Anticipatory and reactive mechanisms of postural control in children and adolescents

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A thesis submitted to the Faculty of Graduate and Post-doctoral Studies in partial fulfilment of the requirements for the degree of Doctor of Philosophy, Department of Human Kinetics, Biomechanics and Motor Control Programme, Faculty of Health Science, University of Ottawa, Canada

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To my wife, Kate.

Authorization

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Acknowledgements

I would like to express my sincere gratitude to my thesis supervisor, Dr Heidi Sveistrup, for her guidance throughout my doctoral education. Her support and direction have helped me to become a better researcher and academic. I would also like to thank my thesis advisory committee members Dr Martin Bilodeau and Dr Yves Lajoie for their engagement in my work. I would also like to acknowledge the Ontario Federation for Cerebal Palsy for their funding of part of my doctoral research, and a sincere thank you to all of the participants who made this work possible.

I would like to direct a special thank you to my wife for her patience and support through each stage of my doctoral studies, and to my parents for their encouragement throughout my undergraduate and graduate work. Finally, I would like to thank my colleagues and friends at the University of Ottawa for their insight and support at various steps along the way.

Funding

The Ontario Federation for Cerebral Palsy (2013): “A Rehabilitation ‘Jump-Start’: Comparing the effect of home-based versus clinic-based virtual reality therapy on functional mobility, physical activity and participation in children and young adults with CP”, University of Ottawa $35,000.00

Publications

Pending Submission

Mills RS and Sveistrup H (2017). Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents. *Submitted to: Experimental Brain Research.*

Mills RS, Levac D, Sveistrup H (2017). Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents with cerebral palsy. *Submitted to: Gait & Posture.*

Mills RS, Levac D, Sveistrup H (2017). The effects of a 5-day intensive virtual-reality based exercise programme on kinematics and postural muscle activity in children and adolescents with cerebral palsy – preliminary findings. *Submitted to: Physical & Occupational Therapy in Pediatrics*

Peer-Reviewed Publications

Levac D, McCormick A, Levin M, Brien M, **Mills R**, Miller E, Sveistrup H (2017). Active Video Gaming for Children with Cerebral Palsy: Does a Clinic-Based Virtual Reality Component Offer an Additive Benefit? A Pilot Study. *Physical & Occupational Therapy in Pediatrics*, published online 4 Apr 2017; 1-14.

Other Refereed Contributions

Mills RS, Levac D, Sveistrup H. 'Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents with cerebral palsy', oral presentation accepted to the Movementis Conference, Oxford, 9-11 July 2017.

Mills RS, Levac D, Sveistrup H. 'The effects of a one-week intensive physiotherapy programme on kinematics and postural muscle activity in children and adolescents with cerebral palsy', poster presentation accepted to the Movementis Conference, Oxford, 9-11 July 2017.

Levac D, Sveistrup H, McMormick A Levin M, Brien M, **Mills R**. Combining clinic- and home-based virtual reality exercise programs for children with cerebral palsy. Poster presentation accepted at the International Conference on Cerebral Palsy and other Childhood-onset Disabilities, Stockholm, 1–4 June 2016.

Levac D, Sveistrup H, McMormick A, Levin M, Brien M, **Mills R**. Using a website to facilitate therapist monitoring of a home-based video-gaming exercise program for children with cerebral palsy. Poster presentation accepted at the International Conference on Cerebral Palsy and other Childhood-onset Disabilities, Stockholm, 1–4 June 2016.

Mills R, Barton G, Lajoie Y, Sveistrup H. *Validation of the Human Body Model against surface electromyography of the lower limb in dynamic movements*. Proceedings from the Canadian Institute for Military and Veteran Health Research Forum, Kingston, Canada, Nov 2012.

Invited Presentations

Mills RS. *Anticipatory and reactive postural control in children and adolescents.* Invited Speaker, International Society of Posture & Gait Research Training School, University of North Texas, United States, November 2016.

Contributions of co-authors to publications

All studies were conducted at the University of Ottawa under the supervision of Dr. Heidi Sveistrup.

Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents

Mills RS: Conceptualization of experiment, data collection and analysis, and writing of manuscript
Sveistrup H: Conceptualization of experiment, data analysis, and writing and critical revision of manuscript

Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents with cerebral palsy

Mills RS: Conceptualization of experiment, data collection and analysis, and writing and critical revision of manuscript
Levac D: Conceptualization of experiment, and writing and critical revision of manuscript
Sveistrup H: Conceptualization of experiment, data analysis, and writing and critical revision of manuscript

The effects of a 5-day intensive virtual-reality based exercise programme on kinematics and postural muscle activity in children and adolescents with cerebral palsy

Mills RS: Conceptualization of experiment, data collection and analysis, and writing of manuscript
Levac D: Conceptualization of experiment Writing of manuscript, and critical revision of manuscript
Sveistrup H: Conceptualization of experiment, data analysis, and writing and critical revision of manuscript

Abstract

Maintaining postural control in standing requires the center of mass (COM) to be kept within the boundaries of the base of support (BOS). As the COM moves to a region outside the BOS, a step is often required, increasing the risk of falling, and therefore injury. All too often, humans are subjected to different perturbations while maintaining upright stance, and so to control the COM in these situations, postural activity through musculature at the ankle, knee, and hip are recruited according to demand associated with the level of perturbation. It is also believed that control of the head allows components of the visual and vestibular systems to contribute stable reference values.

In order to understand human response to, and in preparation for perturbation, researchers have employed a number of experimental techniques, including i) loading and subsequent unloading of body segments such as the arm or leg; ii) single discrete platform movements; and iii) continuous platform movements. While many studies have focussed on examining postural control mechanisms during discrete perturbations in children and adolescents, these mechanisms in response to continual perturbation have not been well documented in observable developmental stages of youth, nor have they been well documented in special populations. Therefore, the primary aim of this doctoral dissertation was to characterize the reactive and anticipatory postural control mechanisms in children and adolescents, as well as to examine and characterize them in the Cerebral Palsy population.

To achieve this overarching goal, three separate studies were performed. The first study characterized the anticipatory and reactive mechanisms of postural control in typically developing children aged 7 to 17 years. Specifically, postural muscle activity in the lower limbs, an index of head anchoring strategy, and body segment cross-correlations were characterized in response to, and in anticipation of, continuous platform oscillation movement at various frequencies. The second experiment characterized these same mechanisms in children of similar ages with cerebral palsy, and compared the results to those found in the first study. The results of these studies indicated a slight shift to anticipatory measures after repeated exposure to a specific frequency of platform oscillation, however, each transition to a greater platform speed resulted in more conservative measures of postural control. Furthermore, youth with cerebral palsy tended to control their posture much in the same way of typically developing children and adolescents under less challenging conditions however, with the increased difficulty associated with higher frequency oscillation were not able to generate adequate postural responses.

The final study in this dissertation investigated the effects of a one-week intensive virtual reality-based exercise programme. In this study, postural control mechanisms were observed before and after a one-week time period, during which half of the participants received the enhanced exercise while the remaining participants received no treatment at all. The results from this study indicated there was no effect of a 5-day VR-based intervention on postural control mechanisms used in response to oscillating platform perturbations.

Taken together, the results from these studies extend the current understanding of reactive and anticipatory mechanisms of postural control in children and adolescents, both typically developing and those with cerebral palsy.

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List of Abbreviations

6MWT: Six Minute Walk Test

AI: Anchoring Index

APA: Anticipatory Postural Adjustment

BOS: Base of Support

CC: Cross-Correlation

CNS: Central Nervous System

COM: Center of Mass

COP: Center of Pressure

CP: Cerebral Palsy

DoF: Degrees of Freedom

(s)EMG: (surface)Electromyography

ETP: Externally-Triggered Perturbation

G: *gastrocnemius muscle*

GMFCS: Gross Motor Function Classification System

GMFM-CM: Gross Motor Function Measure Challenge Module

H: *hamstrings muscle group*

HSSS: Head Stabilized in Space Strategy

HSTS: Head Strapped to Trunk Strategy

IREX: Interactive Rehabilitation EXercise

KP: Knowledge of Performance

KR: Knowledge of Results

M: Mean

MWU: Mann-Whitney U

OCTC: Ottawa Children's Treatment Centre

Q: *quadriceps muscle group*

SD: Standard Deviation

SS: Steady State

STP: Self-Triggered Perturbation

TA: *tibialis anterior muscle*

TD: Typically Developing

TS: Transition State

U: Mann-Whitney U test statistic

VR: Virtual Reality

W: Wilcoxon W test statistic

Chapter 1: General Introduction and Review of Literature

Introduction

Human movements are performed in dynamic environments, with both predictable and unpredictable perturbations, compensated for with reactive and anticipatory postural control mechanisms (Bugnariu & Sveistrup, 2006; Laessoe & Voigt, 2008). Reactive postural control mechanisms are those elicited in response to a perturbation in order to regain balance. Anticipatory postural control mechanisms consist of postural muscle activations prior to an expected perturbation in order to minimize its destabilization effects. In everyday activities, perturbations can be either discrete and/or continuous. For example, a discrete perturbation can result from the initiation of gait and can be compensated by a mechanism of anticipatory postural control. On the other hand, continuous postural perturbations can be experienced while standing on a moving bus, train, or ship, and can elicit either reactive postural control mechanisms if the perturbation is unpredictable or anticipatory control mechanisms if the perturbation is consistent and predictable.

Movement behaviour has been characterized (Bugnariu & Sveistrup, 2006) and it has been shown that, in older adults, anticipatory strategies elicited through continuous predictable perturbations are impaired when compared to those generated by young adults increasing the risk for falls. It has also been shown that increasing sensory information available to the plantar surface of the foot through in-soles (Bugnariu, 2005) results in an improved use of anticipatory muscle activity. Yet it is not only older adults who are at risk of falling. Children and adolescents with neurological impairment also show increased risk of falls and their movement abilities are strongly predictive of participation in activities outside of the home (Bult *et al.*, 2013). Importantly, children with neurological deficits such as cerebral palsy (CP) are less physically active than able-bodied peers (Rimmer, 2001) and participate in fewer leisure activities (Engel-Yeger *et al.*, 2009). It is unclear how impaired components of reactive and anticipatory postural control influence balance, functional mobility, and participation in these children.

Cerebral palsy is a non-progressive lesion in the central nervous system (CNS) that results in heterogeneous motor disability and developmental delays in the affected child. It is the most common physical disability in children (Badawi & Keogh, 2013). Children with CP may have motor deficits (e.g. spasticity, dystonia, ataxis, hypotonia; (Albright, 1996) and sensory deficits (e.g. impaired proprioception and stereognosis; (Cooper *et al.*, 1995)), which contribute to impaired functional mobility. Research suggests that there is a relevant role of postural control in the functional performance of children and adolescents with CP (Girolami *et al.*, 2011). As efficient postural control is important for the performance of voluntary skills, postural abnormalities likely contribute to the delays and impairments seen in the motor skills of the child with CP (Burtner *et al.*, 1998). Anticipatory and reactive postural mechanisms have been identified as significant components necessary to maintain balance when performing voluntary movement (Liu *et al.*, 2007). However, these mechanisms have not been systematically characterized in typically developing children and adolescents nor have they been characterized in children and adolescents with CP.

The following review of literature provides a summary of the various components contributing to postural control and their development in children and adolescents, as well as current methods for evaluating them. This section also provides a brief background on the cerebral palsy population. Finally, the review of literature summarizes the state of research concerning virtual reality and its use in rehabilitation.

1. **Review of the Literature**

1.1 Neurophysiological components of balance

In order to appropriately gauge our relationship with our environments, humans are equipped with several complex neurophysiological systems which are constantly interacting, and aid in the maintenance of balance. The three primary sensory systems involved in balance are the vestibular system, the visual system, and the somatosensory system (Redfern *et al*., 2001). The following briefly describes these three neurophysiological systems, and identifies the roles played by each as well as how they are integrated to maintain balance – unless otherwise stated, the development/time to maturation of each system is assumed to be the same in both typically developing and cerebral palsy populations. A review of the development of these systems as it relates to their integration for maintenance of balance will be covered in section 1.2 – Motor Control of Balance.

1.1.1 The Systems Contributing to Balance

i. Equilibrioception (The Vestibular System)

One of the systems contributing to the maintenance of human balance is the vestibular system (Maurer *et al*. 2000). Although humans are not consciously aware of vestibular sensation, the inputs aid in stabilization of the eyes and help to maintain postural stability during quiet stance as well as throughout gait (Shumway-Cook & Woollacott 2007).

The vestibular system is comprised of the organs of the inner ear: three orthogonally positioned, fluid-filled semicircular canals, and two otolith organs (the utricle and saccule, also positioned orthogonally). These structures are highly sensitive to rotational movements, detected by the semicircular canals, as well as linear accelerations detected by the otoliths. Understanding how the complementary signals of these structures are processed is imperative in order to comprehend the vestibular system's contribution to human balance.

ii. Processing Motion

The many facets of human motion consist of different combinations of rotational and linear accelerations. As such, therein emerges an issue of differentiating between the two types of acceleration. For rotational acceleration, a rotation in one direction causes fluid motion in the opposite direction within the semicircular canals; each canal acts as an angular accelerometer in its respective plane. Similarly, for linear acceleration, movement in one direction causes fluid motion in the opposite direction within the otoliths (Rida & Chen, 2009). For both structures, mechanosensory properties of the tissues and the orientation of the cells allow for proper functioning of the system (Kelly & Chen, 2007).

The brain is able to combine the rotational and linear accelerations into a resolution of orientation and motion relative to the environment. Mathematically, this is a two-step process; first, (1) a temporal integral of rotation (from the semicircular canals) to estimate spatial orientation is computed, then (2) the integral is combined with/compared to the linear accelerations (from the otoliths) to calculate the accelerations due to translation (Angelaki & Cullen, 2008). It has been suggested that acceleration-related inputs to the vestibular system are coded allocentrically, that is to say that world-referenced (as opposed to self-referenced) angular accelerations are available for perception and balance. In a series of studies, Fitzpatrick *et al.* (2006) electrically stimulated vestibular receptors and were able to evoke virtual rotation when walking in the dark. Effectively, this meant that they could ‘steer’ the subjects by perturbing the vestibular system, dependent on the orientation of the head. This suggests that canal signals are resolved according to head posture into allocentric orthogonal components. Each component might have a different function. For example, horizontal rotations are used to control navigation, whereas vertical rotations are used mostly for orientation and balance (Angelaki & Cullen, 2008).

iii. Differentiation of Passive and Active Movements

An important aspect to balance is being able to distinguish between which components of vestibular activation are from self-generated (active) or externally-generated (passive) movements. How is it, exactly, that the brain is able to differentiate between the two? Research over the last century has suggested that the brain makes an internal prediction of sensory inputs from the proposed actions. These predictions are then compared with the actual sensory inputs of the movements, and the difference computed is perceived as self-generated. Moreover, when it comes to rotational and linear accelerations of the head, active “sensory information can be selectively suppressed at the level of afferent neural fibres, or the central neurons to which they project” (Angelaki & Cullen, 2008). Previous studies exclusively investigated the role of the vestibular system by moving the head and body together, but more recent studies have overcome these limits, and have managed to record self-generated (active) movements of the head relative to the trunk. Results of these studies have shown that neurons still continue to respond selectively to passively applied head motion. Thus, to distinguish between active and passive movements, there must be a multimodal convergence of several sensory inputs (vestibular, visual, proprioceptive, etc) and the brain subsequently compares the vestibular and non-vestibular inputs for when movement is expected and when it is not. For example, when head rotation is expected, neck proprioceptors and vestibular receptors are stimulated, but signals are suppressed, as the movement has been anticipated/directed by the brain. If the movement is passive (i.e. unexpected), then no signal attenuation occurs (Roy & Cullen, 2001).

1.1.2 The visual system

The environment is perceived in the visual system by light being captured on the retina of the eye, transmitting a signal to the brain via the optical nerve. This system involves a useful source of information, detailing spatial orientation within the environment (Wade & Jones, 1997). It is clear that its role in balance depends on visual acuity and visual flow. For example, when asked to maintain balance while a 'moving room' was repositioned around them, elderly adults swayed more than young adults in response to the global movements of the visual surround (Wade *et al.*, 1995). In response to predictable visual flow, children aged 3-5 years have been found to exhibit posturally-appropriate responses to visual oscillations (again, by way of 'moving room') between 0.2 Hz and 0.6 Hz (Schmuckler, 2017).

The transformation of light information into a sensory signal allows for the construct of an objective frame of reference in which a theoretical construct of vertical can be used as an internal spatial representation of the world (Bove *et al.*, 2009). Framing a subjective vertical from the visual information when the head is not in line with true vertical is complex, and is not well-understood. Subjective visual vertical is how one perceives the environment from the sensory information received, whether it aligns with true verticality or not (Daddaoua *et al.*, 2008). The visual system relies on subjective information and thus is highly influenced by the other systems, most notably the vestibular system (Yelnik *et al.*, 2002).

1.1.3 The somatosensory system

The somatosensory system is a web of sensory inputs, relying on information from a number of proprioreceptors, including mechanoreceptors and nociceptors. These sources of information all get relayed to, and are integrated in, the primary sensory cortex. The various receptors are found in the many systems of the body, and as such, combine into the complex system that is the somatosensory system (Campbell & Reece, 2002). In particular, proprioception – the sense of relative positions of neighbouring body parts – is an important component in balance, and is considered to be a subsystem of the somatosensory system (Mergner & Rosemeier, 1998; Batson, 2009).

Proprioception plays an important role in achieving and maintaining balance. It incorporates the sensory information from the receptors in the joints, muscles, and tendons to gauge the position and motion of limbs. Information about joint loading and joint motion (velocity, acceleration), nociception for the sensation of pain, and neuromuscular feedback (e.g. muscle force, muscle stretch reflex) are all fed and processed online by the brain (Schmitt *et al.*, 2005). For example, when the body sways, or deviates from the upright position, it creates a passive torque around the ankle joint because of the acceleration of the body due to gravity. This information is relayed from the joint and muscles to the brain in the form of sensory feedback, and a corrective, active torque is applied to maintain balance (Peterka, 2000; Cnyrim *et al.*, 2009).

1.1.4 Systems integration and neurophysiological balance strategies

As aforementioned, the human body is inherently unstable, and is constantly being perturbed. Because of this, we must accommodate for these disruptions of balance in order to avoid the possibility of injury. There are various strategies that integrate the neurophysiological systems that help to maintain and regain balance. Sensory information (sometimes conflicting) from the vestibular, somatosensory (i.e proprioceptive), and visual systems are combined and compared, and are weighted according to the goal(s) of the movement task at hand, as well as the environmental context (Horak, 2006). The general weighting of the sensory systems can vary, whereby the type of action (frequency) defines the primary system at work (Redfern *et al.*, 2001). By changing the sensory environment, it is a necessity to re-weight the relative dependence on the various sensory systems. For example, in a well-lit environment, with a firm base of support, somatosensory inputs account for up to 70% contribution, vision up to 10%, and vestibular up to 20% during normal quiet stance in healthy adults. When standing on an unstable surface, there is a shift to a dependence on the visual and vestibular systems (Horak, 2006). Damage to, or loss of, one of the neurophysiological systems results not in a complete loss of balance, but a major sensory re-weighting. Loss of two systems would be detrimental to one's ability to maintain balance (Ray *et al.*, 2008).

1.2 Motor Control of Balance

In addition to the three neurophysiological sensory systems involved, there is also the motor control component of balance. In response to a perturbation, postural muscles must be activated to restore the centre of mass stability, and typically one of three strategies is employed to maintain balance (Horak & Nashner, 1986). These strategies are based either about the ankle, or about the hip, characterized by which joint remains stiff and about which joint torque is generated. In extreme cases, a stepping strategy may be used. Each strategy has the main goal of restoring balance, but each can be adopted under different conditions, furthering the idea that humans have the ability to accomplish a single task with redundancy in motor outputs (Horak & Nashner, 1986). In this section, muscles synergies, postural control strategies, and their development in both typically developing youth and youth with cerebral palsy will be discussed.

1.2.1 Synergies

In order to ensure that postural control mechanisms are employed as quickly as possible, the central nervous system makes use of postural synergies. Recent findings suggest a central nervous system (CNS)-level simplification of motor control through muscles constrained to act in fixed groups (i.e. *synergies*), whereby one set of muscles is recruited by a single neural command (Torres-Oviedo *et al*., 2006). This central control signal proportionally activates all muscles in the synergy (Latash *et al.*, 2005; Tresch & Jarc, 2009), and the functional coupling of muscle groups allows for task-level goals with less demand on the CNS than if each muscle were to be individually activated. Postural synergies are thought to provide a mechanism based on the central set, where only the desired task-level function (e.g. endpoint forces between the foot and the ground) needs to be specified, not the coordination of individual muscles spanning multiple joints (Ting & Macpherson, 2005; Torres-Oviedo *et al*., 2006). Optimal performance of the task at hand is achieved by regulating the timing of muscle activations within a synergy (Horak & Macpherson, 1996; Torres-Oviedo & Ting, 2007).

Various studies, in both animals and humans, have contributed to the understanding of muscle synergies. d'Avella and Bizzi (2005) found that synergies must be limited in number. For example, in frogs, there are synergies used specifically for certain tasks (walking, jumping, and swimming), as well as synergies that are shared across the same tasks. Ting and Macpherson

(2005) demonstrated in cats that synergies appear to specify forces required to maintain balance in horizontal support surface translations. In humans, understanding of muscle synergies typically comes from, though is not limited to, perturbation-based studies. Muscle synergy recruitment is correlated to center of mass (COM) shifts in standing (Krishnamoorthy *et al.*, 2003), and synergies can be found to coactivate muscles throughout the limbs and the trunk (Ting & Mckay, 2007). Moreover, trial-to-trial variability in muscle activations, similar across subjects, suggests that for any perturbation, one or more synergies can be active (Ting & Mckay, 2007). It is also possible for synergies to be combined in different proportions to perform a task (Ting & Mckay, 2007; Torres-Oviedo & Ting, 2007). To make this possible, control signals to the synergies will vary according to changing task conditions, resulting in parallel changes to all muscles involved (Latash *et al.*, 2005).

Although much research has focused on reactions to perturbations, it is unlikely that muscle synergies are only reflexive, as they represent a central mechanism for coordination of motor outputs (Torres-Oviedo *et al.*, 2006). The use of postural synergies greatly reduces the degrees of freedom in the system (i.e., the musculoskeletal redundancy) and allows for rapid muscle activation of both automatic postural adjustments and voluntary movements. Contributions from each muscle synergy can be modulated by descending influences such as prior experience, sensory feedback, and anticipation (Torres-Oviedo & Ting, 2007).

1.2.2 Synergies & Posture control

The CNS integrates synergies with sensorimotor information in order to maintain balance, or regain balance if the system has been perturbed, through *postural strategies*. When balance is perturbed in normal stance, there are generally three lower-body options to control posture based on direction and magnitude of the perturbation. If the perturbation lies in the anterior/posterior plane, the fixed base of support approach is taken, and either an ankle or hip strategy (or combination thereof) will follow (Horak & Nashner, 1986). If, however, the perturbation is too large, or is in the medial/lateral plane, the person is more likely to adopt a hip or stepping strategy (changing base of support strategy) (Winter *et al.*, 1996). Moreover, the level of imposed attentional demands dictates which strategy is used (Brown *et al.*, 1999; Rankin *et al.*, 2000; Woollacott & Shumway-Cook, 2002).

1.2.3 Ankle, hip, and stepping strategies

In the ankle strategy, torque is primarily generated about the ankle joint (Massion, 1994; Winter, 1995; Runge *et al.*, 1999; Horak, 2006). This strategy is often treated as a flexible inverted pendulum (or cone) where the center of pressure (COP) is regulated by the CNS in such a way that the vertical projection of the COM remains within the base of support. The use of the ankle strategy to regulate the COP is usually associated with small amounts of anterior/posterior sway when standing on a firm surface (Nashner, 1977; Horak, 2006). Studies involving platform translations in the anteroposterior plane have demonstrated that when the platform is translated posteriorly, causing the body to sway forward, muscle activity is initiated with the gastrocnemius at about 90-100ms after the onset of the perturbation. This is followed by the activation of the hamstrings, and finally the paraspinals, in order to restore balance to the system (Nashner, 1977).

When perturbations are too large to be compensated for with the ankle strategy, or when the support surface is compliant or too small, humans will tend to shift to a hip-based strategy to regain control of the system's balance (Horak & Nashner, 1986). In the hip strategy, the COM is returned to a stabilized position by large and rapid movements of the hips with antiphase rotations about the ankles. In response to a posterior translation (forward sway) perturbation, the abdominal muscles are activated approximately 90-100ms following perturbation onset; the quadriceps muscles quickly follow (Shumway-Cook & Woollacott, 2007). The hip strategy is also used in response to medial/lateral perturbations, albeit in a slightly different form. Primary motion in this case occurs through lateral movement at the pelvis, requiring adduction of one leg and abduction of the other (load/unload mechanism) (Winter *et al.*, 1996).

If the postural disturbance is large enough, it is likely that a step must be taken to avoid falling (Burtner *et al.*, 2007). An inadequate feet-in-place response can often be recovered within one effectively placed step (Roncesvalles *et al.*, 2000).

In children as young as 10 months who can stand but not yet walk, directionally-specific responses have been found in the distal muscles of the leg in order to compensate for anterior sway (Woollacott & Shumway-Cook, 1990) indicative of the beginnings of an ankle strategy. Stoffregen *et al.* (1997) showed that small, slow hip movements in response to postural sway are evident in young children 13-14 months old, suggesting this may serve as a basis for the larger hip movements later associated with imposed perturbations. Gradually, as the child continues to develop and walks independently, postural muscle organization emerges in the distal to proximal ascending sequence, but that these responses are slower than those in adults (Forssberg & Nashner, 1982). Children with greater locomotive experience are able to withstand larger postural perturbations (platform displacements and velocities) without the need for stepping (Roncesvalles *et al.*, 2001). In children with CP, however, the contribution of an ankle strategy to postural maintenance is somewhat limited, largely due to poor ankle control mechanisms. In order to ensure balance, these children tend to rely on large contributions from the hip, limb protraction/retraction, and body transverse rotation (Ferdjallah *et al.*, 2002), and struggle to maintain balance (i.e. take steps) at lower platform translation velocities than TD youth (Burtner *et al.*, 2007; Chen & Woollacott, 2007).

1.2.4 Anticipatory postural control

Not all postural control is reflexive. In fact, there is sufficient evidence to suggest that humans are capable of counteracting a disturbance to postural stability even prior to the occurrence of a perturbation, through the use of *anticipatory postural adjustments* (APAs). APAs are a form of feed-forward control, whereby predetermined activity of postural muscles (postural strategies) produces joint torques to minimize an expected disturbance to the equilibrium of the system (Aruin, 2002; Klous *et al.*, 2011). They also serve two other functions: (1) postural preparation for movement (e.g., gait initiation) and (2) assisting movement in terms of force or velocity, e.g., through postural counterperturbation (preparation) during movement (Massion, 1998). Studies involving self-initiated perturbations have demonstrated that anticipatory postural adjustments (i.e., timing and amplitude of muscle activity) scale with the magnitude of the anticipated threat to stability (Aruin & Latash, 1995; Horak & Macpherson, 1996).

Others have demonstrated that there is an ability to quickly adapt to predictable perturbations (e.g., within a few cycles of sinusoidal platform translations) (cf Laessoe & Voigt, 2008; Schmid *et al.*, 2011). For example, Bugnariu and Sveistrup (2006) demonstrated differences in young and old adults' APAs to repeated continuous postural perturbations. Participants were instructed to maintain their balance on a platform that was sinusoidally oscillating in the anterior/posterior plane. Participants were then subjected to unexpected changes in frequency of platform oscillation (termed ‘externally-triggered perturbations’ (ETP) as the perturbations were controlled by the experimenter). Young adults accomplished the task more efficiently than the older subjects with earlier postural muscle onsets and smaller center of pressure (COP) displacements to control the center of mass (COM) position. Additionally, young adults used the predictability of the platform movement following a change in frequency to quickly adapt postural responses to the new frequency and switch to anticipatory mechanisms (e.g. the decrease in platform speed is an indication of the upcoming change in direction of the platform, or upcoming perturbation). In the younger adults, a shift to anticipatory postural strategies occurred within a few cycles at a new constant frequency (Dietz *et al.*, 1993; Bugnariu & Sveistrup, 2006). The older adults, however, did not activate postural muscles in anticipation of change of direction.

In a separate series of experiments Bugnariu and Sveistrup (2006), subjects were asked to complete the same task *while having control over when the change in frequency occurs* (termed ‘self-triggered perturbation’; STP). Younger adults were again able to shift to the anticipatory mechanism within a few cycles immediately following the change in frequency, and within fewer cycles compared to the ETP condition. However, it is important to note that compared to the externally-triggered perturbation condition, older adults were more able to make use of platform movement predictability. It was hypothesized that this was accomplished potentially by decreasing the threshold for detecting changes in platform speed, thus allowing earlier postural muscle activity onset to reduce the destabilization due to the upcoming perturbation. This is indicative of the subjects’ abilities to respond and anticipate changes that could lead to the prevention of falling.

APAs can also be influenced by prior experience to the perturbation (Nashner, 1976). For example, Kennedy *et al.* (2013) have confirmed the findings reported by Dietz *et al.* (1993), Van Ooteghem *et al.* (2008), and Schmid *et al.* (2011), describing postural adaptation during continuous sinusoidal platform translations. More importantly, they have shown that, young adults can transfer the experience gained from one set of continuous perturbations to subsequent sets (i.e. from one trial to the next). This occurs in a two-step process: (1) a significant reduction in COP displacement between trials, and (2) more energy efficient postural muscle responses (earlier muscle recruitment and smaller muscle burst amplitudes).

1.2.5 Synergy development in typically developing children and children with spastic cerebral palsy

i. Typical development

By age 4-5 months, there is a distinct order of muscle activation. First appearing in the neck, development of postural control continues in a cephalocaudal manner, as the trunk and legs, respectively, follow suit (Woollacott & Shumway-Cook, 1990). These postural synergies develop appropriate temporal organization, through experience, with each new skill acquired. Findings from unexpected platform translation perturbation studies suggest that once the synergy has been developed for the ankle strategy, muscle recruitment is organized in a distal to proximal organization (Horak & Nashner, 1986). After 4-5 months, organization of postural muscle activity, while functionally appropriate, is variable until the age of approximately 4-6 years with maturation of postural responses occurring around 7-10 years of age (Sveistrup & Woollacott, 1996). During the developmental period, practice on/experience of a postural task increases the likelihood of functionally appropriate APAs being generated (Sveistrup & Woollacott, 1996, 1997)

At around age 6 years of age, however, development of postural synergies has been shown to regress (Hay & Redon, 1999). At about this age (6 years), evidence has shown postural muscle response organization is more variable (e.g. longer muscle onset latencies; inconsistent muscle activations) than in children 15 months to 3 years of age, as well as 7-10 year olds. This is likely due to their learning of how to resolve intersensory conflict (e.g. visual-vestibular inputs and ankle joint proprioception) during postural control (Shumway-Cook & Woollacott, 1985).

Anticipatory control in children is not innate (Palluel *et al.*, 2008), however, infants and young children exhibit APAs shortly after having acquired the ability to maintain sitting, crawling, or upright posture (Haas *et al.*, 1989). Anticipatory and reactive mechanisms of postural control develop gradually, but anticipatory processes are mastered much later than reactive mechanisms (Hay & Redon, 1999). For example, to determine the involvement of anticipatory and reactive mechanisms during development, Hay and Redon (1999) looked at differences between children and adults in an unloading task. This required subjects to stand eyes-closed holding a load which was then either voluntarily unloaded by the subject or unpredictably removed by the researchers. It was determined that while younger children used anticipatory mechanisms to control their posture in preparation for the unloading perturbation, the older subjects were much more efficient in their use of anticipatory mechanisms. Furthermore, results from forward leg raising experiments in children 8-12 years of age confirm that expression of APAs (for this specific task) is still developing during mid-childhood, while full development of anticipatory strategy doesn't occur until approximately 12 years of age (Palluel *et al.*, 2008). It should be noted that with each new task, however, there is a momentary increase in response latencies and response variability, quickly followed by a return to normal levels with mastery of the task (Woollacott & Sveistrup, 1992). Hay and Redon (1999) noted that changes in balance performance seem to be associated with changes in the nervous system, and not necessarily due to biomechanical factors such as limb and trunk proportions and masses.

ii. Synergy and cerebral palsy

Postural control deficits are a major limitation to motor development in cerebral palsy (CP) (Rha *et al.*, 2010). People with cerebral palsy tend to exhibit increased muscle activity to sustain posture when compared with the typically developed population. They also demonstrate increased agonist-antagonist co-contraction, reduced force production, and restricted voluntary and selective control of movement, which all contribute to their impaired postural control (Girolami *et al.*, 2011).

