ABSTRACT

Title of thesis: A SYSTEMATIC APPROXIMATION TO THE NEURAL MOTOR CONTROL OF FORWARD, BACKWARD AND LATERAL TOE-TAPPING IN CHILDREN AND ADULTS

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The neural motor control of forward, backward and lateral toe-tapping of typically developing adults, 6- and 10-year-old children was investigated using the uncontrolled manifold technique. Our results indicate that the central nervous system (CNS) controls or stabilizes three functional variables (center of mass, toe and head position) by organizing the overall joint variability structure, more than the individual joints. Results reveal: (1) children control forward and backward stepping more than adults, and (2) adults' forward stepping is more controlled than backward or lateral stepping. The relative ranking defining the approximate neural motor control of toe-tapping is: center of mass, toe and head position; indicating the CNS focuses on balance and foot placement. The observed invariance of this structure across movement phase, tap direction, and age, reinforces the idea that the CNS controls multi-directional toe-tap motion using similar neural control strategy.

A SYSTEMATIC APPROXIMATION TO THE NEURAL MOTOR CONTROL OF FORWARD, BACKWARD AND LATERAL TOE-TAPPING IN CHILDREN AND ADULTS

by

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Dedication

To my father, best friend and beloved wife - Tonney, and my unborn child - Ayaat.

Thank you for supporting me, I love you all.

Acknowledgments

This study is an effort undertaken by me under the sublime guidance of the Almighty – Allah. My profound and hearty gratitude goes to Dr. Jane E. Clark, who has been my academic supervisor. She has been affectionate and maternalistic towards me during my entire academic adventure at the University of Maryland, College Park. She has provided me with invaluable and related informations; her expert ideas, suggestions and advices have guided me to the successful completion of this thesis. Without her painstaking tuition, kind patronization, sincere coaching and continuous consultation, I would not have been able to complete the task.

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Mohammad Ehsanul Karim (Ehsan)

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List of Abbreviations

CNS	Central Nervous System
COP	Center of Pressure
COM	Center of Mass
BW	Backward Walking
FW	Forward Walking
UCM	Uncontrolled Manifold
DOF	Degrees of Freedom

Chapter 1: INTRODUCTION

This chapter lays out the motivations of the research by asking the question, How does the central nervous system (CNS) control mobility as a neuro-musculo-skeletal system? Specifically, the problem statement is localized to the study of forward, backward and lateral toe-tapping, and highlights the necessity for understanding the neural motor control structure as a function of tapping direction and age. The chapter concludes by, broadly, outlining the structure of the thesis.

Neural motor control, in the context of this thesis, refers to the question: Does the CNS control individual joints or does it control task-related performance parameters? We call these parameters task or control variables. Intuitively, it is logical to assume that the CNS controls a multitude of different parameters during any movement; however, it is impossible to evaluate all these parameters. Thus, in this thesis we test only a subset of the parameters to see if they are being controlled or not; leading us to the idea of an approximation. Finally, we seek to relatively rank these variables according to their contribution to the motor task, thus systematically approximating the neural motor control of multi-directional toe-tapping task.

1.1 MOTIVATION

Tapping a fixed body-spatial position (anterior-posterior or medial-lateral) with the toe requires asymmetrical motor skills. The entire body weight is placed on the stance leg, while the other leg simultaneously swings toward the target in the specific direction. Thus, while tapping is similar to stepping, it is unique because there is no transfer of body weight onto the tapping leg. Toe-tapping or directional toe-tapping, however, has rarely been studied. Therefore to have a better understanding of this task, we used the locomotion literature as a guide – noting always the critical differences as well as the similarities.

Locomotion, i.e., walking and running, is the most fundamental of human movements. It requires frequent adaptations depending on the environmental conditions and various behavioral goals, e.g., backward walking, running, or jogging. However, from the perspective of movement neuroscience the underlying neural motor control structure of locomotion is not well understood. For generations, locomotion has been analyzed through the nonlinear inverted pendulum model (Dickinson et al., 2000; Full & Koditschek, 1999; Kuo, 2007; Winter, 1995). This mechanistic model, however, does not answer the fundamental question, how is locomotion controlled by the CNS as a neuro-musculo-skeletal system (Dickinson et al., 2000; Full & Koditschek, 1999)? Or, locally thinking, what is the approximate neural motor control structure in the joint space?

Stepping forward is an important part of locomotion. During this phase the center of mass (COM) of the body moves outside the base of support; which drastically alters the criteria of balance and increases the possibility of falling. This is primarily because of the inverted pendulum like weight distribution within the human body: two-thirds of the total body weight is centered in the upper body (head-arm-trunk) (Woollacott & Tang, 1997). The generated potential energy is converted into kinetic energy during the stepping phase. While this conversion can assist us in walking or running, it can also be the reason for falling due to the creation of a destabilizing moment because of the inverted pendulum-like upper body structure (Woollacott & Tang, 1997). David Winter and other researchers have studied the kinetics, kinematics and electromyography (EMG) to explain the biomechanical dynamics of falling and have also explored the internal fall prevention mechanism during the forward stride. These studies describe the contributions of the hip, knee and ankle kinetics in stabilizing the COM and the center of pressure (COP) (Winter, 1995; Woollacott & Tang, 1997).

Backward walking (BW) is a fundamental capability of human locomotion, although little information on BW is available when compared to the volume of information available on forward walking (FW) (Lee, Kim, Son, & Kim, 2013; van Deursen, Flynn, McCrory, & Morag, 1998). Recent studies have suggested that the kinematics of FW and BW are time-reversed; however, some joints do not generate propulsion power as they would in FW (Lee et al., 2013). Moreover, other studies highlighted that gait variability increases with BW; and this increase in variability is correlated with destabilized balance (Freitas & Duarte, 2012; Hackney & Earhart, 2009; Hausdorff et al., 1997). Despite such dissimilarities, it is believed that FW and BW share common elements within the neural circuitry (van Deursen et al., 1998) based on kinematic and electromyographic evidence (Earhart et al., 2001; Lamb & Yang, 2000; van Deursen et al., 1998; Yang, Stephens, & Vishram, 1998).

Lateral walking and stepping have not been extensively studied; however there are some studies conducted with infants. It was found that, if supported, infants (aged 2-11 months) can walk in all directions (forward, backward, and sideways), at different speeds. In all the conditions, the walking pattern defined by (1) limb motion: stance and swing phase duration, and cycle duration; and (2) electromyographic patterns had no significant differences; indicating single neural control mechanism for multi-directional stepping (Lamb & Yang, 2000; Yang et al., 1998).

Control of posture or balance involves the integration of multiple sensory systems: visual, vestibular and proprioception. Therefore the position of the trunk, head-neck, COM, and the foot plays a vital part in balancing. A study involving the steering of locomotion showed the control of the body's COM in the direction of travel is initiated first through appropriate foot placement, i.e., toe position control, and later through the trunk roll motion (Patla, Adkin, & Ballard, 1999); while visual information based compensation was embedded in the head movements (Hirasaki, Moore, Raphan, & Cohen, 1999). Moreover, kinetic and kinematic studies comparing the displacement of the COM among children and adults during walking revealed that improvement in locomotion is achieved gradually through the development of neural control process (Cavagna, Franzetti, & Fuchimoto, 1983; Dierick, Lefebvre, van den Hecke, & Detrembleur, 2004; Hausdorff, Zemany, Peng, & Goldberger, 1999; Preis, Klemms, & Müller, 1997); and evolves until the age of 7 (Dierick et al., 2004).

Most of the studies discussed so far have highlighted the kinematics or kinetics of individual controlled parameters, such as COM and COP, involved in the stepping phase of multi-directional locomotion. However to our knowledge there is no evidence of toe-tapping study in the literature.

Kinematically, stepping and toe tapping are quite similar; they both have a single leg stance, followed by a leg swing and toe touch-down. However, their kinetics are quite different because during the reaching out tapping phase the weight is not transferred onto the tapping leg, as it does during stepping. During the swing phase of both these movements, the COM tends to move out of the base of support thus balancing in both is a challenge. This is a major problem in forward and backward movement, as opposed to the lateral one. Because in the former, the COM tends to move out of the base of support, while the base narrows simultaneously. In the latter, the COM tends to move out of the base; however the base follows the movement in the same dimension. Moreover, consistently tapping an approximate spatial location in a specific body spatial dimension requires the control of the toe position. Based on extant literature, it can be understood that multi-directional toe-tapping requires feedback from the proprioceptive system, additional visual feedback is available, predominantly, for forward and lateral toe-tapping depending on the orientation of the HEAD. Nonetheless, the head with the visual and vestibular system will help stabilize the body regardless of the toe-tapping direction. Furthermore, based on the stepping literature a question can be extrapolated: Does tapping with the toe differ based on the direction of tapping? Finally, based on the developmental literature, it can be speculated that if walking improves with age, maybe similar improvement and development would occur during the forward, backward or lateral toe-tapping. Therefore, we need to comparatively study: (1) the various task or control parameters: the COM, head and toe position and (2) the complex interaction of these variables with tapping direction and age.

1.2 THESIS CONTRIBUTIONS

The purpose of this thesis is to study the forward, backward and lateral toe-tapping by studying the three most involved task-specific control variables: the center of mass (COM), TOE (Patla et al., 1999) and HEAD position (Barberini & Macpherson, 1998). This is accomplished by studying their overall relevant joint motion related variations using the Uncontrolled Manifold (UCM) Technique (Scholz & Schöner, 1999). By overall relevant joint motion we mean the joints that are linked geometrically to mathematically define the task or control variables.

Furthermore, UCM allows us to approximate the neural motor control structure in the joint space by ranking the influence of the various task or control variables related to toe-tapping based on a unique stability measure considering the overall relevant joint structural variability. This comparative framework would allow us to better understand how the CNS stabilizes the multi-segment coordinated forward, backward and lateral toe-tapping. Finally the study compares the neural motor control structure of toe-tapping based on the (1) *three* tapping directions: forward, backward and lateral; and (2) *three* typically developing age groups: six-year-old children, ten-year-old children, and adults. The *three* major contributions of the thesis are enumerated as follows.

1. Systematically approximate the organization of the adult neural motor control of multi-directional toe tapping task: forward, backward, and lateral; it asks, does the CNS control individuals joints, or control of some task-related parameters (i.e., task or control variables: COM, HEAD and the TOE position) are prioritized? And how are these parameters ranked in terms of their control? Here, control means that the overall joint motion variability is organized in a way to utilize the redundancy of the motor task while ensuring stability of the control variables, while lack of control refers to reduced stability (Scholz & Schöner, 1999). Finally to our knowledge, toe position as task-related control variable is being introduced for the first time in the literature.

2. A comparative analysis of the adult neural motor control structure involved in forward, backward and lateral toe-tapping.

3. A developmental study to understand the differences in the neural motor control structure by analyzing the three typically developing age groups: (a) 6-year-old children, (b) 10-year-old children, and (c) young adults.

These analyses are based on the overall structure of the variance in the joint space using the UCM technique (Scholz & Schöner, 1999).

To summarize, what is the neural motor control structure during reaching out and tapping with the toe, and how does this structure differ with the tapping direction and age? Based on the literature, it is reasonable to hypothesize that a combination of multiple task-related control parameters are working together during toe-tapping. Moreover, despite the strategy there would be a gradual improvement in the neural motor control structure with age (Cavagna et al., 1983; Dierick et al., 2004; Hausdorff et al., 1999; Preis et al., 1997).

1.3 READERS' GUIDE

Chapter 2 will provide a brief description of the notion of variability, stability, synergy and the motor abundance principle; and finally introduce the concept of the Uncontrolled Manifold (UCM) Technique. At the end of that chapter a more extensive summary of the research questions and associated hypotheses related to this thesis will be presented and throughly discussed by setting these up in the UCM framework. Chapter 3 will introduce the multi-directional toe-tapping task, the motion data (kinematic) collection and associated data analysis methods, the results and discuss our findings based on existing literature. Finally, chapter 4 concludes the study by providing an overall summary.

Chapter 2: REVIEW OF LITERATURE

This chapter starts by trying to answer the fundamental question of movement neuroscience: how do we (humans) move the way we move; and quickly get stuck in the web of motor redundancy. To help us find an answer, this chapter reviews the notion of variability, stability, synergy and the motor abundance principle; and introduces the concept of the Uncontrolled Manifold (UCM) Technique.

The remaining part of the chapter discusses the concept of UCM: (1) the abstract idea behind the conception, (2) how it relates to variability, stability, synergy, and the motor abundance principle, (3) provides the required mathematical background to understand the conception, (4) emphasizes the strengths of the method to quantify motor learning and development, and finally provides (5) a summary of the thesis with respect to the previous work, while framing the research questions and associated hypotheses in terms of the UCM vocabulary.

2.1 HOW DO WE MOVE THE WAY WE DO?

How do humans move? The most intuitive realization is there are infinite possible combinations of sensory inputs and motion commands that can lead to the same motion output – the motor redundancy problem; also known as the curse of dimensionality (Shadmehr & Krakauer, 2008; Todorov, 2004; Wolpert & Ghahramani, 2000). Researchers understood that the brain runs some kind of optimization scheme to generate motion; but the question remains, what is being optimized and controlled: Is it the individual joints or task-related control parameters?

Therefore, the fundamental question of movement neuroscience is: given the large number of neuro-musculo-skeletal degrees of freedom (DOF), how does the central nervous system (CNS) generate, organize or simplify the control of context-specific multi-joint actuated actions with the human body, while coordinating with the external environment? Another reformulated version asks, in which coordinate or reference frame does the CNS represent and plan multi-joint movements: joint space or the task space (defined by task or control variables)? (Scholz & Kelso, 1989; Scholz & Schöner, 1999). A concrete answer is not yet established; however, a well established explanation is based on the framework of action variability.

2.2 ACTION VARIABILITY, ABUNDANCE, AND SYNERGIES

The most unique attribute of human movement is its variability: No two actions are the same. This phenomenon was initially documented, following the famous studies of Bernstein where professional blacksmiths struck an anvil with a hammer (Fig. 2.1). Bernstein observed that consistent motor performance, defined by similar topologies of repeated trajectories, occurred despite noticeable variations across the fundamental elements (e.g., joint angles, or muscular forces) during the repeated action trials. Bernstein realized, variability is partly related to the redun-

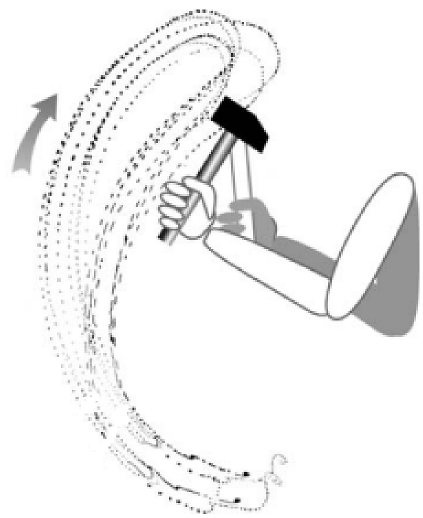

Figure 2.1: Bernstein observed that variability at the arm joints were more than the variability of the hammer tip trajectory. Adapted from (Müller & Sternad, 2009).

dancy of the task (Bernstein, 1967; Müller & Sternad, 2009). The redundancy is related with the multiple available DOF associated with the task.

According to Bernstein, the CNS has a redundant architecture; it allows the existence of infinite solutions which can lead to a similar hammer tip trajectory. Such redundancy of the biological motor system allows variability, which leads to movement flexibility and adaptability. However, the initial question still holds: How does the CNS select from its infinite possible solution sets, a particular solution set to perform a particular voluntary movement? This is well known as the problem of motor redundancy or the DOF problem. Bernstein speculated that the CNS did not control the limb by utilizing the available neuro-mechanical redundancy; rather it tries to reduce and subsequently simplify the redundancy; and concluded that, during any functional movement task the CNS controls the spatial aspects of the performance variable (e.g., the hammer tip position), and not the specific joints (Bernstein, 1967; Gelfand, M, & Latash, 1998; Müller & Sternad, 2009).

An alternative perspective to the problem of motor redundancy is the principle of motor abundance (Gelfand et al., 1998; Latash, 2012). It advocates that the CNS uses all the DOF and organizes them in flexible task-specific structural units (Gelfand, M, Gurfinkel, Fomin, & Tsetlin, 1971; Gelfand et al., 1998; Latash, 2012; Latash, Scholz, & Schöner, 2007). Thus, the principle does not search for a unique solution, but utilizes the multiple available solutions to stabilize specific task-related performance variables (Black, Smith, Wu, & Ulrich, 2007; Latash, 2010; Wu & Latash, 2014). To summarize, the principle of abundance suggests the organization of the DOF into synergies, or task-specific structural units.

Stability is a fundamental property; and an absolute prerequisite in realizing a reliable task-specific motor action. A successful realization requires that the action is designed in terms of its stable DOF (Scholz & Kelso, 1989; Scholz & Schöner, 1999). In the control-theoretic sense, stability is the ability of the system to always return to its stable state, or stay within safe limits of the stable state. According to Schöner and Scholz, the fluctuation of the DOF from its time matched stable versions during a movement task across its multiple trials, i.e., movement variability across multiple trials; can be used to experimentally bring out significant features that can classify the primary task-relevant performance variables; this concept is known as differential stability of variables, and has been used to assess the stability of postural states (Scholz & Kelso, 1989; Scholz & Schöner, 1999).

Synergies can be defined as task or context-specific neural organizations, defined by the combinations of joint angles or muscle forces, that ensure co-variation among elemental variables to stabilize certain performance characteristics of multielemental biological motor system (Freitas, Duarte, & Latash, 2006; Latash, Scholz, & Schöner, 2002; Latash et al., 2007). The elemental variables are joint or segmental angles for kinematic multi-joint movements, muscle forces for joint torque analysis, and motor units for muscle activity pattern analysis (Latash, 2010). Structural units or synergies are task-specific, and they are united by a common goal (Latash, 2012). It is hypothesized that these elemental variables are independent; if one element introduces an error, the others reorganize to compensate by adjusting the covariance among the elemental variables (Freitas et al., 2006). For example, to maintain posture while kicking, a soccer player needs to combine and coordinate many joints of the trunk, and the extremities that are involved in the postural balance (Wu & Latash, 2014). This inter-coordination and coupling of the joints which stabilizes the posture to maintain balance while kicking the ball is called a synergy – a structural unit (Wu & Latash, 2014). The creation of a synergy allows large amounts of variability in the muscle or joint activation space, while preserving the important task-specific performance parameters (Wu & Latash, 2014).

2.3 THE UNCONTROLLED MANIFOLD (UCM) AND SYNERGY

The uncontrolled manifold (UCM) analysis is a computational framework which examines the aforementioned motor redundancy while remaining compatible with the principle of abundance. Moreover, it provides a firm conceptual and methodological sneak-peek into the overall structure of variability (Scholz & Schöner, 1999). The method, at first, establishes a mathematical relationship between the task-relevant fundamental motor elements (e.g., joint angles, or muscle forces) and the task level control variable (e.g., center of mass (COM), HEAD or the TOE position). This relationship allows the UCM technique to generate a complete solution manifold, or a subspace corresponding to all the infinite combinations of the motor elements which conserves the task-specific control variable.

A linearized approximation of the relationship can be found using the Jacobian matrix. This matrix indicates how much variance in the motor elements relate to how much variance in the task level control variable. It is consistent with the manifold idea; different combinations of elemental variable changes lead to different amounts of variance at the task variable level. Most importantly, it implies that a unique solution is not required to stabilize or control the value of a task-related control variable. Moreover, the Jacobian allows the variability to be projected on the solution space. Variability projected onto the UCM solution manifold ($\sigma_{\parallel}$) does not affect the motor task performance. Therefore, the control of the elemental variables in this manifold is unnecessary, hence the term uncontrolled manifold (Scholz & Schöner, 1999; Schöner, 1995). However, variance orthogonal to the UCM subspace ($\sigma_{\perp}$) affects the motor performance (Scholz & Schöner, 1999; Schöner, 1995).

The most attractive features of the UCM technique are as follows: (1) UCM provides a comparative framework which allows systematic ranking of the different task-level control variables based on their variability score, thereby approximating the neural motor control structure used in the completion of the motor task, and (2) it provides a quantitative definition of synergy. If the ratio between ($\sigma_{\parallel}$) to ($\sigma_{\perp}$) is greater than one; it means the CNS is stabilizing or controlling the task-related variables more than the individual joints. Meaning, if one component introduces an error the others would reorient so that the motor performance is not compromised: a synergy has developed. In contrast a ratio less than one means it has not. This conceptualization is also known as the synergistic control of multi-body systems (Freitas et al., 2006; Latash et al., 2002, 2007).

The UCM technique has been utilized to identify the task-related control variables and the associated neural motor control structures (i.e., synergies or structural units) used in several motor tasks. For example maintaining quiet stance (Freitas & Duarte, 2012), multi-finger force production (Kang, Shinohara, Zatsiorsky, & Latash, 2004; Latash, Scholz, Danion, & Schöner, 2001; Scholz, Kang, Patterson, & Latash, 2003), pointing (Domkin, Laczko, Djupsjöbacka, Jaric, & Latash, 2005; Kim et al., 2012; Verrel, Lövdén, & Lindenberger, 2012), sit-to-stand (Scholz & Schöner, 1999), pistol shooting (Scholz, Schöner, & Latash, 2000), walking (Black et al., 2007; Robert, Bennett, Russell, Zirker, & Abel, 2009), reach to grasp (Jacquier-Bret, Rezzoug, & Gorce, 2009), balance recovery (Hsu, Chou, & Woollacott, 2013), gait analysis (Qu, 2012), and hopping (Auyang, Yen, & Chang, 2009). It was found that, in general, these motor tasks are performed by controlling task-specific control variables through the development of synergies.

Moreover, UCM has been utilized to comparatively investigate the age-related differences in neural motor control structure in young and old adults during quiet stance (Freitas & Duarte, 2012), balance recovery (Hsu et al., 2013) and manual pointing (Verrel et al., 2012). Furthermore, the literature also shows a wide array of studies examining the variance structure of the joints ($\sigma_{\|}$ and $\sigma_{\perp}$) involved in

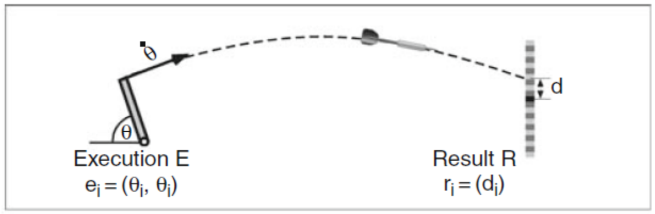

Figure 2.2: The dart throwing task can be defined by the angular position of the release angle θ and the dart release velocity $\dot{\theta}$ in the direction of the target. Image adapted from (Müller & Sternad, 2009).

the motor task to analyze various neurological disorders, mainly C6-C7 quadriplegic injury (Jacquier-Bret, Rezzoug, & Gorce, 2008) through reach and grasp task; Down syndrome (Black et al., 2007; Latash & Anson, 2006; Scholz et al., 2003) by studying multi-finger force production and walking. These studies suggest that age or disease-related changes in the neural motor control structure can be quantified using the UCM conception; and revealed that the strength of the developed synergies affiliated with the task-specific control variables deteriorates with age and disease.

Finally, UCM has also helped in quantifying the effects of practice on motor coordination and learning; allowing physical therapists to quantify changes in the neural structure following a particular physical therapy program by analyzing the $\sigma_{\parallel}$ and $\sigma_{\perp}$ (Kang et al., 2004; Latash, 2010; Müller & Sternad, 2009; Wu & Latash, 2014). These studies showed that with practice the synergies become stronger. A more detailed explanation is provided in section 2.5.

