. This would allow not only for a more precise measurement of C-SCT, but would allow for definitive analysis of cortical dynamics. Second, the current work included healthy population demographics without any clinical population such as actual upper-extremity amputee. Thus, the natural progression of this research line should include participants with upper-extremity loss, and allow for the inclusion of a multitude of prosthetic

devices while considering activities of daily living which present more complex configurations that the TOH used here (e.g., multiple optimal sequences can be considered here), thus also requiring the extension of LD analysis employed in this work.

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