In the developing child with CP, evidence of APA has been shown to be present as young as the age of 1 month (Hedberg *et al.*, 2005), but postural muscle activity is characterized by variation at a young age (Hadders-Algra *et al.*, 1999). Though APAs are not entirely missing in the CP population (Brogren *et al.*, 1998) there is a delayed development in the capacity to recruit direction-specific postural adjustments (de Graaf-Peters *et al.*, 2007). Furthermore, the ability to modulate postural adjustments specifically for a task is deficient in the child with CP (Hadders-Algra *et al.*, 1999). For example, Tomita *et al.* (2010) recorded bilateral arm flexion tasks in individuals with spastic diplegia, Gross Motor Function Classification System (GMFCS) levels II and III. They found that participants (aged 12-22 years) were able to anticipate effects of self-induced perturbations and could activate appropriate responses in postural muscles in advance of the postural disturbance. In a similar arm raising task study, Girolami *et al.* (2011) also found that children with cerebral palsy can, like typically developing children, produce directionally-specific anticipatory postural adjustments in muscles of the trunk and legs prior to flexion and extension movements of the arms. However, the generated APAs are usually of smaller magnitude, and tend to be more variable.

Instead of the typical distal to proximal synergic activity, individuals with CP tend to rely on proximal muscle activity for maintaining standing posture (Rha *et al.*, 2010). Interestingly, changes in postural muscle activity could be due to biomechanical factors (Tomita *et al.*, 2010). Studies have shown that because of differences in postural alignment, for example crouch stance, additional constraints are placed on the musculoskeletal system (Woollacott *et al.*, 1998). In asking typically developing children to stand in the crouch position, mimicking the posture of children with cerebral palsy, (Burtner *et al.*, 1998) found that participants exhibited muscle response patterns to discrete posterior platform translations that resembled those found in the CP population, suggesting that both CNS deficits and biomechanical factors influence balance.

In summary, development of anticipatory and reactive mechanisms of postural control is non-monotonic. Development continues until about age 12 years, with the exception of the noted regression between ages 4-6 years. Anticipatory and reactive mechanisms of postural control are also present in children and adolescents with cerebral palsy, albeit reduced in terms of muscle activity amplitude and more variable.

Though there have been a limited number of studies regarding the anticipatory postural control in children and adolescents, most of the previously reported studies characterizing anticipatory mechanisms are associated with single perturbations that are self-induced due to limb movements (e.g. arm or leg raises). This is in contrast to studies investigating the characteristics of reactive postural control mechanisms, which often make use of discrete platform perturbations. The following introduces different methods of perturbing stance currently used in research.

1.2.6 Perturbation paradigms

i. Discrete perturbations eliciting reactive mechanisms: The discrete translating perturbation paradigm is a common method used to translate the base of support. This generally consists of moving a platform on which a participant stands in different directions with varying magnitudes of displacement, velocity, and/or acceleration. The perturbations induced are similar to trips and slips (Horak *et al.*, 1997). The discrete perturbation, however, consists of only one movement of the platform and elicits the reactive motor strategies discussed previously.

ii. Discrete (self-induced) perturbations eliciting anticipatory mechanisms: Having participants complete self-induced limb movements is a common paradigm used to evaluate anticipatory mechanisms of postural control. There are various methods of accomplishing this, with one common method being the initiation of gait. As someone shifts the COM and lifts a leg to begin walking, the body becomes destabilized. However, the anticipatory synergic responses generated in this manner are not the same as those generated in response to translating platform paradigms, thus the two are functionally different. An anticipatory mechanism deficiency in this paradigm does not necessarily equate to a deficiency in anticipatory mechanisms where the entire base of support is being moved.

iii. Continuous platform translations: The oscillating platform paradigm is a common experimental approach to perturb the support surface (generally in the anteroposterior direction), which results in base of support displacement large enough to upset balance. These perturbations are similar to acceleration/deceleration of a moving surface on which someone is balancing, such as a bus, boat, or moving sidewalk (Horak *et al.*, 1997). As a subject stands on an oscillating platform, s/he must respond to an initial perturbation using a reactive response mechanism. If the platform continues to oscillate with a constant frequency, amplitude, and direction, the participant can switch to an anticipatory mechanism. However, if the protocol calls for a change in frequency of platform oscillations resulting in a perturbation, the participant must then use a reactive mechanism to respond to this change before switching again to the anticipatory mechanism once the platform oscillation frequency is stabilized (Bugnariu and Sveistrup, 2006).

The different forces and movements generated by the self-induced limb movements and platform perturbations naturally require different responses. The advantage of the continuous oscillating translating platform paradigm in only one direction (i.e anteroposteriorly) is that both reactive and anticipatory postural control mechanisms can be generated in order to deal with the same perturbation. This perturbation paradigm consists of increasing the frequency of anteroposterior platform movements within a single trial, thereby increasing the difficulty in maintaining postural control (Bugnariu & Sveistrup, 2006). This paradigm also offers the unique possibility of examining postural control strategies at different time points for each frequency. Immediately following a change in oscillation frequency, termed the *transition state*, the subject must adapt to a new perturbation frequency. With time and repeated cycles at the same frequency, the subject becomes accustomed to the perturbation and adopts an appropriate postural strategy.

1.3 Quantifying Balance

While there are numerous methods of quantifying balance, such as clinical tests like the Berg Balance Scale and the Pediatric Balance Scale, these types of tests do not inform as to *how* balance is maintained. As well as the previously-mentioned relationship between the COM and COP, and postural muscle activity, the following two methods can be used to provide an indication of how body segments are controlled.

1.3.1 Anchoring index

Balance strategies used by children and adolescents involve two functional principles (Assaiante *et al.*, 2005). First, a frame of reference must be identified. Second, a large number of degrees of freedom of the various body joints must be controlled simultaneously. In static and perturbed stance, maintaining control over balance requires control of superimposed body segments, specifically the head-trunk unit for maintaining a stable reference frame. Stabilization of the head can occur in two ways: (1) it can be stabilized on the trunk referred to as the Head Stabilization on Trunk Strategy (HSTS) (Assaiante *et al.*, 2005) or (2) it can be stabilized in space, referred to as the Head Stabilized in Space Strategy (HSSS) (Assaiante & Amblard, 1995; Assaiante *et al.*, 2005). The Anchoring Index (AI, below) quantifies how the head is stabilized on the trunk during movement: a low AI suggests HSTS, whereas a high AI is suggestive of a preference for HSSS. In scenarios with more destabilizing effects, HSTS might be selected as a preferred method of stabilization to provide a stable reference frame. Thus, the Anchoring Index is a useful measure to provide an indication of which method of stabilization (HSTS or HSSS) is being employed as it compares the stabilization of a segment with respect to both external space and its inferior segment (Amblard *et al.*, 1997; Mesure *et al.*, 1999).

$$AI = \frac{\sigma_r^2 - \sigma_a^2}{\sigma_a^2 + \sigma_r^2}$$

where σ_a *is the standard deviation of the absolute angular distribution of the head relative to vertical, and* σ_r *is the standard deviation of the angular distribution of the head relative to the trunk or inferior anatomical segment*

While the AI has been used to quantify head orientation in youth and adults in dynamic situations such as walking (Assaiante & Amblard, 1993) **and sit-to-stand** (Cignetti *et al.*, 2013)**, it has not, to date, been used to quantify balance in quasi-static stance or perturbation situations.**

1.3.2 Cross-correlation analysis

Relationships between kinematic parameters of movement can illustrate how balance is maintained through cross-correlation analysis of marker traces. The cross-correlation analysis involves temporally shifting one signal against another. By recording kinematics, and thus the marker traces, this method provides a correlation indicating the strength of association between two markers, as well as a temporal displacement of one maker trace relative to another.

Previous research has shown that cross correlation values of the ankle, hip and head trajectories provide information on how tightly coupled (i.e., stable) segments of the body are (Corna *et al.*, 1999; Nardone *et al.*, 2006). A value of 1 for a correlation coefficient would indicate an equal pattern and direction of body segment displacement, while a value of -1 would indicate an equal pattern but opposite direction of body segment displacement. A positive value in temporal displacement (i.e. delay) is suggestive of the upper segment of a signal (i.e. marker) pair to be ahead of the bottom segment, while a negative temporal displacement is suggestive of the top segment lagging. For example, if the marker trace of a head segment is compared to that of the ankle segment, and the result is a negative temporal displacement, then the head is considered to be lagging behind the ankle segment. If the result is a positive value, then it can be considered to be leading (or 'ahead of') the ankle segment.

While this method has been used to quantify segmental control in young adults (Corna *et al.*, 1999)**, it is unclear how children and adolescents, and those with CP stabilize body segments relative to one another when faced with quasi-static or perturbed stance situations. Thus, together with the Anchoring Index, these methods provide additional information on how body segments are controlled in space relative to one another, and how the head is controlled during perturbations (expected and unexpected) in order to try to provide a stable reference frame.**

The third manuscript (Chapter 4) presented in this thesis pertains to motor learning and the use of virtual reality as an intervention modality, with the aim of investigating its effects on balance. As such, the following comprises a review of the literature in this area of study.

1.4 Virtual reality and its use as an intervention modality

Virtual reality (VR) can be defined as "the use of interactive simulations created with computer hardware and software, generating a feeling of presence within a virtual environment that appears, sounds, and/or feels similar to the real world" (Rizzo, 2002). In other words, through sensory input augmentation, a person can feel as though a simulated environment is essentially the same as a real world environment. Although having been around for over 20 years, virtual reality is an ever-evolving concept, and only recently becoming a mainstream modality, with the costs of computer hardware and software drastically decreasing, and with technologies rapidly advancing.

In virtual reality, sensory augmentation is often supplied through the vision and auditory systems, however, recent developments in the simulated environment industry include haptic sensory augmentation through the use of specially manufactured gloves designed for object manipulation/sensation in the virtual reality world. Additionally, proprioceptive feedback can be augmented and/or challenged through the use of manoeuvrable platforms.

There are many different types of virtual environments available today. They can be fully immersive, as in the Head-Mounted Display type of virtual reality. Equally, they can appear as semi-immersive, where the subject is in front of a two-dimensional (or curved) screen, usually with an avatar appearing on the display in front of them. This type involves the use of some sort of video capture, whether it be an infrared camera operating off of retro-reflective marker sets, or infrared time-of-flight/depth cameras.

There are also many applications of virtual reality. Although various systems can be used for general enjoyment, i.e. an advanced form of video games, many systems are used for training purposes. Moreover, VR-based training is becoming increasingly popular with therapeutic goals of motor learning and relearning.

Motor learning can be defined generally as "a change in the capability of a person to perform a skill that must be inferred from a relatively permanent improvement in performance as a result of practice or experience" (Magill, 2004) and is a key component of rehabilitation to return function to a pre-injury level or to compensate through different ways of performing a task (Levin *et al.*, 2009). Kleim and Jones (2008) outline ten important principles of experience-dependent neural plasticity (defined as the ability to modify neural structure and function based on training; a response mechanism of relearning). The most relevant of these principles will be discussed with respect to virtual-reality based rehabilitation along with other principles outlined by (Wulf *et al.*, 2010).

1.4.1 Task-oriented and task-specific practice

In order to produce significant neural changes, mere use of the neurons is not enough; it is required that learning or skill acquisition take place. A number of studies have demonstrated that motor skill acquisition is associated with gene expression, dendritic growth, and neural activity in motor cortex and cerebellum (Black *et al.*, 1990; Kleim *et al.*, 1996; Nudo, 2003; Monfils *et al.*, 2005). Skill acquisition has been evidenced in humans by motor cortex activation patterns in fMRI and in movement representations using transcranial magnetic stimulation as a result of task-oriented practice (Kleim & Jones, 2008). Moreover, changes in the motor cortex have been linked to specificity of the task. For example, reaching studies in rats have shown significant changes in the motor cortex contralateral to the trained limb, whereas only minor changes were found on the ipsilateral side. Changes due to practice depend on specific experiences; this would suggest that training in a specific modality may only change a portion of the neural circuitry involved, and may therefore influence how the skill is used in non-trained modalities (Kleim & Jones, 2008). Task-oriented and task-specific training are some of the most direct methods of achieving significant changes.

i. Task-oriented VR training

In recent years, there has been an explosion in the creation of virtual environments designed to train skills for functional tasks. These include (but are in no way limited to) reaching and grasping, obstacle negotiation, and movements pertaining to balancing/postural control skills, all by requiring the user to perform life-like movements in the virtual environment. In each scenario, the user is required to perform movements to accomplish task goals. In a review of a variety of virtual reality systems, for example, Weiss *et al.* (2009) list the GestureTek IREX (Interactive Rehabilitation EXercise) system, with (select) applications in which the user has the goal of blocking soccer balls from entering the net (Soccer application), or a conveyor belt where the goal is to move objects from one side of the screen to the other (Conveyor Belt application) (Sveistrup *et al.*, 2004). Both of these examples required the user to perform movements to achieve goals with the intervention objectives of improving shoulder range of motion and balance retraining.

It should be noted, however, that it is possible unintentional challenges may be introduced that are different to the intervention tasks. For example, Edmans *et al.* (2006) noted that the virtual environment with the task of pouring a hot drink in post-stroke arm rehabilitation was useful, but that difficulties were encountered for various reasons. It was found that their virtual and real-world tasks of making a hot drink were qualitatively different from each other. However, this issue could be resolved with refinement of the virtual environment, and so is not necessarily generalizable to all VR goal-oriented tasking.

ii. Task-specific VR training

In task specific training, the aim is to create practice conditions that resemble, as closely as possible, real-world conditions (Schmidt, 1991). In virtual environments, conditions mimicking the real-world have been designed, such as kitchens, supermarkets, and streets; the possibilities are near endless, provided sufficient imagination and programming skills. These environments can be made such that they include the manipulation of objects within the environment, as well as other constraints of obstacles to be avoided (Rizzo & Kim, 2005). In addition to the virtual environments mimicking the real-world, the tasks/movements elicited should be similar to real-world movements in order for them to be ecologically valid (You *et al.*, 2005; Deutsch *et al.*, 2008).

One of the major benefits of virtual reality training is that the virtual environment is a cost-effective way of replicating real-world scenarios (Deutsch *et al.*, 2008). Moreover, it adds an element of safety such that increasing difficulty (e.g. through the addition of dual-tasking) does not necessarily increase danger, or, for example, in crossing a busy street in a virtual environment (e.g. to improve functional mobility), passing vehicles do not pose any threat to the user (Rizzo and Kim, 2005).

Conversely, however, it has been shown that a lack of haptic feedback (specifically in video-based systems) may influence how users perform in virtual environments (Knaut *et al.*, 2009). Moreover, the ecological validity goals of the created virtual environment may not always be achieved (Edmans *et al.*, 2006).

1.4.2 Repetition & intensity

i. Repetition

It has been well documented that by repeating a new motor skill, long-term retention of that skill is much more likely (Schmidt & Bjork, 1992) and that acquisition of a new skill is not enough. In order to induce lasting neural changes, continued performance (i.e. repetition) of a skill is required (Kleim & Jones, 2008), an important characteristic in terms of motor relearning, specifically in rehabilitation. Moreover, repetitions of a movement/skill may be needed such that the level of neural reorganization in the brain is sufficient to have continued use of the affected function (or relearned skill) once therapy is complete. It should be noted, however, that for repetition to be effective it should be salient and goal-oriented (Gordon & Okita, 2010).

Virtual reality training is very conducive to the concept of repetition – it allows for massed practice with consistent repetitions of a motor skill, whether they are identical or slightly varied between trials. Training within virtual environments can also provide for increased duration, intensity, and/or frequency of practice (Reid, 2002; You *et al.*, 2005; Deutsch *et al.*, 2008; Penn *et* *al.*, 2009; Brien & Sveistrup, 2011). This could be due to a motivation factor, whereby users who are motivated tend to participate longer and more often, allowing for the opportunity for repetition (Holden *et al.*, 1999). Additionally, as Gordon and Okita (2010) point out, if there is purposeful meaning to the action (i.e. through a task goal), children may have more fun, and therefore are more likely to continue resulting in greater repetition of the skill.

ii. Intensive practice

In addition to repetition, neural plasticity is also generated through intense stimulation or training. This can occur through either an increased amount of practice within a certain amount of time and/or an increase in the difficulty of the practice (Kleim and Jones, 2008). There is evidence to suggest that higher intensity stimulation can induce long-term effects (Lisman & Spruston, 2005); animals trained in reaching tasks (400 reaches per day) showed significant changes in the motor cortex (Kleim *et al.*, 2002).

In a single subject virtual reality based training study, Brien and Sveistrup (2011) found that following an intensive training program (90 minutes per day, 5 consecutive days) resulted in significant improvements on functional balance and mobility measures in 4 adolescents with cerebral palsy. While the authors did not report neural changes, the intensity and repetition may have provided opportunity for the "nervous system to build on previous attempts, and coordinate new muscular synergies to accomplish the task goal" (Brien and Sveistrup, 2011). Moreover, the intensity of the practice can be also altered on the go so as to approach the realness of the skill (Holden *et al.*, 1999) without having significant delays due to equipment and/or personnel changes.

1.4.3 Feedback

Much of the research in motor learning is concerned with the informational function of feedback, that is, information provided to the user about their performance related to the task goal. Feedback usually deals with information such as frequency, timing, accuracy, or error estimation (Wulf *et al.*, 2010), and usually comes in the forms of knowledge of performance (KP) and knowledge of results (KR). KP relates to how the task was performed, and is defined as 'augmented feedback providing information about movement characteristics that led to a specific performance outcome; KR, instead, relates to the success of the task attempts, defined as 'augmented feedback providing information on the outcome of a skill performance, or about achieving performance goal(s) (Magill, 2004). Feedback should be provided based on the skill level of the participant (Timmermans *et al.*, 2009).

Virtual reality can provide both KP and KR for motor (re)learning and the feedback is likely to be more consistent in the virtual reality training than it is in real life situations (Subramanian *et al.*, 2010). Moreover, it is possible in virtual settings to customize the environment to provide optimal feedback. For example, Gil-Gómez *et al.* (2011) optimized visual and auditory feedback through customized Wii games for patients with hemiparetic acquired brain injury and found significant improvements in static balance tasks. Subramanian *et al.* (2010) also found more changes in virtual versus physical environments in mild stroke patients, believing the results were due to better-provided feedback (KP), which led to possibly more cognitive effort/planning.

1.4.4 Transference

One of the most important concepts of motor learning is transference. In terms of neural changes, this is the "ability of plasticity within one set of neural circuits to promote concurrent or subsequent plasticity" (Kleim & Jones, 2008). Generally speaking, this concept refers to the ability to apply the learned motor skill from one task to another (or others), based on the experience of the first, and is usually dependent on common traits between the tasks (Bossard *et al.*, 2008).

Evidence for transference of skills from virtual reality training is widespread; much research has been done in fields such flight simulation, military exercises, and medical skills, preparing students to use these skills in the real world working environments. In terms of rehabilitation, Deutsch *et al.* (2008) found improvements in functional balance and mobility in adolescents with cerebral palsy after Wii-based training, and attributed these improvements to transferred skills between posture control in standing, and walking tasks. Kim *et al.* (2009) found similar results in stroke patients: improvements in dynamic balance and walking speeds were attributed to transferable skills from a combination of virtual reality-based and conventional training. Conversely, however, Gil-Gómez *et al.* (2011) did not find any transference from their modified Wii-based rehabilitation as they only found improvements in static stance, not dynamic balance. Edmans *et al.* (2006) also found that their virtual hot beverage task did not transfer to real life scenarios.

In conclusion, VR involves multimodal processes that aide in optimizing motor rehabilitation through task-oriented practice. Each training regimen can be customized to the individual's needs, all the while providing task-oriented training within an ecologically valid context. The safety provided by the environment allows for the subject to take risks in reproduced conditions consistent with real life scenarios, but without the risk of actually being harmed. Additionally, because the virtual environment poses no actual risks (aside from potential cybersickness), and because it can be automated, there is increased opportunity to increase the number of repetitions of the task that the subject can perform (Penn *et al.*, 2009). Furthermore, the level of difficulty can be adjusted continually (automatically within the programming of the software or manually by the administrator) to coincide with the challenge-point theory of motor control and motor learning. Having such control over the intervention allows for optimization of the rehabilitation, through manipulation of the complexity of the task, feedback type, as well as the feedback schedule (Green & Wilson, 2012).

It is known that virtual reality as a treatment modality shifts the focus from the individual's personal efforts to the enjoyment of a meaningful task (Thornton *et al.*, 2005; Bryanton *et al.*, 2006; Levac *et al.*, 2012). Unfortunately, however, there are many conflicting results about the efficacy of virtual reality intervention training. There are studies confirming the benefits of an intensive training schedule, resulting in changes in selective motor control (Brien & Sveistrup, 2011; Green & Wilson, 2012), however, it remains unclear whether these kinds of changes would last after several months (Bryanton *et al.*, 2006; Snider *et al.*, 2010; Brien & Sveistrup, 2011). Furthermore, the relationship between performance in the environment and performance in the real world needs to be examined (Laver *et al.*, 2011).

Finally, there is the important question of which aspects or components of virtual reality are at play. To date, there is a lack of evidence as to which component is primarily responsible for eliciting results in virtual reality intervention training (i.e. is it a certain sensory augmentation, the increased repetitions, higher levels of enjoyment, etc) and so it can only be assumed at this point to take a gestalt approach. In other words, the whole of the virtual reality experience is greater than the sum of the individual components. Perhaps it is that virtual reality provides feedback and an outlet for consistent repetitions of realistic tasks, and that it may motivate users to increase practice duration or intensity (Deutsch *et al.*, 2008; Saposnik *et al.*, 2010), but this is only one piece of the puzzle.

2 Aim of the Dissertation

Postural control mechanisms used to respond to continuous perturbations are not well understood in children and adolescents. Therefore, **the overarching aim of this dissertation was to characterize the anticipatory and reactive mechanisms of postural control in compensating for externally- and self- initiated but predictable postural perturbations in children and adolescents**. Additionally, in order to characterize these postural control mechanisms in youth with cerebral palsy, and to investigate the potential benefits of a tailored physiotherapy programme, these postural control mechanisms first needed to be documented in typically developing youth. Therefore, this main objective was accomplished through a series of complimentary experimental studies to aid our understanding of these mechanisms in developing youth. The specific objectives and hypotheses of each of the three studies are as follows:

Study 1: **Characterization of postural control mechanisms in typically developing children and adolescents**. The overall aim of Study 1 was to characterize the anticipatory and reactive mechanisms of postural control in typically developing youth aged 7-17 years. The specific objectives of this study were to determine whether youth in natural development periods (i.e. ages 6-12 years and 13-17 years) exhibited different postural responses when subjected to continuous platform oscillation at varying frequencies.

An oscillating platform paradigm was used to characterize the displacement of various body segments, the anchoring of the head on the trunk, and postural muscle activity to explain how children and adolescents respond to and anticipate platform movement. The main hypothesis of this study was that following a change to a new frequency (i.e. transition state), participants would exhibit reactive mechanisms of postural control, evidenced by a preference for HSTS, low segmental correlations coupled with high temporal lag, and late muscle onset latencies. During steady state, it was hypothesized participants would shift from reactive to anticipatory mechanisms of postural control, as evidenced by a preference for HSSS, higher segmental correlations with lower temporal lag. It was also hypothesized that when given control over when a change in frequency occurs, participants would exhibit more anticipatory-like measures of postural control during transition state. The results from this experiment act as a foundation for characterizing postural mechanisms in this population when exposed to a continuously oscillating platform. They also serve as the basis for Study 2.

Study 2: **Characterization of postural control mechanisms in children and adolescents with cerebral palsy**. The overall aim of Study 2 was to quantify postural response strategies in youth aged 7-17 with cerebral palsy, and to determine how their control of postural responses differed when compared to an age-matched typically developing (Study 1). Secondary aims of this study were to determine if youth with CP were able to 1) modify postural responses during steady state in an experimenter-triggered perturbation condition, and 2) further modify their chosen strategies when given control over when a change in perturbation speed occurred. The main objectives of Study 2 were to quantify the same postural response strategies as those of Study 1 in CP youth. The main hypothesis of this study was that youth with CP would be less able to modify their responses compared to the typically developing youth. Secondary hypotheses were that CP youth would be less able to shift to anticipatory mechanisms based on knowledge of platform movement, and that they would be less able to further modify postural responses when controlling the change of platform perturbation timing. The results from this study provide a detailed quantification of postural control mechanisms in CP youth when exposed to a continuously oscillating platform, and were used as a fundamental basis for *Study 3*.

Study 3: **Effect of 5-day intensive physiotherapy on postural control mechanisms in children and adolescents with cerebral palsy**. This study was part of a larger study focussed on clinical outcome measures such as the Gross Motor Function Measure Challenge Module (GMFM-CM) and the Six-Minute Walk Test (6MWT) following prescribed active video gaming exercise ((Levac *et al.*, 2017); Appendix 1). The overall aim of Study 3 was to determine the effects of a 5-day intensive VR-based intervention on mechanisms of postural control in children and adolescents with CP through the use of the continuous oscillating platform paradigm. It was hypothesized that changes in postural control in the intervention group would be evidenced through a reduction in total number of steps taken and postural muscle tonic activity, while also demonstrating a shift to a head-in-space strategy.

Chapters 2, 3, and 4 have been submitted to peer-reviewed journals and are formatted according to the individual journal's submission requirements. All studies were approved by the University of Ottawa Health Science Research Grants and Ethics Services.

Chapter 2: Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents

A version of this paper is currently under review at *Experimental Brain Research*[1] and has been formatted according to journal guidelines.

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[1] A revised edition of this manuscript has since been accepted – doi: 10.1007/s00221-018-5228-0.

Full-length original research article for submission to
Experimental Brain Research

Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents

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2.1 Abstract

The aims of this study were to (1) characterize anticipatory and reactive postural strategies in typically developing (TD) children and adolescents; (2) determine if TD youth shift from reactive to anticipatory mechanisms based on knowledge of platform movement; and (3) determine whether TD youth further modify postural strategies when additional information about the perturbation is provided. Sixteen typically developing youth aged 7-17 years stood with eyes open on a movable platform that progressively translated antero-posteriorly (20cm peak-to-peak) through four speeds (0.1 Hz, 0.25 Hz, 0.5 Hz, and 0.61 Hz). Participants performed two trials each of experimenter-triggered (ETP) and self-triggered (STP) perturbations. Postural muscle activity (1000 Hz) of the tibialis anterior (TA), gastrocnemius (G), quadriceps (Q) and hamstrings (H) and 3D whole body kinematics (100 Hz) were recorded. The anchoring Index (AI) and marker-pair trajectory cross-correlations (CC) were calculated as indications of body stabilization. The number of steps taken to regain balance/avoid falling were counted. Transition states (TS) and steady states (SS) were analyzed separately. Generally, the higher frequencies resulted in more steps being taken, lower correlations coupled with greater temporal lags between marker trajectories, and postural muscle activity similar to older adults. The provision of self-triggered perturbations allowed participants to make the appropriate changes to their balance by use of anticipatory postural control mechanisms.

Keywords: postural control, anchoring index, balance mechanisms, oscillation

2.2 Introduction

The concept of static stability limits considers only the position of the centre of mass (COM) with respect to the base of support (BOS), often, for example during quiet stance. Extensive modeling studies however define a concept of more dynamic stability limits (Pai and Patton 1997; Pai et al. 1998; Pai et al. 2003) which simultaneously considers both the relative position and velocity between the COM and the BOS. These studies have identified thresholds for step initiation induced by support surface translations with predictions that stepping would occur if the state space threshold is breached. Control of the COM within the BOS can be achieved through various balance strategies, by controlling multiple joints including the ankle and hip.

Balance strategies used by children and adolescents involve two functional principles (Assaiante *et al.*, 2005). First, there is identification of a frame of reference and, for static balance this can be organized from the support surface in an ascending fashion or from the head to the feet in a descending fashion. Second, children and adults need to simultaneously control large numbers of degrees of freedom of the various body joints. In static or perturbed balance, the task permits the control of superimposed modules such as the head-trunk unit which can be controlled more or less independently from other segment pairs. Stabilization of the head can thus occur in two ways: (a) it can be stabilized on the trunk referred to as the Head Stabilization on Trunk Strategy (HSTS) (Assaiante *et al.*, 2005) or (b) it can be stabilized in space, referred to as the Head Stabilized in Space Strategy (HSSS) (Assaiante et al. 2005; Assaiante and Amblard 1995). The strategy used, in part, depends on the dynamic constraints determining task difficulty and the developmental characteristics of the person (Assaiante *et al.*, 2005). For example, in scenarios with more destabilizing effects, HSTS might be selected as a preferred method of stabilization by decreasing the number of degrees of freedom, while scenarios in which the person is comfortable with their ability to deal with a perturbation results in a preference for HSSS. Thus, the Anchoring Index (AI) can be used to provide an indication of which method of stabilization (HSTS or HSSS) is being employed as it compares the stabilization of a segment with respect to both external space and its inferior segment (Amblard *et al.*, 1997; Mesure *et al.*, 1999).

Studies examining the development of postural control suggest specific observable stages of control (cf Fujiwara et al. 2011; Assaiante et al. 2005). By about age 7 years, children should begin to exhibit adult-like performance in terms of maintaining balance and posture (Woollacott and Shumway-Cook 1990) with the frame of reference organized in a descending fashion (Assaiante, 1998). If the postural disturbance is large enough, it is likely that a step must be taken to avoid falling (Burtner et al. 2007). If the postural disturbance is small, however, balance can be maintained through modulation of joint torque by activating the muscles of the lower leg (e.g. gastrocnemii and tibialis anterior) appropriately, termed *ankle strategy*. If the postural disturbance is somewhere in between, the result is likely to be controlled about the hip, termed *hip strategy*, with proximal to distal activation of postural muscles. It is entirely likely that the response used lies somewhere in between the ankle and hip strategies and depends on multiple factors including the required force or torque to maintain stability, the support configuration, body morphology and initial position, and muscular strength (McCollum and Leen 1989).

Prior knowledge or experience of a disturbance has been shown to result in habituation whereby preparation occurs in an attempt to counteract the upcoming perturbation, resulting in postural muscle activations in advance of or coincident with the perturbation (Kennedy et al. 2013; Schmid et al. 2011; Bugnariu and Sveistrup 2006; Pavol and Pai 2002). Motor adaptations to balance-challenging perturbations occur with the repetition of successive, separate perturbation trials (Buchanan and Horak 1999; Hansen et al. 1988; Perrin et al. 1998; Kennedy et al. 2013). The oscillating platform paradigm provides an experimental approach to perturb the support surface at different frequencies and amplitudes where the initial perturbation elicits a reactive response mechanism and as the platform continues to oscillate, the participant can switch to an anticipatory mechanism. Adaptations to the increasingly predictable perturbations can occur within just a few cycles of sinusoidal platform translations (Schmid et al. 2011; Laessoe and Voigt 2008; Bugnariu and Sveistrup 2006). Changes in the frequency of platform oscillation results in a sudden perturbation and the participant must use a reactive mechanism to respond to this change before switching again to the anticipatory mechanism once they are stabilized.

In the present study, we asked i) whether typically developing children would shift from a head stabilized on trunk strategy to a head stabilized in space strategy when the perturbation characteristics became known; and ii) whether children and adolescents would predict and shift to an earlier use of head stabilized in space postural strategy if they were able to control the perturbation onset.

2.3 Materials and Methods

The study was approved by the University of Ottawa Health Sciences and Science Research Ethics Board, conforming to the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (TCPS2), and fully informed consent was obtained from parents and adolescents. Assent was obtained from the younger children.

Participants:

Sixteen typically developing (TD) children and adolescents aged 7-17 years (7 boys, 9 girls) participated in this study. Mean age, height, and weight (±S.D.) were 12.56 years (±3.16), 160.47 cm (±19.59), and 53.94 kg (±16.82).

Dynamic Balance Protocol:

Participants stood with their eyes open and bare feet shoulder-width apart on a hydraulic movable platform (CAREN platform, Motek Medical, B.V., Amsterdam). They were instructed to maintain their balance while avoiding taking steps unless absolutely necessary. When a step was taken, participants were told to regain their balance and reposition their feet to the initial position that was marked on the platform with stickers.