2.4 THE MATHEMATICAL FOUNDATION OF UCM

To understand the mathematical basis of UCM let us analyze the simplified task of dart throwing. This example is adapted from (Müller & Sternad, 2009). For simplicity, the action is confined in the sagittal plane, the throwing arm is fixed in space and modeled as a single-joint lever arm, much like a trebuchet, as shown in Fig 2.2. During dart throwing, the most critical part is the moment of release; it can be completely characterized by the angular position of the release angle θ and the dart release velocity $\dot{\theta}$ in the direction of the target. The outcome of the throw, the performance, can be defined as the distance between the contact point and the center of the target, $\boldsymbol{d}$. To summarize, the task can, sufficiently, be described by a two dimensional vector, $\boldsymbol{e} = [\theta, \dot{\theta}]$, here $n = 2$; whereas the outcome or the performance is one-dimensional, $r = 1$. Therefore, the task is redundant in the minimal sense, hence satisfying the required criteria of the UCM analysis.

The second requirement is a mathematical relationship between $\boldsymbol{d}$ and $\boldsymbol{e}$. Let us assume that the relationship is known; it is $\boldsymbol{d} = \boldsymbol{f}(\boldsymbol{e})$. In the third step let us collect information from a series of throws defined by i trials, where $i = 1, 2, 3, \ldots, N$. These trials generate the $\mathbf{E}$ and $\mathbf{D}$ sets, where $\mathbf{E}=\{\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_N\}$ and $\mathbf{D}=\{\boldsymbol{d}_1, \boldsymbol{d}_2, \ldots, \boldsymbol{d}_N\}$. Intuitively these repeated throws would not be identical; variability would be present in both the $\boldsymbol{e}$ and the $\boldsymbol{d}$ space, denoted by $\mathbf{V}(\boldsymbol{e})$ and $\mathbf{V}(\boldsymbol{d})$ respectively. UCM provides the mathematical framework to relate the outcome variance of $\mathbf{V}(\boldsymbol{e})$ to $\mathbf{V}(\boldsymbol{d})$; it can thereby figure out the structure of variability which utilizes the redundancy of the elemental variables involved in the task.

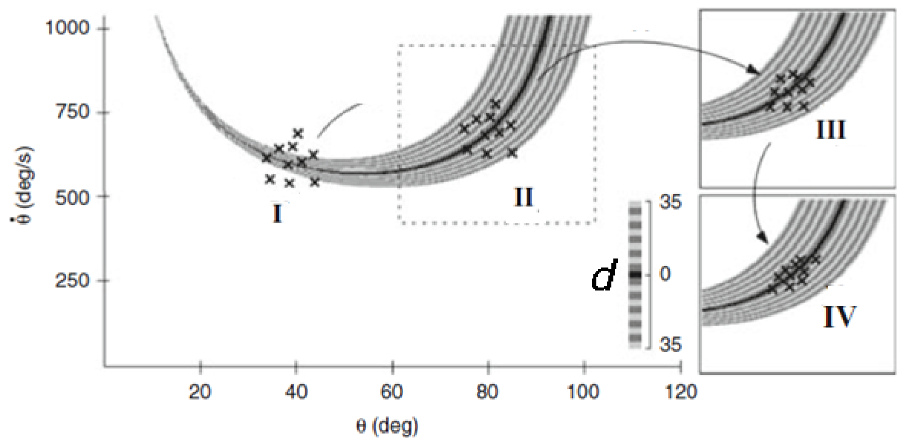

Figure 2.3: The different colored strips define the different unique solution manifolds considering the different outcome values, $\boldsymbol{d}$. Every throw with its two elemental variables $[\theta, \dot{\theta}]$ constitute a data point highlighted by the $\times$ symbol. Each cluster of data points, with the Roman numerals, represents the 10 throws performed by four distinct performers. Image adapted from (Müller & Sternad, 2009).

Using the functional relationship: $\boldsymbol{d} = \boldsymbol{f}(\boldsymbol{e})$, we can generate a solution manifold, or subspace that corresponds to all the infinite possible combinations of $\boldsymbol{e}$ which conserves the task-specific control variable $\boldsymbol{d}$, as illustrated in Fig. 2.3. The dark line defines all the infinite possible combinations of $\boldsymbol{e}$ which leads to the perfect throw ($\boldsymbol{d} = 0$). The grey-shaded error-isobars highlight the solution manifolds related to other position outcomes. Every throw with its two elemental variables $[\theta, \dot{\theta}]$ constitute a single data point, highlighted by the $\times$ symbol. Data points on the white part indicate that the throws have missed the dart board. Furthermore, the figure highlights four distinct scenarios of data point distribution; where two datasets may apparently seem to have similar variability, but they are significantly different depending on their average and dispersion, e.g., case I and IV. Technically, the performer should try to be in case IV, as it would allow the performer to hit the target more often, whereas in case I the performer would miss a lot.

In an actual experimental setting, the mean value ($\mathbf{E}_M$) from all the trials is considered to be the solution manifold. Assuming that outcome $\boldsymbol{d}$ is the accuracy and related to $\boldsymbol{e}$ by $\boldsymbol{d} = \boldsymbol{f}(\boldsymbol{e})$. The function, $\boldsymbol{f}$ is linearized at $\mathbf{E}_M$ through the Jacobian matrix, $J(\mathbf{E}_M)$. The relationship is:

$$\mathbf{d} - \mathbf{d}_M = J(\mathbf{E}_M).(\mathbf{E} - \mathbf{E}_M) \tag{2.1}$$

The dimension of $J\ (\mathbf{E}_M)$ is $r \times n$. The UCM is computed as the null space, $J(\mathbf{E}_M).\epsilon = 0$; i.e., the subspace within which the output (performance variable) remains unchanged. The basis vectors ϵ span the linearized UCM. There are $n - r$ basis vectors having the dimension of $n - r$; these basis vectors are numerically computed at each time slice by considering the Moore-pseudo inverse of the Jacobian matrix (Jacquier-Bret et al., 2009).

$$J^+ = J^T(JJ^T)^{-1} \tag{2.2}$$

The deviations ($\mathbf{E}$- $\mathbf{E}_M$) were resolved into their projection onto the null space (Jacquier-Bret et al., 2009):

$$\mathbf{E}_{\|} = (\mathbf{1} - J^+J).(\mathbf{E} - \mathbf{E}_M) \tag{2.3}$$

where $\mathbf{1}$ is the identity matrix. The component perpendicular to the null space was computed as follows (Jacquier-Bret et al., 2009):

$$\mathbf{E}_{\perp} = (\mathbf{E} - \mathbf{E}_M) - \mathbf{E}_{\|} \tag{2.4}$$

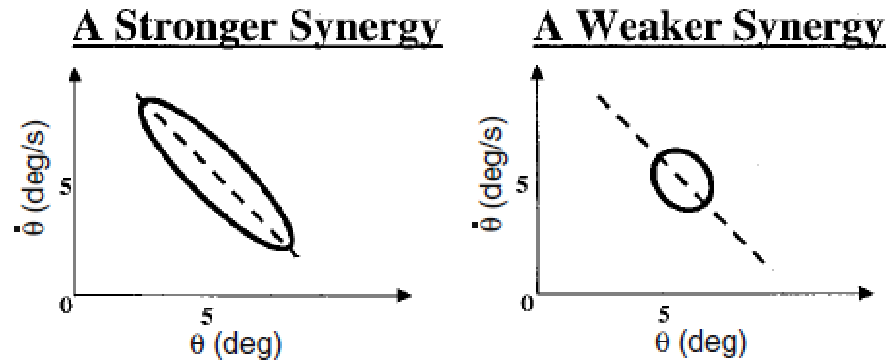

Figure 2.4: The difference between stronger and weaker synergy. Image adapted from (Latash et al., 2002).

The amount of variability per DOF within the UCM is estimated as

$$\sigma_{\parallel}^{2} = (n-r)^{-1} N^{-1} \Sigma \mathbf{E}_{\parallel}^{2} \tag{2.5}$$

where $\mathbf{E}_{\parallel}^{2}$ is the squared length of the deviation vector lying within the linearized UCM. The amount of variability per DOF perpendicular to the UCM is estimated as

$$\sigma_{\perp}^{2} = r^{-1} N^{-1} \Sigma \mathbf{E}_{\perp}^{2} \tag{2.6}$$

$$UCMRatio = \frac{\sigma_{\parallel}}{\sigma_{\perp}} \tag{2.7}$$

If UCM Ratio $>$ 1, it is a synergy; and if the UCM Ratio $<$ 1 then it is not. For example, Figs. 2.3, 2.4, and 2.5 show the quantitative definition of synergy, and pictorially compares a stronger synergy to a weaker one. In case IV of Fig. 2.3, the CNS limits the variability of the elemental variables in directions orthogonal to the UCM more than that which lies within the UCM (Fig. 2.5).

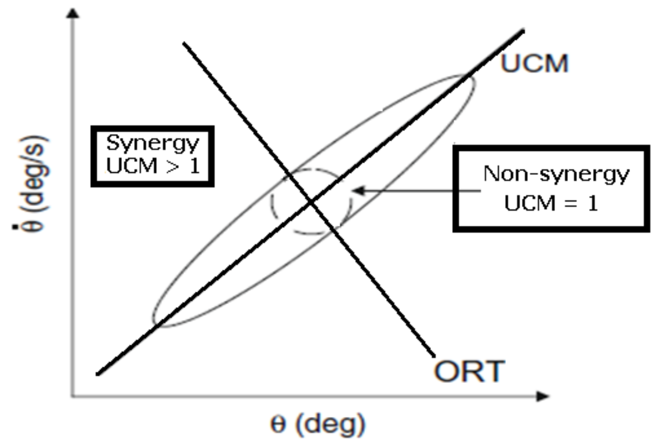

Figure 2.5: Case IV in Fig. 2.3 has developed a synergy, because the distribution of the data points are more spread along the UCM as compared to its orthogonal. Image adapted from (Latash, 2010).

2.5 UCM AND AGE-RELATED CHANGES

Growing up, from the perspective of movement neuroscience, involves getting better at moving. Intuitively, the sufficient condition is that the less variant we are; the better or more accurate we will be. However, what if, we get better at doing the wrong things? UCM provides the necessary conditions, a more robust framework to analyze the effect of aging by studying the structure of variability. It suggests, that improvement or getting better means developing stronger synergies, i.e., higher UCM ratio, or the variance along the orthogonal to the UCM should be reduced, while variance should increase along the UCM (Latash & Anson, 2006). This is motivated from recent studies (Kang et al., 2004; Latash, 2010; Müller & Sternad, 2009) involving the redefinition of learning and its relation to practice by developing stronger motor synergies through practice. This notion of practice and motor learning can easily be translated to development. As we grow, develop and

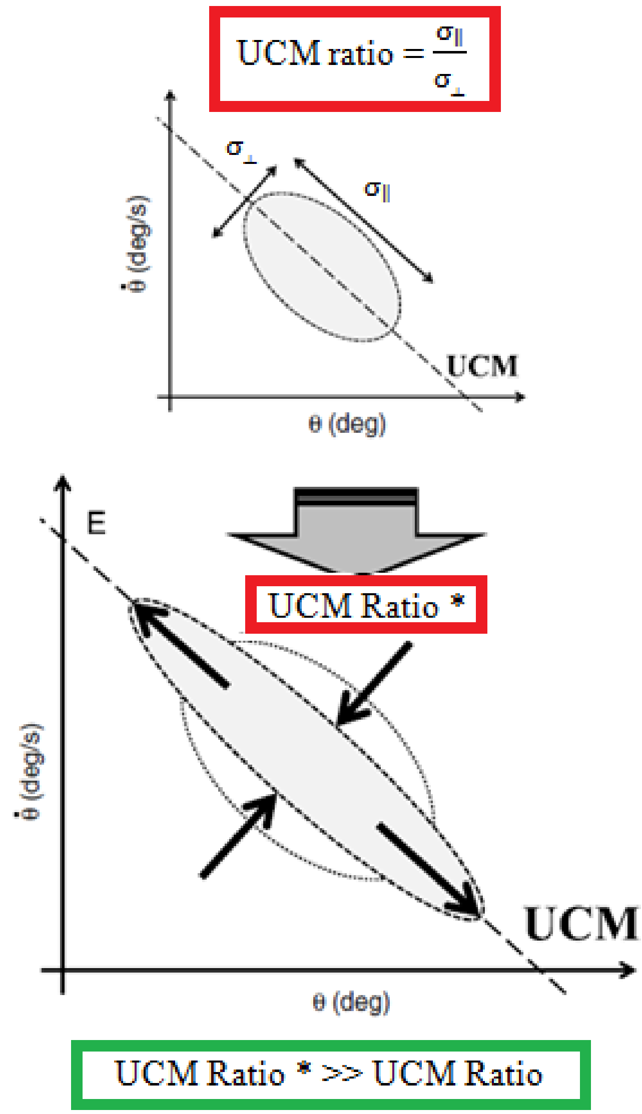

Figure 2.6: As humans grow, their neural control architecture relating to movement develops due to extensive practice. This change can be quantified using the UCM framework. Adapted from (Wu & Latash, 2014).

mature we get to have more practice; according to UCM framework, with practice the UCM ratio gets higher, meaning stronger synergies are developed (Latash & Anson, 2006). The idea is illustrated in Fig. 2.6.

2.6 SUMMARY OF THE THESIS

Approximate neural motor control structure, in the context of this thesis, assumes that the CNS controls the various toe-tapping behavior by controlling the task-related functional parameters like COM, TOE or the HEAD position, irrespective of the variations introduced by the redundant neuro-musculo-skeletal architecture of the human body. Moreover, it is assumed that these parameters are differently controlled, meaning, some of them are more controlled than others – a ranking based on a relative stability measure, defined by the UCM ratio. Here, control means that the redundant architecture is organized in a way which stabilizes the control parameters, irrespective of their overall joint motion variability; lack of control means this stability is reduced (Scholz & Schöner, 1999).

This thesis is concerned with understanding the neural motor control structure involved in forward, backward and lateral toe-tapping motion by systematically analyzing the overall structure of the joint variability related to the *three* most important task-related control variables: COM (Winter, 1995; Woollacott & Tang, 1997), TOE (Patla et al., 1999) and HEAD (Barberini & Macpherson, 1998) position; and how the control (i.e., stability) of these variables changes with the tapping direction? Moreover, the study is extended to a motor developmental framework by comparing *three* different age groups: typically developing adults (18-23 years), six-year-old children and 10-year-old children. These analyses will be performed using the uncontrolled manifold technique (Scholz & Schöner, 1999; Schöner, 1995). The research questions and the hypotheses are enumerated below.

2.6.1 Multiple task-related performance variables contribute to the neural motor control of multi-directional toe-tapping in adults.

Research Question 1: What is the neural motor control structure – ranking of the task-related control variables (defined by the UCM ratio): COM, HEAD and the TOE, as adults perform the (a) forward, (b) backward, and (c) lateral toe-tapping?

Hypothesis 1: The adult CNS controls toe-tapping by controlling or stabilizing all the task-related functional parameters (task or control variables): COM (Winter, 1995; Woollacott & Tang, 1997), TOE (Patla et al., 1999) and HEAD (Barberini & Macpherson, 1998) position more than the individual joint motions, regardless of the tapping direction. This is indicated by the UCM ratio of more than unity for all these task-related performance or control variables.

The CNS prioritizes the control (i.e., stability) of these performance variables based on the task requirements; the ranking of the variables is achieved by using the UCM ratio as the measure. The hypothesized ranking of the variables would be COM, TOE and the HEAD position, because the literature suggests: (1) the control of the COM is initiated first by appropriate changes in the foot position (Patla et al., 1999); and (2) the hip, knee and ankle kinetics, i.e., TOE position control, contributes to the stabilization of the COM and center of pressure (COP)

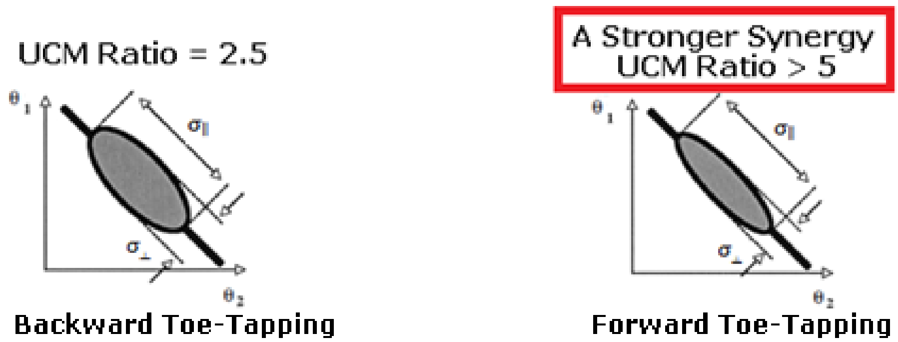

Figure 2.7: UCM ratio for COM is significantly higher in forward toe-tapping when compared to its backward counterpart. Similar pattern resides with the HEAD, and the TOE position. Image adapted from (Latash & Anson, 2006).

(Winter, 1995; Woollacott & Tang, 1997). Consistently tapping a spatial position in space, in the forward and lateral direction, requires continuous feedback from the visual system for dynamic error correction. In general, studying the head position would be important as the vestibular and visual system are installed in the head (Barberini & Macpherson, 1998; Hirasaki et al., 1999).

2.6.2 In adults, the overall neural motor control of toe-tapping is dependent on the tapping direction.

Research Question 2: Is there a difference in the neural motor control based on the direction of tapping, as adults perform the forward, backward and lateral toe-tapping movements?

Hypothesis 2: Adult forward toe-tapping will have a significantly higher UCM ratio; meaning the control variables are more stable in forward toe-tapping than backward or lateral toe-tapping. From the literature on walking, toe-tapping maybe similar to findings on locomotion. For example, compared to forward walking, backward walking does not generate enough propulsive power (Lee et al., 2013), gait

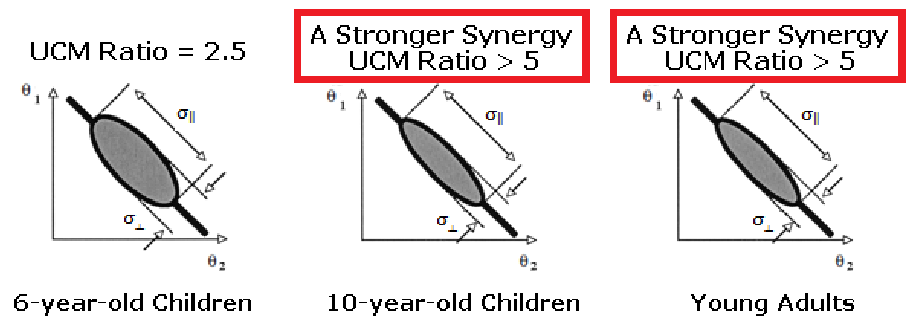

Figure 2.8: The UCM ratio, i.e., strength of the developed synergy for the COM is greater than unity and significantly higher in 10-year olds and young adults when compared to 6-year olds. However, in between them they are not significantly different. Adapted from (Latash & Anson, 2006).

variability is increased which causes destabilized balance (Freitas & Duarte, 2012; Hackney & Earhart, 2009; Hausdorff et al., 1997). Moreover, the kinematic motion pattern at the hip, and the knee, although time-reversed, is simpler than forward walking (Lee et al., 2013); according to Schöner leads to a lower UCM ratio (Scholz & Schöner, 1999). Fig. 2.7 illustrates the idea with an example.

2.6.3 Age-related changes in multi-directional toe-tapping.

Research Question 3: Is there a difference in the neural motor control structure of (a) forward, (b) backward, and (c) lateral toe-tapping based on the age, as six-year-old children, ten-year-old children, and adults perform the tapping movements?

Hypothesis 3: From age-related walking literature we can extrapolate that the overall neural motor control of multi-directional toe-tapping would improve with age (Cavagna et al., 1983; Dierick et al., 2004; Hausdorff et al., 1999; Preis et al., 1997); however the improvement ceases around the age of 7 (Dierick et al., 2004); meaning, there would be no significant differences in the overall control structure for 10-year-old children and young adults. Fig. 2.8 illustrates the idea with an example.

Chapter 3: A SYSTEMATIC APPROXIMATION TO THE NEURAL MOTOR CONTROL OF FORWARD, BACKWARD AND LATERAL TOE-TAPPING IN CHILDREN AND ADULTS

The main objective of this study is to systematically approximate the neural motor control structure of multi-directional unilateral toe-tapping task, and how the structure changes with the tapping direction and age, using the uncontrolled manifold (UCM) conception (Scholz & Schöner, 1999)? By neural motor control we ask the question: Does the central nervous system (CNS) control individual joint motions or does it prioritize task-specific performance variables? Intuitively, there can be several parameters that the CNS can control, however, this study is limited to the testing of center of mass (COM), TOE and the HEAD position; therefore it is an approximation. Finally, based on a relative ranking defined by a unique, unit-less, stability measure (derived from the UCM conception) which considers the multi-joint structural variability, we can systematically rank these variables.

3.1 INTRODUCTION

Reaching out and unilaterally tapping with the toe, i.e., toe-tapping requires asymmetrical motor skills; the body weight is placed on one leg – the stance leg, while simultaneously moving the other leg towards a desired spatial location in a particular body-spatial dimension. The process is kinematically similar to aspects of stepping or reaching with the foot; however, they differ in important ways.

Kinematically stepping and toe-tapping are quite similar. Both involves the periodic combination of double leg stance followed by single leg stance with a leg swing motion and toe touch-down. Among the three, the single leg stance and swing are the most unstable phases. During these phases or in any lower limb movement involving the lifting of the leg, an instability is generated in the lateral direction as the base of support is narrowed causing the COM to generate a lateral destabilizing moment (McIlroy & Maki, 1999), and if it is not appropriately regulated it can result in a stumble or fall.

In the case of voluntary movements, anticipatory postural adjustments (APAs) are initiated to anticipate the destabilizing momentum and maintain overall postural stability – balance in response to the leg swing and tap (L. A. King & Horak, 2008; Maki & McIlroy, 1996, 1997; Mcllroy & Maki, 1995; Patla et al., 1999). The procedure is initiated prior to the lifting of the swing leg by shifting the COM medially towards the stance leg (McIlroy & Maki, 1999).

During volitional leg swing, the swing generated by the leg creates a natural destabilizing momentum, in the direction of the movement, by shifting (or tending to shift) the COM to move outside the base of support (Han, Betker, Szturm, & Moussavi, 2006). For forward or backward movement (Brenière, Cuong Do, & Bouisset, 1987; Brun et al., 1991) this instability occurs in the anterior-posterior direction (horizontal sagittal dimension), while occurring medial-laterally (horizontal frontal plane) for lateral movements. In the former case, the instability is increased because the base of support narrows laterally, while in the latter the instability is reduced because the base follows the COM shift in the direction of the movement. Nonetheless, to neutralize such instability, the most natural reaction is to shift towards a double leg stance in an optimized way to reinstall overall stability, thereby avoiding a fall (Maki & McIlroy, 1997; Mcllroy & Maki, 1995). However during the toe-tapping task the swing leg does not step down (i.e., no transfer of weight onto the swing foot).

Instability in the medial-lateral dimension is vital for balance. Recently, extensive studies have associated impaired balance in the elderly with lateral instability (L. A. King & Horak, 2008; Lord, Rogers, Howland, & Fitzpatrick, 1999). Such findings have inspired a significant amount of research work; leading to the documentation of the various compensatory strategies generated by different age groups (young and older adults) as they are exposed to multi-directional external perturbation (Maki, McIlroy, & Perry, 1996; Mcllroy & Maki, 1995; Mille, Johnson, Martinez, & Rogers, 2005; Rogers, Hedman, Johnson, Martinez, & Mille, 2003). It was found that depending on the direction of the external perturbation the strategy was different (Maki et al., 1996). King and colleagues documented a short summary of these studies while explaining the effect of step length in stabilizing forward fall

(G. W. King, Luchies, Stylianou, Schiffman, & Thelen, 2005). Based on the aforementioned studies, the single leg stance and the swing phase of multi-directional unilateral toe-tapping can cause self-perturbed multi-directional destabilizing momentum, which may impact balance.

Kinetically toe-tapping is quite different from stepping since the tapping phase does not result in the weight transfer onto the tapping leg, like it would in the double leg stance of the stepping process. Thus, maintaining postural balance during toe-tapping can be quite difficult as well. However, to our knowledge toe-tapping has not been, explicitly, studied in literature.

Based on aforementioned literature studies, it can be understood that the phase of the toe-tapping movement is crucial due to different balance-related requirements. The mid air phase defined by the combination of single leg stance and leg swing generates self-perturbed multi-directional destabilizing momentum. These destabilizations occur due to APA-caused lateral instability, and movement inflicted instability due to the shift of the COM in the direction of the toe-tapping movement. In addition, during forward and backward movement the base of support is narrowed laterally, while the base widens along the movement direction in lateral tapping movement. The forward and backward are the most difficult in terms of balancing. Furthermore, during the toe-tapping phase the weight is not transfered onto the tapping leg, thus balancing while tapping can be difficult. Therefore, the mid-air and toe tap phase are both important phases of the movement to look at.

Control of posture or balance during the potentially destabilizing toe-tapping task involves the integration of multiple sensory systems: vestibular, proprioception and visual. Therefore, the position of the COM, HEAD, and the TOE play an important role. Studies involving the forward swing phase of walking reported that the control of the COM is initiated by the appropriate changes in foot position (Patla et al., 1999); such stabilization of the COM is linked with the hip, knee and ankle kinetics; which indicates that the toe position control would be vital during toe-tapping (Winter, 1995, 1995). Moreover, consistently tapping a spatial position in space requires continuous feedback from the visual system for dynamic error correction (for forward and lateral). Therefore, in general, studying the head position would be important as the vestibular and visual system are installed in the head (Barberini & Macpherson, 1998; Hirasaki et al., 1999).

Moreover, multi-directional toe-tapping can be quite tricky. Based on extant literature it can be conjectured that (1) kinematic variability increases during backward toe-tapping; and it can be correlated with destabilizing balance (Freitas & Duarte, 2012; Hackney & Earhart, 2009; Hausdorff et al., 1997); however, (2) studies involving infant (aged 2-11 months) supported multi-directional stepping indicate that the stance, and swing phase duration in multi-directional toe-tapping would not be significantly different (Lamb & Yang, 2000; Yang et al., 1998).

Furthermore, age-related studies involving the multiple balance related control parameters: COM, HEAD and the TOE position, suggest that these sensors are centrally integrated and gradually attenuate with age (Barberini & Macpherson, 1998). Studies involving the age-related improvements in walking suggested that locomotion can gradually improve with age (Cavagna et al., 1983; Dierick et al., 2004; Hausdorff et al., 1999; Preis et al., 1997) through the development of the neural control process, and evolves until the age of 7 (Dierick et al., 2004). Based on such studies we can speculate that similar trends might develop due to age in the step-like toe-tapping task.

3.1.1 THE UNCONTROLLED MANIFOLD (UCM)

The Uncontrolled Manifold (UCM) conception hypothesizes that the CNS performs movement by developing flexible task-specific structural units by utilizing all the elemental variables (e.g., joint angles, segmental angles or muscular forces) which defines the design of the redundant biological motor system. Most importantly, it provides a computational framework to analyze the control-theoretic stability of the various task-specific performance parameters by appropriately controlling the variability of the overall elemental variables associated with these parameters (Scholz & Schöner, 1999; Schöner, 1995).

The UCM technique assumes that the CNS controls task-specific performance parameters more than the involved individual elemental variables. Mathematically the UCM conception suggests that the CNS acts in the state space defined by these elemental variables to create a manifold, i.e., a subspace that represents the infinite sets of elemental variable configurations that corresponds to a particular value of a performance parameter that needs to be controlled for the successful completion of the motor task. The CNS does this by limiting the variability of the elemental variables in direction orthogonal to this manifold ($\sigma_{\perp}$), while relaxing the variability along the manifold ($\sigma_{\parallel}$). Variability of the elemental variables projected onto the

UCM solution manifold ($\sigma_{\|}$) does not affect the motor task performance. Therefore, the control of the elemental variables in this manifold is unnecessary, hence the term uncontrolled manifold (Scholz & Schöner, 1999; Schöner, 1995). However, variance orthogonal to the UCM subspace ($\sigma_{\perp}$) affects the motor task performance (Scholz & Schöner, 1999; Schöner, 1995). By motor task performance we mean the consistency in achieving the goal of the motor task, despite variations in the overall joint motions.

The ratio of $\sigma_{\|}$ to $\sigma_{\perp}$ is called the UCM ratio. The UCM ratio being unit less provides a measure to relatively differentiate the more stable or controlled variables from the less stable ones (Scholz & Schöner, 1999). A specific UCM ratio can occur in multiple combinations of $\sigma_{\|}$ and $\sigma_{\perp}$. Despite the combination, a UCM ratio greater than unity means that $\sigma_{\|} > \sigma_{\perp}$; it suggests that the fluctuations in the elemental variables does not affect the task or control variables, indicating that the CNS prioritizes the task or control variables more than the individual elemental variables. For more information the reader is requested to read the seminal paper (Scholz & Schöner, 1999) introducing the UCM conception.

3.1.2 RESEARCH QUESTIONS

In this study, multi-directional (forward, backward, and lateral) repetitive unilateral toe-tapping at self-preferred-comfortable speed was performed to investigate the neural motor control structure of toe-tapping using the Uncontrolled Manifold (UCM) Technique (Scholz & Schöner, 1999; Schöner, 1995). Moreover, we studied the changes in the control structure due to the tapping direction and age .

Neural motor control structure is mathematically defined using the UCM ratio, where UCM ratio > 1 suggests that task-related performance variable is controlled more than individual elemental variables. Moreover it provides a measure to relatively rank the multiple control variables considering the overall variability of the relevant elemental variable configuration structure. The task-related performance variables (defined as task or control variables) under consideration are the COM, HEAD and the TOE position; and the elemental variables are the segmental angles.

Specifically, we addressed the following questions: (1) Neural motor control structure: What is the neural motor control – ranking of the task or control variables: COM, HEAD and the TOE position, as adults perform the (a) forward, (b) backward, and (c) lateral toe-tapping? (2) Directional effect: Is there a difference in the neural motor control based on the direction of tapping, as adults perform forward, backward and lateral toe-tapping? and (3) Age effect: Is there a difference in the neural motor control of (a) forward, (b) backward, and (c) lateral tapping based on the performer's age, as six-year-old children, ten-year-old children, and adults perform the toe-tapping?

3.2 MATERIALS AND METHODS

3.2.1 PARTICIPANTS

The participants in this study were ten healthy adults (ADULT) (age: 21 $\pm$ 2.6 years old, height: 170 $\pm$ 6.0 cm, weight: 75.2 $\pm$ 18.1 kg); six healthy six-year-old children (Yr 6) (height: 114 ± 3.62 cm, weight: 21.2 ± 1.94 kg); and ten healthy ten-year-old children (Yr 10) (height: 140.5 ± 7.79 cm, weight: 36.8 ± 9.1 kg). No participant had a history of musculo-skeletal injuries or neurological disorders. All the subjects were given a detailed explanation about the experiment and they all signed an informed consent form, which was approved by the Institutional Review Board (IRB) at the University of Maryland, College Park.

3.2.2 EQUIPMENT, SETUP AND THE EXPERIMENTAL PROCEDURE

During the experiment, each participant was asked to change into a tank top and shorts; and their height and weight were measured. Thirty-five spherical reflective markers, 0.5 cm diameter each, were placed on the skin at significant bony landmarks (De Leva, 1996a, 1996b) using double sided, hypo-allergenic adhesive tape and pre-wrapping band (Fig. 3.1).

The markers were placed on the: (1) highest points on the top of the head, (2) superior palpable point of the spine - the seventh cervical vertebra (C7), (3) midpoint of the two collar bones, (4) lateral point of the scapulas acromial process, (5) proximal point on the lateral edge of the radius, (6) humeral medial epicondyle, (7) styloid processes of the radius (lateral and medial), (8) top of the third knuckle, (9) anterior superior iliac spine, (10) posterior superior iliac spine, (11) proximal point on the medial margin of the tibia head, (12) proximal point on the lateral point of the tibia head, (13) lateral point of the lateral malleous, (14) medial point

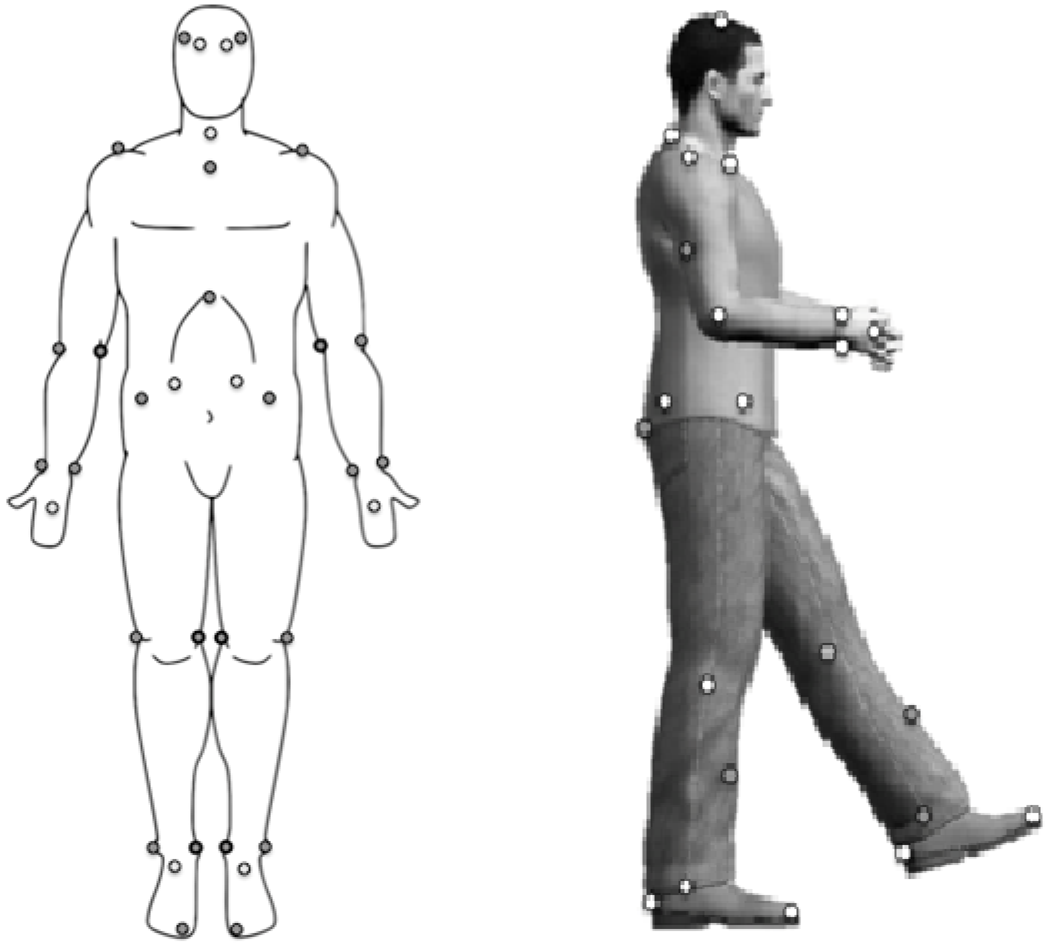

Figure 3.1: Marker Setup. The image was developed for marker display purpose only; in the actual experiment the participant was dressed in tank top and shorts.

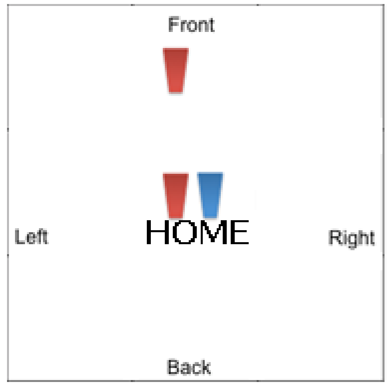

Figure 3.2: The Task Diagram.

of the lateral malleous, (15) posterior point of the heel, and (16) tip of the big toe.

Participants were asked to stand on the home position (Fig. 3.2), located at the center of the experimental space, with their feet, shoulders width apart while holding their arm at 90 degrees elbow flexion, exactly according to Fig. 3.1. The home position was marked with tape to keep the same position consistent across all the trials. Each participant was instructed to perform fifteen continuous repetitions of toe-tapping movement at their comfortable self-paced frequency and comfortable distance in forward, backward and lateral positions with each leg. They were asked to tap the floor with their toe; however, they were explicitly requested not to put their weight on the tapping foot while standing with one leg. A practice session was performed by asking the participants to tap at each direction, three times, before the actual experimental data acquisition started. Participants were given 90 seconds of rest between tapping conditions to avoid fatigue. The order of the foot and direction was randomized and balanced across subjects.

3.2.3 DATA COLLECTION AND REDUCTION

Eight-camera motion capture system (Vicon, Oxford, UK) was used to collect the positions of the reflective markers in three dimensions at a sampling rate of 200 Hz. Participants started their task after auditory signal: Go! The data acquisition was stopped after 15 repetitive toe tapping movements. However, in the data analysis only the twelve most consistent foot tapping data were utilized; the selection process was based on the consistency in the tapping distance, and tapping position. Raw kinematic data were processed and interpolated via the Nexus program (Vicon, Oxford, UK). The data were filtered with a fourth order Butterworth filter at a cutoff frequency of 5 Hz and analyzed using custom-written program using Matlab (Mathworks, Natick, MA). The marker coordinates were used to calculate the segmental angle and the segmental length along the sagittal and the frontal plane. The location of the whole-body center of mass (COM), HEAD, and the TOE position at each time point was calculated based on geometric models developed using the segmental lengths and associated segmental joint angles.

3.2.4 GEOMETRIC MODEL RELATING CONTROL VARIABLES TO SEGMENTAL ANGLES

The geometric model for the COM trajectory is composed of twelve segmental angles (angle and segmental length definition of the: head[1]: vertex to C7; right side: foot[2]: heel to toe, shank[3]: knee joint center to ankle joint center, thigh[4]: hip joint center to knee joint center, upper arm[5]: shoulder joint center to elbow joint center, lower arm[6]: elbow joint center to wrist joint center, mid section: trunk[7]: C7 to mid hip, left side: upper arm[8]: shoulder joint center to elbow joint center, lower arm[9]: elbow joint center to wrist joint center, thigh[10]: hip joint center to knee joint center, shank[11]: knee joint center to ankle joint center, and foot[12]: heel to toe), according to (De Leva, 1996a, 1996b). We applied the geometric model to the sagittal or anterior-posterior (A-P) and frontal or medial-lateral (M-L) planes as shown in Fig. 3.3. The geometric model for COM delimited on the A-P direction i.e., in the horizontal sagittal plane and the M-L direction i.e., horizontal frontal plane are as follows:

$$COM_{AP} = \sum_{n=1}^{12} C_n \times l_n \times m_n \times \cos(\theta_n) \tag{3.1}$$

$$COM_{ML} = \sum_{n=1}^{12} C_n \times l_n \times m_n \times \cos(\theta_n) \tag{3.2}$$

Here, C is the estimated location of the COM on the respective segmental length, m refers to proportion of total body mass of each body segment defined by the segmental length, θ represents the segmental angle (Fig. 3.3), l is the length of the joint segment, and n is the total number of segmental angles as shown in Fig. 3.3 (Black et al., 2007; De Leva, 1996a, 1996b). The segmental length varied within each toe-tapping cycle due to projection related errors (predominantly in the frontal plane) however, previous relevant studies suggested that the standard deviation (SD) of the segmental length at any particular instance of time was extremely small (Black et al., 2007). Therefore we computed a grand mean of individual segmental length

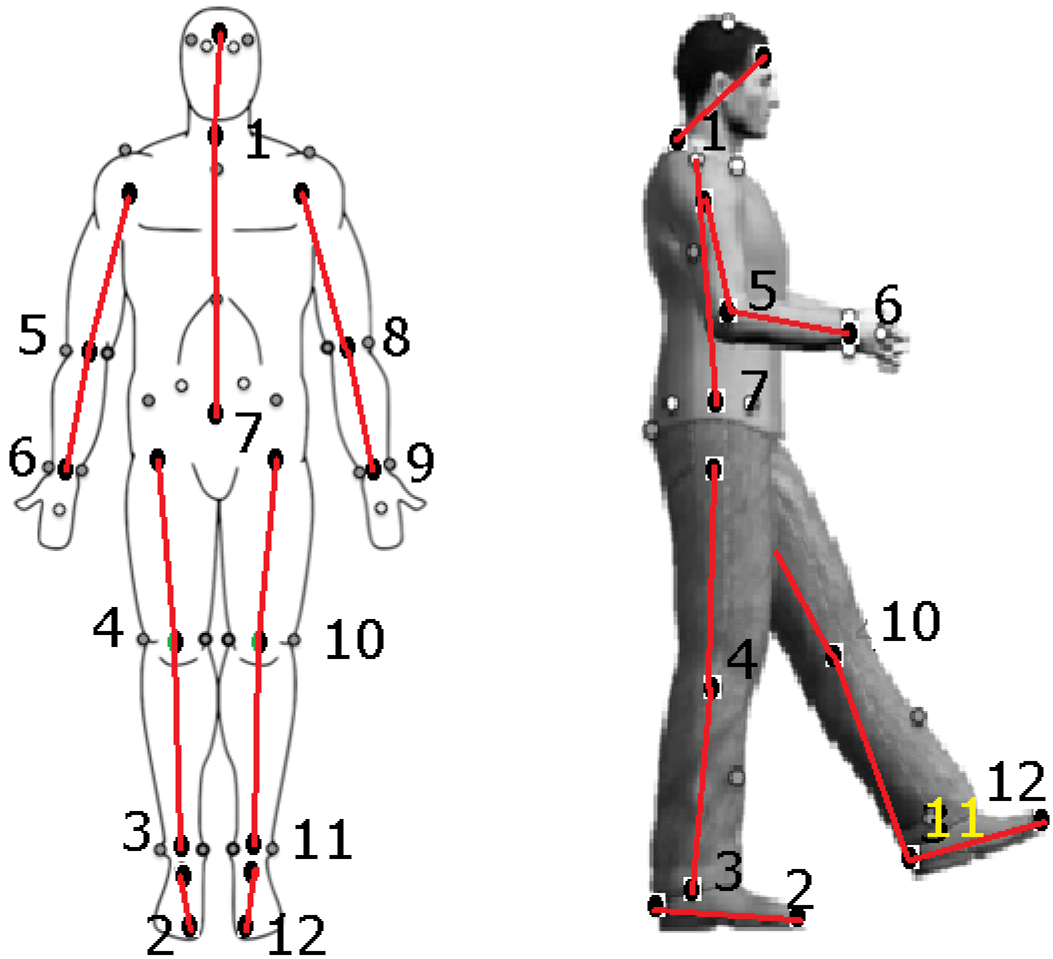

Figure 3.3: Sagittal (A-P) and frontal (M-L) planar view : Geometric model for the COM position is composed of 12 segmental angles.

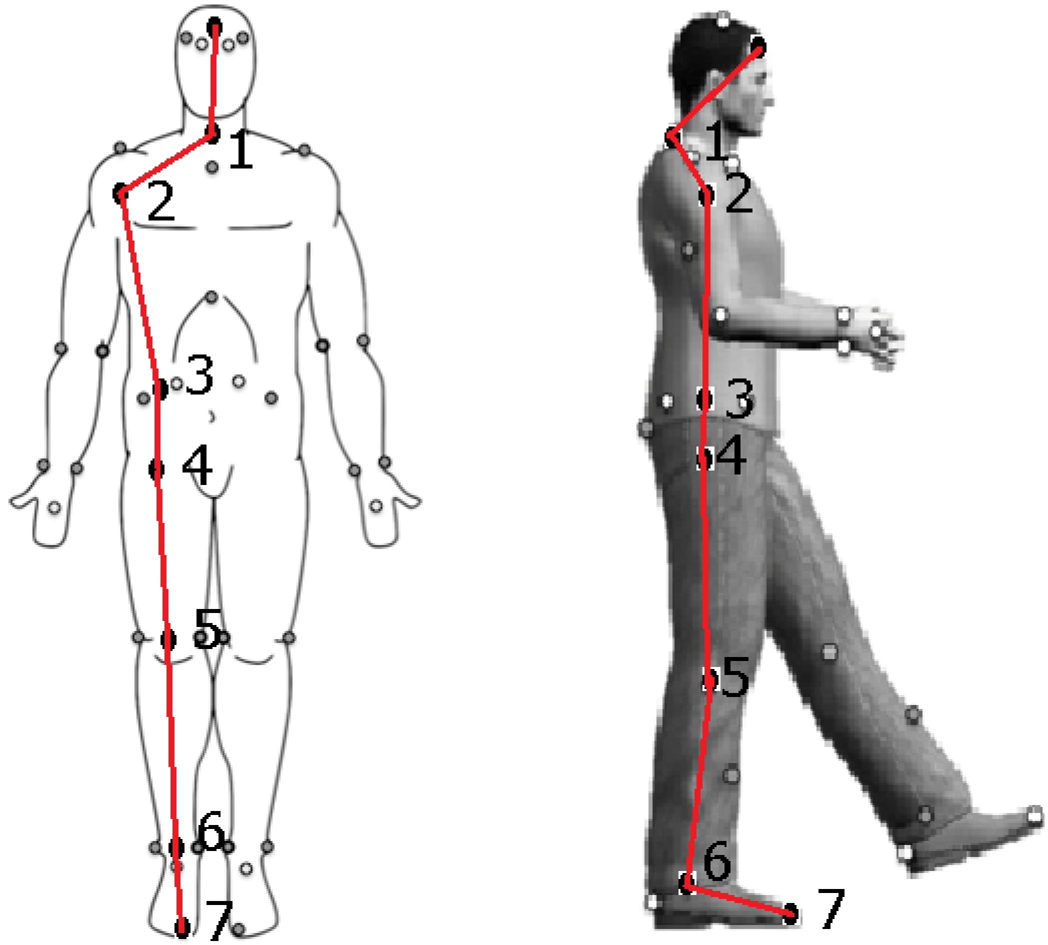

Figure 3.4: Sagittal and frontal view: Geometric model for the HEAD position is composed of 7 segmental angles; and defined with respect to the stance leg.

based on all the repetitive toe-tapping cycles data to be the representative of that specific segmental length (Black et al., 2007).

We were interested in comparing the COM position with the HEAD and the TOE positions. Figs. 3.4 and 3.5 show the geometric link defining the position of the HEAD and the TOE with respect to the fixed stance leg during the toe-tapping task. Example: During the left leg forward toe-tapping the HEAD and the TOE trajectory were modeled with respect to the right stance leg (Figs. 3.4 and 3.5).