The platform translated 20 cm peak-to-peak in the anterior/posterior direction. The sinusoidal oscillations commenced at a frequency of 0.1 Hz. At intervals of 80-100 s, the frequency was increased successively to 0.25, 0.5, and 0.61 Hz. Trials were approximately 342 seconds long and consisted of at least 10 cycles at 0.1 Hz, 20 cycles at 0.25 Hz, 40 cycles at 0.5 Hz, and 50 cycles at 0.61 Hz. Participants performed 2 trials where the change in frequency of the platform oscillation was initiated by the experimenter (externally triggered perturbation: ETP). Participants then performed 2 trials where the increase in oscillation frequency was self-cued (self-triggered perturbation: STP). Regular rests were provided.

Place Fig. 1 near here

Data Acquisition:

Participants were instrumented with retroreflective markers (14mm) to obtain full body kinematics (modified Plug-in Gait model). Motion analysis software recorded body movements at 100 Hz using 7 Vicon T13 cameras (Vicon, Oxford, UK). Surface electromyography (sEMG) data were collected at 1000 Hz using Delsys Bagnoli EMG (Delsys Inc., Natick, USA) systems. Postural muscle activity was recorded by attaching surface electrodes to prime movers of the anterior and posterior kinetic chains of the leg: tibialis anterior (TA), gastrocnemius (G), quadriceps (Q), and hamstrings (H) muscles of the left side of the body (Bugnariu and Sveistrup, 2006). A ground electrode was placed on the left iliac crest.

Data were processed offline. Trials were individually reconstructed, digitally labeled, and filtered for noise reduction in Vicon Nexus 1.8.5, then exported for data analysis. Exported data files were processed for each dependent variable using MATLAB version R2015a (Mathworks Inc., USA)

Data Reduction and Analysis:

In each trial, the first three to five consecutive cycles without stepping at each frequency were considered 'transition-state (TS) periods'. In the last half of the trial at each frequency, a series of 3 to 5 consecutive cycles without stepping at 0.1 Hz and a series of 8 to 10 consecutive cycles without stepping at the remaining frequencies was considered the 'steady-state (SS) period' when anticipatory postural responses would be expected (Bugnariu and Sveistrup, 2006). TS and SS periods were analyzed separately.

1) Stepping responses

The number of steps taken by each subject at every frequency was documented.

2) *Anchoring Index.*

The absolute angles (with respect to the external axis) around the transverse axis were computed for the head and trunk. These values were used to compute the anchoring index (AI) for the head and to determine the stabilization of the head with respect to both external space and the trunk or inferior segment (Amblard *et al.*, 1997, 2001; Mesure *et al.*, 1999). The AI was calculated for transition- and steady-state periods in the pitch plane as follows:

$$AI = [\sigma^2_r - \sigma^2_a] / [\sigma^2_a + \sigma^2_r]$$

where σ_a is the standard deviation of the absolute angular distribution of the head relative to vertical, and σ_r is the standard deviation of the angular distribution of the head relative to the trunk or inferior anatomical segment. A negative AI indicates a preference for stabilization of a segment on its inferior segment (e.g., Head Stabilization on Trunk Strategy/ HSTS), whereas a positive AI indicates a preferred stabilization with respect to the external space (e.g., Head Stabilization in Space Strategy/HSSS).

3) Cross-Correlation Functions

The cross-correlation coefficients of the anterior-posterior linear displacements of the ankle and head markers, hip and head markers, and ankle and hip markers were computed for transition and steady states in each trial. To identify the maximum cross-correlation (CC_{max}), and the temporal relationship (lag/lead), each signal correlation was calculated for up to ±50% time shift of one cycle by shifting one signal temporally one data point at a time. The CC_{max} was recorded as well as the normalized time lag at which it occurred ($CC_{lag/lead}$). Cycles during which the participants took steps were excluded from the CC analysis.

4) Postural Muscle Burst and Tonic Activity

Postural muscle activity was identified as the first burst of activity associated with a perturbation that lasted more than 50 ms and that was greater than two standard deviations above the baseline. In order to be included in the calculations of group muscle activity, responses had to be present in at least 30% of the directionally specific perturbation at each frequency (i.e., anterior muscles for backward perturbation, posterior muscles for forward perturbation) for transition state periods, and 50% for steady state periods. For the 0.1 Hz frequency, this recruitment threshold was reduced to 20% of perturbations (Bugnariu and Sveistrup, 2006).

Tonic postural muscle activity was expressed as a percentage of the baseline tonic activity level in ETP SS 0.1 Hz. This was determined during quiet stance at a point mid-cycle in the lowest frequency where no burst activity was present.

Statistical Analysis:

Participant demographics and stepping data were summarized using descriptive analyses. Statistical analyses were performed using SPSS v 23.0.0.2 (IBM Corp.). The data were determined to be non-normal through inspection of skewness and kurtosis, histograms, and Shapiro-Wilk tests of normality. Non-parametric inferential testing using the Wilcoxon signed rank test for within group differences identified significant differences between transition and steady state periods at each frequency in both ETP and STP conditions (separately). The dependent variables tested were: CC_{max} and $CC_{lag/lead}$ of marker trajectories (ankle-head, ankle-hip, hip-head), the anchoring index, and postural muscle activity (tonic and bursting activity). Comparisons were also made between condition (ETP and STP) for all variables in each of transition and steady states. Results were considered significant at $p < 0.0125$ (Bonferroni adjusted for multiple comparisons).

2.4 Results

Stepping Responses

The total number of steps, the number of participants who stepped, and the range of steps taken immediately following each change of frequency are reported in Table 1. In ETP, no participants stepped during the first two frequencies. Four participants took a total of 26 steps at 0.5 Hz and five participants recording 11 steps at the highest frequency. The number of steps taken by any individual participant was less at 0.61 Hz than at 0.5 Hz.

Insert Table 1 near here

Fewer steps were recorded in the STP condition. A single participant took 2 steps in the transition to 0.25 Hz. There were no steps recorded at 0.5 Hz and a single participant took 2 steps at 0.61 Hz.

Children shift postural responses with experience in a task:

Transition State vs Steady State

Anchoring Index

There were no significant differences in the anchoring index between the transition and steady state periods at any frequency in either ETP or STP condition (Fig. 2). However, for both conditions, there was a trend towards greater Head Stabilization in Space as the platform oscillation frequency increased. This was noted in both transition and steady states except for a marked decrease in the AI during the steady state period at 0.61 Hz in STP.

Place Fig. 2 near here

Inter-Joint Cross Correlation Coefficients

Externally Triggered Perturbation

All CC_{max} remained above 0.8 between transition and steady states at the lower frequencies (Fig. 3), which, in combination with the short time lag of less than 4% of the cycle, suggests that participants kept their bodies relatively rigid. At 0.5 Hz and 0.61 Hz, the ankle-head CC_{max} was significantly lower in the steady state compared to transition state (0.5 Hz: $z = 3.206$, $p = 0.001$; 0.61 Hz: $z = 2.585$, $p = 0.010$). Temporally, the head segment led the ankle at 0.1 Hz, suggesting a slight lean forward in transition state ($z = 3.002$, $p = 0.003$). Although the head lagged the ankle segment at both higher frequencies, the difference between the transition and steady state periods was significant only at 0.5 Hz (0.5 Hz: $z = 2.844$, $p = 0.004$; 0.61 Hz: $z = 1.655$, $p = 0.098$).

Place Fig. 3 near here

Although there was a significant difference in CC_{max} for the ankle-hip pair in ETP at 0.1 Hz ($z = 3.413$, $p = 0.001$), the difference was small (transition state: $M = 0.98$, $SD = 0.02$; steady state: $M = 0.99$, $SD = 0.01$). This finding was likely due to the extremely tight coupling between joints with limited variability between individuals and periods. Though not significant, the time lag however, changed from little hip lag in transition state ($M = -0.038$, $SD = 1.09$ %cycle) to the hip lagging the ankle more in steady state (*M* = -0.84, *SD* = 1.13 %cycle) at 0.25 Hz (*z* = 2.017, *p* = 0.044). This effect was reversed at 0.5 Hz (*z* = 2.482, *p* = 0.013), where the hip lagged the ankle less in steady state (*M* = -1.42, *SD* = 2.45 %cycle) than it did in transition state (*M* = -2.79, *SD* = 1.29 %cycle), while no significant difference was observed at 0.61 Hz.

The CC_{max} and temporal relationships for the hip-head pair did not differ significantly from transition to steady state periods at any frequency in the ETP condition. There was, however a tendency for the CC_{max} to decrease in both transition and steady state periods with the higher frequencies. While not significant, there was also a shift with the head lagging the hip less in steady state (*M* = -4.55, *SD* = 3.56 %cycle) than in transition state (*M* = -6.32, *SD* = 4.47 %cycle) at 0.5 Hz (*z* = 2.217, *p* = 0.030).

Self-Triggered Perturbation

In the STP condition, the ankle-head CC_{max} differed significantly between transition state (*M* = 0.83, *SD* = 0.14) and steady state (*M* = 0.89, *SD* = 0.09) at 0.1 Hz (*z* = 3.181, *p* = 0.001), indicating the two trajectories became more correlated with a shift to the steady state period (Fig. 4). With an increase in frequency to 0.61 Hz, the marker traces were less correlated in the steady state period (*M* = 0.39, *SD* = 0.3) than they were in the transition state period (*M* = 0.56, *SD* = 0.19), although this was not found to be significant (*z* = 2.329, *p* = 0.020). No significant differences were found for the ankle-head cross-correlation temporally, however, transition state (*M* = -5.82, *SD* = 3.19 % cycle) and steady state (*M* = -3.08, *SD* = 3.67 % cycle) at the 0.5 Hz frequency approached significance (*z* = 2.329, *p* = 0.020), indicating the head was lagging the ankle less in steady state.

Place Fig. 4 near here

In STP, the CC_{max} and $CC_{lag/lead}$ analysis revealed significant differences for the ankle-hip marker pairs across two of the four frequencies. The two marker traces were more correlated in steady state (M = 0.97, SD = 0.03) than they were in transition state (M = 0.96, SD = 0.03) at 0.1 Hz (z = 2.556, p = 0.011). The timing was also affected at 0.1 Hz (z = 2.551, p = 0.011), with the hip lagging the ankle less in steady state (M = -0.2, SD = 0.57 % cycle) than in transition state (M = -0.97, SD = 1.06 % cycle). The same effect was observed at 0.25 Hz with the correlation between the two marker traces (z = 2.726, p = 0.006) increasing from transition state (M = 0.94, SD = 0.05) to steady state (M = 0.96, SD = 0.03), and a timing shift (z = 2.755, p = 0.006) from slight hip lead in transition state (M = 0.35, SD = 1.6 % cycle) to slight hip lag in steady state (M = -0.38, SD = 1.1 % cycle). No significant differences were found for amplitude or timing at 0.5 Hz and 0.61 Hz.

No significant differences were found for the hip-head cross correlations (CC_{max} or $CC_{lag/lead}$) between transition and steady state periods at any frequency in the STP condition.

EMG

Onset Latencies

In the ETP condition, the onset latencies did not differ significantly between transition and steady states for any muscle. In the STP condition, the difference between transition and steady states in the G approached significance at 0.25 Hz (z =2.354, p = 0.019), with the muscle onset occurring earlier in steady state (M = -0.56, SD = 0.26 % half cycle) than in transition state (M = -0.18, SD = 0.38 % half cycle). Fig. 5 illustrates the differences in onset latencies for the muscles (directionally specific) at the four frequencies for both ETP and STP conditions, as well as transition and steady states. Though not significant, there is subtle shift to earlier activations in all muscles but the hamstrings in the steady state periods in ETP and STP conditions.

Place Fig. 5 here

Tonic Activity

EMG tonic activity was calculated as a percentage of the baseline value in steady state at 0.1 Hz. Generally, the tonic activity in all muscles increased as a function of frequency in both ETP and STP conditions but tended to decrease from transition to steady state (Fig. 6). In ETP, tonic activity was greater in the TA at 0.5 Hz ($z = 2.543$, $p = 0.011$) in transition state ($M = 146.35\%$ baseline, $SD = 84.66$) than in steady state ($M = 110.18\%$ baseline, $SD = 43.81$). It was greater in the G at 0.5 Hz ($z = 2.543$, $p = 0.011$) in transition state ($M = 130.66\%$ baseline, $SD = 79.61$) than in steady state ($M = 97.53\%$ baseline, $SD = 36.20$). In the STP condition, tonic activity was greater in transition state for TA at 0.61 Hz ($z = 2.613$, $p = 0.009$), Q at 0.61 Hz ($z = 3.010$, $p = 0.003$), and H at 0.5 Hz (z = 3.408, p = 0.001) and 0.61 Hz ($z = 2.691$, $p = 0.007$).

Place Fig. 6 near here

In summary, in both ETP and STP conditions, there was a trend towards HSSS as the oscillation frequency increased, with the exception of 0.61 Hz in steady state. This was accompanied by the head lagging the ankle and hip less during SS at the higher frequencies. No significant differences were observed between transition and steady states in postural muscle onset latencies, however *there was a tendency to shift towards earlier activations in steady state. Tonic activity increased with oscillation frequency, and tended to decrease from transition to steady state.*

Children shift postural responses if they have knowledge about perturbation timing: Externally- vs Self-triggered perturbation comparisons

Anchoring Index

No significant differences between ETP and STP conditions were observed for the Anchoring Index at any frequency in either Transition or Steady State period.

Ankle-Head Trajectory Cross Correlation

The Ankle-Head trajectories (CC_{max}) at 0.1 Hz were found to be more correlated (z = 3.408, p = 0.001) in transition state of the ETP condition (M = 0.91, SD = 0.07) compared to the STP condition (M = 0.83, SD = 0.14), as well at 0.25 Hz (z = 3.010, p = 0.003) (ETP: M = 0.88, SD = 0.07; STP: M = 0.79, SD = 0.13). While no significant differences were found at the lower frequencies, at 0.5 Hz the head lagged the ankle more (z = 3.067, p = 0.002) in the ETP condition (M = -9.11, SD = 3.86 % cycle) compared to the STP condition (M = -5.82, SD = 3.19 % cycle). Though not significant, similar results were found at 0.61 Hz (z = 2.272, p = 0.023) where the ETP condition yielded more head lag in the ETP condition (M = -11.05, SD = 7.00 % cycle) than the STP condition (M = -7.65, SD = 3.52 % cycle). Meanwhile, at 0.25 Hz in steady state, the ankle and head marker tracers were significantly more correlated (z = 3.237, p = 0.001) in the ETP condition (M = 0.86, SD = 0.23) than in the STP condition (M = 0.7, SD = 0.34). Moreover, there was a preference for less head lag in STP (*M* = -3.08, *SD* = 3.67) than in ETP (*M* = -6.61, *SD* = 4.34) at 0.5 Hz (*z* = 2.840, *p* = 0.005).

Ankle-Hip Trajectory Cross Correlation

The difference found for the CC_{max} between ETP (*M* = 0.98, *SD* = 0.02) and STP (*M* = 0.97, *SD* = 0.03) conditions in transition state approached significance at the 0.1 Hz frequency (*z* = 2.385, *p* = 0.017. Differences were revealed in $CC_{lag/lead}$ at 0.5 Hz (*z* = 3.352, *p* = 0.001), indicating a shift from hip lag in the ETP condition (*M* = -2.79, *SD* = 1.13 % cycle) to slightly less hip lag in the STP condition (*M* = -1.28, *SD* = 1.41 % cycle).

In steady state, only the 0.1 Hz frequency saw a significant difference (*z* = 3.067, *p* = 0.002) in CC_{max}, indicating slightly more correlated trajectories in the ETP condition (*M* = 0.99, *SD* = 0.01) than in STP (*M* = 0.97, *SD* = 0.03). Furthermore, while not significant, the hip was found to lag the ankle less in STP (*M* = -1.65, *SD* = 2.6 % cycle) than it did in ETP (*M* = -3.00, *SD* = 3.13 % cycle), but only at 0.61 Hz (*z* = 2.442, *p* = 0.015).

Hip-Head Trajectory Cross Correlation

In transition state, the hip was found to have greater correlation at 0.1 Hz (*z* = 3.124, *p* = 0.002) in ETP (*M* = 0.94, *SD* = 0.07) than in STP (*M* = 0.78, *SD* = 0.42). At 0.25 Hz, the correlation in ETP (*M* = 0.92, *SD* = 0.06) was greater than that of STP (*M* = 0.75, *SD* = 0.45) (*z* = 2.897, *p* = 0.004). In steady state, this correlation was greater (*z* = 2.897, *p* = 004) in ETP (*M* = 0.91, *SD* = 0.22) than in STP (*M* = 0.69, *SD* = 0.59).

Cross correlation analysis also revealed significant differences in the $CC_{lag/lead}$ for the hip-head marker traces at the higher frequencies. At 0.5 Hz, the head lagged the hip significantly more (*z* = 2.528, *p* = 0.011) in the ETP condition (*M* = -6.32, *SD* = 4.47 % cycle) than in the STP condition (*M* = -3.71, *SD* = 4.21 % cycle) and again at 0.61 Hz [(*z* = 3.17, *p* = 0.002); *M* = -10.03, *SD* = 6.70 % cycle in ETP versus *M* = -5.92, *SD* = 3.20 % cycle in STP]. In steady state, however, CC analysis only revealed significant difference for timing between ETP (*M* = -4.554, *SD* = 3.56) and STP (*M* = -2.62, *SD* = 3.18 % cycle) conditions at 0.5 Hz (z = 2.67, *p* = 0.008), indicating less head lag in the STP condition.

EMG

Onset latencies

In transition state, only the quadriceps were activated earlier in STP (*M* = -0.11, *SD* = 0.08 % half cycle) than in ETP (*M* = -0.06, *SD* = 0.09 % half cycle) at 0.61 Hz, however this was not significant (*z* = 2.201, *p* = 0.028). Conversely, in steady state, the gastrocnemius at 0.25 Hz (z = 2.701, *p* = 0.007) were activated earlier in ETP (*M* = -0.60, *SD* = 0.11 % half cycle) than in STP (*M* = -0.41, *SD* = 0.11 % half cycle).

Tonic activity

Though both transition and steady states generally saw an increase in tonic activity with an increase in oscillation frequency, the tonic activity observed in ETP was greater than in STP only during transition state. At 0.1 Hz, the tonic activity in the G was greater (*z* = 2.731, *p* = 0.006) in ETP (*M* = 101.87, = *SD* 25.01 % baseline) than in STP (*M* = 88.19, *SD* = 21.45 % baseline), as was the H (ETP *M* = 108.97, *SD* = 15.41% baseline; STP: *M* = 90.21, *SD* = 15.76 % baseline; *z* = 2.528, *p* =

0.011). The TA and Q exhibited greater tonic activity at 0.5 Hz (z = 2.668, p = 0.008; z = 2.856, p = 0.004, respectively) in ETP (M = 146.36, SD = 84.66 % baseline; M = 161.24, SD =76.40 % baseline, respectively) than STP (M =108.65, SD = 43.06 % baseline; M = 136.10, SD = 72.26 % baseline, respectively). No tonic activity differences were observed between ETP and STP in steady state.

In summary, few differences were observed between ETP and STP conditions. The AI was similar between conditions. The head lagged the ankle and hip more in ETP during transition state at the high frequencies, while the hip lagged the ankle less in STP at 0.5 Hz in ETP and STP. As oscillation frequency increased, tonic activity tended to increase in ETP during transition state only. Generally, no differences were found in onset latencies between conditions.

2.5 Discussion

We characterized the displacement of and relationships between the head, ankle and hip, the anchoring of the head on the trunk, and postural muscle activity in order to explain how children and adolescents respond to and anticipate a continuous perturbation. We initially hypothesized that there would be an effect of period type on these characteristics. The data suggest potential biomechanical constraints and reduced abilities to take advantage of platform movement at the higher frequencies.

The ability to use a step as a compensatory response for balance emerges in young children as they gain walking experience usually between 18-24 months (Roncesvalles, Woollacott and Jensen, 2000). In conditions with discrete perturbations, a young adult stepping response may consist of a single step in the axis of the perturbation to regain control. Older adults however will use multiple steps to regain balance. Moreover, the older adult will often direct their steps laterally in order to regain stability (Mcllroy and Maki 1993; Mcllroy and Maki 1996). The need for stepping and number of steps required to regain stability are heavily influenced by the perturbation amplitude as well as the ability to regulate mediolateral stability. As expected, higher frequencies experienced in the oscillating paradigm elicited the most stepping responses in both ETP and STP conditions with most steps recorded following the changes to 0.5 Hz to 0.61 Hz in the ETP condition. The transition period from 0.25 Hz to 0.5 Hz was the largest increase in perturbation as oscillation frequency doubled at this point. The subsequent shift to 0.61 Hz appeared to be less destabilizing.

Low frequency perturbations are compensated for through increased joint stiffness

The increase in difficulty of perturbation due to increase in oscillation frequency was also reflected in the amount of correlation between marker trajectory pairs decreasing. At the lower frequencies, the high CC_{max} values and low $CC_{lag/lead}$ suggest that as the challenge to balance was modulated, the participants' were able to stand erect to 'ride' the platform (cf. De Nunzio and Schieppati (2007)), modulating their balance control through the use of the ankle strategy. This changed, however, with the increase in oscillation frequency. At 0.5 Hz and 0.61 Hz, where the greatest threats to postural stability were evident, the ankle and head marker traces become less coupled and more temporally displaced, while the ankle-hip pair remains more correlated, suggesting the use of a hip strategy. Previous research suggests that allowing the upper body to follow the platform translation at higher frequencies would be counterproductive, as the required muscle activity to counteract body inertia at the extremes of the platform translation would produce its effects too late, resulting in loss of balance as the platform changes direction on its return path

(Corna *et al.*, 1999). Furthermore, in transition state, the high CC_{max} at relatively low temporal lag values reflect a tight coupling of the marker pairs, suggestive of the participants' unsuccessful attempts to maintain a rigid body while on the platform indicated with increased stepping responses. However, as the participants became more comfortable with the frequency oscillations (i.e. shift to a steady state period), the lower body segments follow the platform movement while a head in space strategy is maintained. This is reflected in the lower CC_{max} values in the steady state periods (compared to the transition state periods) at 0.5 Hz and 0.61 Hz, as well as the increase in temporal lag of the hip and head.

Children use different response strategies under anticipatory situations

Providing the participants with the ability to control/determine when the platform changes frequency (i.e. the STP condition) appears to have allowed them to better stabilize their bodies for the upcoming change in frequency. The overall number of steps taken - and the total number of participants who stepped - in the STP condition decreased compared to ETP. This suggests that 1) the perturbations following change in frequency did not pose as much a threat to the participants' balance as they did in the ETP condition and/or 2) the participants were better able to prepare for the upcoming change in frequency by taking advantage of knowing when the change would occur. The latter is supported by the increase muscle onset latencies, which provides an indication that postural muscles are activated slightly more in advance in the STP condition.

There is some consistency in terms of postural muscle activity with previous reports in the literature. For example, there was some evidence of trends of adaptation between the transition and steady states (Fig. 6) which could be due to transfer of prior experience (Dietz *et al.*, 1993;

Van Ooteghem *et al.*, 2008; Schmid *et al.*, 2011; Kennedy *et al.*, 2013). However, children appear to behave more like older adults in terms of postural muscle activity in this situation, since the timing of the activations occurred generally around the -25% half cycle mark (compared to the ~-50% half cycle mark observed in young adults by Bugnariu and Sveistrup (2006)). This would suggest that the participants were able to shift to anticipatory mechanisms in steady state, but were not able to take full advantage of the platform slowing down to prepare for the upcoming change in direction. While the orders of activation were generally consistent with an ankle strategy (i.e. distal to proximal organization) (Horak and Nashner 1986), the kinematic data are suggestive of a hip strategy. Therefore, we postulate the resulting strategy must be a combination of the two. There is also the possibility that compensation for the perturbation is made through knee flexion (Santos, Kanekar and Aruin, 2010), though joint angles at the knee level were not investigated in this study.

Influence of attentional demands and fear on response strategies

Studies have shown that there are significant attentional requirements for postural control and that in multitask conditions, the inability to allocate sufficient attention to the maintenance of balance is a contributing factor to falls, especially in the elderly, however, not all cognitive tasks affect postural control equally (Woollacott and Shumway-Cook 2002). Shumway-Cook and Woollacott (2000) demonstrated that there may be a hierarchy of attentional demands with respect to postural control. Simple additional tasks tend to be associated with feet-in-place strategies (i.e. ankle or hip strategy), whereas more complex problems elicit more drastic measures like the stepping strategy. An increase in attentional demands results in decreased postural muscle activity during balance recovery, in this case from platform perturbations, which can prompt the use of an alternate response strategy, such as stepping (Rankin *et al.*, 2000) . It could be that an increase in cognitive demand associated with the higher frequencies is responsible for the children attempting to revert to a 'ride' solution as a head in space strategy may have otherwise required the allocation of cognitive demands. This could also explain the increased tonic postural muscle activity in that the final cycles of the steady state would most likely include some sort of preparation for the upcoming change in frequency. This preparation would then be considered a cognitive loading, leading to postural muscle activity closer to (instead of well in advance of) the perturbation onset, as well as the stiffening observed in the kinematics.

Increasing the level of postural threat can also play a large role in the selection of a strategy to maintain (or regain) balance. Adkin et al (2000) and Carpenter et al (2004) have found that by placing subjects on high platforms, thereby inducing an element of fear of falling, the CNS adopts tighter control over postural stability. This control is scaled to the level of threat, as well as the order in which the threat to posture is experienced by the subject, suggesting both physiological *and* psychological factors influence postural control. This may explain the observed changes (large decrease in the number of steps taken by participants, kinematic strategy chosen, earlier postural muscle onsets) when given control over the change in frequency.

In summary, children and adolescents were subjected to oscillatory antero-posterior postural perturbations at various frequencies. Generally, the higher frequencies resulted in more steps being taken, lower correlations coupled with greater temporal lags between marker trajectories, and postural muscle activity similar to older adults. The provision of self-triggered perturbations allowed participants to make the appropriate changes to their balance by use of anticipatory postural control mechanisms.

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2.6 Tables and Figures

Table 1

	Frequency			
	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz
ETP	-	**-**	**26**/4 (3-9)	**11**/5 (2-3)
STP	-	**2**/1 (2)	**-**	**2**/1 (2)

Figure 1

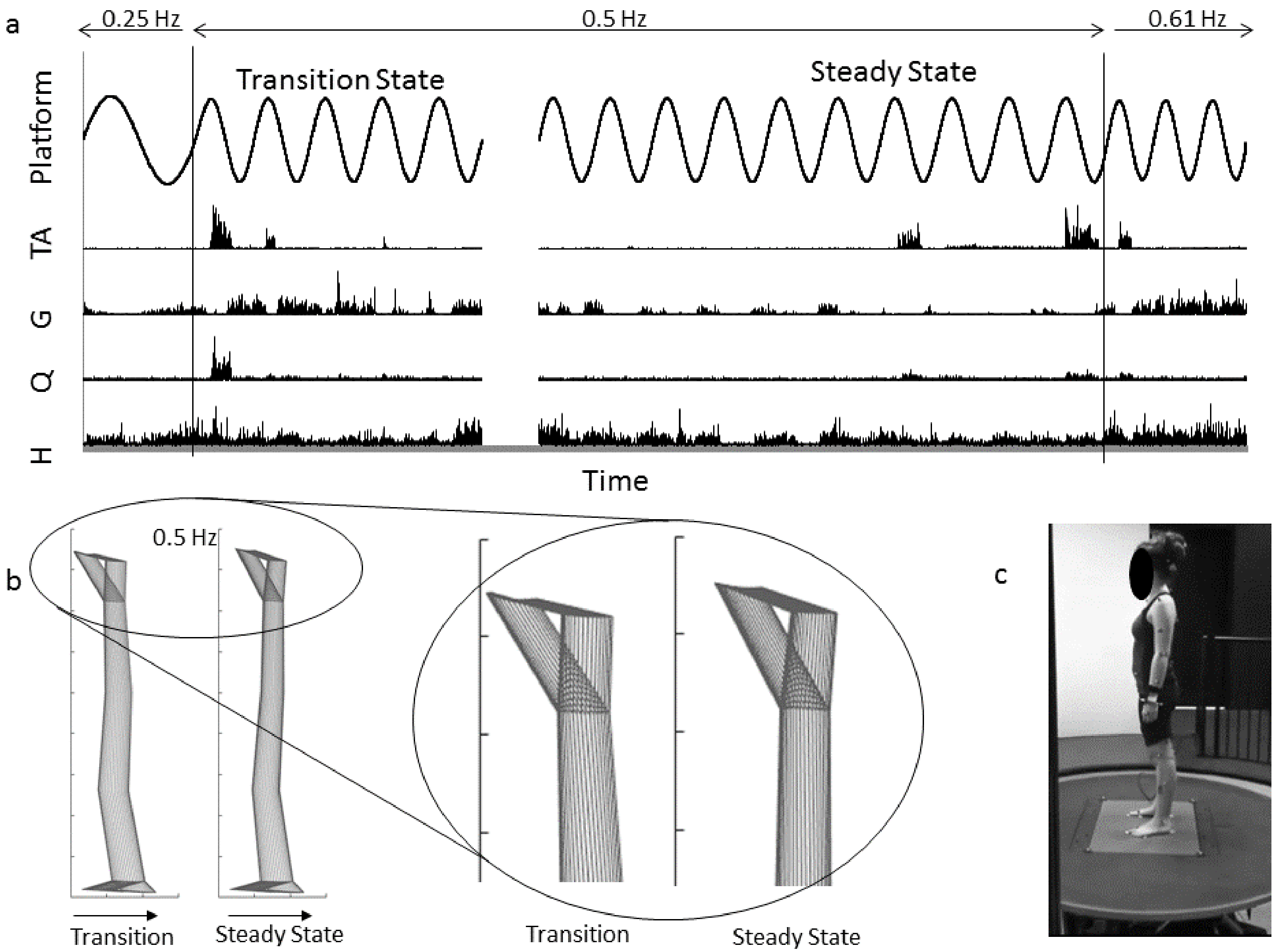
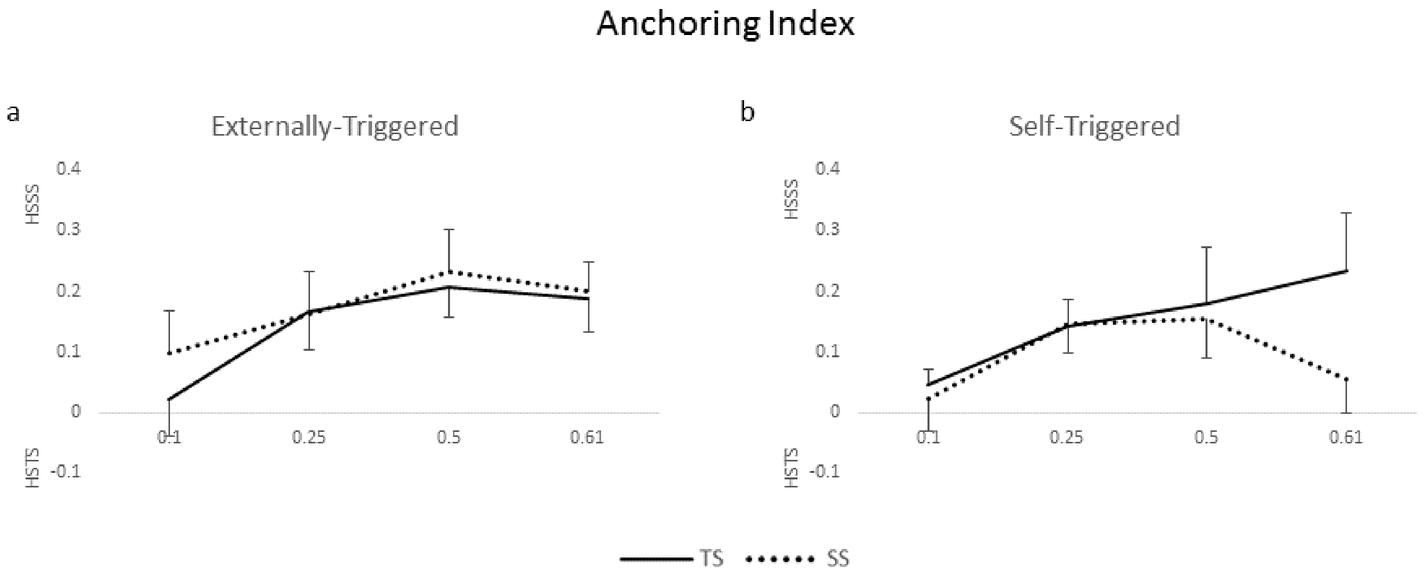
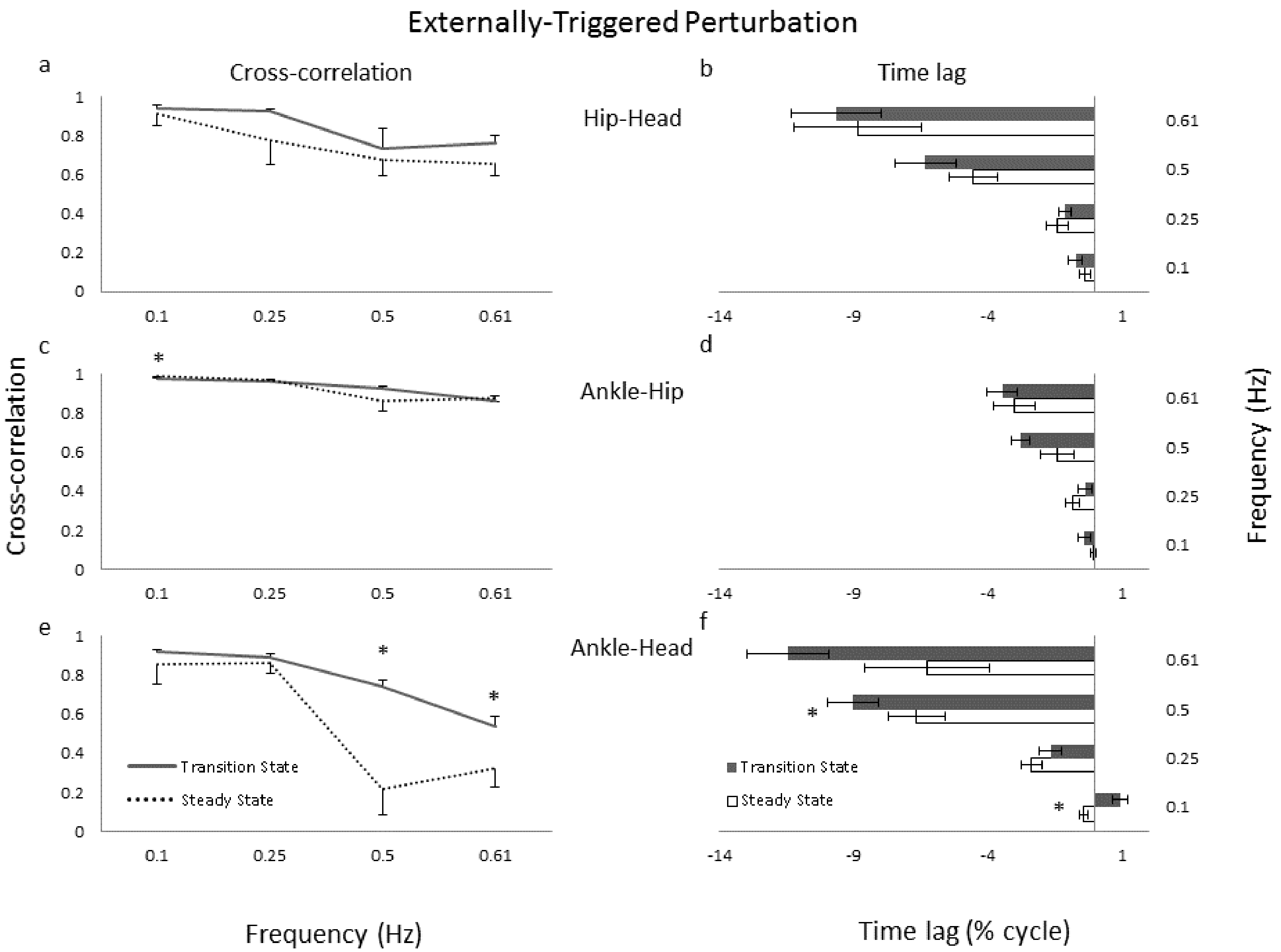

a
0.25 Hz
0.5 Hz
0.61 Hz
Transition State
Steady State
Platform
TA
G
Q
H
Time
b
0.5 Hz
Transition
Steady State
Transition
Steady State
c