For left leg forward toe-tapping, the HEAD trajectory based on the right stance

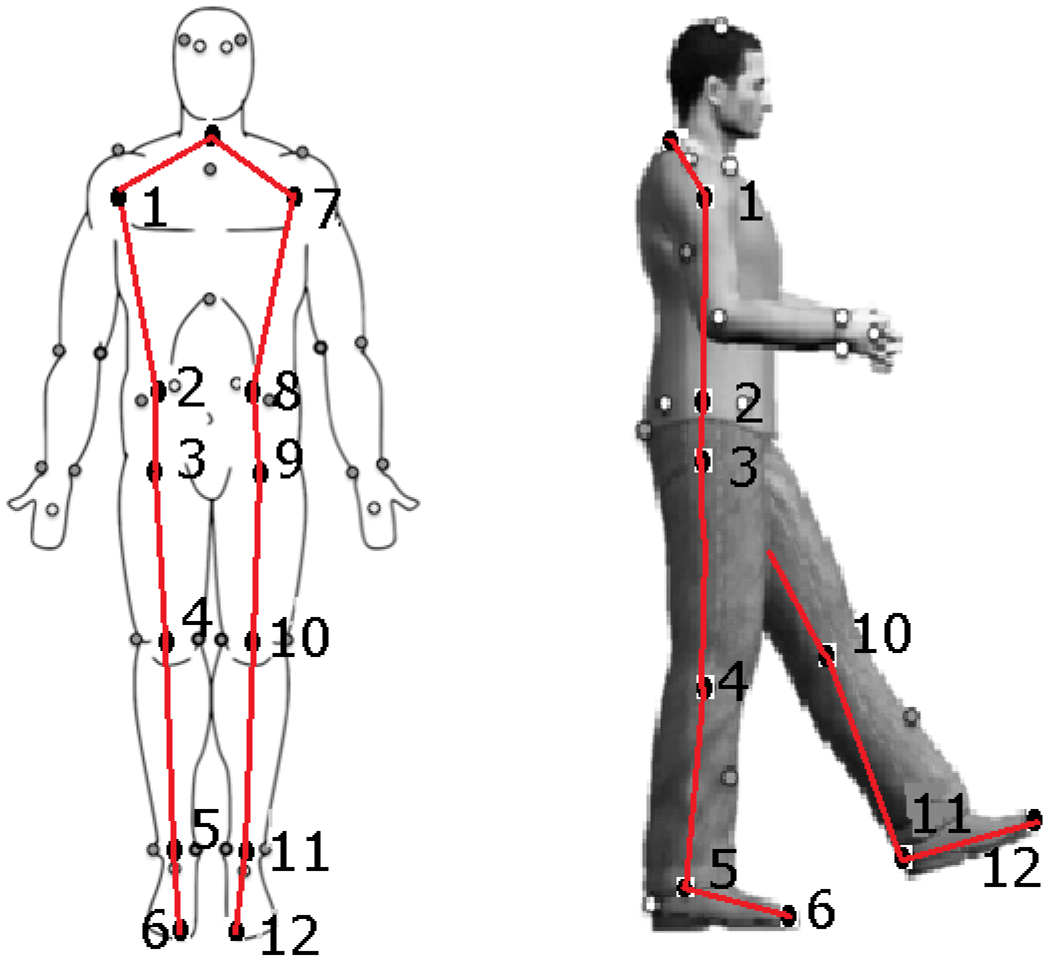

Figure 3.5: Sagittal and frontal view: Geometric model for the TOE position is composed of 12 segmental angles; and defined with respect to the stance leg.

leg is composed of seven segmental angles (angle and segmental length definition of the: head^{1}: vertex to C7; right-side: shoulder-neck^{2}: shoulder to C7, trunk^{3}: mid superior iliac spine to shoulder, pelvic^{4}: mid superior iliac spine to hip joint center, thigh^{5}: hip joint center to knee joint center, shank^{6}: knee joint center to ankle joint center and foot^{7}: ankle joint center to toe), as shown in Fig. 3.4. The geometric model for the HEAD delimited on the A-P direction i.e., in the horizontal sagittal plane and the M-L direction i.e., horizontal frontal plane are as follows:

$$HEAD_{AP} = p + \sum_{n=1}^{7} l_n \times \cos(\theta_n) \tag{3.3}$$

$$HEAD_{ML} = p + \sum_{n=1}^{7} l_n \times \cos(\theta_n) \tag{3.4}$$

here p is the spatial position of the right toe in the VICON coordinate system, along appropriate body spatial dimensions: A-P or M-L; θ represents the segmental angles, l is the length of the joint segment and n is the total number of segmental angles as shown in Fig. 3.4.

For left leg forward toe-tapping, the TOE position based on the right stance leg is composed of twelve segmental angles (angle and segmental length definition of the: right-side: shoulder-neck^{1}: shoulder to C7, trunk^{2}: mid superior iliac spine to shoulder, pelvic^{3}: mid superior iliac spine to hip joint center, thigh^{4}: hip joint center to knee joint center, shank^{5}: knee joint center to ankle joint center, foot^{6}: ankle joint center to toe; left-side: shoulder-neck^{7}: shoulder to C7, trunk^{8}: mid superior iliac spine to shoulder, pelvic^{9}: mid superior iliac spine to hip joint center, thigh^{10}: hip joint center to knee joint center, shank^{11}: knee joint center to ankle joint center, and foot^{12}: ankle joint center to toe) as shown in Fig. 3.5. The geometric model for the TOE delimited on the A-P direction i.e., in the horizontal sagittal plane and the M-L direction i.e., horizontal frontal plane are as follows:

$$TOE_{AP} = p + \sum_{n=1}^{6} l_n \times \cos(\theta_n) - \sum_{n=7}^{12} l_n \times \cos(\theta_n) \tag{3.5}$$

$$TOE_{ML} = p + \sum_{n=1}^{6} l_n \times \cos(\theta_n) - \sum_{n=7}^{12} l_n \times \cos(\theta_n) \tag{3.6}$$

here p is the spatial position of the right toe in the VICON coordinate system, along appropriate body spatial dimensions: A-P or M-L; θ represents the segmental angles, l is the length of the joint segment and n is the total number of segmental angles as shown in Fig. 3.5.

3.2.5 THE UCM COMPUTATIONAL FRAMEWORK

To setup the geometry inspired mathematical models in the UCM computational framework, we then computed the mean of each segmental angle at each, 100% normalized, integer time instance across all the repetitions (i.e., toe-tapping related gait cycles). Our geometrical models are inspired from forward kinematic model thus they are nonlinear. Therefore, the Jacobian matrix was computed to estimate a linear approximation of these models. The Jacobian was computed based on the grand mean of the segmental angles. This matrix of partial derivatives corresponds to changes in the task-level control variable with respect to the changes in the individual segmental angles. The null space of the Jacobian, ϵ, was computed to determine the basis vectors spanning the linearized UCM. There were $n - r$ basis vectors, where n represents the number of dimensions in the joint configuration space defined by segmental angles and r represents the number of dimensions of the individual task variable. For the COM, HEAD and TOE position, the number of dimensions in the joint configuration space defined by n were 12, 7 and 12 respectively as shown in Figs 3.3, 3.4 and 3.5; while dimension of the task-level variable is $r = 1$.

At each integer percent time instance event, the deviation from the grand mean for each segmental angle was computed to obtain a deviation matrix, $\theta - \bar{\theta}$. The deviations $(\theta - \bar{\theta})$ which were projected onto the null space (Jacquier-Bret et al., 2009) represent the joint-level deviations which occur without altering the value of the task-level control variables were computed as follows:

$$\theta_{\parallel} = \epsilon.(\theta - \bar{\theta}) \tag{3.7}$$

The deviation matrix component perpendicular to the null space represents the joint-level deviations which alters the value of the task-level control variables were computed as follows (Jacquier-Bret et al., 2009):

$$\theta_{\perp} = (\theta - \bar{\theta}) - \theta_{\parallel} \tag{3.8}$$

The amount of variability per DOF within the UCM is estimated as:

$$\sigma_{\parallel}^2 = (n - r)^{-1} N^{-1} \Sigma \theta_{\parallel}^2 \tag{3.9}$$

where $\sigma_{\parallel}^2$ is the squared length of the deviation vector lying in the linearized UCM. The amount of variability per DOF perpendicular to the UCM was estimated as:

$$\sigma_{\perp}^2 = r^{-1} N^{-1} \Sigma \theta_{\perp}^2 \tag{3.10}$$

$$UCMRatio = \frac{\sigma_{\parallel}}{\sigma_{\perp}} \tag{3.11}$$

The UCM hypothesis states that the CNS specifies the stable state in the task space, and not in joint space; meaning, the CNS controls the task-level variables, more than the individual joints. As a result, the overall variability of the configuration parallel to the UCM is predicted to be much bigger than that perpendicular to the UCM; leading to a UCM ratio higher than unity. If the UCM ratio for a task variable is greater than unity, it means that the control variable is given priority over the segmental angles by the CNS.

3.2.6 DEPENDENT VARIABLES

The primary dependent variables used in subsequent analyses for each hypothesized control variables are $\sigma_{\parallel}$ and $\sigma_{\perp}$. These variables are not directly comparable across hypotheses about different task variables (i.e., COM, HEAD, or TOE) because of the differences in the DOFs comprising the joint configuration space for each. Therefore, the variable UCM ratio was derived to compare the different control variables statistically. Moreover, task variable variability was also considered a dependent variable. These dependent variables, each, have two components, one for each dimension: horizontal sagittal or anterior-posterior (A-P), and horizontal frontal or medial-lateral (M-L).

The dependent variables were calculated for each participant at 25% and 50% of the normalized task period of the trajectory, for each condition. Here, the 25%

represents the mid air phase – when the COM is shifted towards the stance leg (Han et al., 2006; McIlroy & Maki, 1999; Patla et al., 1999), and 50% occurred during the toe tapping or during the foot placement phase. Thus we present and statistically analyze, only, the mid-air – 25% and toe-tap – 50% phases of the task period.

3.2.7 INDEPENDENT VARIABLES

The independent variables that were directly manipulated for the repeated measures ANOVA were: (1) the age groups (6-year-old children, 10-year-old children and adults); (2) the movement direction (forward, backward, and lateral); (3) the movement phase (mid-air – 25% and toe-tap – 50%); and (4) the task or control variable (COM, HEAD, and TOE position).

3.2.8 HYPOTHESIS AND STATISTICAL ANALYSIS

We hypothesized: (1) Neural motor control structure: In adults, all the task or control variables (COM, HEAD and the TOE) would always be controlled more than the individual joint motions; i.e., the UCM ratio would be more than unity regardless of the movement direction (forward, backward, and lateral) or phase (mid-air – 25% and toe-tap – 50%) (Barberini & Macpherson, 1998; Hirasaki et al., 1999; Patla et al., 1999; Winter, 1995; Woollacott & Tang, 1997); (2) Direction effect: Adult forward toe-tapping, during both the mid-air – 25% and toe-tap – 50% phase, is more controlled than the backward or lateral toe-tapping (Freitas & Duarte, 2012; Hackney & Earhart, 2009; Hausdorff et al., 1997; Lee et al., 2013); and (3) Age effect: Based on walking literature, we hypothesize the overall control structure of step-like toe-tapping would improve with age (Cavagna et al., 1983; Dierick et al., 2004; Hausdorff et al., 1999; Preis et al., 1997); however the improvement occurs until the age of 7 (Dierick et al., 2004); meaning, there is no significant differences in the overall control structure for 10-year-old children and young adults.

For statistical analysis, repeated measures analysis of variance (ANOVA) was conducted using the SAS statistical software and the level of significance for all statistical tests was set at $p < 0.05$. The independent variables in the ANOVA model depended on the hypothesis; detailed explanation of the ANOVA model associated with the individual hypothesis is provided in their respective result section. When particular interaction effects, related to our hypotheses, were found to be significant, further post-hoc analysis was performed using the Bonferroni correction. The graphs were generated using SPSS statistical software.

3.3 ASSUMPTIONS

DIRECTION SPECIFIC MODELING

In section 3.4 and 3.6, the analyses for the forward and backward toe-tapping were performed in the horizontal sagittal dimension; while the lateral tapping was studied in the horizontal frontal dimension. This specific constraint in the analysis was set because the experimental protocol required the participants to consistently tap a self-selected spatial spot (approximately fixed position) with their toe, in these body-spatial dimensions; this is evident from Figs. 3.6, 3.7, and 3.8. Moreover,

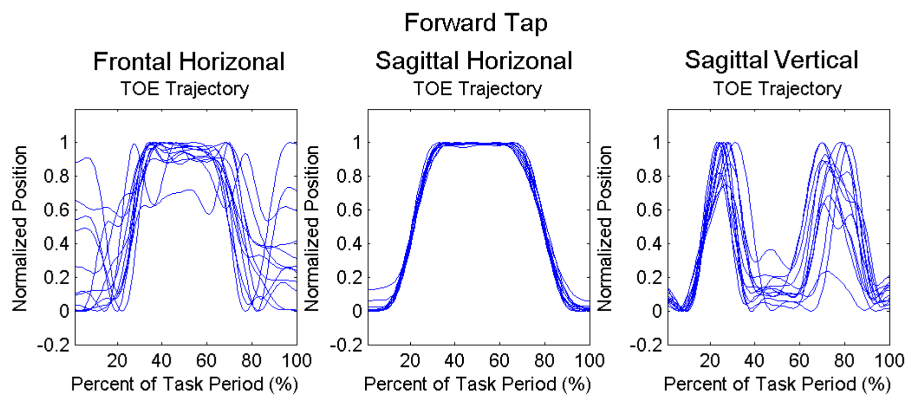

Figure 3.6: Exemplar data (CT102) shows that during forward toe-tapping, the most consistent tapping occurs in the sagittal horizontal body-spatial dimension.

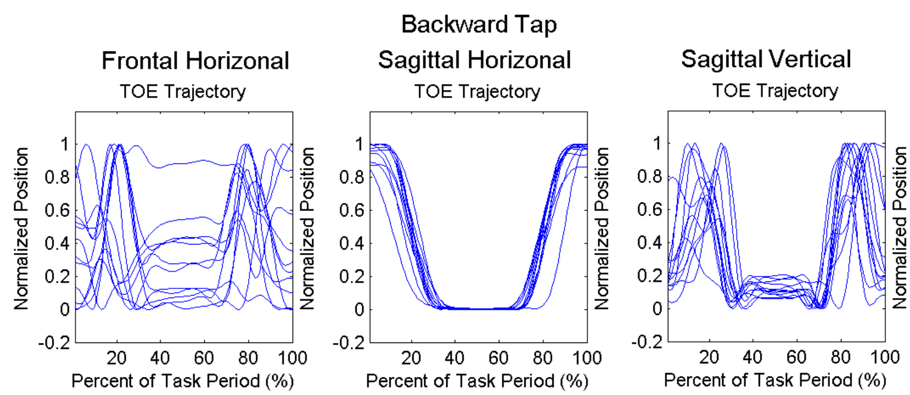

Figure 3.7: Exemplar data (CT102) shows that during backward toe-tapping, the most consistent tapping occurs in the sagittal horizontal body-spatial dimension.

during the toe-tapping phase – 50%, as the toe touches the ground there is no change or very minimal change in the vertical toe position. Therefore, to keep consistency and compatibility with other analyses the vertical direction was ignored.

RESULTANT HORIZONTAL DIMENSION

The forward, backward and lateral toe-tapping were studied in different dimensions. Therefore running the repeated measures variance analysis (ANOVA), independently, on separate dimensions to test how the toe-tapping differs based on

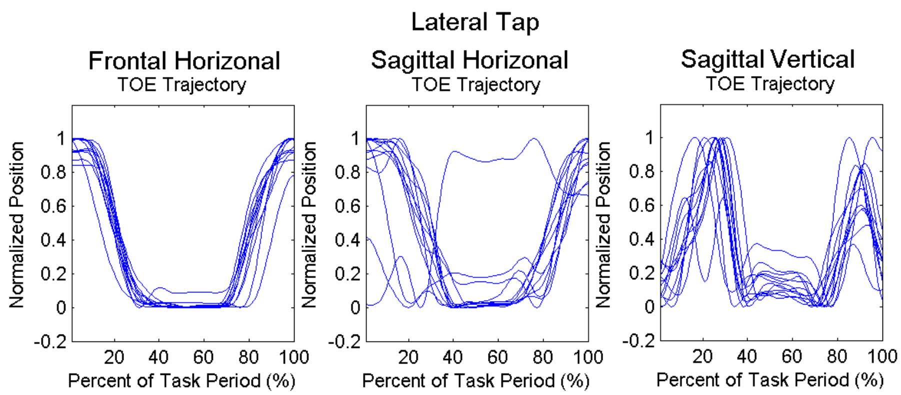

Figure 3.8: Exemplar data (CT102) shows that during lateral toe-tapping, the most consistent tapping occurs in the frontal horizontal body-spatial dimension.

movement direction, would not be logical. To get around the issue, the statistical analysis was, instead, performed by considering a resultant horizontal dimension by combining the two dimensions: horizontal frontal and horizontal sagittal. It is on this resultant dimension that the analyses testing the directional effect in section 3.5 were conducted. For complete discloser we have also presented the results obtained along the decomposed component dimension, as well.

COMBINED LEG DATA

None of the statistical analyses considered the leg as an independent variable because it was assumed that the forward, backward and lateral toe tapping movements were similar for both legs. To test this assumption we have performed all our analyses, separately, on the right and the left leg data as well; and found no significant differences between the legs. Therefore data from the two legs were not studied separately but were combined.

3.4 RESULTS: NEURAL MOTOR CONTROL STRUCTURE

3.4.1 TASK OR CONTROL VARIABLE VARIABILITY

Figs. 3.9, 3.10 and 3.11 represent the mean (±SEM: Standard Error of Mean) movement variability of all the task variables: COM, HEAD, and the TOE position; at two phases of the leg movement: mid air, toward the tap – 25% and toe tap – 50%, while adults performed the forward (Fig. 3.9), backward (Fig. 3.10) and lateral (Fig. 3.11) toe-tapping respectively; with both the right and left leg.

In the following sections 3.4.1.1, 3.4.1.2, and 3.4.1.3, the results of the 3 (control variable) $\times$ 2 (phase of the toe-tapping movement) repeated measures ANOVA for the three directions of tapping (forward, backward, and lateral) using task variability, as the dependent variable, are presented. Overall, note that across all three directions COM varied the least and TOE varied the most.

3.4.1.1 FORWARD TOE-TAPPING

Significant effects were observed for the main effect of the control variable (p = 0.0004), and interaction between the control variable and the phase ($p = 0.0158$). Further post-hoc analysis using the Bonferonni correction showed that, during mid air phase – 25%, the TOE was significantly more variable than the COM (p = 0.0005) and the HEAD ($p = 0.0144$); the results are summarized in Fig. 3.9.

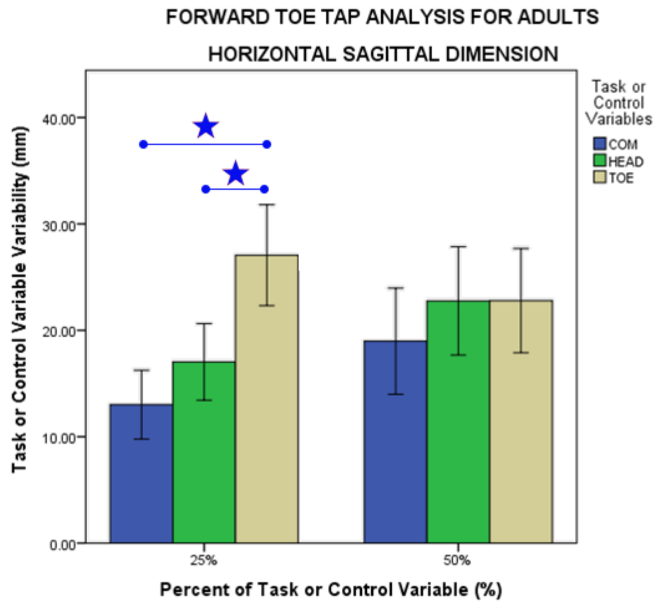

Figure 3.9: Mean (±SEM) variability of the control variables, along the horizontal sagittal dimension, at two phases: mid air – 25% and toe tap – 50%; for adults performing the forward toe-tapping movement.

3.4.1.2 BACKWARD TOE-TAPPING

During backward toe-tapping, significant effects were revealed for the control variable ($p < 0.0001$) and the phase ($p = 0.0129$). Post-hoc analysis showed that the toe tap (50%) phase was significantly more variable than the mid air (25%) phase ($p \ll 0.05$). Similar to the forward analysis: the HEAD ($p = 0.006$) and the TOE ($p < 0.0001$) were significantly more variable than the COM; in addition, the TOE was significantly more variable than the HEAD ($p = 0.0022$) across the two phases. The result suggests, in terms of variability (worst to best) the ranking of these task variables is: TOE > HEAD > COM.

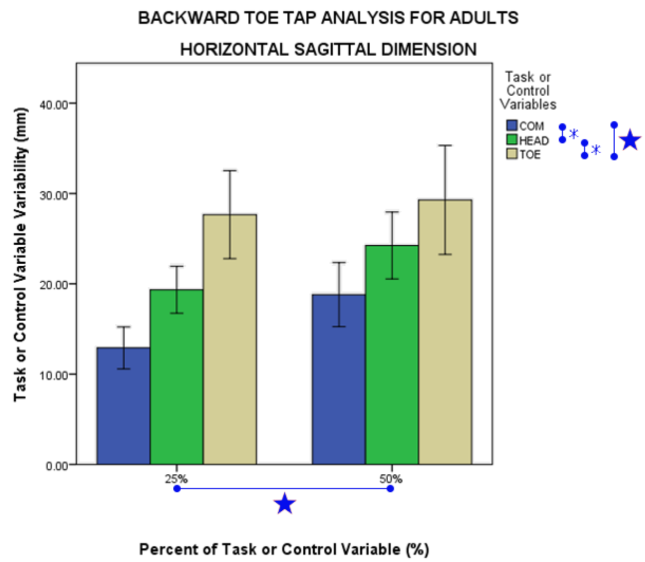

Figure 3.10: Mean (±SEM) variability of the control variables, along the horizontal sagittal dimension, at two phases: mid air – 25% and toe tap – 50%; for adults performing the backward toe-tapping movement.

3.4.1.3 LATERAL TOE-TAPPING

During lateral toe-tapping, a significant main effect was found, only, for the control variable ($p = 0.001$). Fig. 3.11 summarizes the result, it illustrates that the HEAD ($p = 0.0247$) and the TOE ($p = 0.0009$) were more variable than the COM.

3.4.1.4 SUMMARY OF THE VARIABILITY MEASURE

The aforementioned results indicate that during the toe-tapping movement the most consistent task variable is the COM, followed by the HEAD and the TOE: COM > HEAD > TOE, irrespective of the phase. These results, however do not, necessarily, conclude that (1) the task variable consistency is a consequence of the precise consistent control of the individual joint motions, or, (2) that consistency

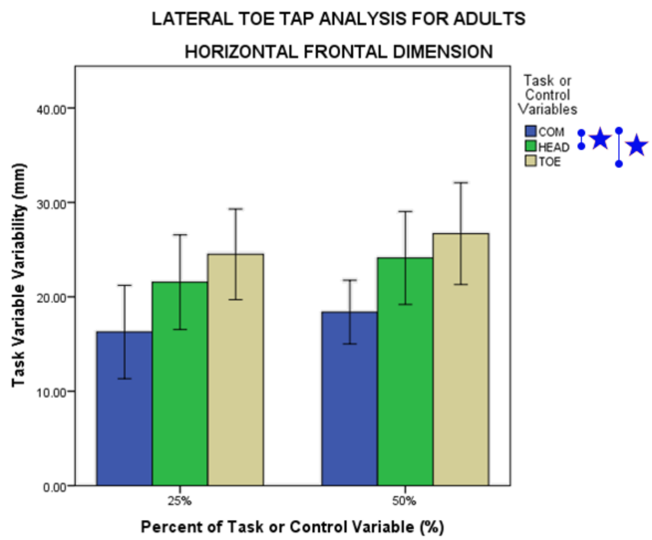

Figure 3.11: Mean (±SEM) variability of the control variables, along the horizontal frontal dimension, at two phases: mid air – 25% and toe tap – 50%; for adults performing the lateral toe-tapping movement.

is occurring regardless of larger joint trajectory variability. This question can be addressed by setting up a similar analysis using the Uncontrolled Manifold (UCM) technique. The UCM conception provides a systematic framework for analyzing the joint variability structure of the task variables: parallel and orthogonal to the multi-dimensional UCM engraved in the segmental angle based state space. A relative comparison between these two joint variability structures may provide a better answer to how the task or control variables are stabilized and controlled.

UCM ANALYSIS: JOINT CONFIGURATION VARIABILITY

Figs. 3.12, 3.13 and 3.14, each, illustrates the mean (±SEM) joint configuration variance parallel to ($\sigma_{\parallel}$) and perpendicular ($\sigma_{\perp}$) to the linearized uncontrolled manifold (UCM) while adults perform forward (Fig. 3.12), backward (Fig. 3.13) and lateral (Fig. 3.14) toe-tapping respectively. The figures show the distribution

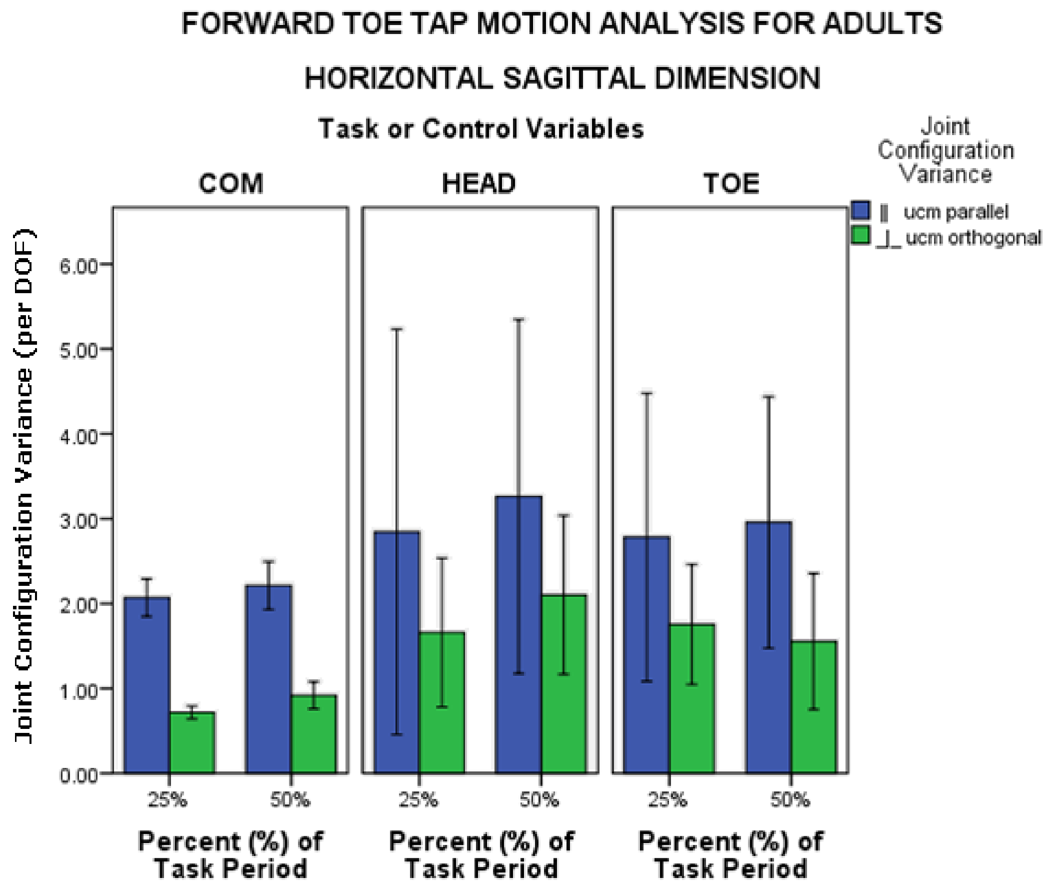

Figure 3.12: Mean (±SEM) joint configuration variance parallel to (‖) and perpendicular (⊥) to the linearized uncontrolled manifold (UCM) associated with the task variables at mid air – 25% and toe tap – 50% as adults perform forward toe-tapping.

of these two measures for the task or control variables, at the two phases: mid air and toe tap.

In general, it can be observed in Figs. 3.12, 3.13 and 3.14 that the component of the joint variable arranged parallel to the uncontrolled manifold is greater than the perpendicular component. This is true for all the conditions, and at all phases of the movement. It suggests that the overall fluctuations in the joint configuration describing and subsequently affecting the COM, HEAD and TOE position are reduced, in contrast to the joint configuration that does not affect these variables;

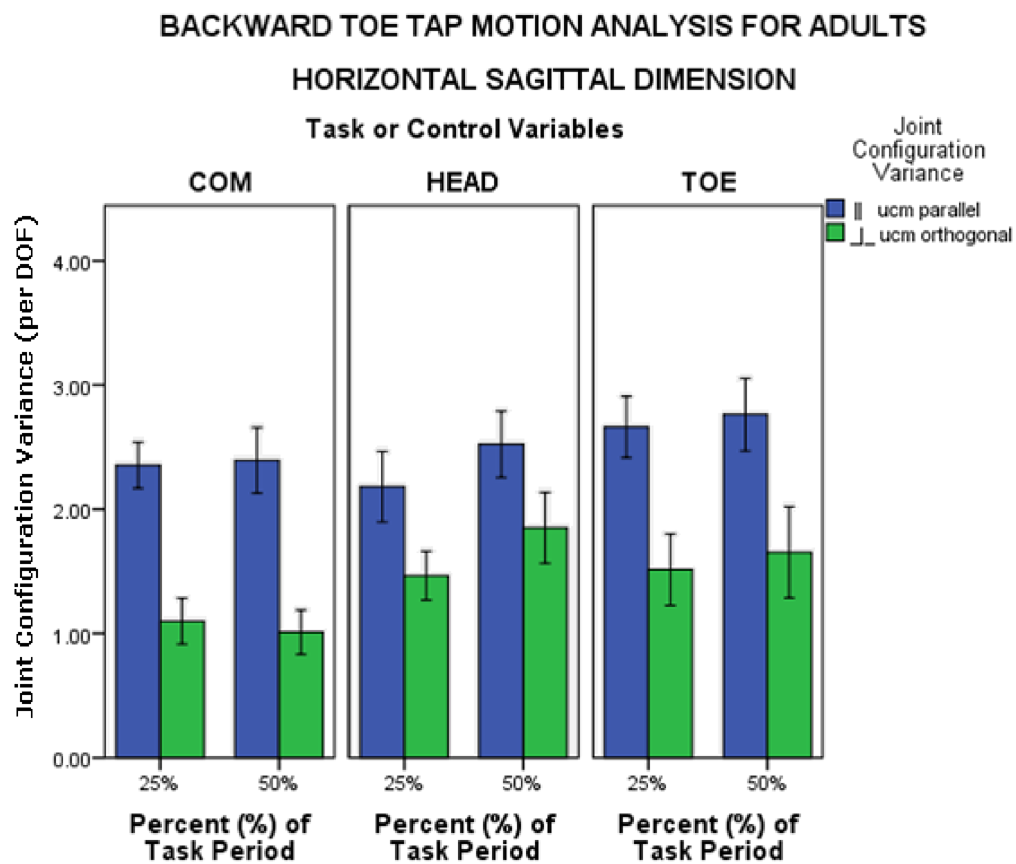

Figure 3.13: Mean (±SEM) joint configuration variance parallel to (‖) and perpendicular (⊥) to the linearized uncontrolled manifold (UCM) associated with the task variables at mid air – 25% and toe tap – 50% as adults perform backward tapping.

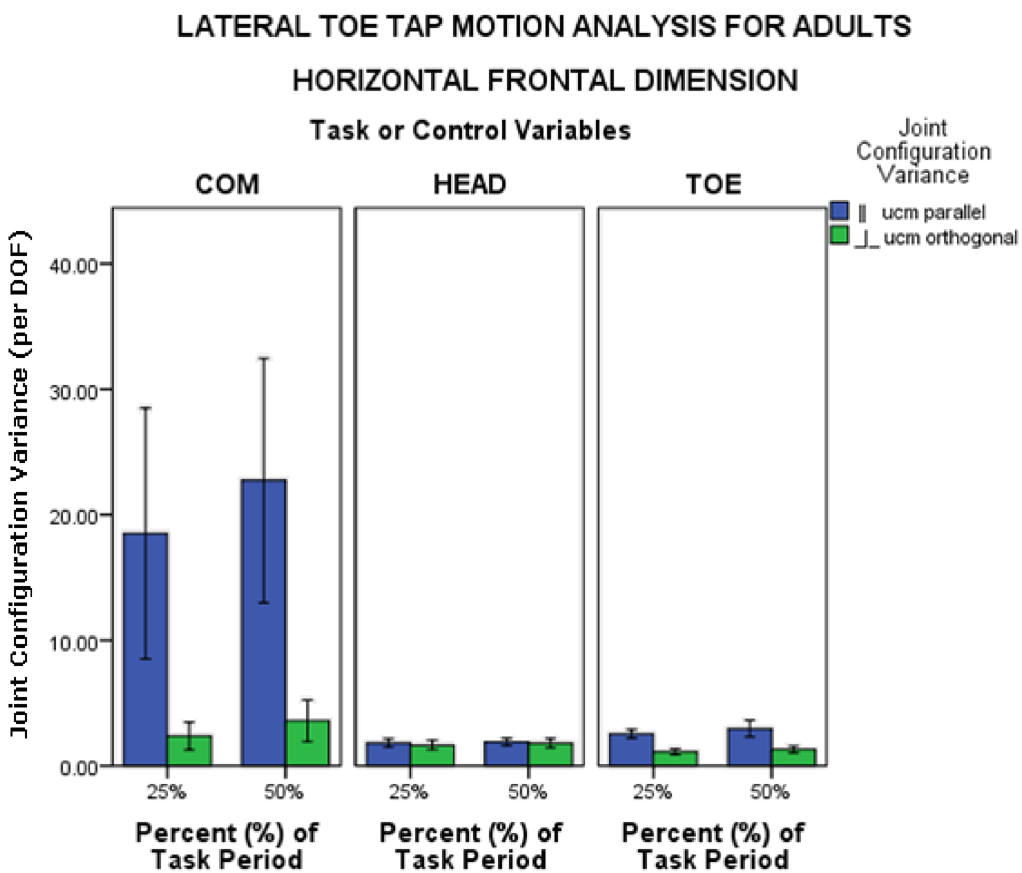

Figure 3.14: Mean (±SEM) joint configuration variance parallel to (‖) and perpendicular (⊥) to the linearized uncontrolled manifold (UCM) associated with the task variables at mid air – 25% and toe tap – 50% as adults perform lateral toe-tapping.

indicating that the control of these task variables are greater than the individual joint trajectory control. Based on the relative variability between the perpendicular and orthogonal component (Figs. 3.12, 3.13 and 3.14), it can be well understood that the COM is the most controlled, closely followed by the TOE and the HEAD.

3.4.2 UCM ANALYSIS: COMPARISON OF TASK VARIABLES

Figs. 3.15, 3.16, and 3.17 show the mean UCM ratio (±SEM) associated with all the task variables at the two phases, while adults perform the forward (Fig. 3.15), backward (Fig. 3.16) and lateral (Fig. 3.17) toe-tapping respectively. These figures show the distribution of the UCM ratio under all conditions, at all the phases. It can be observed that, in all the conditions, the UCM ratio associated with the COM is the highest, followed by the TOE and then the HEAD; these speculations were supported by the 3 (control variable) $\times$ 2 (phase) repeated measures ANOVA using the UCM ratio as the dependent variable.

3.4.2.1 FORWARD TOE-TAPPING

The 3 (control variable) $\times$ 2 (phase) repeated measures ANOVA for the forward tapping revealed significant main effect of the control variable ($p < 0.0001$) and interaction of the control variable and phase ($p < 0.0438$). Post-hoc Bonferonni correction revealed that UCM ratio for the COM was significantly larger than that for the TOE ($p < 0.0005$). Moreover, it was significantly larger in comparison to the HEAD at all the phases: mid air ($p = 0.0004$) and toe tap ($p = 0.0085$). The

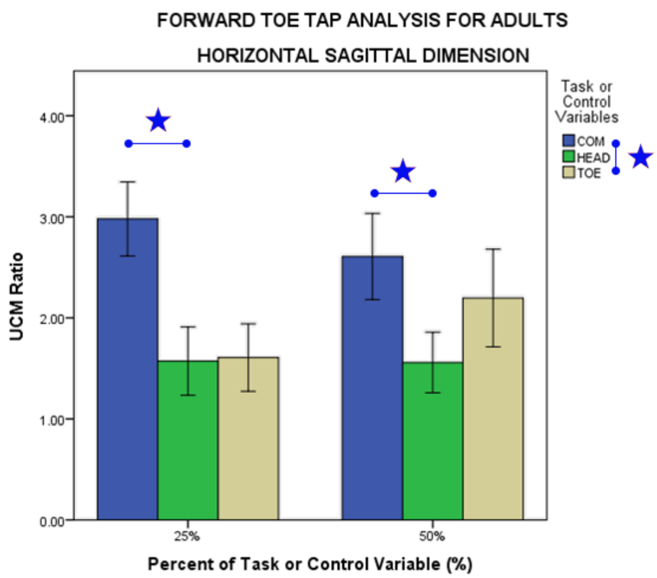

Figure 3.15: Mean (±SEM) UCM ratio for the task or control variables at two phases: mid air – 25% and toe tap – 50%, while adults perform forward toe-tapping.

results are summarized in Fig. 3.15.

3.4.2.2 BACKWARD TOE-TAPPING

Fig. 3.16 suggests that the UCM ratio structure in backward tapping is similar to its forward counterpart: COM > TOE > HEAD. The 3 (control variable) × 2 (phase) repeated measures ANOVA analysis revealed a significant main effect of the control variables ($p = 0.0003$). Post-hoc analysis revealed that the UCM ratio for the COM was significantly larger than that for the HEAD ($p = 0.0002$). Moreover, the ratio for the COM was larger than that for the TOE ($p = 0.0505$); while the value for the TOE was larger than that for the HEAD ($p = 0.06$), although it did not reach statistical significance.

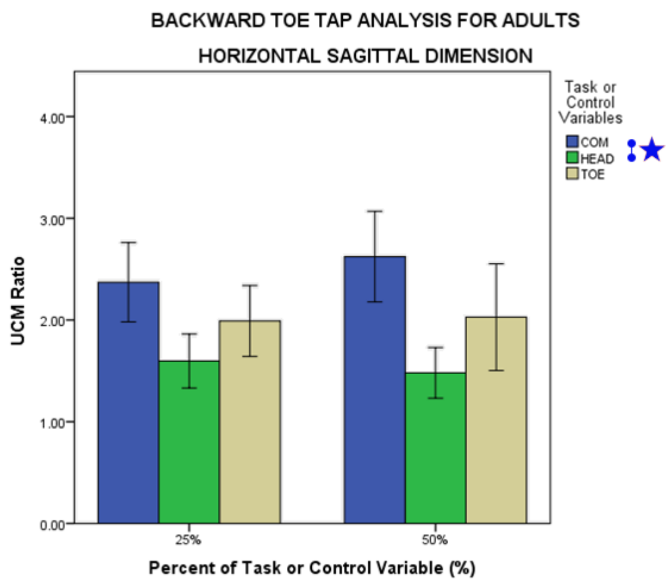

Figure 3.16: Mean (±SEM) UCM ratio for the task or control variables at two phases: mid air – 25% and toe tap – 50%, while adults perform backward toe-tapping.

3.4.2.3 LATERAL TOE-TAPPING

Fig. 3.17 shows that, during lateral tapping the UCM ratio for the COM is significantly more than that for the other task variables. The 3 (control variable) × 2 (phase) repeated measures ANOVA supports these differences with a significant main effect of the task variable ($p < 0.0001$). Post-hoc analysis revealed that the UCM ratio for the COM was significantly larger than that of the HEAD ($p < 0.0001$) and the TOE ($p = 0.0001$).

3.4.2.4 SUMMARY: JUSTIFYING THE UCM ANALYSIS

According to section 3.4.1.4, we can understand that the relative variability between the perpendicular ($\sigma_{\|}$) and orthogonal ($\sigma_{\perp}$) component of the uncontrolled

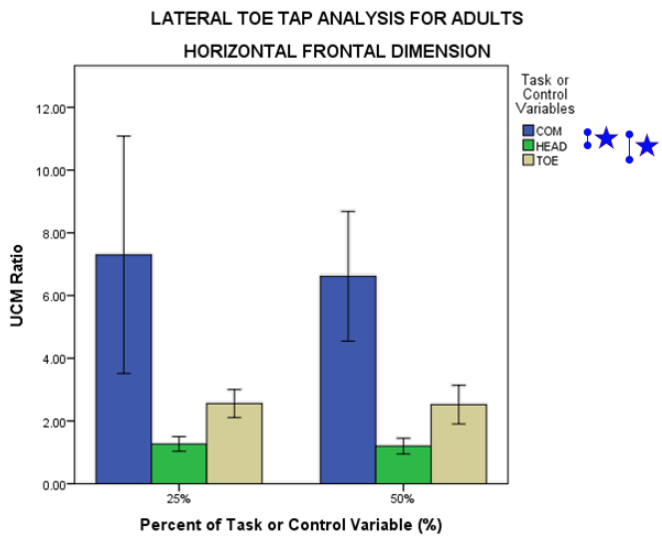

Figure 3.17: Mean (±SEM) UCM ratio for the task variables at two phases: mid air – 25% and toe tap – 50%, while adults perform lateral toe-tapping.

manifold (UCM) can help in identifying, and subsequently differentiate the more controlled variables from the less controlled ones. However, the UCM mathematical framework does not allow us to directly compare the different control variables based on these measures, unless the control variables are modeled using the same joint configuration. Meanwhile, the UCM ratio, defined by the ratio of ($\sigma_{\|}$) to ($\sigma_{\perp}$), allows a relative comparison of the degree of control-theoretic stability among the various task variables. UCM ratio of more than unity signifies that the individual joint configuration variance is organized in a manner that reduces the variation of the control variables. Thus, based on the UCM ratio a relative ranking of the task variables can be made, which provides the basis for the approximation of the neural motor control structure.

Based on the control-theoretic stability measure (UCM ratio) distribution as shown in Figs. 3.15, 3.16, and 3.17, we can suggest that the neural motor control structure (the relative ranking of the task or control variables) for toe-tapping is: (1) COM, followed by (2) HEAD and the (3) TOE. However, before making a final comment about this structure of the control variables during the forward, backward or lateral toe-tapping; we analyzed the data, further, to investigate if there is any direction or age effect. These analyses were done separately using the same analysis framework used in section 3.4, meaning, each analysis was conducted first on the task variable variability measure, and later using the UCM analysis.

3.5 RESULTS: DIRECTIONAL EFFECT

3.5.1 DIRECTIONAL VARIABILITY

Figs. 3.18 and 3.19 represent the mean (±SEM) variability associated with the task variables while adults perform the forward, backward and lateral toe-tapping movement at mid air – 25% (Fig. 3.18) and toe tap – 50% (Fig. 3.19) phase respectively. Moreover, the figures highlight the statistical significances that were observed during the 3 (control variable) $\times$ 3 (toe-tapping direction) repeated measures ANOVA with the task variable variability as the dependent variable.

3.5.1.1 MID AIR PHASE – 25%

Fig. 3.18 summarizes the results obtained from the 3 (control variable) $\times$ 3 (toe-tapping direction) repeated measures ANOVA for testing the directional effect, considering the mid air phase – 25%. The analysis revealed significant main effect for the task or control variable ($p < 0.0001$). The post hoc significance was consistent

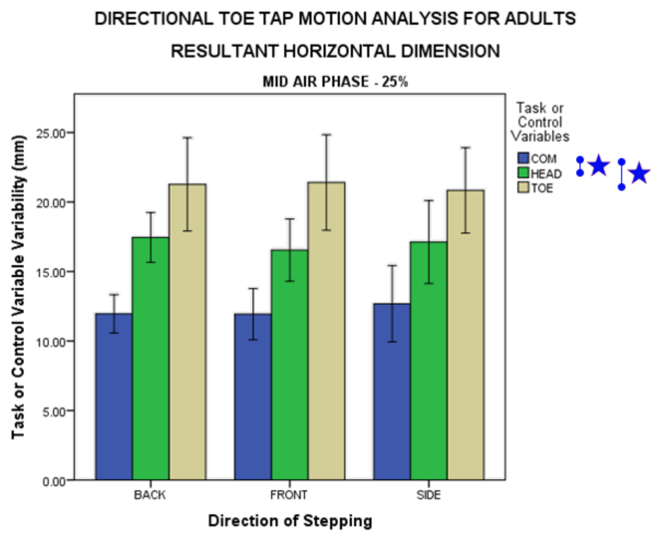

Figure 3.18: Mean (±SEM) variability of the task variables at mid air (25%) phase as adults perform the forward, backward and lateral tapping in the resultant dimension.

with the Fig. 3.18: the HEAD (p = 0.0004) and the TOE (p = 0.0001) were significantly more variable than the COM.

3.5.1.2 TOE TAP PHASE – 50%

Fig. 3.19 reveals similar variability structure at the toe tap phase – 50%. Significant main effect of the control variable (p = 0.0002) was observed. Post-hoc analysis revealed that the HEAD (p = 0.0026) and the TOE (p = 0.0002), both, were more variable than the COM.

Surprisingly, none of the analyses revealed significant main effect of the direction; however, similar analyses using the UCM ratio as the dependent variable provided a different view.

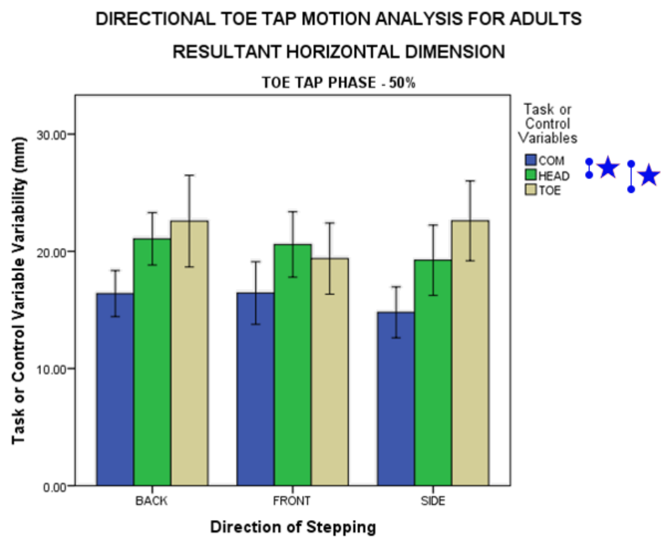

Figure 3.19: Mean (±SEM) variability of the task variables at toe tap (50%) phase as adults perform the forward, backward and lateral tapping in the resultant dimension.

3.5.2 UCM ANALYSIS: COMPARISON OF DIRECTION

Figs. 3.20 and 3.22 display the mean (±SEM) UCM ratio for the task variables as adults perform forward, backward and lateral toe-tapping movement at mid air (25%) (Fig. 3.20) and toe tap (50%) (Fig. 3.22) phase respectively. The figures are similar to Fig. 3.18 and 3.19 respectively; however, these figures display the UCM ratio as the dependent variable instead of the task variable variability.