Figure 2



Anchoring Index
a
Externally-Triggered
b
Self-Triggered
HSSS
HSTS
0.4
0.3
0.2
0.1
0
-0.1
0.1
0.25
0.5
0.61
TS
SS

Figure 3



Externally-Triggered Perturbation
a
Cross-correlation
b
Time lag
Hip-Head
c
d
Ankle-Hip
e
f
Ankle-Head
Cross-correlation
Frequency (Hz)
0
0.2
0.4
0.6
0.8
1
0.1
0.25
0.5
0.61
-14
-9
-4
1
*
Transition State
Steady State
Frequency (Hz)
Time lag (% cycle)

Figure 4

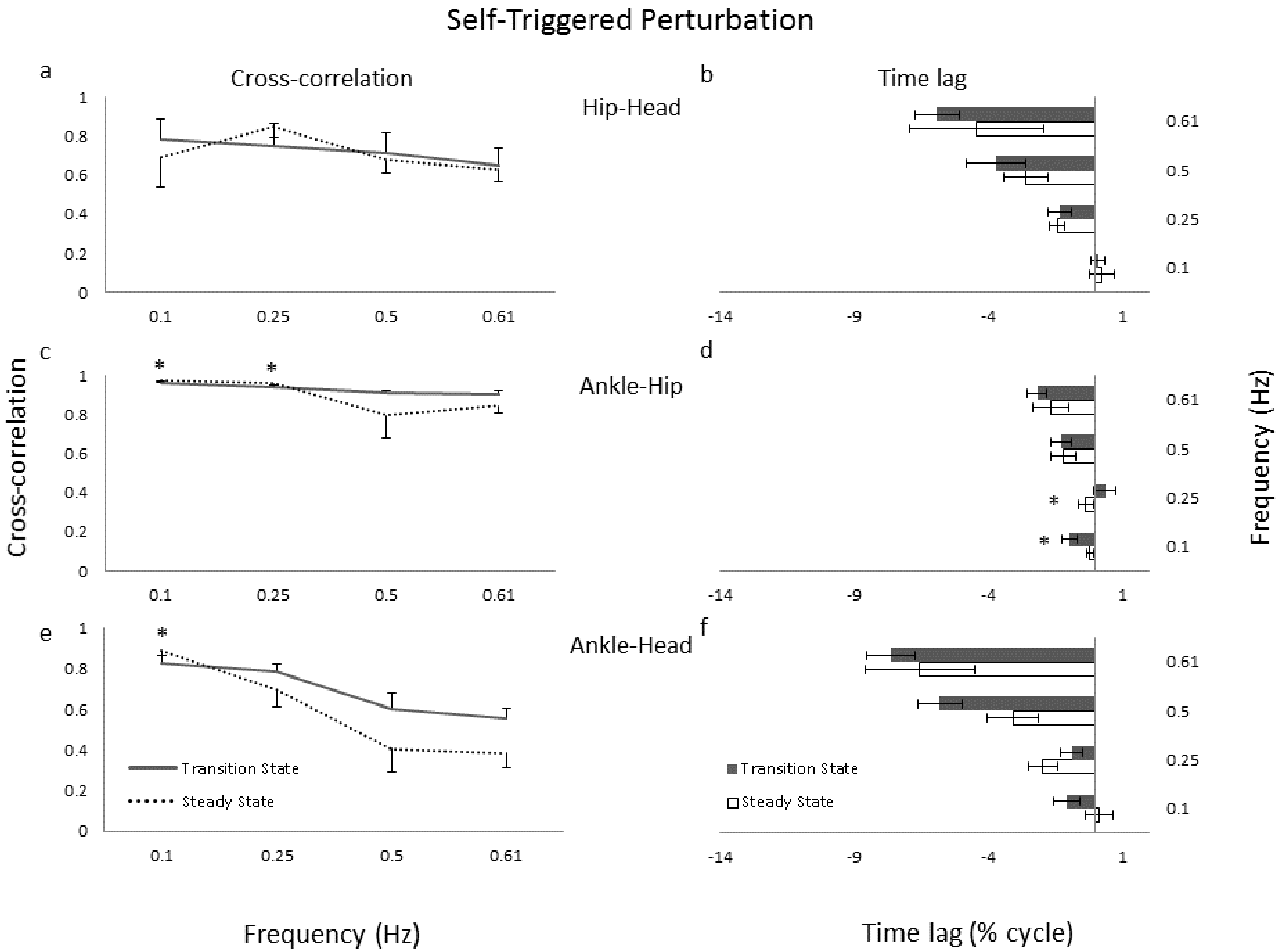
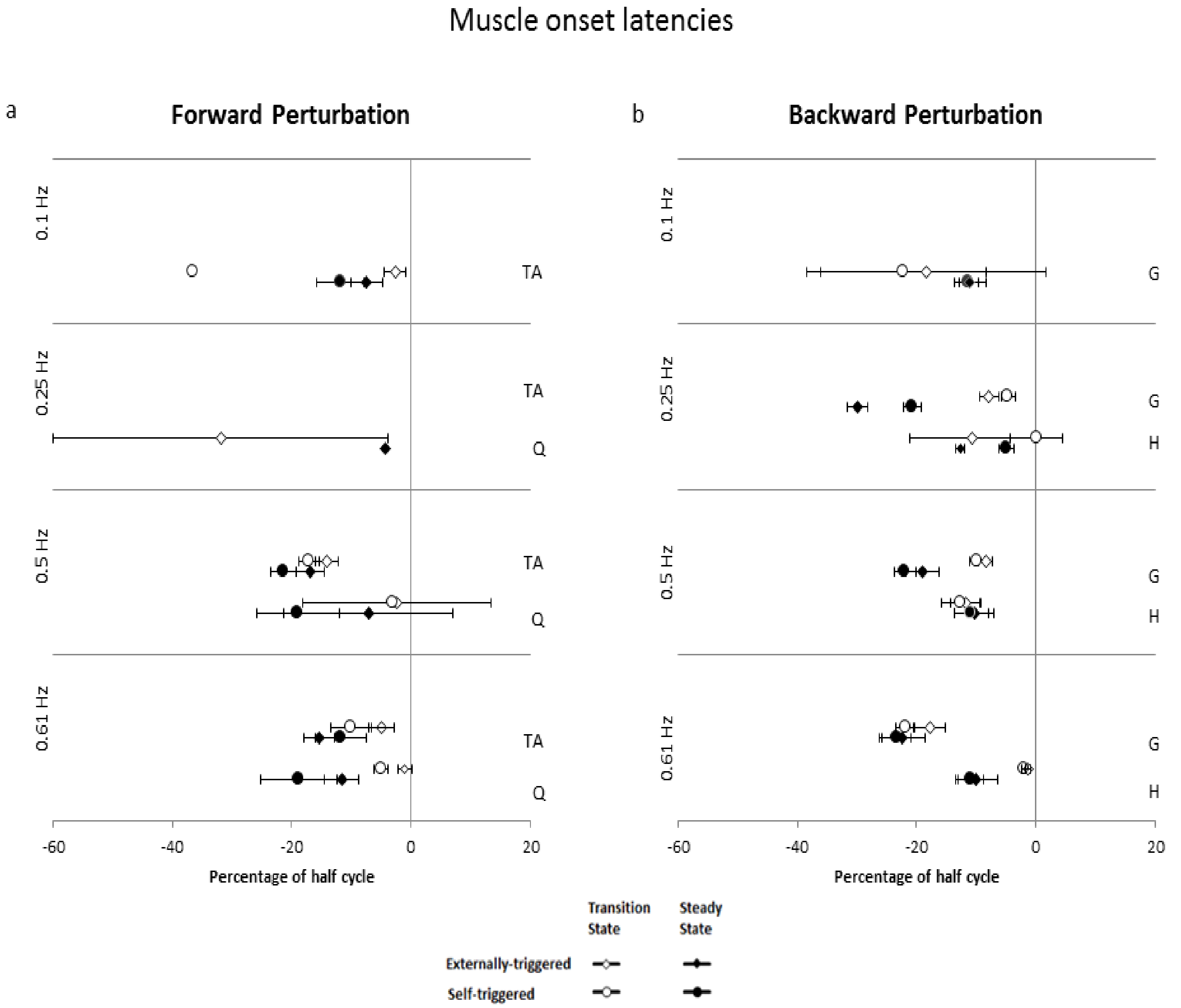
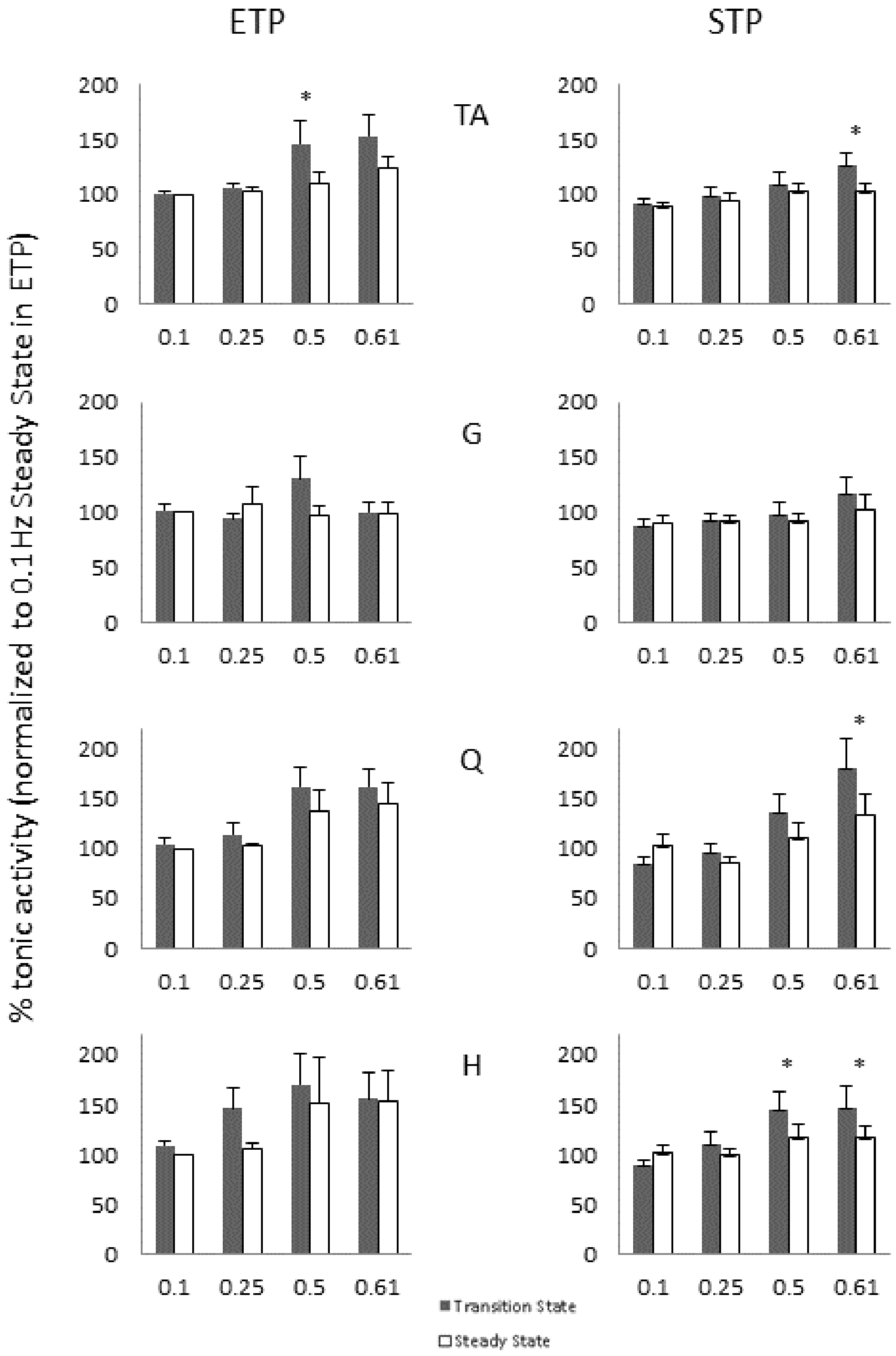

Self-Triggered Perturbation
a
Cross-correlation
b
Time lag
Hip-Head
c
d
Ankle-Hip
e
f
Ankle-Head
*
*
*
*
*
Cross-correlation
Frequency (Hz)
1
0.8
0.6
0.4
0.2
0
0.1
0.25
0.5
0.61
-14
-9
-4
1
Transition State
Steady State
■ Transition State
□ Steady State
Frequency (Hz)
Time lag (% cycle)

Figure 5



Muscle onset latencies
a
Forward Perturbation
b
Backward Perturbation
0.1 Hz
0.25 Hz
0.5 Hz
0.61 Hz
TA
Q
G
H
-60
-40
-20
0
20
Percentage of half cycle
Transition State
Steady State
Externally-triggered
Self-triggered

Figure 6


ETP
STP
% tonic activity (normalized to 0.1Hz Steady State in ETP)
TA
G
Q
H
0
50
100
150
200
0.1
0.25
0.5
0.61
*
■ Transition State
□ Steady State

2.7 Table and Figure Captions

Table Captions

Table 1 Stepping Responses immediately following change in frequency

The total number of steps taken is presented in bold text, followed by the number of participants who stepped for the period immediately following a change in frequency. The range of steps taken is presented in parentheses.

Figure Captions

Fig. 1 Perturbation protocol depicting platform oscillation and corresponding EMG signals (a) from tibialis anterior (TA), gastrocnemius (GAS), quadriceps (Q), and hamstring (H) muscles during the transition and steady state periods at 0.5Hz. Panel (b) depicts a participant's posture during backward platform displacement at 0.5Hz in transition (left) and steady (right) states. Expanded head-neck stick figure shows a shift to Head Stabilization in Space Strategy. Panel (c) A participant with markers and EMG electrodes

Fig. 2 Anchoring Index (AI) values of transition and steady states (solid and broken lines, respectively) across the four platform oscillation frequencies (mean +/- SE). The externally triggered condition is presented in panel a, and the self-triggered condition is presented in panel b. A positive AI value indicates a Head Stabilization in Space Strategy (HSSS), while a negative AI value indicates a Head Strapped to Trunk Strategy (HSTS)

Fig. 3 Mean (+/- SE) cross-correlation function peak values (CC_{max} – panels a, c, e, left) and time lags ($CC_{lag/lead}$ – panels b, d, f, right) for the hip-head, ankle-hip, and ankle-head marker pairs trajectories in transition (solid lines, filled bars) and steady (dashed lines, open bars) states in the Externally Triggered condition. Asterisks (*) denote significant differences

Fig. 4 Mean (+/- SE) cross-correlation function peak values (CC_{max} – panels a, c, e, left) and time lags ($CC_{lag/lead}$ – panels b, d, f, right) for the hip-head, ankle-hip, and ankle-head marker pairs trajectories in transition (solid lines, filled bars) and steady (dashed lines, open bars) states in the Self Triggered condition. Asterisks (*) denote significant differences

Fig. 5 Postural muscles onset latencies (mean +/- SE) during forward (a) and backward (b) perturbations at the four frequencies of platform oscillation. Onset latencies are expressed as a percentage of half-cycle time for muscles normally associated with forward (TA and Q in panel a) or backward (G and H in panel b) perturbations. Results from transition and steady states are represented by open and filled icons, respectively, while ETP and STP are represented by diamonds and circles, respectively. Zero (0) represents the time at which the platform changed direction and the platform begins to slow down at the -50% half cycle mark. Transition and steady state icons are offset for clarity purposes. Q and H onset latencies not presented for 0.1Hz as these muscles did not meet minimum activation requirements

Fig. 6 EMG tonic activity for (top to bottom panels) tibialis anterior (TA), gastrocnemius (G), quadriceps (Q), and hamstring (H) muscles in ETP (left side) and STP (right side) conditions.

Comparisons were made to baseline tonic activity of each muscle in the steady state period at 0.1Hz in ETP. Asterisks (*) denote significant differences between transition and steady states

Chapter 3: Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents with cerebral palsy

A version of this paper is currently under review at *Gait & Posture* and has been formatted according to journal guidelines.

Full-length original research article for submission to
Gait & Posture

Kinematics and postural muscular activity during continuous oscillating platform movement in children and adolescents with cerebral palsy

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Keywords: postural control, anchoring index, balance mechanisms, cerebral palsy

Running title: Postural control in CP youth

3.1 Abstract

Reactive (RPA) and anticipatory (APA) postural activity has been described in single discrete perturbations in youth with cerebral palsy (CP) but not in continuous perturbation situations. In this study, we compared APA and RPA in youth with CP to strategies used by typically developing (TD) age-matched youth. We sought to determine if youth with CP modify strategies based on knowledge of platform movement and/or when provided with control of the perturbation. Eleven youth with CP and sixteen TD youth aged 7-17 years stood with eyes open on a movable platform progressively translated antero-posteriorly through four speeds in experimenter-triggered (ETP) and self-triggered (STP) perturbations. Postural muscle activity and 3D kinematics were recorded. The Anchoring Index (AI) and marker-pair trajectory cross-correlations indicated body stabilization. Transition states (TS) and steady states (SS) were analysed. Mann Whitney-U tests analysed between-group differences. TD youth adopted significantly higher AI in ETP TS at 0.61Hz. Gastrocnemius muscle tonic activity levels were higher in the CP group in TS in ETP at 0.61Hz as well as tibialis anterior in STP. Higher frequency platform movements proved more difficult for youth with CP, however, like TD youth, they shifted from RPA to APA in SS by taking advantage of knowledge of platform movement. When given control over perturbation onset, further APA was observed in TS.

Keywords: postural control, anchoring index, balance mechanisms, cerebral palsy

3.2 Highlights

- Youth with CP are less able to maintain balance in more challenging conditions
- Youth with CP can change their postural control strategy with experience
- Youth with CP can further modify strategy when additional information about the upcoming perturbation is available

3.3 Introduction

Appropriate use of postural control strategies is required to stabilize balance and prevent falls. Typically, when faced with a small perturbation, balance is maintained through modulation of joint torques about the ankle. If a postural disturbance is larger, the center of mass must be kept within the confines of the base of support using larger movements about the hip. A large enough perturbation may require a step to avoid falling [1]. By having knowledge or previous experience of an upcoming perturbation, it is possible to prepare for the postural disturbance by using anticipatory postural mechanisms [2-4].

Cerebral palsy (CP) is a non-progressive lesion in the central nervous system that results in heterogeneous motor disability and developmental delays. It is the most common physical disability in children [5] with individuals demonstrating motor [6] and sensory [7] deficits. These deficits contribute to impaired functional mobility and are associated with disruptions in postural control [8]. Youth with CP show increased risk of falls and their movement abilities are strongly predictive of participation in activities outside of the home [9].

Research suggests postural control plays an important role in the functional performance of children and adolescents with CP [10]. As efficient postural control is important for the performance of voluntary skills, postural abnormalities likely contribute to the delays and impairments observed in the motor skills of children with CP [11]. Anticipatory and reactive postural mechanisms have been identified as significant components necessary to maintain balance in children and adults during both discrete and continuous perturbations [12,13].

In addition to timing of postural responses, relationships between kinematic parameters of movement can illustrate how balance is maintained. Research demonstrates that cross correlation values of the ankle, hip and head trajectories provide information on how tightly coupled (i.e., stable) segments of the body are [14], and are an indication of balance control. The Anchoring Index (AI) quantifies how the head is stabilized on the trunk during movement: a low AI suggests a head stabilization on trunk strategy (HSTS), whereas a high AI is suggestive of a preference for a head stabilization in space strategy (HSSS) [15]. During locomotion, typically developing (TD) children start to utilise HSSS, which benefits visual input to balance, around the age of 7 years. We have previously characterized the AI strategies in TD youth when exposed to repeated, predictable perturbations [12]. However, it is unclear how youth with CP stabilize their head in this situation and whether the AI is related to inferior body segment coordination.

While reactive and anticipatory mechanisms of postural control have been described in single discrete perturbations in youth with CP (perturbation via limb movement [10] and platform movement [1]), they have not been characterized in continuous (i.e. repeated) perturbation situations. The advantage of the continuous oscillating platform paradigm is that both reactive and anticipatory postural control mechanisms are generated in order to deal with the same perturbation. It remains unclear how postural impairments in youth with CP impact their ability to maintain balance in reactive and anticipatory situations and their ability to shift from one mechanism to the other.

The primary aim of this study was to determine how the ability to control postural responses (as reflected in the number of steps taken, postural muscle activity, and marker-pair trajectory cross-correlations) differs between TD youth and age-matched youth with CP when exposed to various frequencies of continuous platform oscillation. Secondary aims were to determine if youth with CP were able to 1) take advantage of knowledge of platform movement in order to modify postural responses, and 2) further modify their postural responses when given control of when the perturbation occurs. We hypothesized that youth with CP would be less able to shift from reactive to anticipatory mechanisms 1) as compared to their TD counterparts and 2) both after having been exposed to the platform oscillation, and when given control of the timing of platform perturbation.

3.4 Methods

Participants

Eleven youth (N=11; 6 boys and 5 girls), aged 7-17 years with confirmed diagnosis of CP Gross Motor Function Classification System (GMFCS) levels I or II [16] participated in this study. Two participants were diagnosed as right hemiplegic, three were left hemiplegic, and six were spastic diplegic. All participants and/or parents provided written informed consent. Ethical approval was granted through the University of Ottawa research ethics board. Exclusion criteria were visual, cognitive or auditory impairment that would interfere with understanding of and/or ability to carry out instructions, and lower limb orthopedic surgery or Botox injections in the previous twelve months. Exclusion criteria were evaluated as self-reported by family.

Experimental Protocol

The experimental paradigm is described in [3,12]. Participants stood barefoot with eyes open and feet shoulder-width apart on a platform that translated in the anterior/posterior direction with an amplitude of 20cm peak-to-peak. They were told to maintain their balance while avoiding taking steps. Participants performed two trials in each of two test conditions: experimenter-triggered (ETP) and self-triggered (STP) increases in oscillation frequency. A minimum number of cycles at each frequency (10, 20, 40, and 50 cycles at 0.1 Hz, 0.25 Hz, 0.5 Hz, and 0.61 Hz, respectively) was required before advancing to the next frequency.

Motion analysis software (Vicon, Oxford, UK) recorded full body kinematics (100 Hz). Bilateral surface electromyography (EMG; Delsys Inc., Natick, USA) was recorded for tibialis anterior (TA), gastrocnemius (G), quadriceps (Q), and hamstring (H) muscles, with the reference electrode placed on the iliac crest. The EMG signals were pre-amplified and sampled at 1000 Hz.

The first three to five consecutive cycles without stepping at each frequency were considered 'transition-state' (TS) and were analyzed separately. In the last half of each frequency following TS, a period of 3 to 5 consecutive cycles without stepping at 0.1 Hz and a period of 8 to 10 consecutive cycles without stepping at the remaining frequencies were considered 'steady-state' (SS) during which the movement of the platform has been shown to be predictable [3].

Outcome Measures

The number of steps taken was counted for each frequency. The anchoring index (AI) was used to determine the stabilization of the head with respect to both external space and the trunk [17] and was calculated as follows:

$$AI = [\sigma^2_r - \sigma^2_a] / [\sigma^2_a + \sigma^2_r]$$

where σ_a is the angular dispersion of the head with respect to the absolute (external space), and σ_r is the angular dispersion of the head relative to the trunk.

Cross-correlations (CC) of anterior-posterior linear displacements of the ankle-head, hip-head, and ankle-hip marker pairs were calculated. Each CC temporal relationship (lag/lead) was calculated for ±50% time shift of one cycle: a positive value indicates the second segment is leading, while a negative value indicates the second segment is lagging. The maximum correlation (CC_{max}) was calculated as well as the percent time shift at which it occurred ($CC_{lag/lead}$).

Electromyography signals were full-wave rectified. Bursts were identified as activity greater than two standard deviations above baseline lasting for at least 50 ms. Postural muscle burst frequencies were expressed as a percentage of cycles in which bursts occurred. Tonic activity levels were expressed as percentage of baseline tonic activity at ETP SS 0.1 Hz.

Statistical Analysis

We did not undertake power analyses for this study since our aim was to initially characterize these outcome measures in the CP population for subsequent studies. CP participant demographics and stepping data were summarized using descriptive analyses. Trials where participants continued to step throughout all cycles of a frequency were not analyzed as periods consisting of the required number of step-free cycles were needed to calculate the AI and cross-correlations for TS and SS periods. All outcome measures were compared to TD youth values obtained from a previous study [12].

Statistical analysis was performed using SPSS v 23.0.0.2 (IBM Corp.). The data were determined to be non-normal through inspection of skewness and kurtosis, histograms, and Shapiro-Wilk tests of normality. Non-parametric inferential testing using the Mann Whitney-U test for between group (TD vs CP) differences was undertaken. These tests were performed for stepping, AI, CC_{max} and $CC_{lag/lead}$, and EMG tonic and bursting activity outcome measures at each frequency with an adjusted (Bonferroni) accepted significance level of $p < 0.0125$.

3.5 Results

All TD participants were able to complete all frequencies in both trials for ETP and STP conditions. In contrast, youth with CP had difficulty completing higher frequencies. One participant with hemiplegia (JS04) would not attempt 0.5 Hz and 0.61 Hz for both trials in the ETP condition, and declined to complete any STP trials. Three participants with spastic diplegia (JS08, JS10, and JS11) attempted but could not complete the 0.5 Hz and 0.61 Hz in ETP or STP without continuous stepping; JS09 was GMFCS level II and could only complete 0.1 Hz in either condition. JS10 also declined any STP trials.

Stepping Responses

The number of steps taken by CP participants was compared to the TD average at each frequency in ETP and STP conditions. Statistical testing did not reveal any significant differences between groups. Generally, the lowest frequencies (0.1 Hz and 0.25 Hz) did not elicit stepping responses from either group. The highest frequencies (0.5 Hz and 0.61 Hz) tended to result in stepping responses in the majority of CP participants and more steps were elicited in ETP than in STP. Specifically, nine of the eleven children with CP used a stepping response for a total 78 steps at 0.5 Hz in ETP, compared to only four who stepped for a total of 19 steps at the same frequency in STP. While most of TD youth were able to complete the trials with minimal stepping, five youth with CP were unable to complete trials without stepping at 0.5 Hz and 0.61 Hz in ETP, and 0.5 Hz in STP, and four were unable at 0.61 Hz in STP. Full stepping response data can be found in the supplementary material online.

Anchoring Index

Typically developing youth had a tendency to adopt a higher AI (HSSS), compared to similarly aged participants with CP (Figure 1). Group differences were significant in the ETP condition at the higher frequencies (TS at 0.61 Hz: $U = 12$, $p = 0.012$; SS approached significance at 0.61 Hz: $U = 13$, $p = 0.015$). There were no significant differences between groups in STP at any frequencies.

Place figure 1 (anchoring index) near here

Cross Correlations

No significant differences were found between groups in the cross-correlation comparisons for ankle-head and ankle-hip trajectories. Time-lag comparisons for the ankle-hip revealed the CP group had a greater hip lag during TS at 0.25 Hz in the ETP condition ($U = 31.5$, $p = 0.009$). During TS at the higher frequencies, the TD group tended to have a greater hip lag than the CP group. This approached significance at 0.5 Hz in the ETP condition ($U = 29.5$, $p = 0.032$) and at 0.61 Hz in the STP condition ($U = 24$, $p = 0.047$).

Place figures 2 (ETP kinematics) and 3 (STP kinematics) near here

The TD group tended to have a greater correlation between hip-head marker trajectories during TS in ETP at 0.5 Hz (approached significance, $U = 28$, $p = 0.027$), however no differences were found at any other period or frequency in either condition. No significant differences were detected for hip-head time lag. Figures 2 and 3 depict cross-correlation analysis results in both ETP and STP conditions.

EMG Tonic and Bursting Activity

In the ETP condition, TA tonic activity levels were higher in the CP group during TS at 0.25 Hz ($U = 24.5$, $p = 0.002$), while the G tonic activity approached significantly higher levels in TS at 0.61 Hz ($U = 17$, $p = 0.021$). The TA also had approached significantly higher tonic activity levels in the CP group during TS in the STP condition, especially at the higher frequencies (0.25 Hz: $U = 27$, $p = 0.034$; 0.5 Hz: $U = 17$, $p = 0.029$; and 0.61 Hz: $U = 18$, $p = 0.036$). No significant differences were found between groups in Q and H muscles.