At the mid-air phase considering the resultant horizontal dimension (Fig. 3.20), significant main effects were observed for the control variable ($p < 0.0001$) and direction ($p = 0.0079$). Post-hoc analysis revealed that the UCM ratio for the forward tapping was significantly larger than that for the backward ($p = 0.0233$) and the lateral ($p = 0.0149$). If the analysis was, further, decomposed based on the constituent horizontal dimensions, it can be seen that similar pattern in the

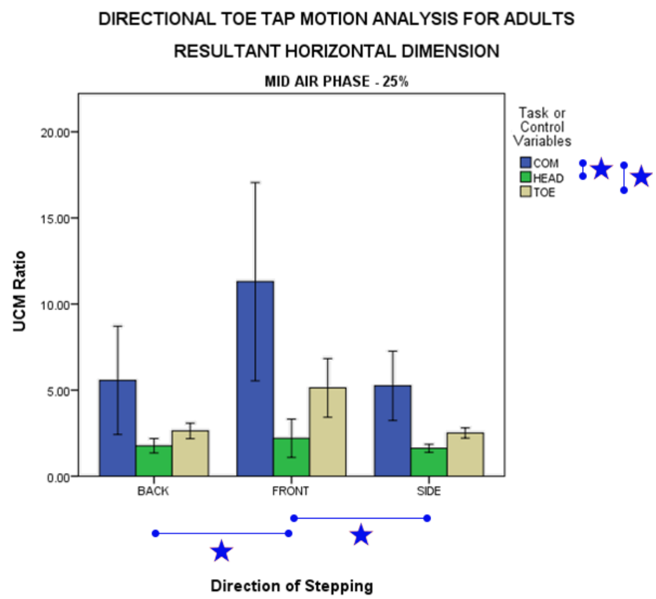

Figure 3.20: Mean (±SEM) UCM ratio for the control variables at mid air phase – 25% as adults perform the forward, backward and the lateral toe-tapping.

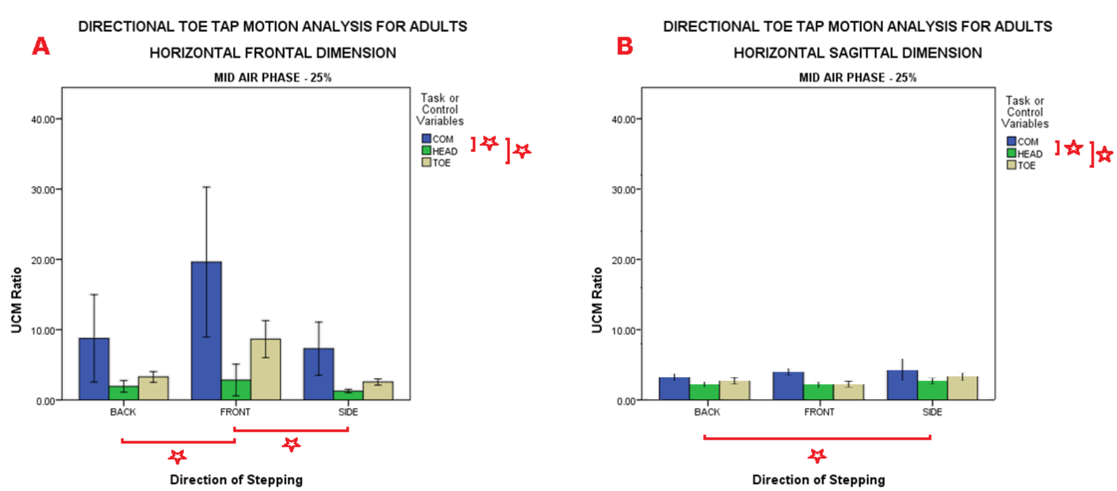

Figure 3.21: Mean (±SEM) UCM ratio for the control variables at mid air phase – 25% as adults perform the forward, backward and the lateral toe-tapping, considering the (A) frontal and the (B) sagittal horizontal dimension.

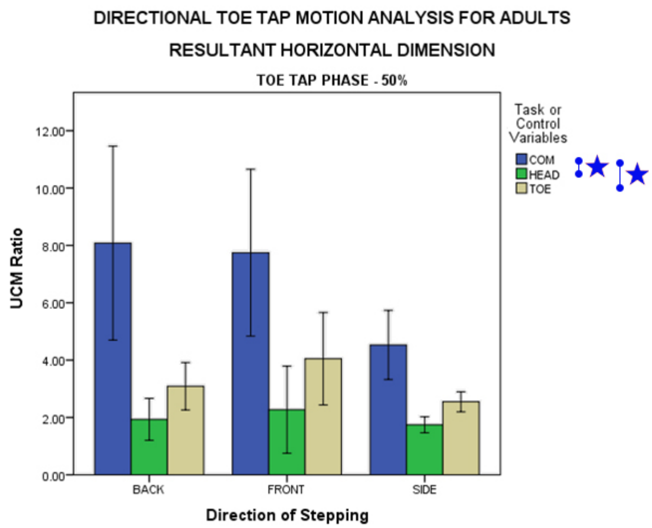

Figure 3.22: Mean (±SEM) UCM ratio for the control variables at toe tap phase – 50% as adults perform the forward, backward and the lateral toe-tapping.

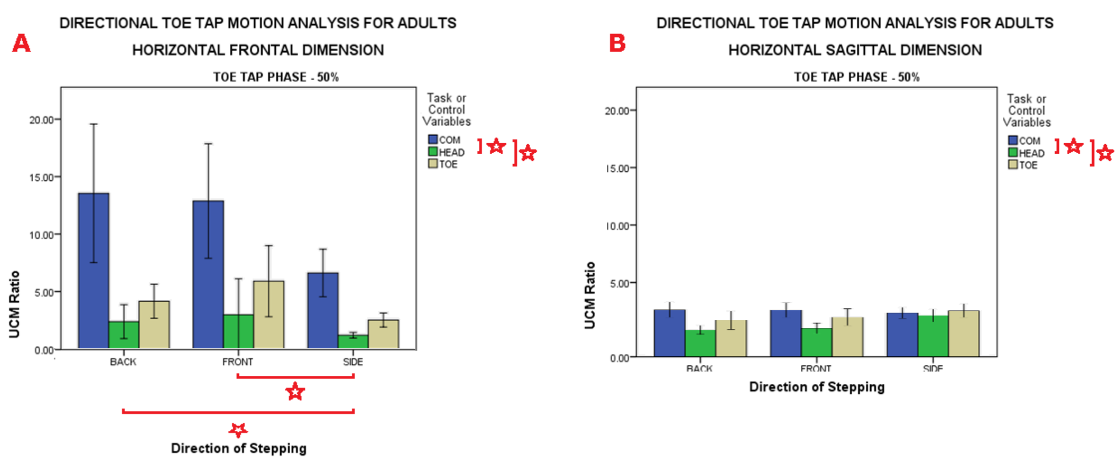

Figure 3.23: Mean (±SEM) UCM ratio for the control variables at toe tap phase – 50% as adults perform the forward, backward and the lateral toe-tapping, considering the (A) frontal and the (B) sagittal horizontal dimension.

distribution of the UCM ratio existed in both the M-L and the A-P dimensions (Fig: 3.21); M-L being the predominant one (Fig: 3.21 (A)). In both cases A (M-L dimension) and B (A-P dimension): significant main effects were observed for the control variable ($p \ll 0.05$) and direction ($p \ll 0.05$). The respective associated post-hoc results are summarized in Fig. 3.21.

Similar results were observed in the toe-tapping phase (50%) considering the resultant horizontal dimension (Fig. 3.22): a significant main effect for the control variable ($p < 0.0001$), however, the directional effect ($p = 0.0512$) did not quite reach the statistical significance. Post-hoc analysis revealed that the UCM ratio for the forward tapping was larger than that for the lateral ($p = 0.0681$), however it did not reach statistical significance. Furthermore, if the analysis was decomposed based on the constituent horizontal dimensions, it can be seen that similar pattern in the distribution of the UCM ratio existed in both the M-L and the A-P dimensions (Fig: 3.23); M-L being the predominant one (Fig: 3.23(A)). In both cases A and B: significant main effect was observed for the control variable ($p \ll 0.05$). In addition, in the M-L dimension there was effect of direction ($p = 0.0104$); while in the A-P dimension, this effect did not quite reach statistical significance level ($p = 0.0540$). The respective post-hoc results are summarized in Fig. 3.23. Furthermore, in all the aforementioned analyses (mid-air and toe tap), the UCM ratio for the COM was significantly larger than that for the HEAD ($p \ll 0.05$) or the TOE ($p \ll 0.05$).

The distribution of the mean ($\pm$SEM) joint configuration variance parallel to ($\sigma_{\parallel}$) and perpendicular ($\sigma_{\perp}$) to the linearized uncontrolled manifold (UCM) associated with the UCM ratios shown in Fig. 3.20 and Fig 3.22, are displayed in Figs.

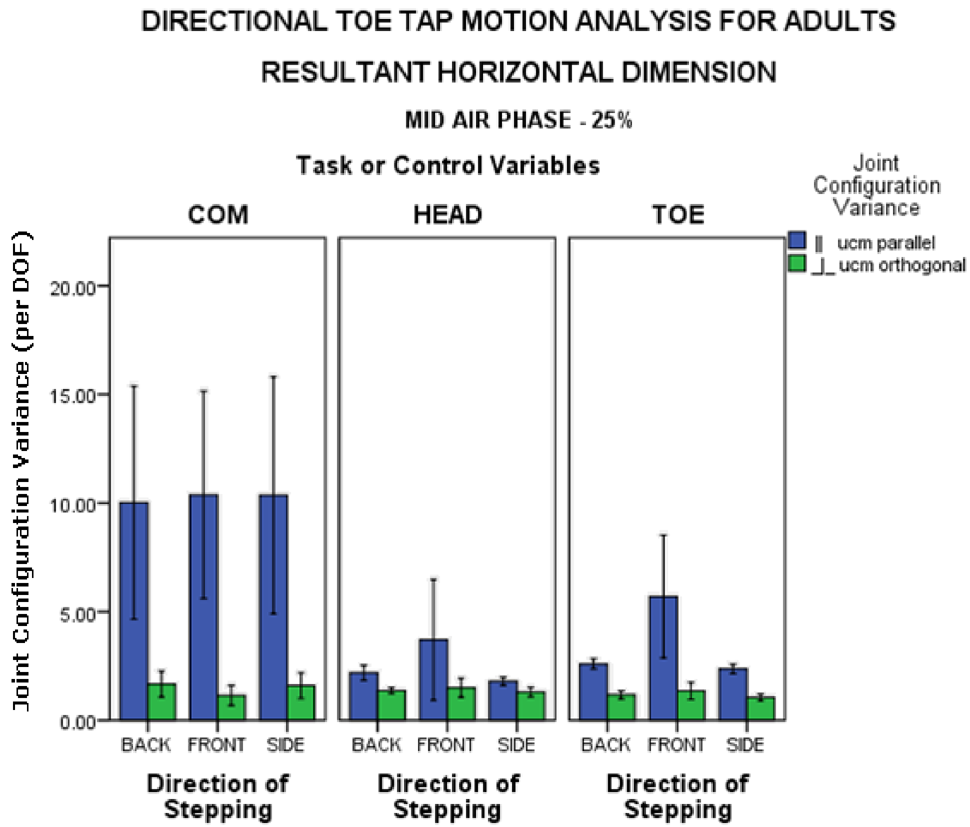

Figure 3.24: Mean (±SEM) joint configuration variance parallel (‖) to and perpendicular (⊥) to the linearized UCM associated with the task variables at the mid air – 25% phase; as adults perform the forward, backward and lateral toe-tapping.

3.24 and 3.25 respectively. These figures reinforce the aforementioned findings; it can be observed that in both the cases: mid air phase (Fig. 3.24) and toe tap phase (Fig. 3.25); the component of the joint variable arranged parallel ($\sigma_{\|}$) to the uncontrolled manifold is much greater than the component perpendicular ($\sigma_{\perp}$) to it.

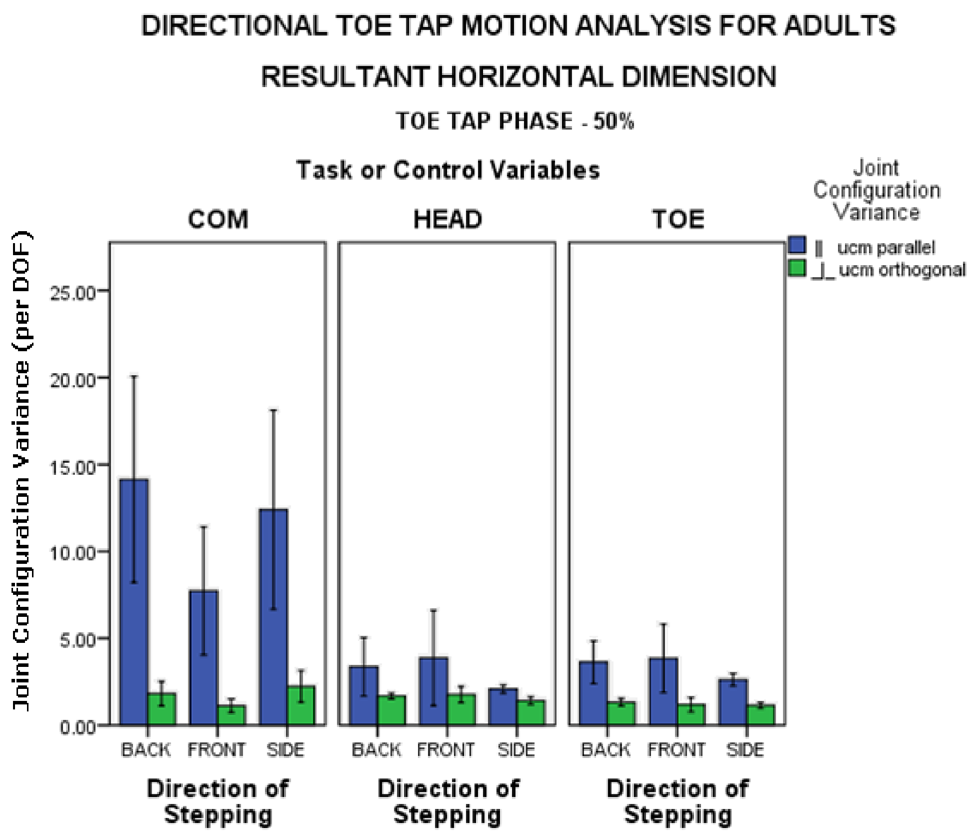

Figure 3.25: Mean (±SEM) joint configuration variance parallel (‖) to and perpendicular (⊥) to the linearized UCM associated with the task variables at the toe tap – 50% phase; as adults perform the forward, backward and lateral toe-tapping.

3.6 RESULTS: AGE EFFECT

3.6.1 AGE-RELATED VARIABILITY

3.6.1.1 FORWARD TOE-TAPPING

Figs. 3.26 and 3.27 represent the mean ($\pm$SEM) variability of the task variables as adults, 6- and 10-year-old children perform the forward toe-tapping at mid air – 25% (Fig. 3.26) and toe tap – 50% (Fig. 3.27) phase respectively. These figures also display the results of the 3 (age) $\times$ 3 (control variable) repeated measures ANOVA performed, separately, on the two phases during forward toe-tapping.

During the mid air phase – 25%, significant main effect of the control variable ($p < 0.0001$) and interaction of age and control variable ($p = 0.0042$) were found. Post hoc analysis showed that the adult TOE was significantly more variable than its COM ($p < 0.0001$) or HEAD ($p = 0.0029$). Moreover, both the 6- and 10-year-old children displayed significantly more variability with their HEAD ($p \ll 0.05$) and the TOE ($p \ll 0.05$) movements compared to their COM.

During the toe tap phase (50%), there were significant main effect for the age ($p = 0.0298$), task variable ($p < 0.0001$) and the interaction of age and task variable ($p = 0.0225$). Post hoc analysis showed that the 6-year-olds were significantly more variable than 10-year-olds ($p = 0.0269$); and displayed significant variability in the HEAD ($p = 0.0017$) and the TOE ($p < 0.0001$) movements compared to the COM. The results from, both, the aforementioned analyses are summarized in Figs. 3.26 and Fig. 3.27 respectively.

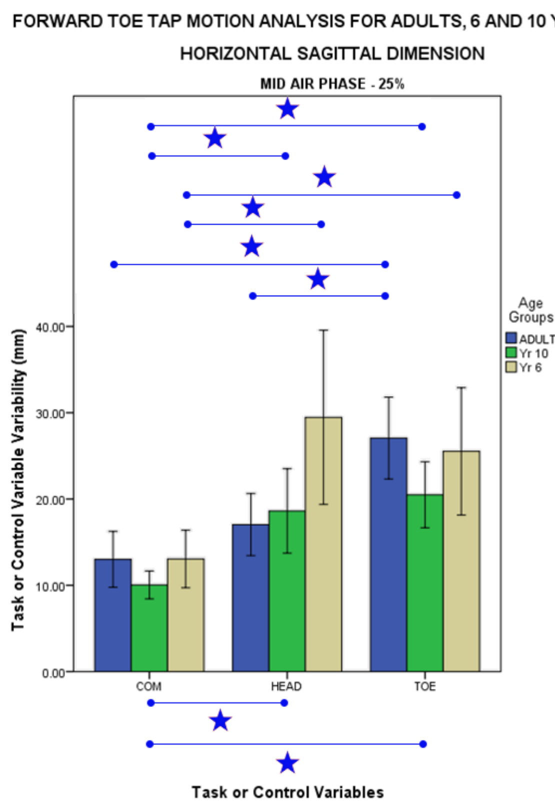

Figure 3.26: Mean (±SEM) variability of the task variables at mid air phase – 25%, as adults, 6- and 10-year-olds perform the forward toe-tapping.

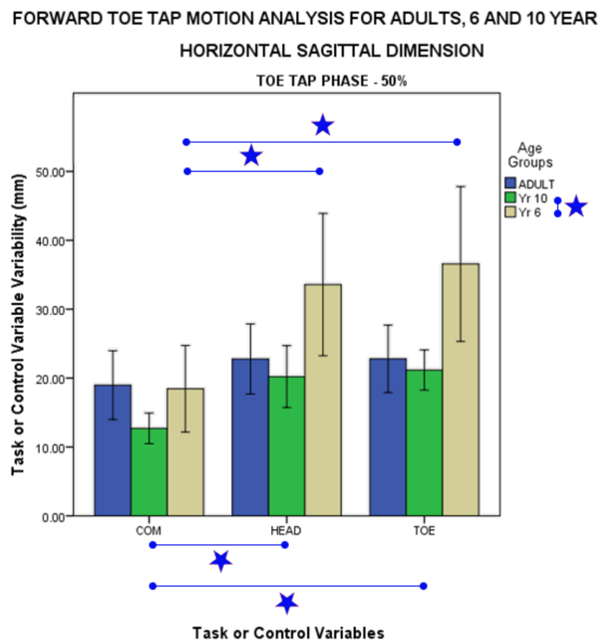

Figure 3.27: Mean (±SEM) variability of the task variables at toe tap phase – 50%, as adults, 6- and 10-year-olds perform the forward toe-tapping.

3.6.1.2 BACKWARD TOE-TAPPING

Figs. 3.28 and 3.29 represent the mean (±SEM) variability of the task variables while adults, 6- and 10-year-old children perform the backward toe-tapping at mid air – 25% (Fig. 3.28) and toe tap – 50% (Fig. 3.29) respectively. These figures also display the results of the 3 (age) × 3 (control variable) repeated measures ANOVA performed, separately, on the two phases during backward toe-tapping.

During the mid air phase – 25%, the main effect of the control variable ($p < 0.0001$) and interaction of age and control variable ($p = 0.0413$) were significant. Post hoc analysis showed that the adult TOE was significantly more variable than its COM ($p < 0.0001$) or HEAD ($p = 0.0181$). Moreover, both the 6- and 10-year-old groups displayed significantly more variability with their HEAD ($p \ll 0.05$) and

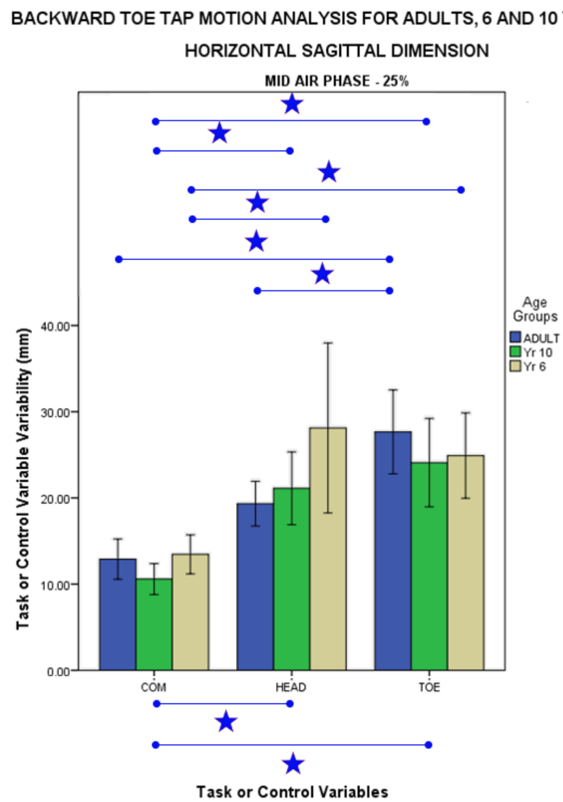

Figure 3.28: Mean ($\pm$SEM) variability of the task variables at mid air phase – 25%, as adults, 6- and 10-year-olds perform the backward toe-tapping.

TOE ($p \ll 0.05$) movements compared to their COM.

During the toe tap phase – 50%, the main effect of the control variable ($p < 0.0001$) was significant. Post hoc analysis revealed that the HEAD ($p < 0.0001$) and the TOE ($p < 0.0001$) were, both, significantly more variable compared to the COM; while the TOE was more variable compared to the HEAD ($p = 0.0004$). The results of the aforementioned analyses are summarized in Figs. 3.28 and 3.29 respectively.

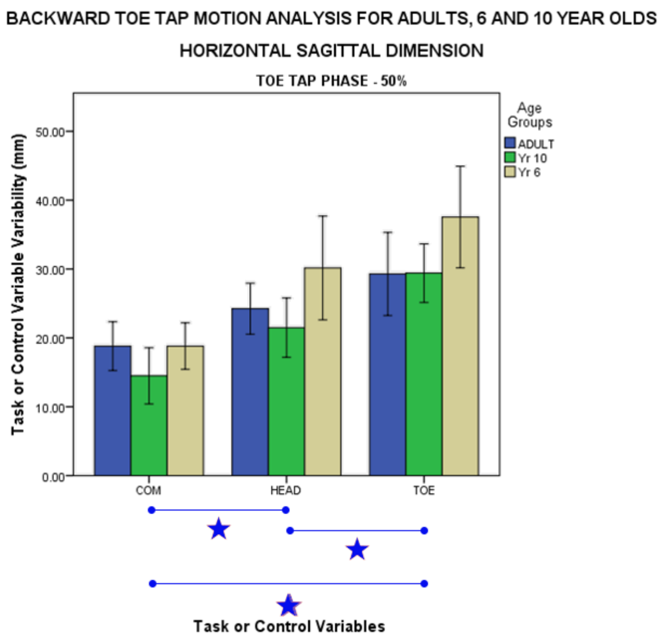

Figure 3.29: Mean (±SEM) variability of the task variables at toe tap phase – 50%, as adults, 6- and 10-year-olds perform the backward toe-tapping.

3.6.1.3 LATERAL TOE-TAPPING

Figs. 3.30 and 3.31 represent the mean (±SEM) variability of the task variables while adults, 6- and 10-year-old children perform the lateral toe-tapping at mid air – 25% (Fig. 3.30) and toe tap – 50% (Fig. 3.31) respectively. These figures also display the results of the 3 (age) × 3 (control variable) repeated measures ANOVA performed, separately, on the two phases during lateral toe-tapping.

During the mid air phase – 25%, the main effect of the control variable ($p < 0.0001$) and interaction of age and control variable ($p = 0.0141$) were significant. Post hoc analysis revealed that the adult TOE was significantly more variable than its COM ($p = 0.011$). The 6-year-olds showed significantly more variability with their HEAD ($p = 0.0003$) and TOE ($p = 0.0381$) movements when compared to

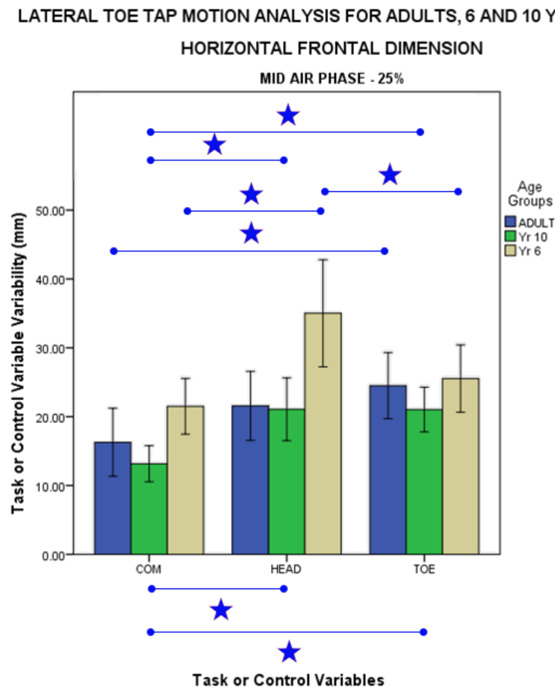

Figure 3.30: Mean (±SEM) variability of the task variables at mid air phase – 25%, as adults, 6- and 10-year-olds perform the lateral toe-tapping.

their COM and HEAD movements respectively. The 10-year-olds, also, showed significantly more variability with their HEAD ($p = 0.0173$) and TOE ($p = 0.0183$) compared to their COM.

During the toe tap phase – 50%, a significant main effect of the age ($p = 0.0004$), the control variable ($p < 0.0001$) and the interaction of age and control variable ($p < 0.0001$) were observed. Post hoc results showed that the COM and the HEAD were, both, significantly more variable in the 6-year-olds compared to the adults ($p \ll 0.05$) and 10-year-olds ($p \ll 0.05$). Moreover, in the 6-year-olds the HEAD was significantly more variable compared to the COM ($p = 0.0332$) and the TOE ($p < 0.0001$). The results of these two analyses were summarized in the Figs. 3.30 and 3.31 respectively.

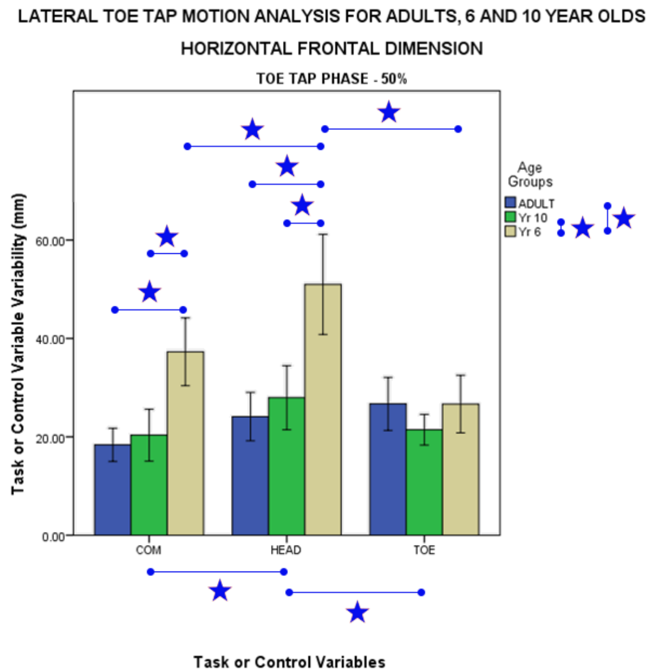

Figure 3.31: Mean (±SEM) variability of the task variables at toe tap phase – 50%, as adults, 6- and 10-year-olds perform the lateral toe-tapping.

3.6.2 UCM ANALYSIS: COMPARISON OF AGE

3.6.2.1 FORWARD TOE-TAPPING

Figs. 3.32 and 3.33, each, displays the mean (±SEM) UCM ratio for the control variables as adults, 6- and 10-year-old children perform the forward toe-tapping at mid air – 25% (Fig. 3.32) and toe tap – 50% (Fig. 3.33) phase respectively. The figures summarize the results obtained from running two, independent, repeated measures ANOVA considering the UCM ratio as the dependent variable, while the (3) age and (3) control variable served as the independent variables.

In the mid air phase, significant main effects were observed regarding the control variable ($p < 0.0001$) and age ($p = 0.0049$). Post-hoc analysis revealed

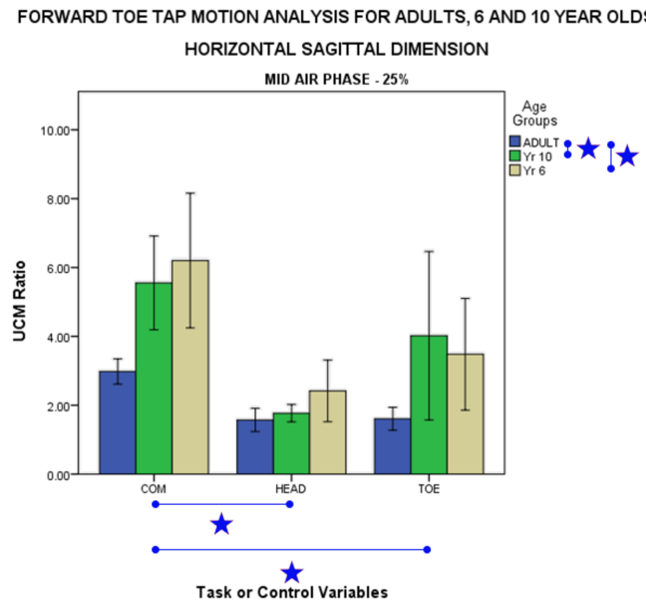

Figure 3.32: Mean (±SEM) UCM ratio for the task or control variables at mid air phase – 25% as adults, 6- and 10-year-olds perform the forward toe-tapping.

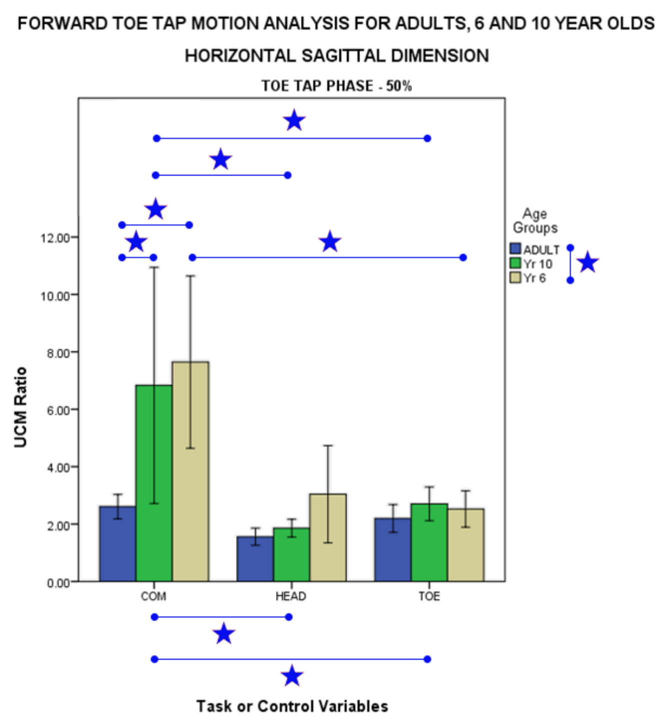

Figure 3.33: Mean (±SEM) UCM ratio for the task or control variables at toe tap phase – 50% as adults, 6- and 10-year-olds perform the forward toe-tapping.

that during forward toe-tapping, the UCM ratio for the 6- ($p = 0.0152$) and 10-year-olds ($p = 0.0144$) were significantly larger than that observed for the adults. Furthermore, the UCM ratio for the COM was significantly more than that for the HEAD ($p < 0.0001$) or TOE ($p = 0.0009$). Meanwhile, the UCM ratio for the TOE was more than that for the HEAD ($p = 0.074$), however, it did not reach statistical significance.

The results for the tapping (50%) phase: significant main effects of the control variable ($p < 0.0001$), age ($p = 0.0205$); and interaction of age and control variable ($p = 0.04$) were found. Post-hoc analysis showed that, both, the 6- ($p = 0.0165$) and the 10-year-olds ($p = 0.0236$) had significantly larger UCM ratios for their COM compared to that for the adults' COM. Moreover, both these groups displayed significantly large UCM ratios for their COM, compared to that for the HEAD ($p < 0.05$) or the TOE ($p < 0.05$). However for the 6-year-olds, the UCM ratio for the COM, although, larger compared to that for the HEAD, did not quite reach the desired significance level ($p = 0.0879$). Figs. 3.34 and 3.35 reinforce the aforementioned findings; it can be observed that in both the cases: mid air (Fig. 3.34) and toe tap (Fig. 3.35) phase ; the component of the joint variance arranged parallel ($\sigma_{\parallel}$) to the UCM is much greater than its perpendicular ($\sigma_{\perp}$) component.

3.6.2.2 BACKWARD TOE-TAPPING

Figs. 3.36 and 3.37 show the mean (±SEM) UCM ratio for the control variable as adults, 6- and 10-year-old children perform the backward toe-tapping, at two

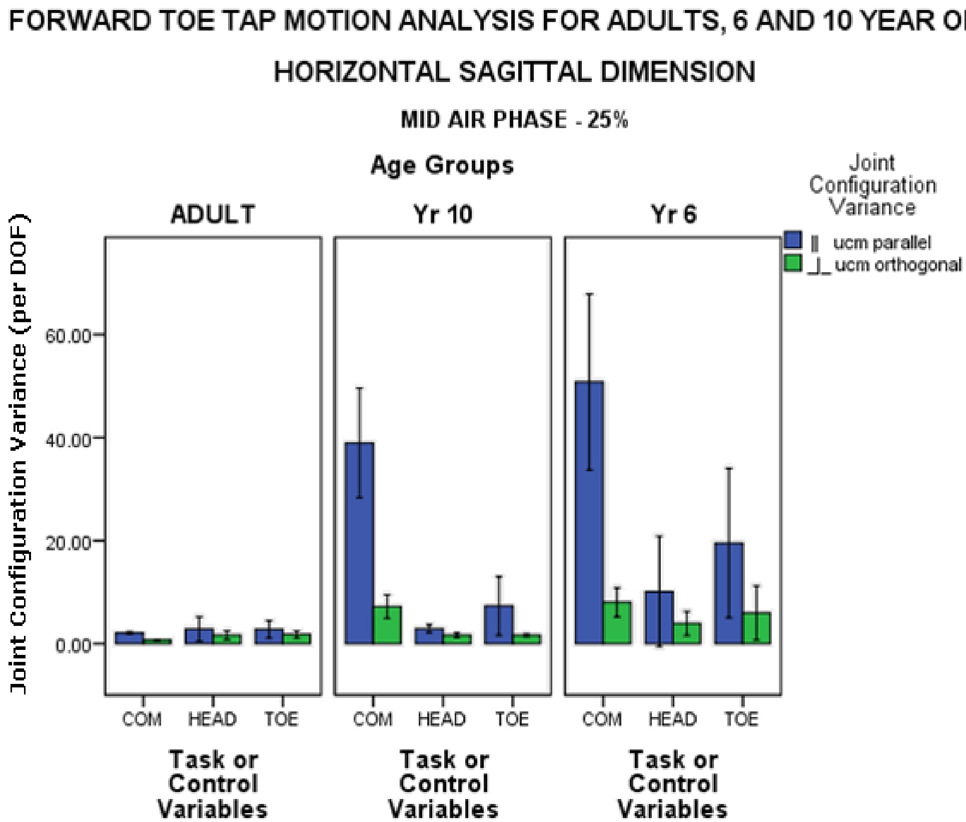

Figure 3.34: Mean (±SEM) joint configuration variance parallel (‖) to and perpendicular (⊥) to the linearized UCM associated with the task variables at the mid air phase – 25% as adults, 6- and 10-year-olds perform the forward toe-tapping.

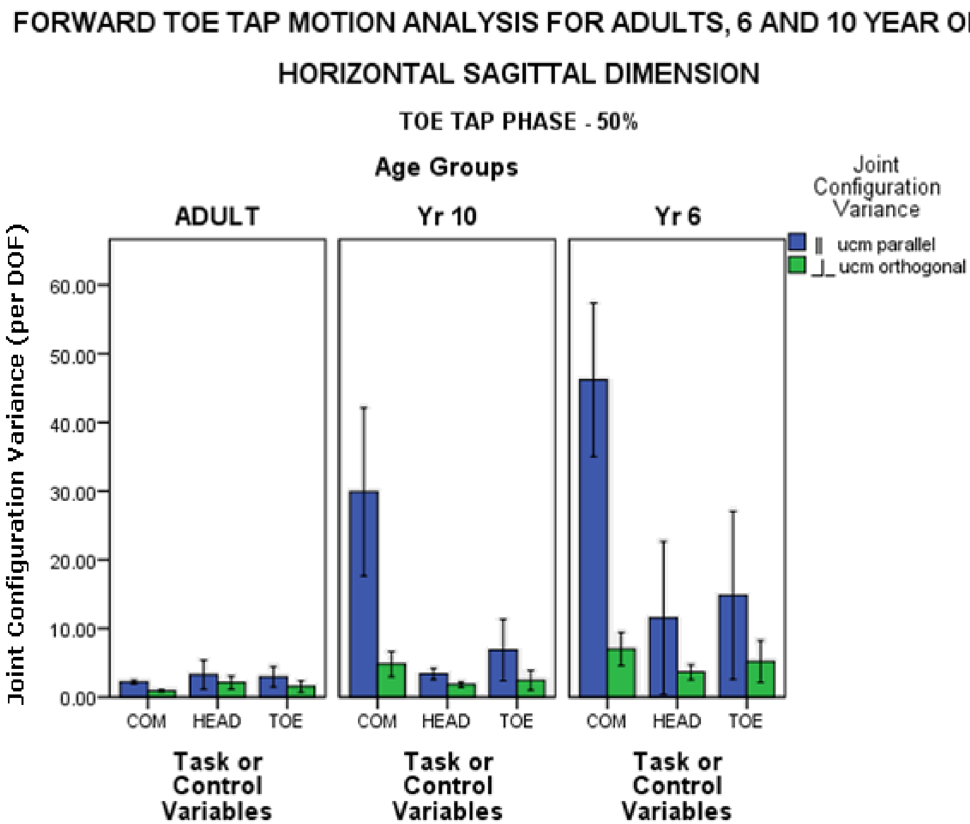

Figure 3.35: Mean (±SEM) joint configuration variance parallel (∥) to and perpendicular (⊥) to the linearized UCM associated with the task variables at the toe tap phase – 50% as adults, 6- and 10-year-olds perform the forward toe-tapping.

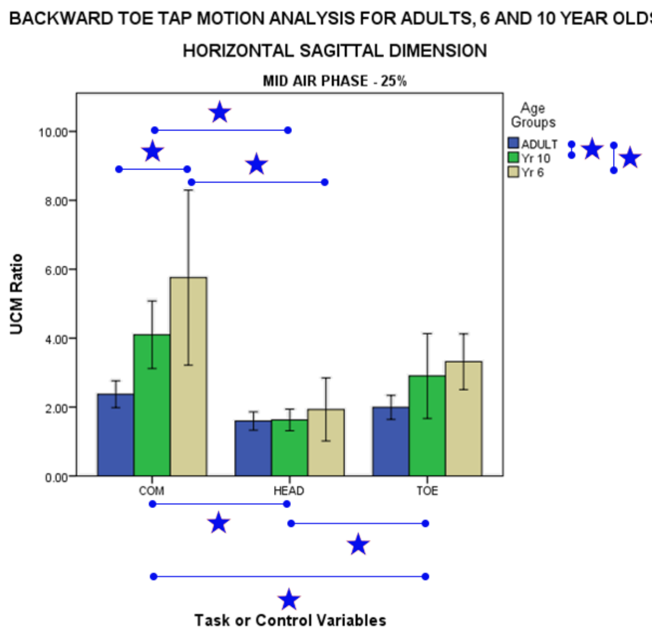

Figure 3.36: Mean (±SEM) UCM ratio for the task or control variables at mid air phase – 25% as adults, 6- and 10-year-olds perform the backward toe-tapping.

phases: mid air – 25% (Fig. 3.36) and toe tap – 50% (Fig. 3.37) respectively.

In the mid air phase (25%), significant effects for the main effect of the age ($p <$ 0.0001), control variable ($p < 0.0001$) and interaction of age and control variable (p = 0.0334) were observed. The UCM ratio for the 6- ($p < 0.0001$) and 10-year-olds (p = 0.0107) were significantly larger than that for the adults; however in between them 6-year olds ($p = 0.0586$) was larger, but did not quite reach significance. Moreover, both children groups showed significantly larger UCM ratios for the COM compared to that for the HEAD ($p < 0.05$). In addition, the UCM ratio for the 6-year-olds' COM was larger than that for the TOE, but it did not reach significance (p = 0.0765).

During the tapping (50%) phase: a significant main effect of the control variable ($p < 0.0001$), and the age ($p = 0.0166$) were observed. Post-hoc analysis

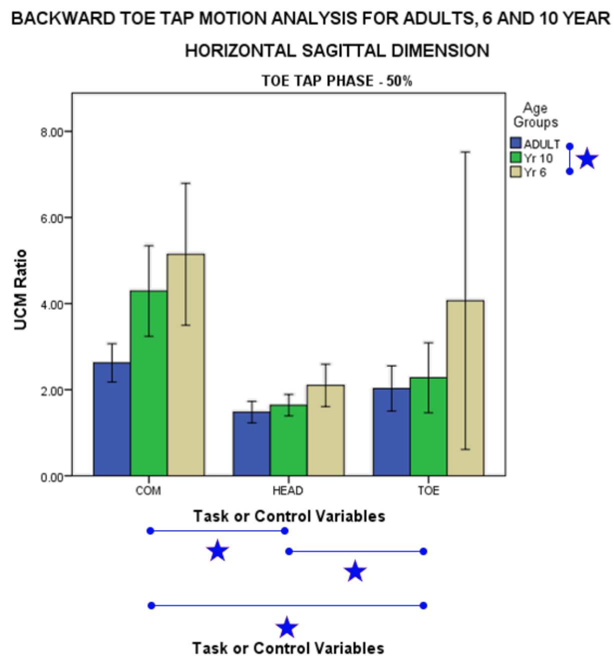

Figure 3.37: Mean (±SEM) UCM ratio for the task or control variables at toe tap phase – 50% as adults, 6- and 10-year-olds perform the backward toe-tapping.

revealed that the UCM ratio for the COM was significantly larger than that for the HEAD ($p < 0.0001$) or the TOE ($p = 0.0079$); while the value for the TOE was significantly more than that for the HEAD ($p = 0.0274$). Furthermore, the UCM ratio for the 6-year-olds was significantly more than that for the adults ($p < 0.05$). Figs. 3.38 and 3.39 reinforce these findings; as it can be observed that in both the cases: mid air phase (Fig. 3.38) and toe tap phase (Fig. 3.39); the component of the joint variable arranged parallel ($\sigma_{\parallel}$) to the uncontrolled manifold is much greater than the perpendicular ($\sigma_{\perp}$) component.

3.6.2.3 LATERAL TOE-TAPPING

Figs. 3.40 and 3.41, each, shows the mean (±SEM) UCM ratio associated with the control variable as adults, 6- and 10-year-old children perform the lateral

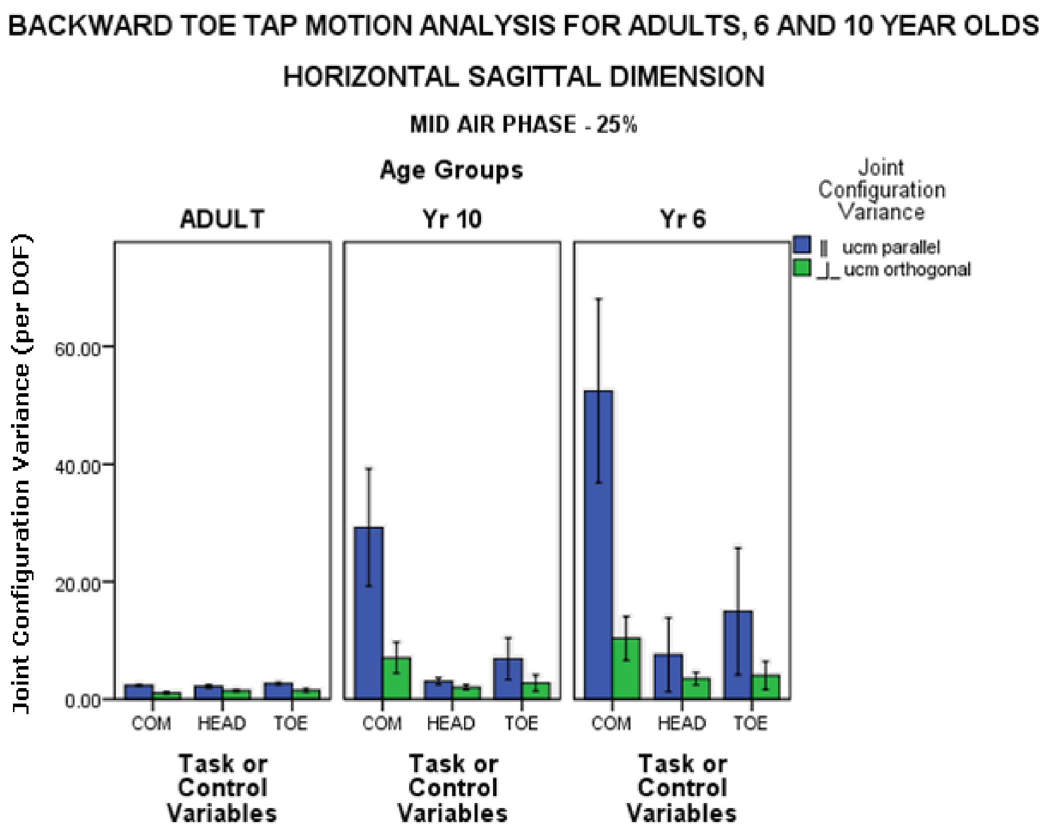

Figure 3.38: Mean (±SEM) joint configuration variance parallel (‖) to and perpendicular (⊥) to the linearized UCM associated with the task variables at the mid air phase – 25% as adults, 6- and 10-year-olds perform the backward toe-tapping.