Briefly, the gastrocnemius muscle was consistently activated more often in the TD group than in the CP group across all frequencies and conditions except for in STP TS at 0.25 Hz. Similarly, the hamstrings were found to be more active in the TD group at the higher frequencies (0.5 Hz and 0.61 Hz) for both conditions. No significant differences were found between groups for TA and Q at any frequency or condition. Summary information are presented in Table 1.

Place Table 1 (test summary) near here

Place figures 4 (tonic activity) and 5 (burst activity) near here

3.6 Discussion

This is the first study to characterize postural strategies in response to and in anticipation of oscillatory platform movement in children and adolescents with cerebral palsy.

1. Youth with CP are less able to maintain balance at high oscillation frequencies

Overall, our results indicate that youth with CP behaved similarly to their TD counterparts when dealing with a continuously oscillating platform, especially at the lower frequencies. However, the higher number of steps recorded in both groups at the higher frequencies reflects the large increase in difficulty in the task and the CP group were clearly unable to maintain balance at this stage. This is consistent with reported findings in the literature [3,18,19], whereby the increased risk of falling results in a response strategy outside the foot-in-place response, forcing one to take steps. While at the lower frequencies both groups made use of the 'ride' pattern [20] (i.e., standing straight), the youth with CP were unable to switch to 'head fixed' (i.e., allowing the lower body to pass under trunk/head) with the increased platform velocity. This may function as an attempt to remain stiff (evidenced by HSTS, increased muscle tone) resulting in segment temporal lag, an inability to disconnect the upper and lower segments to absorb the platform movement, and ultimately, more stepping responses. The higher level of baseline tonic activity exhibited by the CP group compared to the TD group is to be expected as a function of the hypertonia associated with spastic CP [11]. With the increasing frequency of the platform movement, and thus the increased duration of each trial, the increased tonic activity could be due to the prolonged activation due to spasticity [21].

2. Youth with CP are able to modify strategy with experience

Like the TD group, the CP group demonstrated evidence of a shift in postural response strategy from reactive mechanisms during TS to anticipatory mechanisms in SS perturbations through less reliance on HSTS and reduced segmental temporal lags. This modification corresponds to previous studies in which it has been shown there is a period of postural adaptation to meet the requirements of a new motor task [2,22]. One possible explanation is Bernstein's motor equivalence problem in which the body's degrees of freedom are 'frozen' to reduce redundancy when learning a new motor task [23,24]. This allows for initially keeping a rigid system with stiff joints, which can then be re-integrated with experience of the task, allowing the optimization of movement through the use of all available degrees of freedom [25]. The higher levels of tonic activity during TS in both groups can be interpreted as a functional method of joint stiffening [26] which is then decreased, as evidenced through lower tonic activity levels and reduced segmental temporal lag in SS. The reduction in temporal lag indicates an ability to shift from the previously mentioned inability to effectively use the 'ride' strategy, to the more effective 'head fixed' strategy.

3. Control of Change in Frequency

The third aim of our study was to determine if youth with CP were able to modify their postural responses when given control over a change in frequency. Similar to other studies [10,13], our data suggest that youth with CP have the ability to use directionally specific anticipatory mechanisms of postural control when faced with continuous perturbation. Like TD youth, youth with CP are able to take advantage of the knowledge/cueing of the upcoming change in frequency when given control over perturbation onset and prepare an appropriate postural response in advance. The most compelling difference observed in the CP group between the ETP and STP conditions was the reduction in total number of steps taken, especially at the higher frequencies. This ability to take advantage of the knowledge of frequency change is further supported by a large reduction in tonic activity in G, specifically in TS, less temporal lag between marker-pair trajectories, and a shift to preference for HSSS in the AI.

While able to make the shift to anticipatory mechanisms at lower frequencies, youth with CP still struggled to maintain their balance during higher frequency perturbations when compared to TD youth. At the higher frequencies, the youth with CP may not have been able to overcome the difficulty of the platform translation and instead relied on reactive mechanisms, suggesting an inability to generate appropriate muscle timings, whereas the TD youth were able to make the shift to anticipatory mechanisms. Previous research has established youth with CP to have poorly organized muscle activation [11,27]. Together with our data, this suggests that physiotherapists could target appropriate muscle order activation and timing to deal with larger perturbations. Future studies should make smaller increments in the platform oscillation to determine at which velocity youth with CP cease to shift to anticipatory mechanisms.

In summary, the data from the present study demonstrated that when subjected to a continuous platform perturbation at various frequencies, youth with CP behave in a similar manner to a group of age-matched TD controls. Higher frequency perturbations proved to be more difficult for the CP group, as evidenced through a greater number of steps taken, a preference for HSTS, low marker-pair correlations with high temporal lag, and increased tonic activity. Like the TD group, however, CP participants were able to take advantage of the knowledge of platform movement during SS, and while able to make appropriate postural changes when given control of the perturbation, continued to struggle with large perturbations. The results from this study suggest targeting muscle timing and weakness, and inappropriate muscle activation in youth with CP by practicing muscle sequencing and reactive/anticipatory postural response activities within intervention programs focused on improving postural control.

Compliance with Ethical Standards:

Funding: This study was funded through the Ontario Federation for Cerebral Palsy and the University of Ottawa Faculty of Health Sciences.

Conflict of interest: None.

Ethical approval: All procedures performed involving human participants were in accordance with the institutional research committee standards.

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3.8 Tables and Figures

Table 1 – Results of Mann-Whitney U comparisons between typically developing and cerebral palsy groups for muscle bursting activity

			Frequency															
			0.1Hz				0.2Hz				0.5Hz				0.61Hz			
			MWU	Z	p	r	MWU	Z	p	r	MWU	Z	p	r	MWU	Z	p	r
ETP	TS	TA	83.5	-0.24	0.827	-0.05	61	-0.961	0.363	-0.19	42.5	-0.409	0.693	-0.09	47	-0.075	0.971	-0.02
		GAS	38.5	-2.535	0.013	-0.49	38.5	-2.204	0.027	-0.43	25	-1.71	0.098	-0.36	31	-1.272	0.231	-0.27
		Q	55	-2.24	0.11	-0.43	44	-2.003	0.06	-0.39	41.5	-0.486	0.641	-0.10	29	-1.419	0.178	-0.30
		HAM	77.5	-0.672	0.61	-0.13	66	-0.843	0.484	-0.17	16.5	-2.339	0.017	-0.50	11	-2.769	**0.005**	-0.59
	SS	TA	86	-0.118	0.942	-0.02	54	-1.381	0.182	-0.27	37.5	-0.777	0.449	-0.17	40	-0.593	0.59	-0.13
		GAS	33	-2.829	**0.006**	-0.54	37.5	-2.246	0.023	-0.44	15.5	-2.412	0.013	-0.51	22	-1.922	0.059	-0.41
		Q	56	-2.555	0.121	-0.49	48	-1.877	0.097	-0.37	44	-0.3	0.802	-0.06	31	-1.26	0.231	-0.27
		H*AM*	72	-0.979	0.451	-0.19	74.5	-0.305	0.776	-0.06	7	-3.038	**0.001**	-0.65	7.5	-2.998	**0.001**	-0.64
STP	TS	TA	56.5	-0.783	0.519	-0.16	54.5	-0.365	0.728	-0.08	33	-0.942	0.381	-0.35	44	-0.078	0.97	-0.02
		GAS	16	-3.134	**0.001**	-0.64	13.5	-3.026	**0.001**	-0.63	16.5	-2.252	0.023	-0.49	19.5	-2.005	0.045	-0.44
		Q	61.5	-0.551	0.726	-0.11	37.5	-2.48	0.149	-0.52	44.5	-0.039	0.97	-0.01	44.5	-0.04	0.97	-0.01
		HAM	63.5	-0.367	0.815	-0.07	54	-0.428	0.728	-0.09	10	-2.755	**0.005**	-0.60	9.5	-2.78	**0.003**	-0.61
	SS	TA	66.5	-0.071	0.953	-0.01	53.5	-0.431	0.681	-0.09	24.5	-1.6	0.112	-0.02	24	-1.643	0.112	-0.36
		GAS	13	-3.342	**0.001**	-0.68	7	-3.447	**0**	-0.72	7	-2.971	**0.002**	-0.65	10.5	-2.696	**0.005**	-0.59
		Q	61.5	-0.551	0.726	-0.11	51	-0.662	0.591	-0.14	36	-0.706	0.519	-0.15	39.5	-0.43	0.677	-0.09
		HAM	63.5	-0.367	0.815	-0.07	53.5	-0.445	0.681	-0.09	6	-3.052	**0.001**	-0.67	8	-2.89	**0.002**	-0.63

NOTE: Tibialis anterior (TA), gastrocnemius (GAS), quadriceps (Q) and hamstring (HAM); Transition State (TS); Steady State (SS); externally-triggered (ETP); self-triggered (STP). N for ETP = 27, 26, 22, 22, for 0.1Hz, 025Hz, 0.5Hz, 0.61Hz respectively. N for STP = 24, 23, 21, 21, for 0.1Hz, 025Hz, 0.5Hz, 0.61Hz respectively; Significant results represented by bold table values.

Figure 1

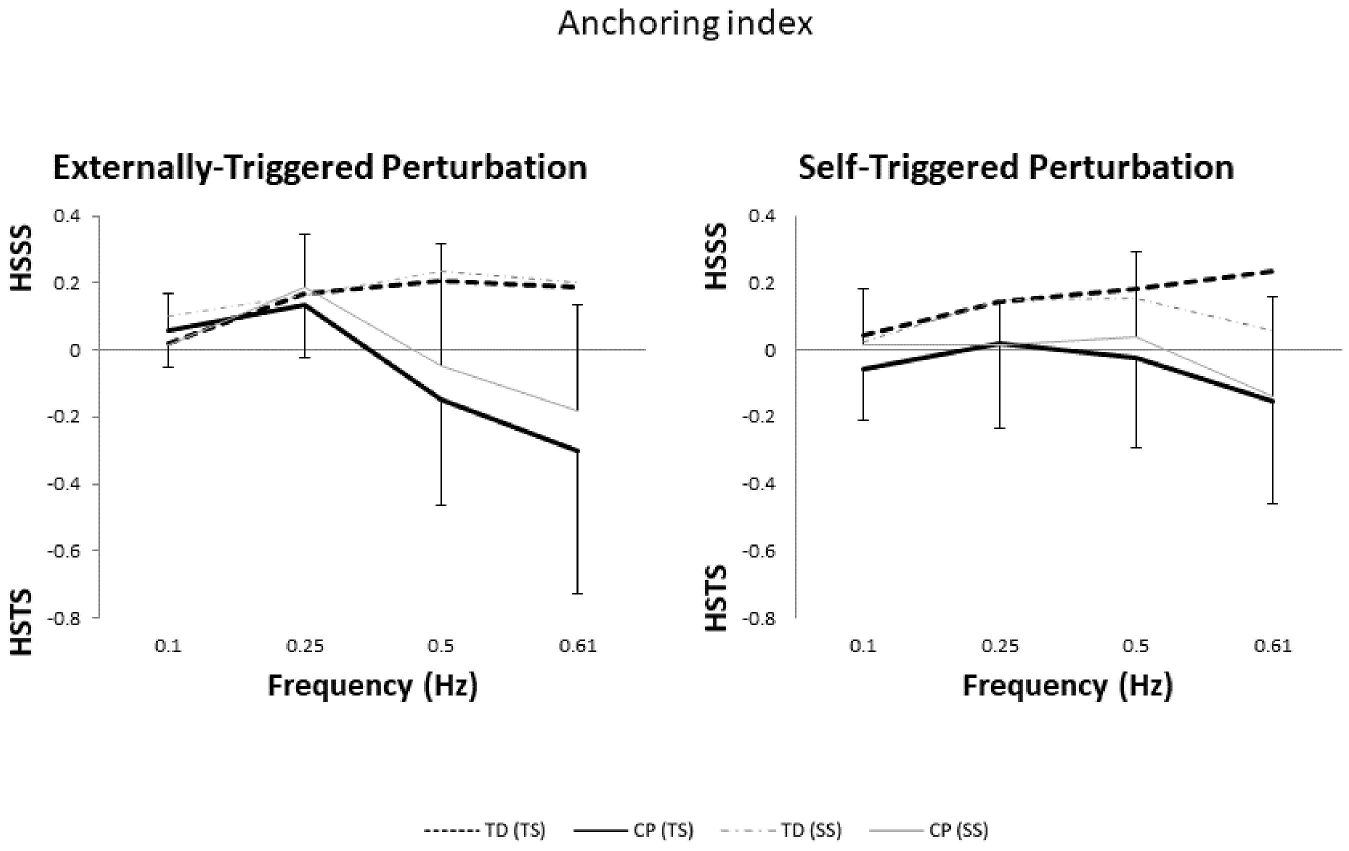

Anchoring index
Externally-Triggered Perturbation
Self-Triggered Perturbation
HSSS
HSTS
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0.1
0.25
0.5
0.61
Frequency (Hz)
TD (TS)
CP (TS)
TD (SS)
CP (SS)

Figure 2

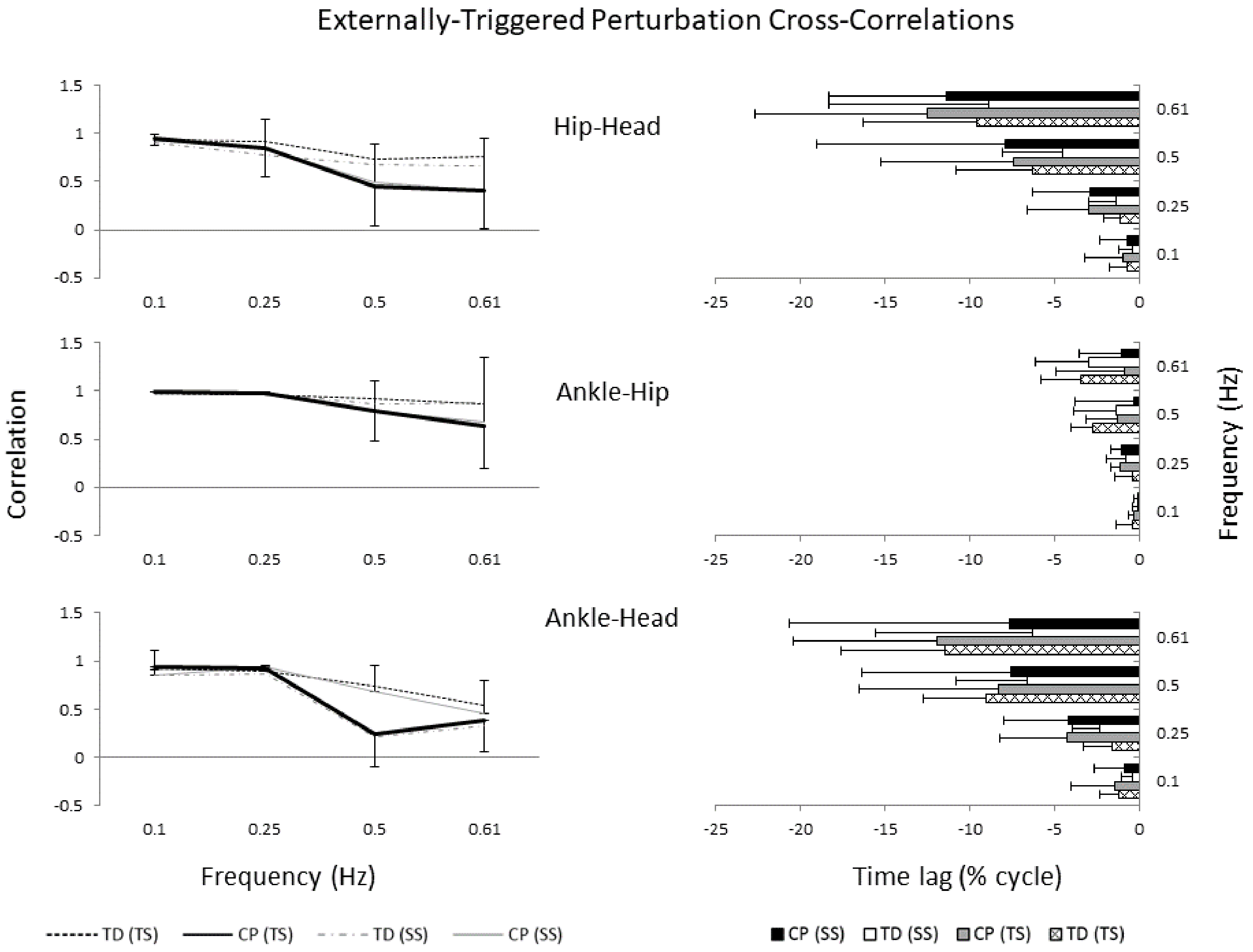

Externally-Triggered Perturbation Cross-Correlations
Hip-Head
Ankle-Hip
Ankle-Head
Correlation
Frequency (Hz)
Time lag (% cycle)
1.5
1
0.5
0
-0.5
0.1
0.25
0.5
0.61
-25
-20
-15
-10
-5
0
TD (TS)
CP (TS)
TD (SS)
CP (SS)
■ CP (SS)
□ TD (SS)
▨ CP (TS)
☒ TD (TS)

Figure 3

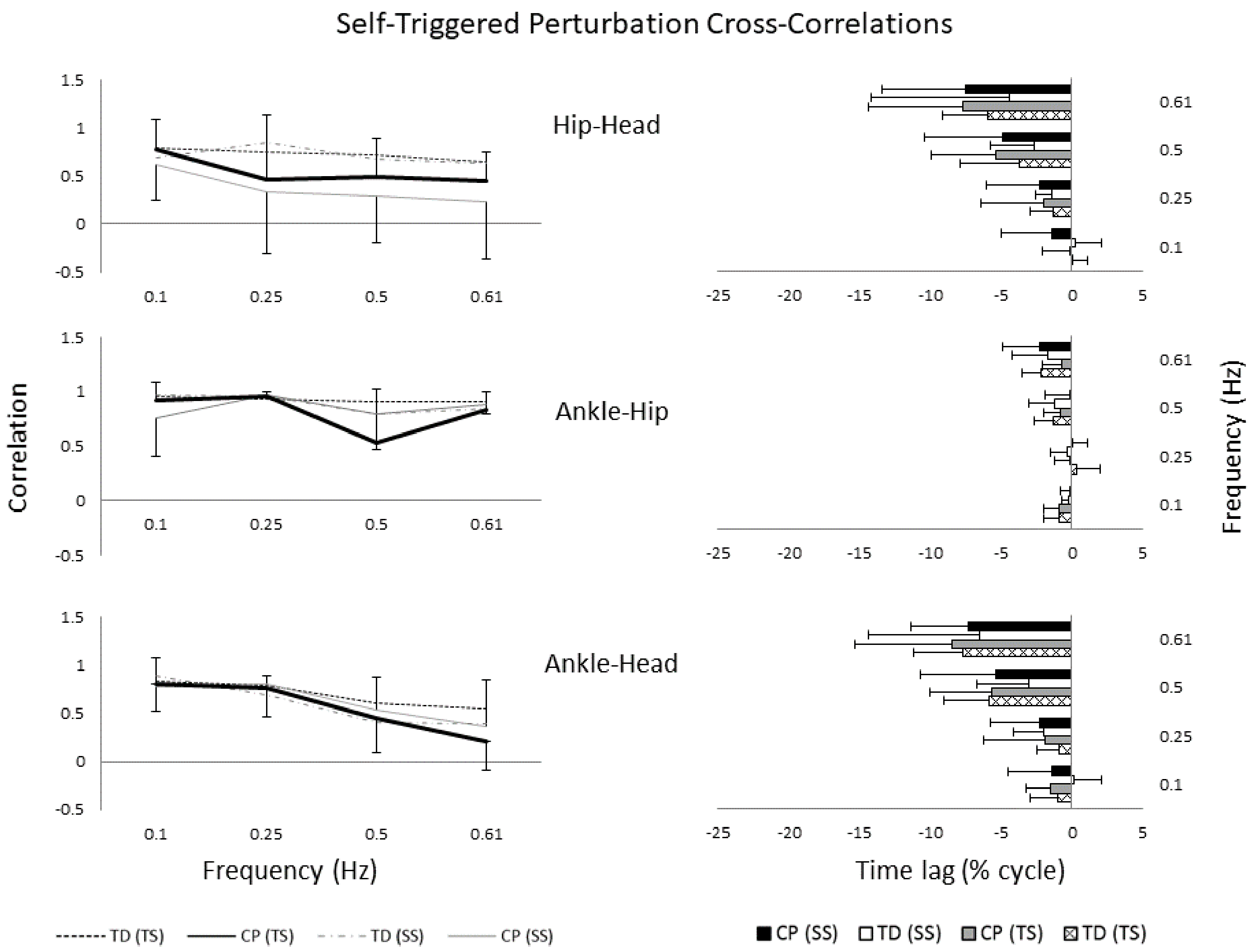

Self-Triggered Perturbation Cross-Correlations
Hip-Head
Ankle-Hip
Ankle-Head
Correlation
Frequency (Hz)
Time lag (% cycle)
Frequency (Hz)
1.5
1
0.5
0
-0.5
0.1
0.25
0.5
0.61
-25
-20
-15
-10
-5
0
5
------- TD (TS)
—— CP (TS)
-·-·- TD (SS)
—— CP (SS)
■ CP (SS)
☐ TD (SS)
▨ CP (TS)
⊠ TD (TS)

Figure 4

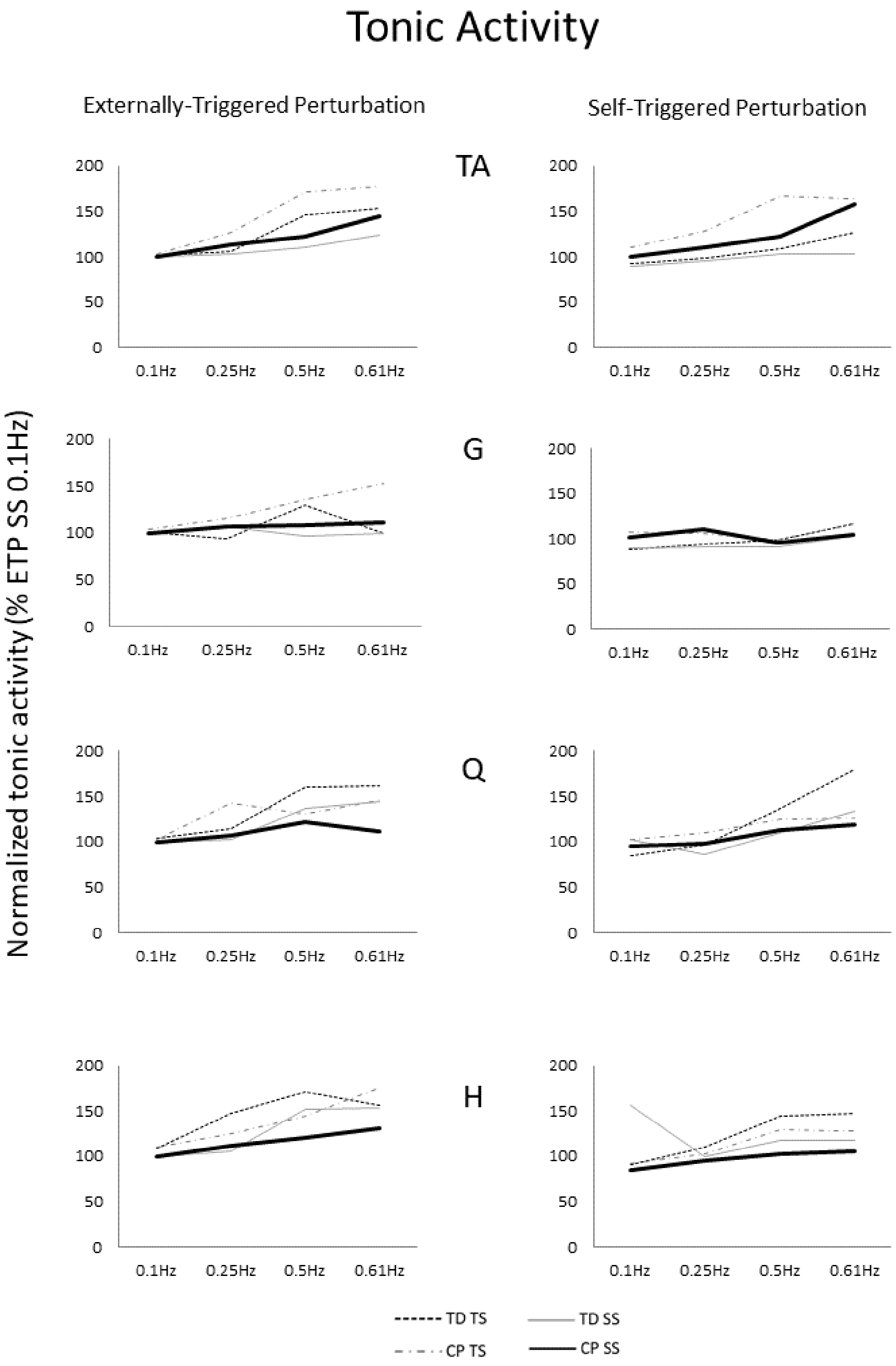
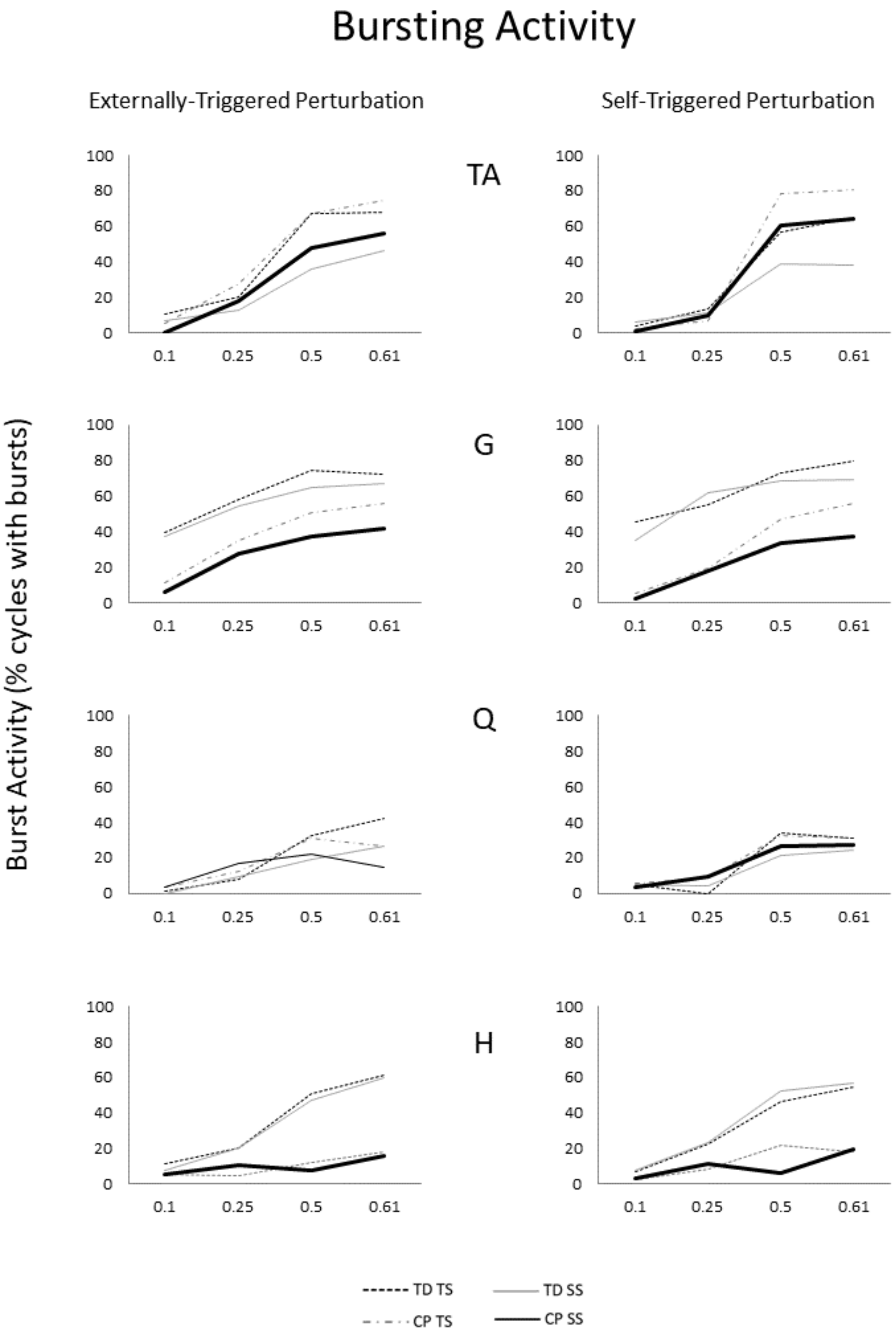

Tonic Activity
Externally-Triggered Perturbation
Self-Triggered Perturbation
TA
G
Q
H
Normalized tonic activity (% ETP SS 0.1Hz)
200
150
100
50
0
0.1Hz
0.25Hz
0.5Hz
0.61Hz
TD TS
TD SS
CP TS
CP SS

Figure 5



Bursting Activity
Externally-Triggered Perturbation
Self-Triggered Perturbation
TA
G
Q
H
Burst Activity (% cycles with bursts)
100
80
60
40
20
0
0.1
0.25
0.5
0.61
TD TS
TD SS
CP TS
CP SS

3.9 Figure captions

Figure 1 – Anchoring Index obtained from typically developing (TD) youth and youth with cerebral palsy (CP). Transition State (TS) and Steady State (SS) periods across four frequencies are presented in Externally (left) and Self-triggered (right) perturbations. Positive values indicate a preference for a Head Stabilization in Space Strategy (HSSS), while negative values indicate a preference for a Head Strapped to Trunk Strategy (HSTS). Values around 0 indicate no preference for either strategy.

Figure 2 - Mean cross-correlation function peak values (CC_{max} – left panels) and time lags ($CC_{lag/lead}$ – right panels) in typically developing (TD) and cerebral palsy (CP) youth. The hip-head, ankle-hip, and ankle-head marker pairs trajectories are presented in transition (TS) and steady (SS) states in the Externally Triggered condition. For clarity, Standard Error bars presented for typically developing (TD) youth only in left panels.

Figure 3 - Mean cross-correlation function peak values (CC_{max} – left panels) and time lags ($CC_{lag/lead}$ – right panels) in typically developing (TD) and cerebral palsy (CP) youth. The hip-head, ankle-hip, and ankle-head marker pairs trajectories are presented in transition (TS) and steady (SS) states in the Self Triggered condition. For clarity, Standard Error bars presented for typically developing (TD) youth only in left panels.

Figure 4 – Tonic activity for (top to bottom panels) tibialis anterior (TA), gastrocnemius (G), quadriceps (Q), and hamstring (H) muscles in ETP (left side) and STP (right side) conditions. Comparisons were made to baseline tonic activity of each muscle in the steady state period at

0.1Hz in ETP. Transition (TS) and steady (SS) states presented for typically developing (TD) and cerebral palsy (CP) youth.

Figure 5 – Muscle bursting activity for (top to bottom panels) tibialis anterior (TA), gastrocnemius (G), quadriceps (Q), and hamstring (H) muscles in ETP (left side) and STP (right side) conditions. Comparisons were made to baseline tonic activity of each muscle in the steady state period at 0.1Hz in ETP. Transition (TS) and steady (SS) states presented for typically developing (TD) and cerebral palsy (CP) youth.

Chapter 4: The effects of a 5-day intensive virtual-reality based exercise programme on kinematics and postural muscle activity in children and adolescents with cerebral palsy

A version of this paper has been submitted to *Physical & Occupational Therapy in Pediatrics*

Full length original research article for submission to
Physical & Occupational Therapy in Pediatrics

The effects of a 5-day virtual-reality based exercise programme on kinematics and postural muscle activity in youth with cerebral palsy – preliminary findings

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Keywords: postural control, anchoring index, balance mechanisms, cerebral palsy, IREX, virtual reality

Funding: This study was funded in part by a grant through the Ontario Federation for Cerebral Palsy (OFCP) and the University of Ottawa Faculty of Health Sciences

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[redacted]

4.1 Abstract

The effects of a 5-day virtual-reality based exercise programme on kinematics and postural muscle activity in youth with cerebral palsy

Aims: To determine the effects of a 5-day virtual reality (VR)-based intervention on anticipatory and reactive mechanisms of postural control in children and adolescents with cerebral palsy (CP).