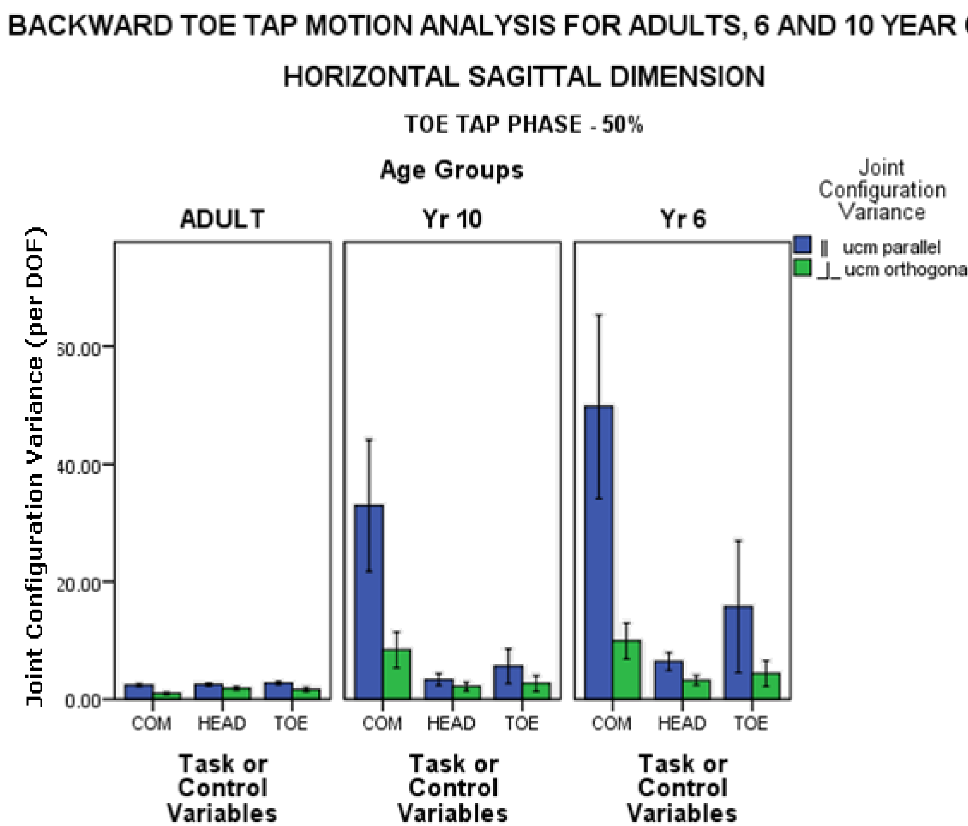

Figure 3.39: Mean (±SEM) joint configuration variance parallel (‖) to and perpendicular (⊥) to the linearized UCM associated with the task variables at the toe tap phase – 50% as adults, 6- and 10-year-olds perform the backward toe-tapping.

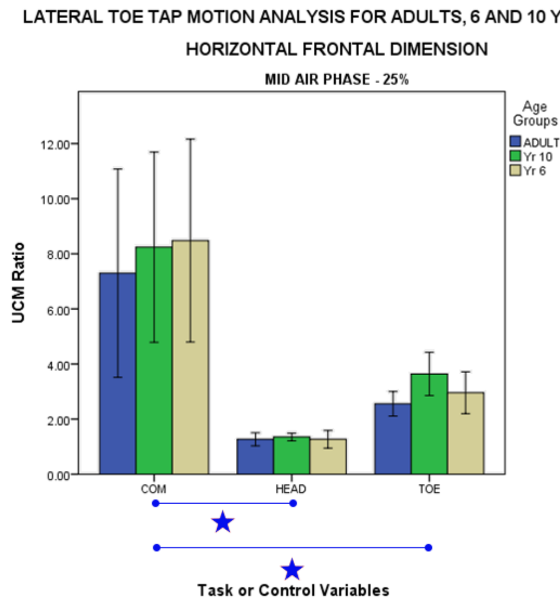

Figure 3.40: Mean (±SEM) UCM ratio for the task variables at mid air phase – 25% as adults, 6- and 10-year-olds perform the lateral toe-tapping.

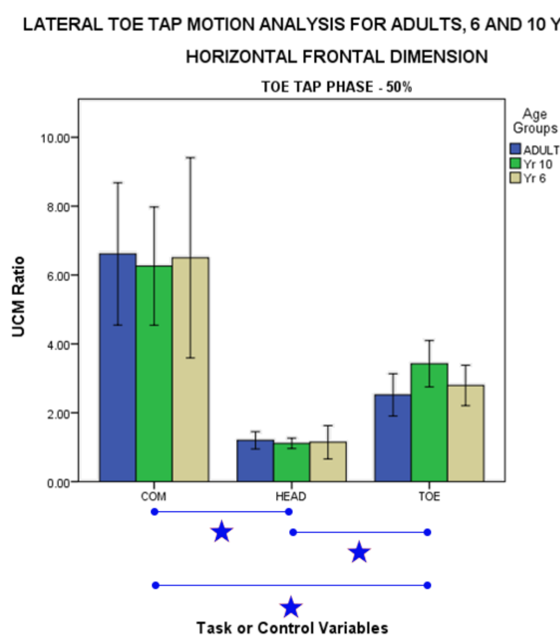

Figure 3.41: Mean (±SEM) UCM ratio for the task variables at toe tap phase – 50% as adults, 6- and 10-year-olds perform the lateral toe-tapping.

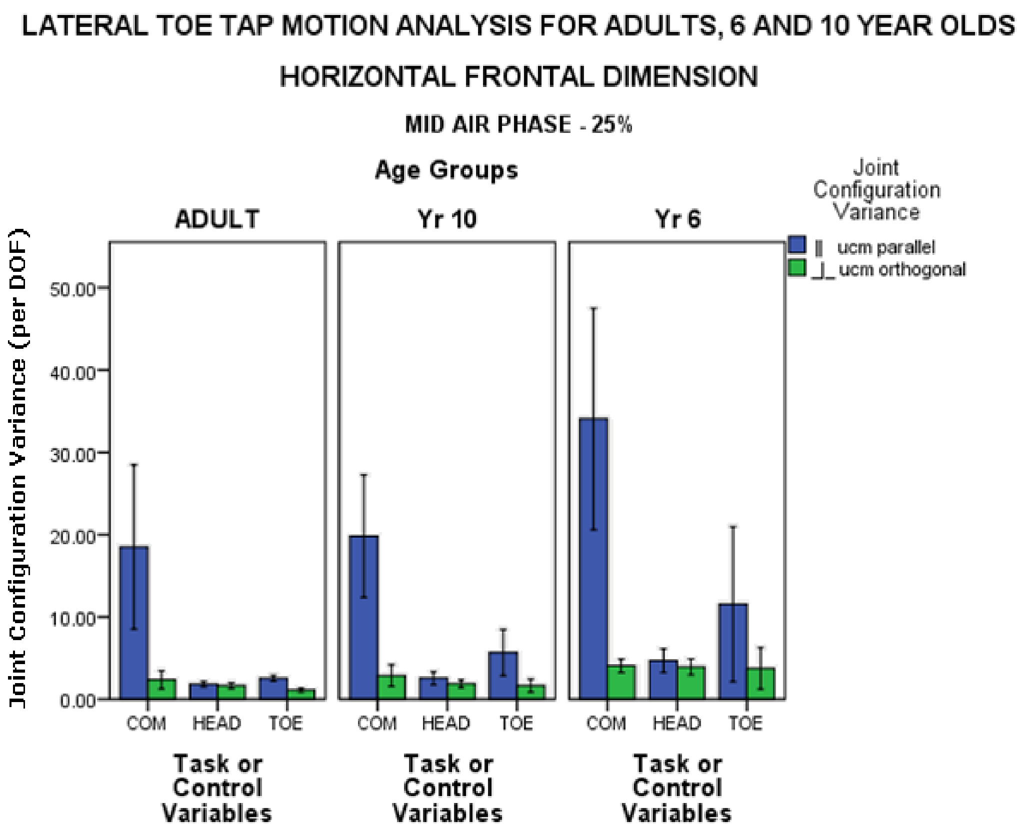

Figure 3.42: Mean (±SEM) joint configuration variance parallel (‖) to and perpendicular (⊥) to the linearized UCM associated with the task variables at the mid air phase – 25% as adults, 6- and 10-year-olds perform the lateral toe-tapping.

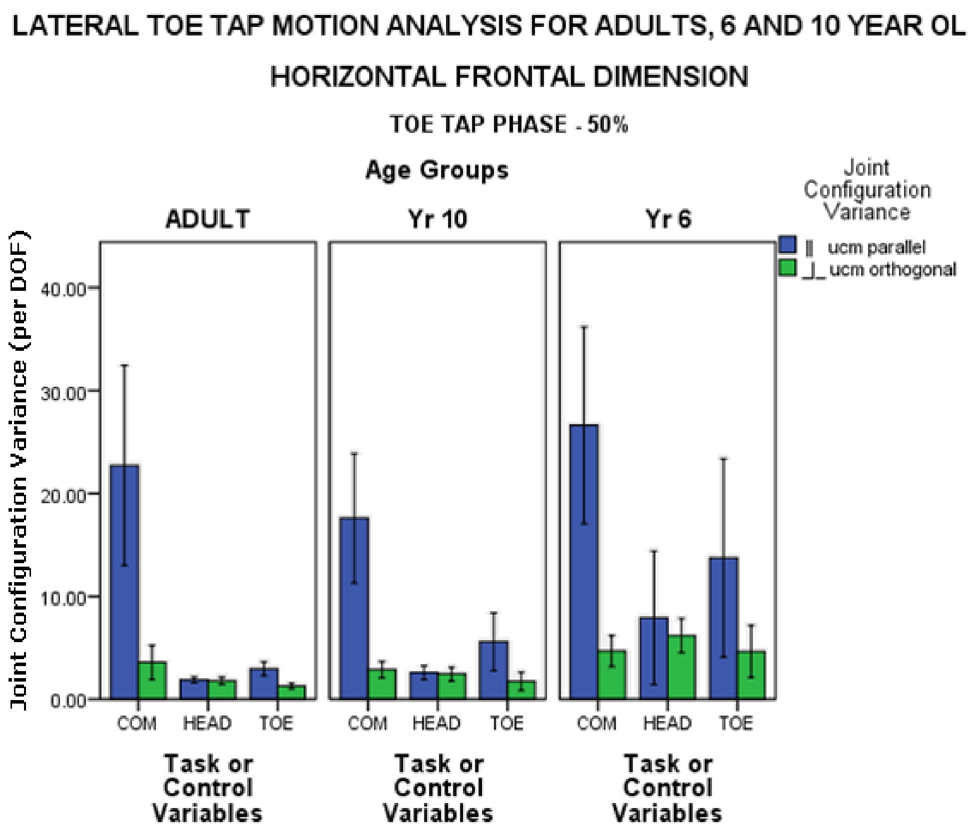

Figure 3.43: Mean ($\pm$SEM) joint configuration variance parallel ($\|$) to and perpendicular ($\perp$) to the linearized UCM associated with the task variables at the toe tap phase – 50% as adults, 6- and 10-year-olds perform the lateral toe-tapping.

toe-tapping, at two phases: mid air – 25% (Fig. 3.40) and toe tap – 50% (Fig. 3.41) respectively; and summarizes the results obtained from running two, independent, repeated measures variance analysis (ANOVA), similar to the ones described in Fig. 3.30 and 3.31; however considering the UCM ratio as the dependent variable. These figures show that in both the two phases there was a significant main effect of the control variable; however, there was no significant main effect for age.

3.7 DISCUSSION

This study presents the results of an experiment designed to investigate the nature of neural motor control involved in the kinematics of forward, backward and lateral toe-tapping movement using the Uncontrolled Manifold (UCM) conception. This analysis provides an approximation to the neural motor control structure - the relative ranking of the task or control variables based on the UCM ratio: center of mass (COM), HEAD and the TOE position, involved in the toe-tapping – forward, backward and lateral – movements. Moreover, the study analyzes the difference in the tapping mechanism based on the direction of the tapping, in adults. Finally, the motor developmental study, comparatively analyzes the neural motor control utilized by the three age groups: (a) 6-year-old children, (b) 10-year-old children and (c) young adults; during the multi-directional unilateral toe-tapping movement.

3.7.1 Adult CNS predominantly controls balance and foot placement.

As hypothesized, it was found that during any kind of multi-directional adult toe-tapping movement: forward, backward or lateral: the control of the COM, HEAD and the TOE position received more priority over the joint motions. This is indicated by the high contrast between $\sigma_{\parallel}$ and $\sigma_{\perp}$ ($\sigma_{\parallel} > \sigma_{\perp}$) for all the control variables, at all the phases of the different directional tapping movements (Figs. 3.12, 3.13, and 3.14). It was found that the COM is more controlled than the HEAD or the TOE position. In between the TOE and HEAD, the TOE is more controlled than the HEAD position (Figs. 3.15, 3.16 and 3.17). To summarize, in adults the neural motor control structure – the relative ranking of the task or control variables based on their control-theoretic stability is: (1) COM, followed by (2) TOE, and (3) HEAD position.

These results are supported by extant literature, which suggests that balance control is the primary concern of the CNS, for the generation of any successful movement (Winter, 1995; Woollacott & Tang, 1997). Moreover, the position control of the TOE – foot placement – is also important in any kind of stepping, and therefore would presumably be so for a step-like movement such as toe-tapping (McIlroy & Maki, 1999; Patla et al., 1999). Furthermore, since the experiments only involved the movement of the foot for the completion of consistent toe-tapping tasks; we suggest that the stability of the COM maybe partly related to the precise control of the TOE position. This statement is reinforced by the fact that during the toe-tapping motion the predominant changes in the COM occurs because of the moving leg. Most importantly, according to literature: (1) the control of the COM is initiated first by appropriate changes in the foot position (McIlroy & Maki, 1999; Patla et al., 1999), and (2) the hip, knee and ankle kinetics, suggesting TOE position control, contributes to the stabilization of the COM and the COP (Winter, 1995; Woollacott & Tang, 1997).

The UCM ratio of more than unity for the HEAD suggests that the HEAD position is more controlled than the joint motions. This is understandable since (1) during forward and lateral toe-tapping visual feedback is required to compensate for the errors in consistent toe-tapping motion, and most importantly (2) the vestibular system is physically located in the HEAD. Therefore, the HEAD position and orientation is important for controlling the TOE position during toe-tapping movements (Hirasaki et al., 1999; Patla et al., 1999).

3.7.2 Adult CNS is efficient in controlling forward toe-tapping.

MID-AIR PHASE: STANCE AND LEG SWING

In adults, the forward toe-tapping is the most controlled of all the tapping movements; this is evident from the findings comparing the three directional tapping movements at the mid-air – 25% phase based on the UCM ratio (Figs. 3.20 and 3.21). The result is intuitive because among the three tapping motions; swing phase of forward tapping, kinematically being much like stepping, is the most practiced; it is the primitive building block of forward walking, running, or jogging. Thus the neural motor control structure involved in forward swing phase of toe-tapping can be assumed to be highly developed and practiced, leading to a significantly larger UCM ratio. The conclusion is consistent with the literature relating the improvement in the UCM ratio based on practice (Kang et al., 2004; Latash, 2010; Müller & Sternad, 2009; Wu & Latash, 2014). Furthermore, to reinforce the validity of this finding, the complexity in the control of forward toe-tapping movement at the mid-air –25% phase should be considered. During forward toe-tapping movement, mid-air –25% phase is the most unstable phase because (1) the COM is outside the base of support causing instability in the anterior direction; and (2) there is lateral instability in the medial lateral dimension (McIlroy & Maki, 1999; Patla et al., 1999), this is evident from the distribution of the UCM ratio for the COM in the M-L dimension (Fig. 3.21 (A)). According to Schöner, the UCM ratio is increased to accommodate to the difficulty of the task (Kim et al., 2012; Scholz & Schöner, 1999).

As expected the UCM ratio for backward toe-tapping was significantly lower than its forward counterpart during the mid-air –25% phase (Figs. 3.20 and 3.21). This is mainly expected due to lack of practice, but we did not expect such lowering of the UCM ratio because the backward mid-air phase, too, is very unstable. A logical explanation for such lowering of the UCM ratio can be related to (1) the different distances transversed during forward, backward and lateral toe-tapping, (2) the different trajectory of the toe-tapping foot: high elevation hyperbolic or low elevation sliding trajectory, or (3) both. The explanation is consistent with the backward walking (BW) literature, which suggests that (1) BW involves shorter absolute swing and support (Vilensky JA, 1987), (2) it does not generate much propulsion power (Lee et al., 2013), (3) the kinematics of the knee and the hip joint, is reversed but simpler than forward walking (Lee et al., 2013), leading to a lower UCM ratio (Scholz & Schöner, 1999), and (4) backward gait variability is increased which might affect the orthogonal component to the UCM to rise and subsequently lower the UCM ratio, as shown in Fig. 3.24 (Freitas & Duarte, 2012; Hackney & Earhart, 2009; Hausdorff et al., 1997). However, the experimental verification is beyond the scope of this study.

TOE-TAP – 50% PHASE

Surprisingly, there was no difference between the forward and backward toe-tapping movement in the actual toe tap – 50% phase. Unlike forward and backward stepping which is quite stable due to the the weight transfer onto the stepping leg during the actual step phase; repeated toe-tapping in similar directions might be relatively more difficult. During the toe-tapping task the weight is not shifted onto the tapping leg, thus the instability in the medial lateral or anterior posterior direction is not reduced; the high UCM ratios for the COM in Figs. 3.22 and 3.23 provide evidence to this idea. Moreover, repetitive consistent toe-tapping task would require constant balance control against repetitive-self-perturbed multi-directional instability. Such unique dynamic balance control issue might make the toe-tapping motor task novel, for the CNS, equally in both these directions due to the lack of sufficient practice unlike the stepping phase; leading to similar UCM ratio distribution in the forward and backward direction.

Finally, during both the phases (mid air – 25% and toe-tap – 50%) lateral toe-tapping is significantly less controlled than forward toe-tapping (Figs. 3.20, and 3.22). This makes sense because the tapping direction and the mechanical design of the human foot, reduces the effect of lateral, anterior or posterior destabilization. Most importantly (1) the tapping trajectory constraints the COM to remain within the base of support, and (2) the movement is the least practiced of all the movements.

3.7.3 Children have more control over forward and backward toe-tapping than the adults.

Contrary to our hypothesis, we observed that during the forward (Figs. 3.32 and 3.33) and backward (Figs. 3.36 and 3.37) toe-tapping, both the 6- and 10-year-old children have more control on the task or control variables than the adults, at all the phases. This is not intuitive, as we expected that (1) the control structure would develop with age (Cavagna et al., 1983; Dierick et al., 2004; Hausdorff et al., 1999; Preis et al., 1997), leading to a higher UCM ratio; and (2) development would cease around the age of 7 (Dierick et al., 2004), meaning, there would be no significant difference in the toe-tapping pattern, described by similar UCM ratio for the 10-year-old children and young adults, but the 6-year-olds would differ from both the age groups.

However, an extended look into the literature has helped us in realizing the validity of our findings. The study of the multi-directional supported walking of infants concluded that infants (aged 2-11 months), those who can walk forward, can also walk backward and sideways, irrespective of the movement speed (Lamb

& Yang, 2000). Moreover, a recent study involving young infants reaching for toys (with the hands or the feet), found that infants more often used their feet to reach for objects; and suggested that early leg movements can be precisely controlled and not require extensive lengthy practice (Galloway & Thelen, 2004). Moreover, a pencil-tapping study with young children suggested that children are very careful and slow while making consistent tapping movement; as the speed increases, consistency gradually decreases with increasing age (Connolly, Brown, & Bassett, 1968).

Regarding the adults, the reduced UCM ratio implies that the relative difference between the $\sigma_{\parallel}$ and $\sigma_{\perp}$ is not big enough. This implies three possible scenarios: (1) the $\sigma_{\parallel}$ defining the flexibility of the redundant system while ensuring motor performance has reduced; suggesting that maybe with age-related development the adult CNS has developed motor consistency but became rigid or less flexible in their usage of the available redundancy; (2) the $\sigma_{\perp}$ has increased, meaning the increased joint flexibility is effecting the motor performance; or (3) both. According to Figs. 3.34, 3.35, 3.38, 3.39, 3.42, and 3.43 it seems to be the first case; compared to the children the adults have very low $\sigma_{\parallel}$ for all the control variables – the adults are very rigid in their toe-tapping movements.

However, during lateral toe-tapping there is no significance difference in the control structure based on the age (Figs. 3.40 and 3.41), meaning, the different age groups acted similarly. This makes sense because lateral toe-tapping is probably the least practiced and therefore by extension lateral tapping, thus it is equally difficult across all the ages, leading to a similar UCM ratio distribution pattern (Kang et al., 2004; Latash, 2010; Müller & Sternad, 2009; Wu & Latash, 2014).

3.7.4 CNS controls multi-directional toe-tapping using similar neural control strategy.

Based on our study, it was found that the approximate control structure (i.e., ranking of the task or control variables) of multi-joint coordinated toe-tapping (forward, backward, and lateral) is: (1) COM, followed by (2) TOE and the (3) HEAD position. The identified neural motor control structure is invariant across movement phase, tapping direction and age. Our results, based on such invariance, reinforces the idea that the CNS controls multi-directional toe-tapping using a single neural control strategy.

This conclusion is logical because there are infinite tapping directions, thus having customized control strategy for each would be very difficult for the CNS (Lamb & Yang, 2000; Robert et al., 2009; Yang et al., 1998). Moreover, supported multi-directional stepping (forward, backward, and sideways) study involving infants (aged 2-11 months) showed that stepping pattern defined by the (1) limb motion kinematics: the stance and swing phase duration, and cycle duration, and (2) electromyographic patterns, had no significant differences across a range of speeds; indicating a single neural control strategy for step-like toe-tapping (Lamb & Yang, 2000; Yang et al., 1998).

3.7.5 UCM provides deeper insight than standard variability analysis.

All our repeated measures statistical analyses of variance (ANOVA) were performed considering the (1) UCM ratio and (2) task variable variability as dependent variables, separately; the results were strikingly different. It was found that the most variable control variable using the standard approach was the TOE, followed by the HEAD and the COM position, in all conditions for all the phases, across all the ages. These results are somewhat different – misleading to be precise; because the analysis based on the task or control variable variability measure does not consider the structure of the variance of the joint motions that are involved in the generation of the trajectory variability.

This is evident from the analysis which tested the directional effect. Standard analysis using the task variable variability measure could not find significant difference in the structure of the different toe-tapping tasks (for example, please compare Fig. 3.18 to 3.20 and 3.21), meanwhile UCM analysis provided a deeper insight and revealed that the adult CNS is efficient in controlling forward toe-tapping compared to backward or lateral tapping.

Chapter 4: CONCLUSION

This study summarizes the results obtained after analyzing the kinematic motion data of multi-directional unilateral toe-tapping (forward, backward and lateral) using the Uncontrolled Manifold Technique. Our results suggest that the central nervous system controls the various task-related functional control variables more than the individual joints involved in the toe-tapping motion. The control of the various task-related functional important parameters is organized by controlling the overall structure of the joint variance in a manner which stabilizes the control variables while ensuring consistent performance. Our results indicate that children have more controlled forward and backward toe-tapping than adults; however they all follow similar toe-tapping movement strategy in the lateral direction. Moreover, in adults, forward toe-tapping is more controlled than backward or lateral tapping. In all our studies, it was found that the central nervous system predominantly controls balance and foot placement during the potentially destabilizing reach out and toe-tapping movement; this is evident from the identified control structure. The relative ranking defining the approximate neural motor control structure for tapping is: (a) center of mass (COM), (b) TOE and (c) HEAD position. We found this structure to be invariant of phase, tap direction and age. Such findings reinforce the idea that the central nervous system controls multi-directional toe-tapping motion using a single neural control mechanism.

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