Methods: Eleven youth with CP were allocated to intervention (N=5) and control (N=6) groups. Both groups attended balance assessment sessions 1 week apart. Participants in the intervention group attended 5 consecutive days between assessments of 1 hour one-on-one physiotherapist-supervised VR balance games.

For balance assessments, participants stood erect with eyes open on a movable platform that translated progressively through four speeds in the anterior/posterior direction. Participants performed two trials each of experimenter-triggered and self-triggered perturbations. Postural muscle activity and kinematics were recorded. The Anchoring Index and body segment cross-correlations were calculated as an indication of body stabilization, and the number of steps taken to regain balance/avoid falling were counted. Mann Whitney-U tests for between group differences in change scores were undertaken with an accepted significance level of 0.0125.

Results: No consistent differences in change scores were identified between groups.

Conclusions: There was no effect of a 5-day VR-based intervention on postural control mechanisms used in response to oscillating platform perturbations. Subsequent studies will further tailor VR interventions to patients’ functional balance needs.

Running footer: Virtual reality exercise and postural control

4.2 Introduction

Cerebral palsy (CP) is a non-progressive lesion in the central nervous system (CNS) resulting in motor disability and developmental delays. It is the most common physical disability in children, (Badawi & Keogh, 2013) affecting 2.11 persons per 1000 live births (Oskoui et al., 2013). Children with CP have motor deficits which contribute to impaired functional mobility and are associated with disruptions in postural control (Assaiante et al., 2005; Schmit et al., 2016). Loss of functionality in individuals with CP can limit participation in physical activity (Bult et al., 2013; Engel-Yeger et al., 2009), which can then lead to further de-conditioning resulting in subsequent reduction in daily functional performance (Hombergen et al., 2012).

Children and adolescents with CP are at an increased risk of falls (Bult et al., 2013). Because balance is an important aspect of daily living, functional performance of children and adolescents with CP is dependent on the role of postural control (Girolami, Shiratori, & Aruin, 2011). We have recently characterized anticipatory and reactive mechanisms of postural control in youth with CP on a continuously oscillating platform (Mills et al., n.d.). When exposed to repeated oscillations on a moving platform, we showed that at lower speeds, children and adolescents with CP generally behaved similarly to typically developing age-matched controls. However, at higher frequencies, youth with CP took more steps and maintained increased levels of tonic activity in response to the platform movements. Furthermore, youth with CP exhibited a preference for a head strapped to trunk strategy (HSTS) (Amblard et al., 2001), a measure of upper body stabilization during movement. Comparatively, typically developing youth tended to prefer the head stabilized in space strategy (HSSS) as a means of stabilizing the head, which helps to contribute a stable visual reference input to balance. We proposed that these changes at the higher frequencies were mostly due to the CP participants' (1) inability to control the body's multiple degrees of freedom during the task, and (2) incapacity to generate appropriate muscular responses.

Physiotherapy interventions that require users to use full body movements to interact with a virtual environment during treatment have been found to improve static and dynamic standing balance (Brien & Sveistrup, 2011; Dewar et al., 2015). For example, replacing regular physiotherapy sessions with training using the Nintendo Wii for 3 weeks (four 25-minute sessions per week) resulted in improved balance scores as well as clinical motor function/performance testing in children with CP (Jelsma et al., 2012) and those with poor motor performance as identified by physical education teachers (Mombarg et al., 2013). Meanwhile, feasibility studies in specially developed virtual reality (VR) games for children with CP have demonstrated clinical improvements in functional balance and gait measures (Bonnechere et al., 2017; Jaume-I-Capó et al., 2014).

There is strong evidence that supports the use of full-body movement VR-based exercise such as that promoted by GestureTek Health's (Toronto, Canada) rehabilitation-specific Interactive Rehabilitation Exercise System (IREX) as an intervention to improve functional balance and mobility outcomes in children with CP (Levac et al., 2017; Glegg et al., 2014; Weiss et al., 2009). For example, we have previously demonstrated that an intensive 1-week IREX intervention improves short-term balance and functional mobility in adolescents with CP (Brien & Sveistrup, 2011). While functional improvements were noted for clinical measures including the Community Balance and Mobility Scale, the Six-Minute Walk Test and the Timed Up and Down Stairs, the effects of VR and serious gaming interventions on anticipatory and reactionary mechanisms of postural control have not been reported.

For the current study, we investigated the effects of a 5 day, 60 minutes/day VR-based intervention on mechanisms of postural control in children and adolescents with CP. We hypothesized that immediately following the one-on-one supervised IREX intervention, measures of anticipatory and reactive postural control would improve compared to the same measures observed in the children who received no intervention. We hypothesized that changes would be evidenced through a reduction in (1) total number of steps taken and (2) postural muscle tonic activity, while demonstrating an increase in (1) preference towards a head stabilization in space strategy, and (2) correlations between movements of body segments. The preliminary data reported in this article form part of a larger study on the effects of a 6-week, therapist-monitored home VR gaming program for children and adolescents with CP (Levac et al., 2017).

4.3 Methods

Participants

Eleven children and adolescents aged 7-17 years with confirmed diagnosis of cerebral palsy GMFCS levels I or II (Rosenbaum et al., 2008) participated in this study (N=11; 6 boys and 5 girls; participant demographics presented in table 1). All participants and/or parents provided written informed consent. Ethical approval was granted through the University of Ottawa research ethics board in accordance with the Tri-Council policy statement (CIHR et al., 2014). Exclusion criteria were visual, cognitive or auditory impairment that would interfere with understanding of and/or ability to carry out instructions and/or play the video games, and orthopaedic surgery or Botox injections in the past 12 months. Children were recruited via study information letters mailed from the Ottawa Children's Treatment Centre (OCTC) and disseminated in schools by physical and occupational therapists via the Community Care Access Centre. We did not undertake power analyses for this pilot study as our goal was to generate effect size and variability estimates to power a subsequent trial.

[Insert table 1 about here]

Intervention design

Participants were non-randomly assigned to either the IREX group ("Intervention", N=5) or the control group ("Control", N=6) based on their self-declared ability to attend the 1-week of VR sessions at OCTC. The 5 day IREX intervention program consisted of 60 minutes of VR-based balance training for 5 consecutive days. The program (Brien & Sveistrup, 2011; Levac et al., 2017) was delivered in the VR therapy room of the OCTC using the commercially available system consisting of a 32" widescreen display, a computer, video camera, and a green screen for computer-generated images (Interactive Rehabilitation Exercise System (IREX), Gesturetek Health, Toronto, Canada). The participants interacted with virtual objects in each game to achieve tasks with adjusted difficulty levels, which challenged dynamic standing balance, coordination, and timing. Games were ranked as 'Easy', 'Medium', or 'Hard' based on physical and cognitive demands when played on the lowest game parameters (Levac et al., 2017). Each exercise program was tailored to the individual's needs, with suggested games, challenge parameters, and progression across the 5 days.

Procedures: Assessment schedule, protocol, and outcome measures

All participants attended two test sessions, each consisting of i) a balance testing protocol and ii) a clinical testing protocol. For the intervention group, participants completed a testing session the weekend prior to and the weekend following a 5-day intensive therapy block. Participants in the control group completed two testing sessions scheduled one week apart.

i. Balance testing and outcome measures

The balance testing paradigm used was the same as that used previously in our lab (Bugnariu & Sveistrup, 2006). Briefly, participants stood upright on an oscillating platform (anterior/posterior) with their eyes open, and barefoot with feet shoulder-width apart. They were told to maintain their balance and to avoid taking steps unless necessary. Two trials in each of two test conditions were observed: experimenter-triggered (ETP) and self-triggered (STP) increases in oscillation frequency. A minimum number of cycles at each frequency (10, 20, 40, and 50 cycles at 0.1 Hz, 0.25 Hz, 0.5 Hz, and 0.61 Hz, respectively) were completed before initiating the next frequency.

Full body kinematics (100 Hz) were recorded using motion analysis software (Vicon, Oxford, UK). Bilateral surface EMG (Delsys Inc., Natick, USA) was recorded at 1000 Hz for tibialis anterior, gastrocnemius, quadriceps, and hamstring muscles, with a reference electrode placed on the iliac crest.

The first three (0.1 Hz) to five (0.25 Hz, 0.5 Hz, 0.61 Hz) consecutive cycles without stepping for each frequency were considered 'transition-state' (TS). In the last half of each frequency following the transition state, a period of 3 to 5 consecutive cycles without stepping (0.1 Hz) and 8 to 10 consecutive cycles (0.25 Hz, 0.5 Hz, 0.61 Hz) without stepping were considered ‘steady-state (SS) periods’ during which the movement of the platform was considered to be predictable .

The number of steps taken at each frequency during the oscillating platform paradigm was counted. The Anchoring Index (AI) was used to determine the stabilization of the head with respect to external space and/or the trunk (Amblard et al., 1997, 2001; Mesure et al., 1999) and was calculated as follows:

$$AI = [\sigma^2_r - \sigma^2_a] / [\sigma^2_a + \sigma^2_r]$$

where σ_a is the dispersion of the head with respect to the absolute vertical (external space), and σ_r is the angular dispersion of the head relative to the trunk. A negative AI indicates a preference for a Head Strapped to Trunk Strategy (HSTS), whereas a positive AI indicates a preferred Head Stabilization in Space Strategy (HSSS).

Cross-correlations (CC) of anteroposterior linear displacements of the ankle-head, hip-head, and ankle-hip marker pairs were calculated. Each CC temporal relationship (lag/lead) was calculated for ±50% time shift of one cycle. The maximum correlation and percent cycle at which it occurred were recorded.

Raw EMG signals were full-wave rectified. Postural muscle bursting activity was expressed as the percent of cycles in which bursts occurred. Tonic activity levels were expressed as a percentage of the measured tonic activity at ETP SS 0.1 Hz.

ii. Clinical testing and outcome measures

Following the balance testing protocol, participants were offered a period of 10-15 minutes rest before continuing with the clinical testing. Clinical testing consisted of the 6-minute walk test (6MWT) (Maher et al., 2008) to assess the functional capacity for walking a prolonged distance. This was followed by the Gross Motor Function Measure Challenge Module (GMFM-CM) to assess gross motor skills of balance and postural control, coordination, agility, speed, and strength. Scores were converted to percentages. The 6MWT and GMFM-CM clinical outcome measures were recorded by accredited physiotherapists.

Data analysis

Participant demographics and stepping data were summarized using descriptive statistics. Statistical analyses of clinical, kinematic, and postural muscle outcome measures were performed using SPSS v 23.0.0.2 (IBM Corp.). In the balance testing protocol, cycles during which steps were taken were excluded from statistical analyses. Data were determined to be non-normally distributed through inspection of skewness and kurtosis, histograms, and Shapiro-Wilk tests of normality. First, baseline comparisons were made for between group differences, followed by inferential testing using the non-parametric Mann Whitney U (MWU) test for between group differences of the change scores (difference between assessments, i.e. assessment 2-1). Cases where baseline measures were found to be significantly different between groups were excluded from the change-score analyses to ensure any differences detected were as a result of the intervention. Results considered significant for $p < 0.0125$ (Bonferroni adjusted).

4.4 Results

Baseline comparisons

Significant difference between groups was identified at baseline for the Ankle-Head marker trajectory pair correlation at 0.1 Hz (U = 1, p = 0.009) in the ETP TS condition. This measure was excluded from subsequent change-score analyses. No significant differences between groups at baseline were detected in the STP conditions, nor in the clinical outcome measures.

Clinical Outcome Measures

There were no significant differences in change scores between groups found in the 6MWT and the GMFM-CM (see figure 1).

[Insert Figure 1 about here]

Balance Testing Outcome Measures

Stepping Responses

Statistical analysis was not performed for the stepping response data as many participants were unable or unwilling to complete trials in the first assessment, but could complete trials at the second assessment. Thus, no change scores could be calculated for this measure. Results for the stepping responses taken by all CP participants at 0.5 Hz and 0.61 Hz in ETP and STP conditions are presented in Table 2. Generally, the lower frequencies (0.1 Hz and 0.25 Hz) did not elicit stepping responses in either condition. A greater number of steps was observed at the higher frequencies (0.5 Hz and 0.61 Hz) in both conditions. More steps were taken in the ETP condition compared to the STP condition, and a reduction in steps taken between assessments was observed in both the IREX and control groups.

[Insert Table 2 about here]

Anchoring Index

Although no significant differences were found between groups for the change in Anchoring Index at any frequency in any condition, both groups initially demonstrated a preference for HSTS in most cases. Following the one-week period, the participants in both groups exhibited less reliance on HSTS and adopted either no preference for HSTS/HSSS, or switched to HSSS entirely – this was especially noticeable in the TS periods in both ETP and STP conditions. Results for the AI MWU tests can be found in Table 3.1.

[Insert Figure 2 about here]

Kinematics

Few significant differences were found between groups in the cross-correlation (CC) analyses. In the ETP condition during steady state periods, the Ankle-Head CC at 0.25Hz tended to decrease more (U = 0, p = 0.024) in the IREX group (M = -0.624; SD = 0.47) than in the control group (M = -0.02; SD = 0.03). The Ankle-Hip CC at 0.1 Hz was found to increase more (approached significance: U = 1, p = 0.019) in the IREX group (M = 0.45; SD = 0.35) than in the control group (M = -0.18; SD = 0.49) following the 1-week intensive program. No significant differences between groups were detected in any marker-pair trajectory CC in the other frequencies/conditions. Full results of the CC analyses can be found in Tables 3.2 and 3.3.

Postural muscle activity

The tonic activity of the hamstrings in the ETP condition during steady state (0.25 Hz) increased more (approached significance: U = 1, p = 0.019) in the IREX group (M = 9.72; SD = 12.34) than in the control group (M = -6.46; SD = 11.47) following 1-week intensive therapy. No other significant differences between groups were detected in either tonic activity levels or bursting activity for all muscles in all other frequencies/conditions. Full results of the postural muscle activity MWU tests are presented in Tables 3.4 and 3.5.

4.5 Discussion

In this study, we examined the effect of a 1-week VR-based intensive exercise program on anticipatory and reactive mechanisms of postural control in children and adolescents with CP. Contrary to our hypotheses, children and adolescents with cerebral palsy who participated in the program did not exhibit significant changes to postural control mechanisms following the exercise program.

The lack of differences in change scores in the kinematic and muscle activity analyses could be explained by limited redundancy in responses. During acquisition of new motor tasks (or re-learning of old ones), it has been hypothesized that development occurs in phases (Woollacott & Sveistrup, 1992) whereby initially the control of degrees of freedom throughout the body (eg. hips, knees, and ankles) is poor and a clear behavioural strategy in response to a postural perturbation is not exhibited. In the second phase of learning, the degrees of freedom are constrained or ‘frozen’ to a minimum, allowing for a strong, rigid system, before being ‘released’ and re-integrated with practice in phase 3 for fluid movement (Vereijken et al., 1992; Bernstein, 1967). Thus, the participants in the current study may still have been constrained to a phase 2 stage of motor (re)learning (i.e. no redundancy in responses) with insufficient time and practice to consolidate response reorganization. Future studies would ideally investigate the effect of an intensive VR-based intervention over several weeks, with multiple baselines.

Because many of the games played during the VR-based intervention largely required lateral movements, it is possible that any postural control benefits gained in the lateral direction may not have carried-over to the postural balance mechanisms in the anteroposterior direction of the platform oscillations. For example, in a systematic review of balance training interventions, Kümmel et al. (2016) discussed how training can improve balance and performance on a trained task but not necessarily in a non-trained, related task. Indeed, Giboin et al. (2015) showed that balance training only had an effect on the trained tasks, even if the non-trained tasks were performed on a similar platform but in a different direction of perturbation. Moreover, it was found that groups outperformed others only on the tasks in which they were trained. Thus, the authors suggested identifying and training exactly those tasks requiring improvement.

Recent studies have demonstrated benefits of VR training on dynamic balance control, but have mostly focussed on clinical assessments, such as the Berg Balance Scale or Paediatric Balance Scale (PBS). For example, Cho et al. (2016) found that virtual reality treadmill training improved scores on the PBS, while Pavao et al. (2014) observed similar changes on the PBS following VR-based therapy. However, our aim was to understand if anticipatory and reactive postural control mechanisms are necessary for functional balance and mobility. The results from our study suggest that this dosage of VR-based exercise alone did not result in significant changes in anticipatory and reactive mechanisms of postural control in youth with CP. While this may be a result of employing multiple mechanisms for achieving the same task, improvements in postural control for this population may rely on improving the ability to generate appropriate muscle responses. The VR games in this study did not target specific muscles for strength training and muscle activation timing.

There are also several possible limitations as to why no changes were observed in either group. Most notably, the sample size was small and not powered to detect change. The number of participants recruited was limited to those who volunteered for the study, which greatly influenced the effect sizes of our statistical analyses. Due to the small sample size and large variability in our data, it is possible that benefits gained by some participants were within the magnitude of the grouped variability. However, while we have previously demonstrated improvements on clinical measures in four CP youth following a 5-day intensive VR program (Brien & Sveistrup, 2011), it is possible the intervention was not sufficiently challenging or intense, as there may not have been enough repetition to obtain improvement. The relatively shorter duration of the daily program – 60 minutes per day in our intervention compared to the 90 minutes per day in Brien & Sveistrup's study – might not have provided the required intensity of stimulation for improvement. Furthermore, it is possible the participants who received the IREX intervention simply used this exercise to replace another physical activity they would have otherwise done throughout the week.

4.6 Conclusions

Five days of VR-based intervention did not alter the anticipatory or reactive postural control mechanisms used in response to oscillating platform perturbations in children with cerebral palsy, consistent with the results of our previous study in which no changes in clinical measures were observed following a 5-day intensive VR program (Levac et al., 2017). In subsequent studies, increasing the sample size and increasing the intensity, specificity, and duration of the activity may inform physiotherapists of the potential benefits to an intensive VR-based exercise program. The use of head-mounted displays to provide 3D VR environments may also encourage movements in both medio-lateral and antero-posterior planes.

Declaration of interest

The authors declare that they have no conflict of interest.

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4.8 Tables and Figures

Table 1 – Participant demographics

Participant	Age	Sex	Diagnosis	GMFCS Level
JS01	14y 1mo	F	Left hemiplegia	I
JS02	15y 2mo	M	Spastic diplegia	I
JS03	9y 9mo	F	Spastic diplegia	I
JS04	13y 0mo	M	Right hemiplegia	I
JS05	8y 9mo	F	Left hemiplegia	I
JS06	16y 1mo	M	Left hemiplegia	I
JS07	11y 9mo	M	Right hemiplegia	I
JS08	7y 8mo	F	Spastic diplegia	I
JS09	12y 5mo	M	Spastic diplegia	II
JS10	16y 0mo	F	Spastic diplegia	I-II
JS11	15y 10m	M	Spastic diplegia	I-II

Table 2 – Stepping responses in the externally-triggered condition. The number of steps recorded in both IREX and control groups are presented for the two highest frequencies. In most cases, a decrease in the number of steps taken was observed from 1st to 2nd session.

			Assessment							
			SESSION 1				SESSION 2			
			Frequency (Hz)				Frequency (Hz)			
			0.5		0.61		0.5		0.61	
GROUP	Participant by age	Trial #	ETP	STP	ETP	STP	ETP	STP	ETP	STP
IREX	JS05	1	15	-	27	-	-	-	-	-
		2	4	-	4	1	5	-	4	-
	JS03	1	^	6	11	18	19	1	37	13
		2	22	-	32	14	10	2	29	12
	JS04	1	*	*	*	*	32	*	*	*
		2	*	*	*	*	^	*	*	*
	JS09	1	*	*	*	*	*	*	*	*
		2	*	*	*	*	*	*	*	*
	JS06	1	23	-	8	-	-	-	-	-
		2	-	-	2	-	-	-	-	-
Control	JS08	1	^	^	*	^	22	19	^	20
		2	^	^	^	^	17	7	^	^
	JS07	1	^	7	^	9	3	-	-	-
		2	7	2	18	7	-	-		-
	JS01	1	5	4	4	-	-	-	-	-
		2	-	-	2	4	-	-	-	-
	JS10	1	^	*	*	*	^	*	*	*
		2	*	*	*	*	^	*	*	*
	JS02	1	2	-	3	-	-	-	-	-
		2	-	-	-	-	-	-	-	-
	JS11	1	*	*	*	*	*	*	*	*
		2	*	*	*	*	*	*	*	*

Notes:

- no steps taken

^ unable to complete trial without stepping

* did not attempt

Table 3.1 Anchoring Index Mann-Whitney U Test Statistics

	ETP TS				STP TS			
Frequency	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz
N	11	10	6	6	9	8	6	6
U	12	11	4	2	8	6	1	4
Z	-0.548	-0.213	-0.218	-1.091	-0.49	-0.447	-1.528	-0.218
p	0.662	0.914	1	0.4	0.73	0.786	0.2	1
effect size (*r* , abs)	0.165228	0.067357	0.088998	0.445399	0.163333	0.158038	0.623803	0.088998

	ETP SS				STP SS			
Frequency	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz
N	11	10	6	6	9	8	6	6
U	13	10	3	2	6	5	4	2
Z	-0.365	-0.426	-0.655	-1.091	-0.98	-0.745	-0.218	-0.1091
p	0.792	0.726	0.7	0.4	0.413	0.571	1	0.4
effect size (*r* , abs)	0.110052	0.134713	0.267403	0.445399	0.326667	0.263397	0.088998	0.04454

NOTES:
N = sample size
U = Mann-Whitney U test result
Z = z-score
p = p value (significance $p < 0.0125$)

ETP = Externally Triggered Perturbation
STP = Selt Triggered Perturbation

TS = Transition State
SS = Steady State

Table 3.2 Cross Correlation Mann-Whitney U Test Statistics

			ETP TS				STP TS			
			0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz
Ankle-Head	Correlation	*N*	10	9	7	7	9	7	7	6
		U	4	4	4	5	7	3	6	4
		Z	-1.706	-1.291	-0.707	-0.354	-0.735	-0.775	0	-0.218
		p	0.114	0.262	0.629	0.857	0.556	0.571	1	1
		effect size (*r*, abs)	0.5394846	0.4303333	0.2672209	0.1337994	0.245	0.2929225	0	0.0889981
	Temporal lag	*N*	10	9	7	7	9	7	7	6
		U	9	5	3	5	7	1	0	3
		Z	-0.64	-1.033	-1.061	-0.354	-0.735	-1.563	-2.121	-0.655
		p	0.61	0.381	0.4	0.857	0.556	0.19	0.057	0.7
		effect size (*r*, abs)	0.2023858	0.3443333	0.4010203	0.1337994	0.245	0.5907585	0.8016626	0.2674026
Ankle-Hip	Correlation	*N*	10	9	6	6	9	8	6	7
		U	8	3	3	2	9	7	3	1
		Z	-0.853	-1.549	-0.463	-1.091	-0.245	-0.149	-0.463	-1.1768
		p	0.476	0.167	0.8	0.275	0.905	1	0.8	0.114
		effect size (*r*, abs)	0.2697423	0.5163333	0.189019	0.4453989	0.0816667	0.0526795	0.189019	0.4447886
	Temporal lag	*N*	10	9	6	6	9	8	6	7
		U	10.5	9	3	1	7	6	1	4
		Z	-0.322	0	-0.463	-1.528	-0.375	-0.447	-1.389	-0.707
		p	0.762	1	0.8	0.2	0.556	0.786	0.267	0.629
		effect size (*r*, abs)	0.1018253	0	0.189019	0.6238034	0.125	0.1580384	0.5670569	0.2672209
Hip-Head	Correlation	*N*	10	9	7	6	10	8	7	6
		U	8	9	2	4	10	5	3	4
		Z	-0.853	0	-1.414	0	-0.426	-0.745	-1.061	0
		p	0.476	1	0.229	1	0.762	0.571	0.4	1
		effect size (*r*, abs)	0.2697423	0	0.5344418	0	0.134713	0.2633973	0.4010203	0
	Temporal lag	*N*	10	9	7	6	10	8	7	6
		U	9	7	4	3.5	6	5.5	0	1
		Z	-0.64	-0.516	-0.707	-0.235	-1.279	-0.6	-2.121	-1.389
		p	0.61	0.714	0.629	0.8	0.257	0.571	0.057	0.267
		effect size (*r*, abs)	0.2023858	0.172	0.2672209	0.0959383	0.4044553	0.212132	0.8016626	0.5670569

NOTES:

N = sample size U = Mann-Whitney U test result Z = z-score *p* = p value (significance $p < 0.0125$)

ETP = Externally Triggered Perturbation STP = Self Triggered Perturbation TS = Transition State

Table 3.3 Cross Correlation Mann-Whitney U Test Statistics

			ETP SS				STP SS			
			0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz
Ankle-Head	Correlation	*N*	10	9	7	7	9	6	7	6
		U	7	0	5	4	6	0	3	4
		Z	-1.066	-2.324	-0.354	-0.707	-0.98	-1.964	-0.1061	-0.218
		p	0.352	0.024	0.857	0.629	0.413	0.1	0.4	1
		effect size (*r* , abs)	0.3370988	0.7746667	0.1337994	0.2672209	0.3266667	0.8017996	0.040102	0.0889981
	Temporal lag	*N*	10	9	7	7	9	6	7	6
		U	4	3	2	6	8	2	1	1
		Z	-1.706	-1.556	-1.414	0	-0.49	-1.091	-1.768	-1.528
		p	0.114	0.167	0.229	1	0.73	0.4	0.114	0.2
		effect size (*r* , abs)	0.5394846	0.5186667	0.5344418	0	0.1633333	0.4453989	0.6682412	0.6238034
Ankle-Hip	Correlation	*N*	10	9	6	6	9	8	6	7
		U	1	2	3	0	5	6	0	5
		Z	-0.2345	-1.807	-0.463	-1.964	-1.225	-0.447	-1.852	-0.354
		p	0.019	0.095	0.8	0.1	0.286	0.786	0.133	0.857
		effect size (*r* , abs)	0.0741554	0.6023333	0.189019	0.8017996	0.4083333	0.1580384	0.7560758	0.1337994
	Temporal lag	*N*	10	9	6	6	9	8	6	7
		U	4.5	4	1	2	3.5	3	3	4
		Z	-1.604	-1.291	-1.389	-1.091	-1.599	-1.342	-0.463	-0.707
		p	0.114	0.262	0.267	0.4	0.111	0.25	0.8	0.629
		effect size (*r* , abs)	0.5072293	0.4303333	0.5670569	0.4453989	0.533	0.4744687	0.189019	0.2672209
Hip-Head	Correlation	*N*	10	9	7	6	10	8	7	6
		U	10	5	5	4	11	6	5	4
		Z	-0.426	-1.033	-0.354	0	-0.213	-0.447	-0.354	0
		p	0.762	0.381	0.857	1	0.914	0.786	0.857	1
		effect size (*r* , abs)	0.134713	0.3443333	0.1337994	0	0.0673565	0.1580384	0.1337994	0
	Temporal lag	*N*	10	9	7	6	10	8	7	6
		U	9	8	1	4	6	7	1	1
		Z	-0.64	-0.258	-1.768	0	-1.279	-0.149	-1.768	-1.389
		p	0.61	0.905	0.114	1	0.257	1	0.114	0.267
		effect size (*r* , abs)	0.2023858	0.086	0.6682412	0	0.4044553	0.0526795	0.6682412	0.5670569

NOTES:

N = sample size U = Mann-Whitney U test result Z = z-score *p* = p value (significance $p < 0.0125$)

ETP = Externally Triggered Perturbation STP = Selt Triggered Perturbation SS = Steady State

Table 3.4 Postural Muscle Activity Mann-Whitney U Test Statistics

			ETP TS				STP TS			
			0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz
TIBIALIS ANTERIOR	Burst Activity	*N*	11	10	7	6	11	10	7	6
		MWU	12	5.5	3.5	3.5	14	11	3	4
		Z	-0.563	-1.399	-0.892	-0.443	-0.2	-0.216	-1.07	-0.221
		p	0.662	0.171	0.4	0.7	0.931	0.914	0.4	1
		effect size (*r* , abs)	0.1697509	0.4424026	0.3371443	0.180854	0.0603023	0.0683052	0.404422	0.0902229
	Tonic Activity	*N*	11	10	7	6	11	10	7	6
		MWU	15	11	4	4	15	7	4	3
		Z	0	-0.213	-0.707	-0.218	0	-1.066	-0.707	-0.655
		p	1	0.914	0.629	1	1	0.352	0.629	0.7
		effect size (*r* , abs)	0	0.0673565	0.2672209	0.0889981	0	0.3370988	0.2672209	0.2674026
GASTROCNEMIUS	Burst Activity	*N*	11	10	7	6	11	10	7	6
		MWU	11	4.5	4	3.5	14	10	5.5	3
		Z	-0.766	-1.629	-7.14	-0.449	-0.211	-0.428	-0.18	-0.655
		p	0.537	0.114	0.629	0.7	0.931	0.762	0.857	0.7
		effect size (*r* , abs)	0.2309577	0.515135	2.6986663	0.1833035	0.0636189	0.1353455	0.0680336	0.2674026
	Tonic Activity	*N*	11	10	7	6	11	10	7	6
		MWU	14	10	6	2	15	5	6	4
		Z	-0.183	-0.426	0	-1.091	0	-1.492	0	-0.218
		p	0.931	0.962	1	0.4	1	0.171	1	1
		effect size (*r* , abs)	0.0551766	0.134713	0	0.4453989	0	0.4718118	0	0.0889981
QUADRICEPS	Burst Activity	*N*	11	10	7	6	11	10	7	6
		MWU	4.5	8.5	4	1	10	8.5	5	3
		Z	-2.113	-0.775	-0.734	-1.528	-0.998	-0.758	-0.367	-0.664
		p	0.052	0.476	0.629	0.2	0.429	0.476	0.857	0.7
		effect size (*r* , abs)	0.6370935	0.2450765	0.2774259	0.6238034	0.3009083	0.2397006	0.138713	0.2710769
	Tonic Activity	*N*	11	10	7	6	11	10	7	6
		MWU	5	11	5	4	15	10	4	3
		Z	-1.826	-0.213	-0.354	-0.218	0	-0.426	-0.707	-0.655
		p	0.082	0.914	0.857	1	1	0.762	0.629	0.7
		effect size (*r* , abs)	0.5505597	0.0673565	0.1337994	0.0889981	0	0.134713	0.2672209	0.2674026
HAMSTRINGS	Burst Activity	*N*	11	10	7	6	11	10	7	6
		MWU	14	9	1.5	0	12.5	5.5	1	1
		Z	-0.187	-0.65	-1.605	-1.993	-0.468	-1.39	-1.768	-1.55
		p	0.931	0.61	0.114	0.1	0.662	0.171	0.114	0.2
		effect size (*r* , abs)	0.0563826	0.205548	0.606633	0.8136388	0.1411073	0.4395566	0.6682412	0.6327849
	Tonic Activity	*N*	11	10	7	6	11	10	7	6
		MWU	15	1	6	4	8	6	4	2
		Z	0	-2.345	0	-0.218	-0.853	0	-0.707	-1.091
		p	1	0.019	1	1	0.476	1	1	0.4
		effect size (*r* , abs)	0	0.7415541	0	0.0889981	0.2571892	0	0.2672209	0.4453989

NOTES:
N = sample size U = Mann-Whitney U test result Z = *z*-score *p* = p value (significance $p < 0.0125$)
ETP = Externally Triggered Perturbation STP = Selt Triggered Perturbation TS = Transition State

Table 3.5 Postural Muscle Activity Mann-Whitney U Test Statistics

			ETP SS				STP SS			
			0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz
TIBIALIS ANTERIOR	Burst Activity	*N*	10	9	7	6	10	9	7	6
		MWU	9	7.5	5.5	4	12.5	5.5	3.5	4
		Z	-0.824	-0.615	-0.178	-0.218	0	-1.107	-0.892	-0.218
		p	0.548	0.556	0.857	1	1	0.286	0.4	1
		effect size (*r* , abs)	0.2605717	0.205	0.0672777	0.0889981	0	0.369	0.3371443	0.0889981
	Tonic Activity	*N*	10	9	7	7	10	9	7	7
		MWU	8	9	2	4	7	10	2	2
		Z	-0.94	-0.245	-1.414	-0.707	-1.149	0	-1.414	-1.414
		p	0.421	0.905	0.229	0.629	0.31	1	0.229	0.229
		effect size (*r* , abs)	0.2972541	0.0816667	0.5344418	0.2672209	0.3633457	0	0.5344418	0.5344418
GASTROCNEMIUS	Burst Activity	*N*	10	9	7	6	10	9	7	6
		MWU	5.5	8	5	4.5	10	9.5	5	4
		Z	-1.514	-0.494	-0.357	0	-0.532	-0.123	-0.354	-0.218
		p	0.151	0.73	0.857	1	0.69	0.905	0.857	1
		effect size (*r* , abs)	0.4787688	0.1646667	0.1349333	0	0.1682332	0.041	0.1337994	0.0889981
	Tonic Activity	*N*	10	9	7	7	10	9	7	7
		MWU	12	7	6	6	5	10	6	4
		Z	-0.104	-0.735	0	0	-1.567	0	0	-0.707
		p	0.917	0.556	1	1	0.151	1	1	0.629
		effect size (*r* , abs)	0.0328877	0.245	0	0	0.4955289	0	0	0.2672209
QUADRICEPS	Burst Activity	*N*	10	9	7	6	10	9	7	6
		MWU	4.5	9	3	3.5	10	7	2	3
		Z	-1.89	-0.257	-1.061	-0.443	-0.643	-0.751	-1.414	-0.655
		p	0.095	0.905	0.4	0.7	0.69	0.556	0.229	0.7
		effect size (*r* , abs)	0.5976705	0.0856667	0.4010203	0.1674383	0.2033345	0.2503333	0.5344418	0.2475667
	Tonic Activity	*N*	10	9	7	7	10	9	7	7
		MWU	9	7	3	5	3	7	3	2
		Z	-0.731	-0.735	-1.061	-0.354	-1.984	-0.735	-1.061	-1.414
		p	0.548	0.462	0.4	0.857	0.056	0.556	0.4	0.229
		effect size (*r* , abs)	0.2311625	0.245	0.4010203	0.1337994	0.6273959	0.245	0.4010203	0.5344418
HAMSTRINGS	Burst Activity	*N*	10	9	7	6	10	9	7	6
		MWU	10.5	7.5	0	4	6	8	3	0
		Z	-0.516	-0.643	-2.141	-0.232	-1.671	-0.492	-1.061	-1.993
		p	0.69	0.556	0.057	1	0.222	0.73	0.4	0.1
		effect size (*r* , abs)	0.1631735	0.2143333	0.8092219	0.0947136	0.5284166	0.164	0.4010203	0.8136388
	Tonic Activity	*N*	10	9	7	7	10	9	7	7
		MWU	10	7	3	6	5	8	6	6
		Z	-0.522	-0.735	-1.061	0	-1.567	-0.49	0	0
		p	0.69	0.556	0.4	1	0.151	0.73	1	1
		effect size (*r* , abs)	0.1650709	0.245	0.4010203	0	0.4955289	0.1633333	0	0

NOTES:
N = sample size U = Mann-Whitney U test result Z = z-score *p* = p value (significance $p < 0.0125$)
ETP = Externally Triggered Perturbation STP = Self Triggered Perturbation SS = Steady State

Figure 1

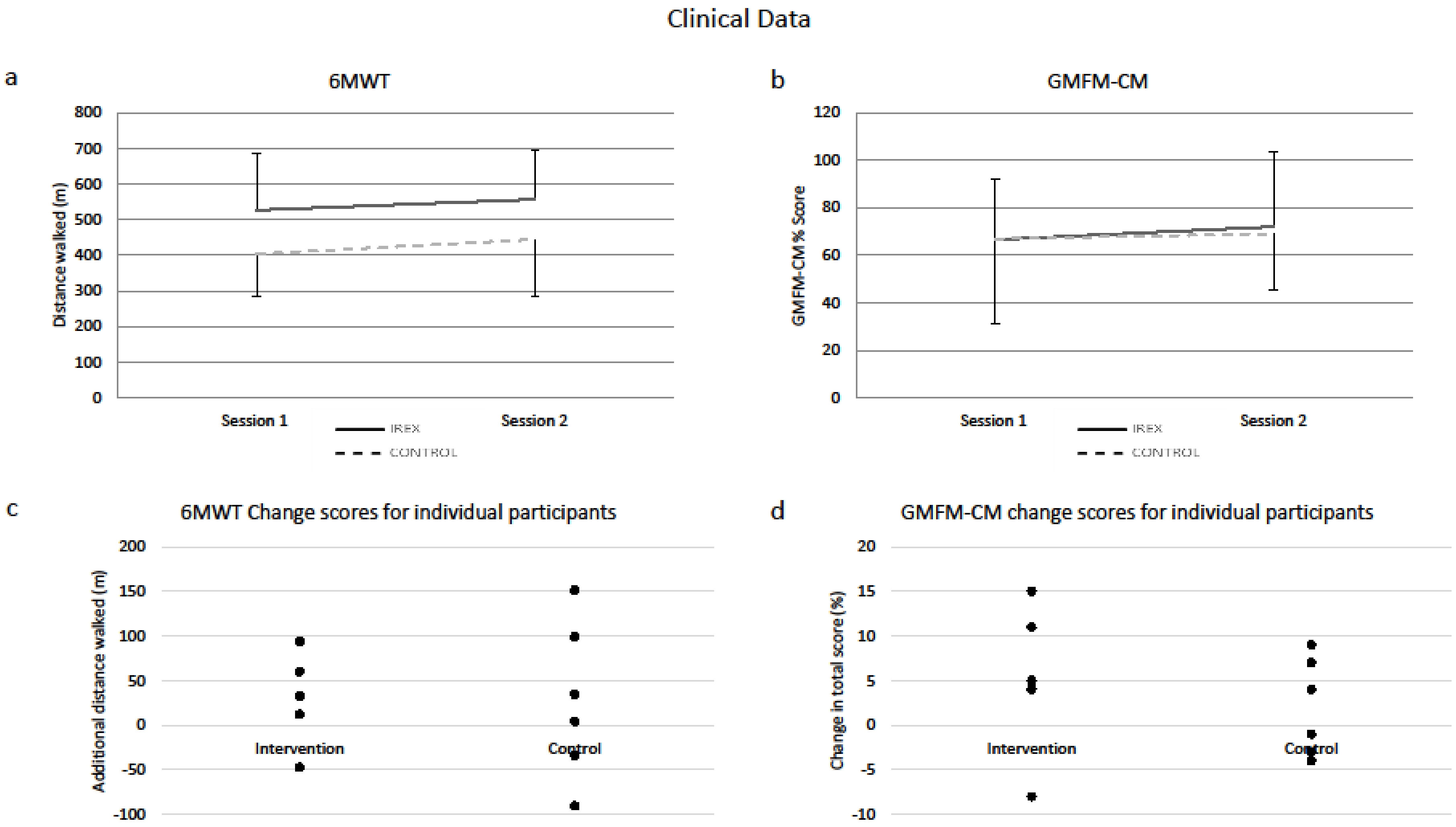
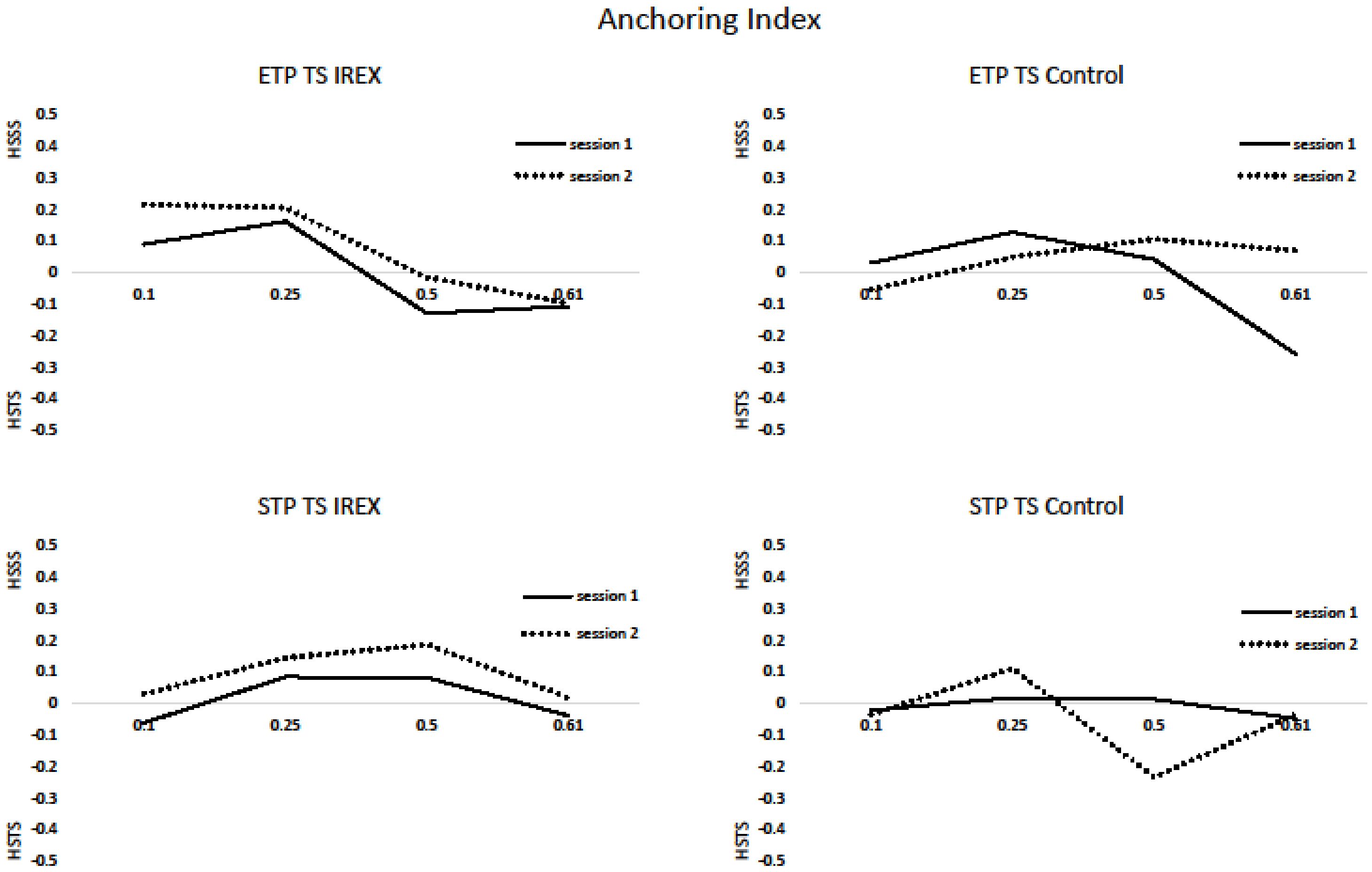

Clinical Data
a
6MWT
800
700
600
500
400
300
200
100
0
Distance walked (m)
Session 1
Session 2
IREX
CONTROL
b
GMFM-CM
120
100
80
60
40
20
0
GMFM-CM % Score
Session 1
Session 2
IREX
CONTROL
c
6MWT Change scores for individual participants
200
150
100
50
0
-50
-100
Additional distance walked (m)
Intervention
Control
d
GMFM-CM change scores for individual participants
20
15
10
5
0
-5
-10
Change in total score (%)
Intervention
Control

Figure 2


Anchoring Index
ETP TS IREX
ETP TS Control
STP TS IREX
STP TS Control
HSSS
HSTS
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0.1
0.25
0.5
0.61
session 1
session 2

4.9 Figure Captions

Fig. 1 – Results from the 6 Minute Walk Test (a) and GMFM-CM (b) at assessment sessions 1 and 2 for both Intervention and Control groups. Change in distance walked (6 Minute Walk Test) presented in panel (c). Positive values indicate an increase in distance walked from 1st to 2nd assessment point, while negative values indicate a decrease in distance walked. Increases (positive values) and decreases (negative values) in GMFM-CM score presented in panel (d).

Fig. 2 – Anchoring Index during Transition State in the Externally- and Self-Triggered Perturbation conditions in intervention and control groups. Positive values greater than 0.3 indicate a preference for Head in Space Strategy. Negative values greater than -0.3 indicate a preference for Head Stabilization on Trunk Strategy. Values around 0 indicate no preference for either strategy.

Fig. 3 – Anchoring Index during Steady State in the Externally- and Self-Triggered Perturbation conditions in intervention and control groups. Positive values greater than 0.3 indicate a preference for Head in Space Strategy. Negative values greater than -0.3 indicate a preference for Head Stabilization on Trunk Strategy. Values around 0 indicate no preference for either strategy.

4.10 Chapter 4 Addendum – Supplementary analysis for Anchoring Index by grouped data

4.10.1 Context

The results from this experiment led to the question of whether or not there was an effect of testing on these postural control mechanisms. Thus, a supplemental analysis on this effect was performed for the main outcome variable (Anchoring Index) by combining both test groups (IREX and Control). It was hypothesised there would be an effect of testing on this primary outcome variable.

4.10.2 Methods

The Anchoring Index data from the two groups (IREX and Control) were combined into one dataset. Data were again determined to be non-normally distributed through inspection of skewness and kurtosis, histograms, and Shapiro-Wilk tests of normality. Inferential testing using the non-parametric Wilcoxon test for differences between assessments (i.e. assessment 2-1) in each condition (Experimenter and Self-Triggered, Transition and Steady States) was performed. All statistical analysis was performed using SPSS v 23.0.0.2 (IBM Corp.). Results considered significant for $p < 0.0125$ (Bonferroni adjusted).

4.10.3 Results

Statistical testing for the Anchoring Index revealed no statistically significant differences between assessments (i.e. assessment 1 vs assessment 2). Summary test statistics (p-values) for between-assessment tests for grouped data in each of the four conditions can be found in Table A.1, below.

Table A.1 Wilcoxon test results for effect of testing on Anchoring Index

Condition	0.1 Hz	0.25 Hz	0.5 Hz	0.61 Hz
ETP TS	0.534	0.646	0.463	0.246
ETP SS	0.657	0.575	0.917	0.028
STP TS	0.110	0.161	0.917	0.753
STP SS	0.374	0.401	0.917	0.173

4.10.4 Discussion

The results from this statistical test suggest there was no effect of testing (e.g. *test-retest*) on the Anchoring Index (primary outcome variable) when data from both groups were collapsed.

Chapter 5: General Discussion

5.1 Major findings and their significance

This thesis provides a more complete understanding of the mechanisms of postural control in children and adolescents, both typically developing (TD) and those with cerebral palsy (CP), as they are subjected to postural perturbations. It was important to first quantify and characterize the reactionary and anticipatory mechanisms of postural control in the TD population before doing so for the CP population to have an understanding of typical postural control strategies. Finally, having characterized the CP population, the effects of an intensive virtual reality-based intervention on these mechanisms could be investigated. To accomplish this overarching goal, three experiments were designed and implemented to characterize postural control mechanisms when subjected to experimenter-triggered and self-triggered perturbations at various frequencies of platform oscillations. The data from these studies have been addressed in detail in the manuscripts presented in this thesis. Thus, the focus of this discussion section will be to evaluate the individual findings from each manuscript as they relate to the general aims and hypotheses of the studies as presented in the introduction section, as well as to each other. Finally, potential future research directions and general conclusions will be presented in this section.

5.1.1 Postural control mechanisms in typically developing youth, and those with cerebral palsy

The initial phase of this dissertation was focussed on characterizing anticipatory and reactive postural control mechanisms in typically developing youth between the ages of 7 and 17 years. The oscillating platform paradigm that was used in this study was designed such that it is possible to elicit both types of postural control from one trial in both externally-triggered and self-triggered conditions. It was hypothesized that the postural control mechanisms chosen by the participants would depend on transition and steady states. For example, it was predicted that during the transition period, participants would rely more on reactive mechanisms (e.g. longer muscle onsets, reliance on HSTS, increased stepping responses), and in the second half of a frequency where oscillations are considered to be predictable, would switch to reliance on anticipatory mechanisms (e.g. earlier muscle onsets, lowered muscle tone, use of HSSS, no stepping). It was essential to initially characterize these mechanisms in typically developing youth in order to understand the characteristics of TD youth to which we could compare a cerebral palsy population in the subsequent phase of the dissertation.

The results from the first study indicated that TD youth have the ability to shift from reactive to anticipatory mechanisms of postural control. While the lower frequencies of 0.1 and 0.25 Hz saw little change in kinematics and postural muscle activity, the higher frequencies proved to be more difficult. The jump from 0.25 to 0.5 Hz elicited a large number of stepping responses in the transition period followed by fewer steps through the remaining cycles. At the lower frequencies, remaining rigid through joint stiffness was a suitable mechanism, allowing the body to ride the platform (Buchanan & Horak, 2001). At the higher frequencies, however, allowing the upper body to follow the platform movement is inefficient, as it requires additional muscular activity to counteract the COM inertia generated by the platform (Corna *et al.*, 1999). The participants tried to remain rigid during transition state, demonstrated by high cross-correlations and larger temporal lag of the head segment when compared with the hip and ankle segments. During steady state periods, these values decreased. Earlier muscle onset latencies were also observed in steady state compared to transition state.

Similar results have previously been observed in both young and old adults. For example, Bugnariu and Sveistrup (2006), noted earlier muscle activations in steady state periods when compared to transition state, and that older adults do not activate postural muscles as early as younger adults. Our results suggest that TD youth behave more like older adults when it comes to postural muscle activation. While there was a shift to earlier onsets in steady state, the timings were not as early as those of the young adults in Bugnariu and Sveistrup's study. This suggests then, that TD youth were not able to take full advantage of the cue (i.e. platform slowing down) to prepare for the upcoming change in direction.

When given control over the change in oscillation frequency, youth are able to better stabilize their bodies for the upcoming perturbation. Providing youth with control over when a change in oscillation frequency occurs (i.e. the STP condition) allows for postural mechanisms to be activated well in advance of the postural disturbance to reduce the likelihood of falling or having to take steps to regain balance. As a general indicator of their ability to anticipate an upcoming perturbation, typically developing youth exhibited much fewer stepping responses during the cycles immediately following a change in frequency. Somewhat remarkably, there was a drastic reduction in steps taken during this period following the largest jump in oscillation frequency: at 0.5 Hz in ETP, 26 steps were taken by 4 individuals immediately following the change in frequency, while no steps were taken whatsoever in the STP condition.

This reduction in the number of steps taken suggests that the participants were able to modify their postural responses by taking advantage of knowing when exactly the change in frequency would occur. This is further supported by the kinematics and postural muscle activity.

For example, there was a general reduction in temporal lag of the upper body segments when compared to the ETP condition, indicating that the participants were more successful in their attempts to ride the platform, especially at the higher frequencies. The muscles tended to be activated earlier, allowing for postural preparation, consistent with the literature on discrete perturbations (both expected and unexpected) suggesting youth have the ability to prepare for an upcoming perturbation (Grasso *et al.*, 1998; Hay & Redon, 1999; Palluel *et al.*, 2008). Again, while these changes were observed, the postural strategies were more conservative, in line with those observed in older adults rather than young adults. Thus, while they are able to better stabilize their bodies for the upcoming perturbation when given control over when the change in frequency occurs, youth are not able to take full advantage of this control.

The second phase of this dissertation focussed on characterizing anticipatory and reactive control postural control mechanisms in youth with CP and evaluated these responses compared to those exhibited by typically developing youth. By following the same protocol as that used in the first study, it was hypothesized children and adolescents with CP would be less able to modify their postural responses (i.e. shift from reactive to anticipatory mechanisms) as compared to their TD counterparts. It was also predicted the youth with CP would be less able to modify postural responses when having been exposed to the platform oscillation (i.e. shift to anticipatory mechanisms), and less able to modify postural responses in advance when given control of the timing of platform perturbation. It was necessary to first characterize these mechanisms such that an appropriate intervention protocol could be established[2].

The results from this study indicated that when subjected to a continuous platform perturbation, children and adolescents with cerebral palsy behave in a similar manner to a group of age-matched typically developing controls at lower frequencies. Somewhat unexpectedly, youth with CP demonstrated evidence of a shift in postural response strategy during steady state periods much like their TD counterparts. However, it appears the CP youth achieved this shift in a different way to typically developing youth. Whereas the TD youth rely on a combination of ankle/knee/hip strategies during the transition state, CP youth exhibit an initial increased reliance on muscle tone which results in a functional stiffening of joints to aid in controlling the body's degrees of freedom (DoF) (Needle *et al.*, 2014) – while this strategy may have been effective at lower frequencies, it was not successful at the higher frequencies. With the experience of a few repeated cycles, this muscle tone is reduced in steady state, allowing greater fluidity in controlling the DoF.

The higher level of baseline tonic activity exhibited by the CP group compared to the TD group is to be expected as a function of the hypertonia associated with spastic CP (Woollacott *et al.*, 1998). With the increasing frequency of the platform movement, and thus the increased duration of each trial, the increased tonic activity could be due to the prolonged activation due to

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[2] The CP cohort included in this study was recruited as part of a larger study (Levac et al, 2017). As such, the intervention protocol had already been defined and tested in third study presented in this manuscript. The intervention protocol was based on results from Brien and Sveistrup (2011).

spasticity (Bar-On *et al.*, 2015). This increase in tonic activity could, however, also be explained by the change in visual conditions as the platform moved forward and back. For example, Slaboda *et al.* (2013) found that when subjected to rotating visual conditions, adults with CP attempted to maintain their balance by increasing muscle responses as a strategy for joint stabilization. While we did not manipulate the visual condition itself to examine its effect on muscle tone, it is possible that the visual perturbation associated with the platform oscillation is interpreted as a challenge to postural balance. This perception of a visual perturbation then results in a change in tonic activity. This is also supported by (Donker *et al.*, 2008) who reported children with CP tend to rely more on visual information for postural control.

While they exhibited evidence of shifting from reactionary to anticipatory mechanics at the lower frequencies, however, **youth with CP are less able to maintain their balance at the higher frequencies when compared to typically developing youth.** This is not entirely unsurprising, as while youth with CP have been shown to demonstrate evidence of anticipatory postural control, they tend to differ (e.g. larger variability, lower magnitude anticipatory adjustments) from those of TD children (Liu *et al*, 2007; Stackhouse *et al.*, 2007; Tomita *et al.*, 2010; Girolami *et al.*, 2011). Furthermore, youth with CP have been observed to take steps in response to platform oscillation at lower platform velocity when compared to TD youth (Burtner *et al.*, 2007; Chen & Woollacott, 2007). While all of the TD participants were able to complete trials, some having to take steps, most of the youth with CP either (1) could not complete trials without stepping at 0.5 and 0.6 Hz, or (2) would not attempt these frequencies. In the trials the CP youth could complete with a period of non-stepping cycles (i.e. steady state), they could not effectively switch from the HSTS to HSSS in the anchoring index, had higher temporal lags of upper body segments, and exhibited greater muscle tone and bursting activity. We postulated this could be due to poorly organized muscle activation or the youth with CP's inability to generate the appropriate muscle activity. For example Burtner *et al*. (1998) established proximal muscles in children with CP to be activated before distal muscles in response to postural disruption, with high degree of antagonist co-activation.

Providing control over when the platform changes speed allows for further modification of the chosen postural response strategy in youth with CP. Much like their TD counterparts, youth with CP have the ability to alter their postural control mechanisms by taking advantage of the knowledge of an upcoming change in platform frequency. CP youth exhibited a large reduction in muscle tone in the self-triggered condition and a shift to less reliance on HSTS, suggestive of a greater control over more DoF.

It is important to note (for both the TD and CP participants) that because the values of each variable in steady state were obtained during the last ten cycles of each frequency, the results immediately before the change in frequency may be partially skewed in the STP condition. Participants were given control over when the change in frequency occurs, and as such, may have altered postural muscle activity (and thus kinematics) during the last few cycles of steady state in order to prepare for the upcoming frequency change.

5.1.2 Improving postural control mechanisms in youth with cerebral palsy through a virtual-reality based intervention

The final phase of this dissertation sought to examine the effect of a 5-day intensive virtual reality-based physiotherapy intervention on postural control mechanisms in youth with CP. It was hypothesized that, immediately following an intensive one-on-one supervised VR-based intervention, measures of anticipatory and reactive postural control would improve compared to the same measures observed in the children who received no intervention. It was predicted that changes would be evidenced through a reduction in (1) total number of steps taken, (2) postural muscle tonic activity, and (3) marker-pair trajectory time lag, while demonstrating an increase in (1) reliance on HSSS, and (2) marker-pair trajectory correlation. It was also hypothesized that following this intervention, participants who received treatment would exhibit improvements on clinical measures, including the Gross Motor Function Measure Challenge Module (GMFM-CM) and the Six Minute Walk Test (6MWT), while those who did not receive treatment would show no change.

The results from this study indicated no benefit from the 5-day intervention programme (Levac *et al.*, 2017)**.** Contrary to the initial hypothesis, no consistent differences in change scores were identified between the intervention and control groups. Specifically, following the intervention, both intervention and control groups exhibited a shift from reliance on HSTS in the anchoring index, to either HSSS or no preference, and cross-correlation and postural muscle activity analyses revealed few differences. The stepping responses could not be evaluated statistically due to some participants not completing trials pre-intervention but completing them post-intervention.

One of the main reasons we observed no differences in change scores following the intervention might be redundancy in postural response re-organization. The current theories of motor learning, for example Vereijken's 3-stage model (Vereijken *et al.*, 1992) and Fitts and Posner's 3-stage model (Fitts & Posner, 1967), suggest an initial period with poor control over the body's various degrees of freedom (DoF). In the case of the CP youth, this is evident in their disorganized behavioural strategies in response to the postural perturbations on the platform. Following this initial period, the DoF become constrained to a minimum in order to reduce extraneous movement (i.e. maintaining a rigid body, as seen in the AI and CC analyses, as well as increased tonic activity). The final stage involves gradual re-integration of the DoF with practice of the task. Thus, it may be that because this is a novel task for both groups, the **youth with CP were still constrained to the second stage of motor learning at the assessment point following the intervention/end of the week**.

While we did not investigate neural plasticity in these studies, it is worth briefly discussing principles of motor (re-)learning here. Motor (re-)learning requires a number of criteria in order to be effective and long-lasting, both in the healthy and damaged brain. Four of the important principles necessary for neural plasticity (Kleim & Jones, 2008) can be applied here to help explain a lack of behavioural changes following the intervention set. The first two principles are related: *specificity* and *transference*. The former states that 'the nature of the training experience dictates the nature of the plasticity'. This suggests that training in a specific modality may make limited changes to the neural circuitry, but that it does not necessitate learned behaviour to general tasks. The latter, transference, states that 'training [in one] experience can enhance the acquisition of similar behaviours'. In the context of this intervention study, these two principles are suggestive of two consequences. The first is that the VR-based rehabilitation may have made neural changes possible to accomplish the VR-based tasks, but that it could not be applied to general functional balance and mobility. The second suggests that the largely mediolateral balance training in the VR tasks may not have transferred to the similar, but non-trained, anteroposterior balance assessment tasks. This may also be supported in our study which focussed on the clinical measures following this intervention (Levac *et al.*, 2017): the youth with CP who completed the VR-based intervention did not demonstrate enhanced gross motor skills of functional mobility.

The last two principles we can apply are also related to one another: *repetition* and *intensity*. Repetition involves repetitive performance of a task, while intensity is dictated by the number of repetitions within a certain period of time to make lasting changes. In a similar study previously conducted in our laboratory, Brien and Sveistrup (2011) demonstrated clear improvements on clinical measures of functional balance and mobility (such as the 6MWT and the Clinical Balance and Mobility Scale) following a 5-day intensive VR program. The main difference between our current intervention study and the Brien & Sveistrup study is that ours consisted of a relatively shorter duration of the daily program – 60 minutes per day in our intervention compared to their 90 minutes per day. Thus, it is possible our intervention was not sufficiently challenging or intense, as there may not have been enough repetition to obtain improvement. To complicate matters, it is possible the participants who received the IREX intervention simply used this exercise to replace another physical activity they would have otherwise done throughout the week, thus reducing the repetition and intensity of required balance training tasks. This may also explain why no significant improvements were observed in the clinical measures obtained as part of the larger study investigating the effects of a 5-day intensive VR-based physiotherapy intervention on functional mobility (Levac *et al.*, 2017).

5.1.3. Fear, anxiety, and postural control

The oscillating platform paradigm can be considered as a new, unconventional task for youth, especially those with cerebral palsy. The platform in the laboratory was situated within a large pit, and participants were required, for health and safety reasons, to be equipped with a full-body harness in order to prevent risk of injury due to falling into the pit. There is substantial evidence to suggest the level of postural threat helps dictate the chosen strategy when faced with a postural disturbance. For example, Adkin *et al.* (2000) and Carpenter *et al.* (1999) found that postural stability is more tightly controlled when inducing a fear of falling, such as being placed on a high platform. The younger typically developing participants in study #1 may have felt anxious when they could not predict the change in oscillation frequencies. When given control over when the change in frequency occurred, however, this level of anxiety may have been reduced, helping to explain the changes observed above. The youth with CP, who have deficits contributing to disruptions in postural control (Nashner *et al.*, 1983; Schmit *et al.*, 2016), may have felt a greater degree of anxiety still, especially at the higher oscillation frequencies which could explain the non-attempts at 0.5 Hz and 0.6 Hz. However, when given control over the change in frequency, the anxiety may have been reduced, similar to the TD participants.

5.2 Limitations

While questionnaires were used to gather information on the general activity levels of the participants, it may have been helpful to measure psychological effects of anxiety caused by the experimental protocol. For instance, the movement of the platform, combined with the perceived height due to the platform being located in a pit (approximately 3 m in diameter, 1.5 m deep), and the addition of the harness which may be fear-invoking in and of itself, may have had an effect on anxiety levels, previously shown to change the postural strategies chosen by participants (Adkin *et al.*, 2000; Carpenter *et al.*, 2004). This may have had an effect on the participants with CP, who were already cautious of the postural control task, evidenced by some refusing to complete full trials. However, as there was still a difference in postural control strategy between transition and steady states, anxiety or fear was not an overbearing factor.

The number of participants included in each of the studies was relatively small. Because of this, the resulting effect sizes were small, so each of the three studies were not powered to detect change. Furthermore, the developmental age ranges of 7-12 and 13-17 years were chosen based on existing literature in postural development. Though it is not likely the 13-17 year olds would have exhibited large differences in their postural strategies, a 7 year-old still developing might have chosen a considerably different strategy to that chosen by a 12 year-old. Furthermore, participants around the 12 years mark (i.e. 11-13 years) might possibly have been considered part of the other age group based on development, but because of age were allocated to their respective groups.

Finally, the virtual reality intervention was largely based on lateral movements. The games chosen for the intensive exercise sessions mostly required mediolateral movements to achieve a specific target in the games. Thus, it is possible that this training may not have carried-over to the anteroposterior platform oscillations, which may account for the lack of observed differences between the intervention and control groups' postural control strategies.

5.3 Future research directions

While this thesis has contributed to the understanding of reactive and anticipatory postural control mechanisms in typically developing children and adolescents, as well as those with cerebral palsy and the effect of an intervention on postural mechanisms in these youth, there are still many opportunities to extend the scope of this research. The limitations previously mentioned outline clearly some issues which will need to be considered for future work in this area. Nevertheless, the following are a few potential research questions that will further our understanding of postural control mechanisms in youth.

5.3.1 Development of reactive and anticipatory postural control mechanisms in youth

Although the studies presented in this thesis demonstrated the abilities of typically developing youth and youth with CP to make use of reactive and anticipatory postural control mechanisms, it was only possible to characterize these mechanisms in general age groups. The broad age groups were defined (children, aged 7-12 years, and adolescents, aged 13-17) based on the existing literature in postural development which outlines stages of development with clear characteristics such as child- or adult-like movement behaviours. As mentioned in the limitations section, this presents a problem in that youth on the borderline of each group (e.g. aged 11-13 years) may present with postural control strategies opposite of the group into which they have been allocated based on age alone. This is also a problematic method as those at the lower ages of the child range (i.e. around 7 years) may choose entirely different strategies to those of a 12 year-old. Thus, the question of anticipatory and reactive postural control could be divided further into developmental sub-stages of 1 year. This would allow for identifying when anticipatory postural mechanisms make clear developments, and would coincide with other developmental work in the area (c.f. Assaiante & Amblard (1993, 1995)).

5.3.2 How does fatigue affect postural control mechanisms in youth, and specifically youth with CP?

Previous work from our laboratory has demonstrated that peripheral and central fatigue (Kennedy *et al.*, 2012) contribute to the overall effectiveness of postural control. As children with CP are easily fatigued, it would make sense to amalgamate fatigue and oscillating platform protocols to understand the effect of fatigue on anticipatory and reactive postural control in children and adolescents, specifically those with CP and similar populations. While it is possible to request youth with CP to perform maximal effort tasks on a dynamometer, it may not necessarily be ecologically valid for this particular population, and so other tests, such as walking up and down stairs until tired may serve this purpose. The results of such a study may form the basis of other future intervention studies designed to help to inform health care practitioners of the benefits of general physical fitness in special populations on postural control mechanisms.

5.3.3 The effect of perturbation size on postural responses

The results from our studies indicated that typically developing youth and youth with CP generally did not have difficulty in dealing with perturbations at low frequencies, but that the higher frequencies would often result in stepping response strategies. Previous research has shown a lower tolerance to platform oscillation velocity in children with CP when compared to TD youth (Burtner *et al.*, 2007), however, it may be worth investigating whether youth with CP are more able to respond appropriately to (i) larger frequencies by reducing the amplitude of the oscillation, or (ii) larger amplitudes by reducing the frequency. Reducing the size of shift from one frequency to the next may obtain different results to those observed in this dissertation. For example, our current protocol contains a doubling in frequency from 0.25 Hz to 0.5Hz which most found more destabilizing than the shift from 0.5 Hz to 0.61 Hz. Reducing this to a shift from 0.25 Hz to 0.3 Hz, to 0.4 Hz, and then to 0.5 Hz for instance, might be more manageable, particularly for youth with CP.

5.3.4 What is the effect of dual tasking on anticipatory and reactive mechanisms of postural control in youth?

The use of the controller in the self-triggered condition could be viewed as the addition of a task led us to the question of how the addition of a task might affect anticipatory and reactive postural control in youth. Research has shown there are significant attentional requirements for postural control, and conditions with multitasking requires allocation of attention away from the maintenance of balance, which can result in falling (Woollacott & Shumway-Cook, 2002). While adding simple tasks tends to result in feet-in-place strategies (i.e. ankle or hip strategy), more complex problems elicit more drastic measures like the stepping strategy. Moreover, increasing attentional demands results in decreased postural muscle activity during balance recovery, which can prompt the use of an alternate response strategy, such as stepping (Rankin *et al.*, 2000). However, these effects are not well understood in youth. Possible methods of introducing additional tasks could include reverse counting (e.g. backwards from 100 by 7) or the modified Stroop test.

5.4 Conclusion

The oscillating platform is a useful method for studying reactive and anticipatory mechanisms of postural control: this particular method provides the benefit of observing reactive mechanisms of postural control and the subsequent shift to anticipatory mechanisms. This thesis is the first to have characterized both of these postural control mechanisms together in children and adolescents, and those with cerebral palsy. This work is also the first to investigate the effects of a virtual reality-based 5-day intensive exercise program on postural control mechanisms in youth with CP.

Through this dissertation, it has been shown that:

(1) When subjected to oscillatory antero-posterior postural perturbations at different frequencies, typically developing youth have the ability to shift from reactive to anticipatory mechanisms of postural control, however, they tend to have postural control characteristics similar to older adults, especially at the higher frequencies. Similarly, youth

with CP also have the ability to shift from reactive to anticipatory mechanisms, but are much less able to maintain their balance at higher frequencies when compared to typically developing youth. Thus, it may be more practical to evaluate anticipatory and reactive mechanisms of postural control by scaling the size of the perturbation as a function of participant size and/or age.

(2) When given control over when the change in oscillation frequency occurs, typically developing youth are able to stabilize their bodies in advance of the upcoming perturbation. This results in fewer steps being taken immediately following the change in frequency, thereby reducing the risk of falling. This provision also allows for further modification of the chosen postural strategies in youth with CP.

(3) The 5-day virtual reality-based intensive exercise program provided no benefit to postural control mechanisms in youth with CP. It may be that youth with CP were constrained to an early state of motor learning at the final assessment point. The results from this study are suggestive of the importance of key principles in motor learning, such as specificity, transference, intensity, and repetition, and so further studies may be required to understand its effects completely.

To conclude, while the results from this doctoral dissertation are informative, there is still opportunity for exciting research on the development of reactive and anticipatory postural control mechanisms, and the use of virtual reality-based physiotherapy to improve these mechanisms in special populations.

Addendum

The following information was added to the thesis document following the oral defense in response to questions and comments from the examining committee.

6.1 Given the different age-related stages of postural development in the study sample, a sub-group analysis based on age for TD children and adolescents would have been interesting.

As mentioned in the General Introduction section, there is a slight regression of postural synergy development around age 6 years (Hay & Redon, 1999), which then continues to develop steadily between the ages of 8-12 years, with full development occurring around 12 years of age. Thus, the original intention of characterizing the postural control mechanisms in children and adolescents was to test two sub-groups ages based on developmental periods between 7-12 (children) and 13-17 years (adolescents). Unfortunately, due to the low number of participants we were able to recruit (16 in Study #1, and 11 in Study #2), study power was insufficient for sub-group analysis and these groups had to be collapsed into one group.

6.2 Definition of tonic and phasic muscle activity

For the purposes of the studies included in this manuscript, *tonic* muscle activity was defined as a quiet period between bursts lasting at least 200 ms. All tonic activity was normalised to the tonic activity measured in transition state during the externally-triggered condition at 0.1 Hz. *Bursting* activity was defined as a period of muscle activation greater than 2 standard deviations from baseline measure *and* lasting for more than 50 ms.

6.3 What does a ~1% difference in the Cross-Correlation$_{max}$ mean?

Statistical tests revealed a significant difference in the Cross-Correlations (CC) between transition and steady states (e.g., Ankle-Hip CC$_{max}$ in Study # 1) with CC$_{max}$ values approximately 1% apart. It should be noted that while statistically significant, these values are not necessarily clinically meaningful.

6.4 Power Analysis

The low numbers of participants recruited in the manuscripts presented in this thesis resulted in low study power. While the aim of Studies #1 and #2 were to characterize postural mechanisms in children and adolescents and those with CP, post-hoc analyses were conducted based on means and standard deviations, as well as the effect sizes for Study #3. Because the effect sizes were mostly small across the numerous variables tested, the resulting numbers of participants suggested for future studies reach between 70 and 120. Future studies should therefore increase the number of participants, however, given the difficult nature of recruiting children, and more specifically children with CP to an intervention study, such high numbers are unlikely. Future work planned based on the results of the studies reported in the thesis will focus on the use of alternate and more active intervention programs and modifications in the outcome measures targeted.

6.5 What was the functional level of the children included in the study (i.e., Gross Motor Function Classification System level)?

The participants included in Studies #2 and 3 were classed as GMFCS levels I or II. These levels are indicative of the level of self-initiated mobility, and range from level I (walks without limitations) to level V (transported in a [manual] wheelchair). At level II, limitations to movement/performance of gross motor skills may require adaptations to enable participation in sport or activity (Palisano *et al*., 2007). Evidence of content validity of the GMFCS has been reported for the age range studied (Palisano *et al*., 2008).

6.6 Please explain the rationale for platform oscillation frequencies selected.

The frequencies chosen for the studies in this manuscript (0.1, 0.25, 0.5, and 0.61 Hz) were based on a previously validated protocol that has been used in our lab (cf. Bugnariu & Sveistrup, 2006; Kennedy *et al*., 2012). This protocol was partially based on the work by Dietz *et al.* (1993) in which oscillation frequencies of 0.25, 0.3, and 0.5 Hz were used.

6.7 What was the justification for the use of VR for improvement of postural control in children with CP?

Though relatively new, the use of virtual reality as an intervention modality for children and adolescents with CP is expanding. In a recent systematic review, Ravi *et al.* (2017) provided up-to-date evidence of the effectiveness of this type of intervention. In the review, the authors noted that of the 31 studies included, each of the 9 studies to test balance control demonstrated moderate evidence of improvement following the intervention. These interventions primarily consisted of semi-immersive 2-D video (active) gaming interventions, through use of the Nintendo Wii, Microsoft Kinect for Xbox 360, and IREX systems. The protocol used was modelled on a previous study from our group that showed significant clinical improvements following one week of intense VR exercise in adolescents with cerebral palsy (Brien & Sveistrup, 2011).

6.8 Why was the IREX system used for the VR intervention?

The IREX system (Immersive Rehabilitation Exercise, GestureTek Health, was chosen as the intervention modality for Study #3 of this manuscript. This system was previously used in our lab and has been shown to improve clinical measures such as the 6 Minute Walk Test, Community Balance and Mobility, and Timed Up and Down Stairs in four adolescents with CP GMFCS levels I & II (Brien & Sveistrup, 2011). This system is commercially available. One benefit of the IREX system is the use of the *just right challenge principle* where the difficulty of the games can be adjusted throughout each session (to be easier or harder), based on the participant's performance as assessed by the physiotherapist.

6.9 Was the IREX system the ideal programme for improving anticipatory and/or reactive postural control mechanisms?

As discussed in Study #3, the VR intervention did not elicit the expected results in terms of changes in anticipatory and reactive control mechanisms as tested in the antero-posterior direction. While it may not be possible to identify the 'ideal' programme for improving these mechanisms, it is agreed that it is necessary for any intervention to challenge both the anticipatory and reactive postural control mechanisms in multiple directions to maximize transference. For example, by using hippotherapy (horse riding) for children and adolescents ages 6-14 years with CP (GMFCS levels I & II), Champagne *et al.* (2017) demonstrate that riding in different positions (e.g. sitting, standing, kneeling, reverse kneeling etc), resulted in improvement in balance measures immediately following the intervention. The authors noted that for each session participants are required to make approximately 3000 postural adjustments, providing the required intensity for motor training.

6.10 What mechanisms were in place to reduce the fear of falling during the perturbation trials?

Every effort was made to ensure participants did not fall and injure themselves. For example, participants were strapped into a harness suspended securely from the ceiling, and were encouraged to test the harness system by simply sitting while the oscillating platform was still. Even still, there may have been an element of fear of falling, as discussed in the *Limitations* section of Chapter 5.

6.11 Please define how the terms 'Pre/Post-testing' and 'retention' are used in the context of this study.

For the purposes of the manuscript reported in Chapter 4, the term *post-test* is used synonymously for '*retention*'. The term *post-testing* suggests testing should occur immediately follow the intervention, and *retention* testing during any period thereafter. As it was generally not possible to test immediately after the 5th IREX intervention session due to the length and fatigue level of the participants following the final training session, the 'post' test occurred within the subsequent 24-48 hour period.

6.12 Why were the participants not allocated in a random fashion to the two groups in the IREX intervention (Chapter 4)?

In Chapter 4, participants with CP were non-randomly allocated to either the intervention (IREX) or the control group. As participants were recruited from the Ottawa Children's Treatment Centre, they could potentially have come from anywhere in Eastern Ontario. As such, participants living within a 50 km radius of Ottawa *and* willing to attend the 5 continuous days at the physiotherapy clinic were allocated to the IREX group. Participants who had other commitments and were unable to attend the 5 days at the clinic were allocated to the control group. Though unlikely, it is possible that the non-randomized allocation may have had an influence on the data obtained.

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Annexed Information

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Appendix A – Levac et al (2017) Active Video Gaming for Children with Cerebral Palsy: Does a Clinic-Based Virtual Reality Component Offer an Additive Benefit? A Pilot Study, *Physical & Occupational Therapy in Pediatrics*, published online 4 Apr 2017; 1-14

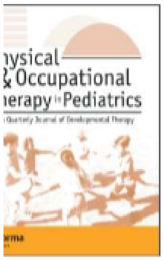
Appendix B – Consent forms and recruitment text (English only)

Appendix C – Ethical approval and renewal certificates

APPENDIX A

Active Video Gaming for Children with Cerebral Palsy: Does a Clinic-Based Virtual Reality Component Offer an Additive Benefit? A Pilot Study

Levac et al (2017), appears in: *Physical & Occupational Therapy in Pediatrics*, published online 4 Apr 2017; 1-14



Physical & Occupational Therapy In Pediatrics

ISSN: 0194-2638 (Print) 1541-3144 (Online) Journal homepage: http://www.tandfonline.com/loi/ipop20

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To cite this article: Danielle Levac, Anna McCormick, Mindy F. Levin, Marie Brien, Richard Mills, Elka Miller & Heidi Sveistrup (2017): Active Video Gaming for Children with Cerebral Palsy: Does a Clinic-Based Virtual Reality Component Offer an Additive Benefit? A Pilot Study, Physical & Occupational Therapy In Pediatrics, DOI: 10.1080/01942638.2017.1287810

To link to this article: http://dx.doi.org/10.1080/01942638.2017.1287810

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PHYSICAL & OCCUPATIONAL THERAPY IN PEDIATRICS
http://dx.doi.org/10.1080/01942638.2017.1287810

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Active Video Gaming for Children with Cerebral Palsy: Does a Clinic-Based Virtual Reality Component Offer an Additive Benefit? A Pilot Study

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ABSTRACT

Aims: To compare changes in gross motor skills and functional mobility between ambulatory children with cerebral palsy who underwent a 1-week clinic-based virtual reality intervention (VR) followed by a 6-week, therapist-monitored home active video gaming (AVG) program and children who completed only the 6-week home AVG program. *Methods:* Pilot non-randomized controlled trial. Five children received 1 hour of VR training for 5 days followed by a 6-week home AVG program, supervised online by a physical therapist. Six children completed only the 6-week home AVG program. The Gross Motor Function Measure Challenge Module (GMFM-CM) and Six Minute Walk Test (6MWT) evaluated change. *Results:* There were no significant differences between groups. The home AVG-only group demonstrated a statistically and clinically significant improvement in GMFM-CM scores following the 6-week AVG intervention (median difference 4.5 points, interquartile range [IQR] 4.75, $p = 0.042$). The VR + AVG group demonstrated a statistically and clinically significant decrease in 6MWT distance following the intervention (median decrease 68.2 m, IQR 39.7 m, $p = 0.043$). All 6MWT scores returned to baseline at 2 months post-intervention. *Conclusion:* Neither intervention improved outcomes in this small sample. Online mechanisms to support therapist-child communication for exercise progression were insufficient to individualize exercise challenge.

ARTICLE HISTORY
Received 9 May 2016
Accepted 21 January 2017

KEYWORDS
Active video games; cerebral palsy; home exercise programs; virtual reality

Children with cerebral palsy (CP) whose abilities are classified at Levels I and II of the Gross Motor Function Classification System (GMFCS) have balance and gross motor skill impairments (Pavao et al., 2014) that can limit participation in physical activities (Lauruschkus et al., 2013; Mitchell et al., 2015; Shikako-Thomas et al., 2013). Interventions incorporating virtual reality (VR) systems in which children use body movements to interact with objects in a virtual environment can improve balance and gross motor skills (Dewar et al., 2015; Fehlings

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et al., 2013; Weiss et al., 2014). VR systems offer standardization of task practice conditions, presentation of visual and auditory feedback supporting error detection (Biddiss, 2012; Levin, 2011), and an enriched environment that may motivate users to practice more frequently (Tatla et al., 2013). Compared to VR systems that are designed specifically for rehabilitation, off-the-shelf active video games (AVGs) that use similar motion-capture technology have significantly less capacity to individualize task difficulty parameters and capture therapeutically-relevant performance metrics (Biddiss, 2012; Levac & Galvin, 2012). However, AVGs are less expensive, more accessible for home use and have a wider game variety.

The evidence for AVG use to improve gross motor skills in children with CP has primarily been reported for Nintendo's Wii and WiiFit, systems in which interaction with the game is via a hand-held controller or a force platform (e.g., Chiu et al., 2014; Do et al., 2016). Full body movement is the medium for game interaction in Microsoft's Xbox360 Kinect motion-capture sensor games. Two studies in children with CP have found improvements in upper limb function (Luna-Oliva et al., 2013), walking endurance and gross motor skills (Zoccolillo et al., 2015) following 8-week Kinect AVG interventions. In contrast, more evidence supports use of GestureTek Health's rehabilitation-specific, clinic-based motion-capture Interactive Rehabilitation Exercise System (IREX). There is strong level III evidence (AACPDM; https://www.aacpdm.org/education/reviews-reports) for IREX-training to improve functional balance and mobility outcomes in children with CP (Glegg et al., 2014; Weiss et al., 2009). In a single subject research design, we demonstrated that an intensive 1-week IREX intervention can improve short-term balance and functional mobility in four adolescents with CP at GMFCS Level I (Brien & Sveistrup, 2011).

Access to clinic-based VR systems can be challenging for busy families. Instead, AVGs offer a promising option for home exercise programming. Adherence to traditional home exercise programs is often poor for children with CP (Peplow & Carpenter, 2013). AVGs are recommended for home use because of their potential to motivate children to increase practice dosage (Biddiss, 2012). Children with CP are motivated to participate in short-term VR-based exercise (Bryanton et al., 2006; Tatla et al., 2013). However, previous research has shown that sustaining motivation over a lengthy (i.e., multiple weeks) AVG home intervention program can be problematic (Golomb et al., 2010; James et al., 2015).

Given that therapists cannot remotely access Kinect Xbox360 game play parameters, we created an interactive website for children and families to record adherence to their AVG home program, communicate with therapists and respond to weekly questions about motivation and challenge levels. The website was designed to inform therapists' decisions about AVG exercise program progression. While our goal was to evaluate the effectiveness of the 6-week Kinect home AVG program, we questioned whether beginning the program with an evidence-based (Brien & Sveistrup, 2011) 1-week intensive clinic-based VR '*jump-start*' might offer a benefit. Specifically, we expected this benefit to be twofold. Firstly, participants would derive exercise benefits from an intense VR intervention, and secondly, they would be exposed to a more sophisticated clinic-based VR system under the direct supervision of a physiotherapist who could reinforce optimal movement during game interaction and enhance participants' motivation to adhere to the home-based AVG program. We expected that this would in turn translate to improved outcomes as compared to the AVG-only group. As such, the purpose of this study was to compare changes in gross motor skills and functional mobility between children with CP at GMFCS levels I or II who underwent a 1-week intensive clinic-based VR intervention followed by a therapist-monitored 6-week home AVG program to children who completed only the 6-week therapist-monitored home AVG program. We hypothesized that outcomes immediately following the AVG intervention

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Table 1. Participant demographics and baseline data.

	VR + AVG group	AVG-only group
N	5	6
Sex	3 male, 2 female	3 male, 3 female
Mean Age (SD)	12 (2.74)	13.33 (3.08)
Diagnosis (n)	Hemiplegia (3), diplegia (2)	Hemiplegia (2), diplegia (4)
GMFCS Level (n)	I (4), II (1)	I (5), II (1)
Active video gaming exposure (n)	Wii (5), Kinect (1)	Wii (5), Kinect (4)
Recreational sports (n)	Yes (3), No (2)	Yes (5), No (1)
Competitive sports (n)	No (5)	No (5), Yes (1)
Baseline median GMFM-CM score (Range)	82 (7-97)	63.5 (33-104)
Baseline median 6MWTdistance (Range)	515 m (385.3 m–787.3 m)	435.7m (207.5 m–536.5 m)
AVG exercise program (n)	Easy (2), Hard (3) Sports (4), Activity (1)	Easy (2), Hard (4) Sports (4), Activity (2)
VR exercise program (n)	Easy (2), Medium (2), Hard (1)	n/a

and at 1 and 2 months post-intervention would improve more for children who completed the combined VR + AVG program than children who completed the AVG program alone.

Methods

Study Design

Pilot nonrandomized controlled trial. Ethics approval was obtained from the University of Ottawa Research Ethics Board and the Ottawa Children's Treatment Center (OCTC) Research Ethics Committee. Informed consent and assent were obtained from parents and children. We did not undertake power analysis to estimate sample size for this pilot study because our goal was to generate effect size and variability estimates to power a subsequent trial.

Participants

The participants were 11 Children and youth between the ages of 7 and 18 years with a confirmed diagnosis of CP at GMFCS levels I or II. Inclusion criteria were the ability to follow directions on standardized testing in English or French (as determined by parent), Internet access at home; and access to a television at home in a space suitable for Kinect play. Exclusion criteria were visual, cognitive or auditory impairment that would interfere with game play, orthopedic surgery or lower extremity BOTOX injections in the past 12 months; and regular past use of an AVG system at home (defined as greater than 1 hour/week for more than 4 weeks in the past year). Children were recruited via study information letters mailed from the OCTC and disseminated in schools by physical and occupational therapists via the Community Care Access Centre. Table 1 provides participant details. There were no significant differences between groups in terms of age, baseline GMFM-CM score ($Z = -.366$, $p = .792$) or baseline 6MWT distance ($Z = -1.095$, $p = .329$). Only one child (in the VR + AVG group) received physical therapy (once weekly) during the intervention and follow up period. One participant in the VR + AVG group did not return for the final 2 assessment occasions.

Kinect AVG Programs

The first author, MB and 3 physical therapists developed the exercise programs. We selected the following discs with games that incorporated full body movements: Big League Sports, Adventures, Sports Season 2, Just Dance Kids 2, Dance Central 2, Motion Sports, and Motion Sports Adrenaline. We undertook a task analysis within game play sessions in which we

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categorized games according to movements elicited (e.g., weight-shifting inside base of support, weight-shifting outside of base of support, jumping, squatting, and reaching). We classified each game as activity- or sport-based. Finally, we ranked games with respect to physical (e.g., extent of cardiovascular challenge, number and range of movements elicited) and cognitive (e.g., amount of competing visual and auditory stimuli, amount and speed of decisions required about movements and obstacle avoidance) challenges when played at the easiest level. We then developed Easy and Hard Activity- and Sports-Based programs. In the easy version, the physical challenge level was lower in terms of game requirements, difficulty level, speed and nature of suggested progressions. Each program included progressions across the 6 weeks and alternative game play suggestions, including use of hand weights or balance board, or different ways to play the game (e.g., while standing on 1 foot). Each day's exercise program included a 'free choice' game that the child could select him/herself.

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IREX VR Program

The first author, MB and three physical therapists played each of the 9 IREX games and undertook a task analysis using the same body movement requirements as previously described. The games (Birds n' Balls, Drums, Conveyor, Formula Racing, Gravball, Shark Bait, Soccer, Snowboard, and Zebra Crossing) were then ranked as "Easy," "Medium," or "Hard" on the basis of their physical and cognitive challenge when played using the lowest game parameters. Three 5-day exercise programs were developed (Easy, Medium, and Hard) which provided suggested games, challenge parameters and progressions across the 5 days.

Website Development

A website was created to provide information about the games, enable participants to record adherence to the exercise programs, communicate with therapists, and allow therapists to specify each week's exercise program. Interfaces for younger children and adolescents differed in presentation but not content. Therapists and children/families could send messages that would be received as emails in their usual email accounts. The website also featured a calendar that the therapist or participant could use to record study visits and Kinect game play days. We did not ask children to report their exact AVG program each day, but rather to record which required and which free choice game they had played most and least often each day that week. Children were also asked to report frequency of daily physical activities. The website required that Kinect game play and physical activity information be entered for 5 of the past 7 days before enabling the weekly questionnaire (see Outcome measures for description) consisting of questions probing enjoyment, challenge and boredom with that week's program.

Outcome Measures

Outcome measures were performed in the following order at all measurement sessions:

Computer Assisted Rehabilitation Environment. Postural responses to externally triggered perturbations of a support surface. This outcome measure was chosen to capture impairment-level changes in balance as a result of the intervention. Results are not reported in this study.

Six Minute Walk Test (6MWT): Assesses functional capacity for walking a prolonged distance. The 6MWT was chosen to measure activity-level changes in functional mobility following the intervention. The 6MWT has excellent test–retest reliability in this population (Maher et al., 2008; Thompson et al., 2008).

Gross Motor Function Measure Challenge Module (GMFM-CM) (Glazebrook & Wright, 2014): Tests advanced gross motor skills of balance and postural control, coordination, agility,

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speed and strength. The GMFM-CM was chosen to measure activity-level changes in gross motor skills (specific to the functional level of the study sample) following the intervention. Test–retest reliability ICC is 0.94 in this population (Wright FV, personal communication). Scores were converted to percentages.

Participant perceptions of the AVG exercise program: Each week participants indicated their agreement with 5 statements about enjoyment, fatigue, ease, difficulty and boredom of the week's Kinect activities using a 7 point Likert Scale (1 Strongly disagree [1] – Strongly agree [7]). This measure was developed for the study.

Procedures

IREX interventions took place in the OCTC's VR-based therapy room. AVG exercise programs took place in participants' homes. Participants were assigned to either the VR or the AVG group based on their self-declared ability to come to OCTC to participate in the 1-week VR session. Figure 1 outlines the study procedures, including timing of outcome measurement.

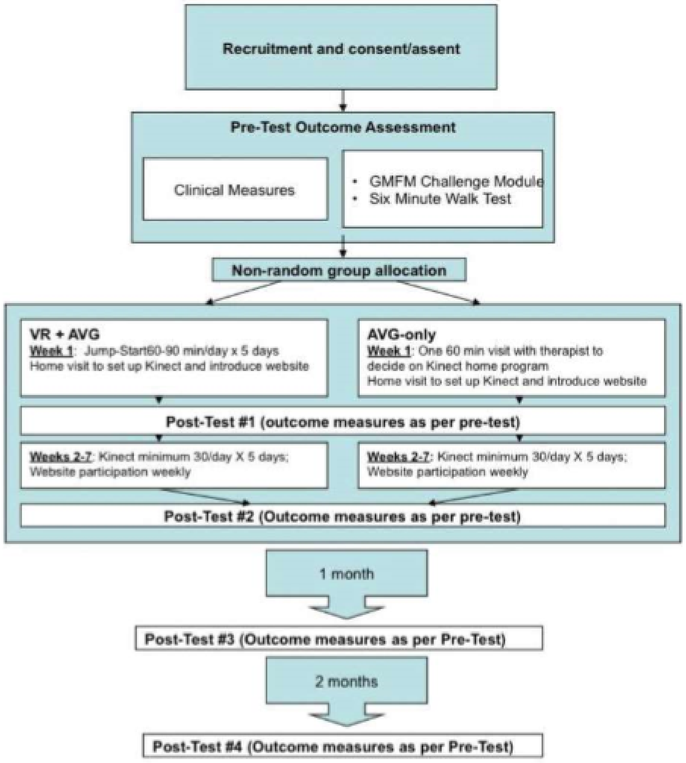

Figure 1. Study procedures.

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VR + AVG group: Therapists selected a pre-determined exercise program on Day 1 of the intensive VR intervention, which was progressed or altered based on observation of game play as well as participant report of physical challenge, enjoyment or fatigue. The PT introduced the Kinect in an additional hour following the final session. The research assistant undertook a home visit with the child and family to install the Kinect system, ensure that they were able to operate the system, and familiarize the child and family with features of the study website. Children then completed the 6-week AVG program as described below.

AVG-only group: In the week prior to the AVG program, children visited the clinic once for 1 hour to meet the therapist who would introduce the Kinect. The RA then undertook a home visit. Children then completed the 6-week AVG program. All participants were instructed to undertake their home exercise program for 30 minutes/day, 5 days per week. They were encouraged to play for a full 30 minutes, not including rest time and time to switch between disks. They were asked to play each game in that day's program at least once, and could select the frequency with which they repeated each game during the session. We felt that it was overly prescriptive to stipulate the exact frequency of game play and that more choice would enhance children's motivation and autonomy.

Therapists followed suggestions determined during exercise program development to progress exercise program challenge over the 6-week period by increasing game difficulty, adding therapeutic adaptations (e.g., weights, altered support surface; supplied by the therapist), moving to a more challenging game, and adding a cognitive dual-task. Communication between children/families and therapists occurred as follows. Children and/or their parents used the website to record the activities that they were participating in weekly and to respond to the weekly questionnaire. The website was programmed to send an email reminder to the child or parent if there had been no login for the past 4 days. Therapists were also asked to check the website daily and send gentle email reminders. Therapists responded to any questions posed by the child and or family via emails sent and received through the website. Progressions to exercise programs were made on the basis of information from children's website entries.

Intervention Fidelity

All participants in the AVG-only group completed the 6-week program. One participant in the VR + AVG group completed only the first 5 weeks, and 2 participants in this group took a 1 week break due to previously scheduled vacation activities, returning to complete the final week. Ten of the 11 participants used the website to record adherence and answer the weekly questions; the final participant (in the VR + AVG group) recorded adherence information on paper. Participants logged in to the website an average of 32.2 times (range 11-84 logins per participant). Each therapist logged in between 32-84 times each (this range represents the number of logins to monitor all the participants assigned to each therapist) and updated exercise programs for each client at least once weekly.

Data Analyses

Descriptive analyses summarized participant demographics and exercise program adherence. SPSS v. 21.0 was used for statistical analysis. Normality testing of the data was undertaken by examining skewness and kurtosis values and histograms. The data was determined to be non-normal and non-parametric inferential testing using Wilcoxon test for within-group changes and Mann–Whitney *U* test for between group changes was undertaken. These tests were

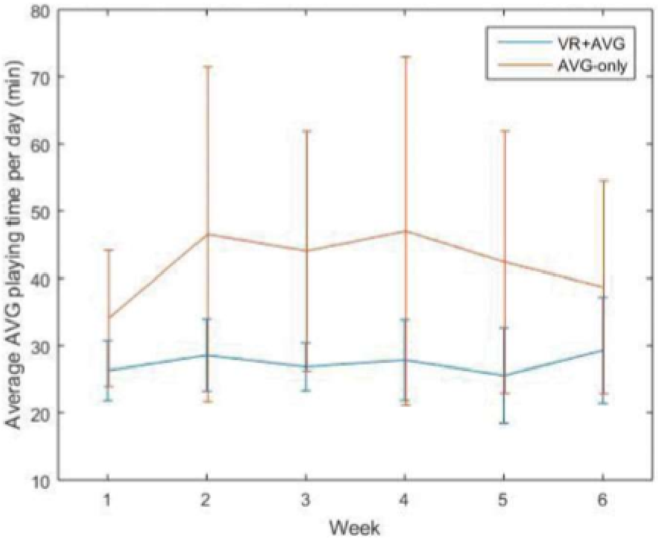

Figure 2. Self-reported average daily home AVG exercise dosage per week.

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undertaken for each outcome measure at each assessment point. Qualitative content analysis (Hsieh & Shannon, 2005) was used to analyze the email content. Email content was grouped into categories, which were then tallied in frequency counts.

Results

Figure 2 illustrates the mean playing time per week for each group for the 6-week AVG home program. The AVG-only group played an average of 42.1 min (SD 4.9 min) per day, which is an average of 14.71 (SD 4.85) minutes more per day throughout the 6 weeks as compared to the VR + AVG group (mean 27.4 min, SD 1.4 min). Exercise program adaptions included playing against an opponent (36 times), standing on a different surface (1 time), and changing game rules (9 times).

Email Content Analyses

An average of 6.2 e-mails per participant were exchanged. Figure 3 illustrates the content categories that were covered most and least frequently in emails from therapists and from children/families.

Responses to Weekly Questions

Figures 4 and 5 illustrate mean participant responses to 5 questions (0 = strongly disagree; 6 = strongly agree) asking agreement about statements of enjoyment, difficulty, boredom and fatigue over the 6-week exercise program. No inferential testing was undertaken.

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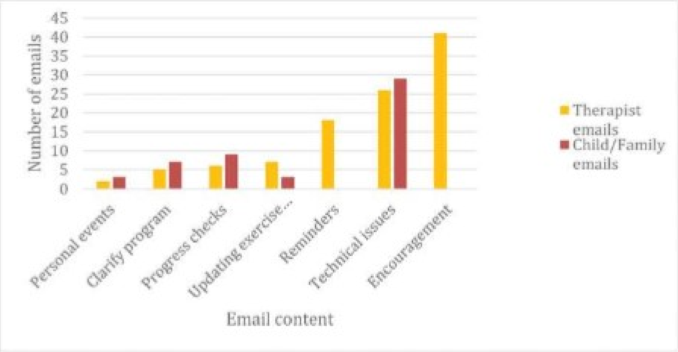

Figure 3. Content of emails exchanged between therapists and participating children/families.

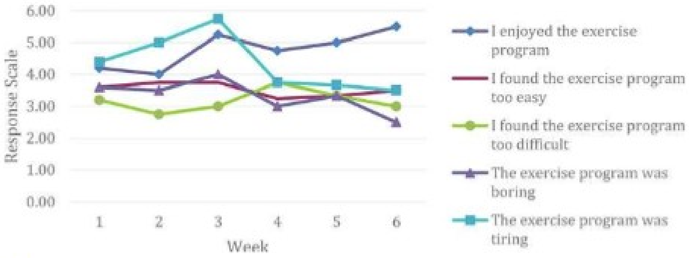

Figure 4. VR + AVG group mean responses to weekly questions.

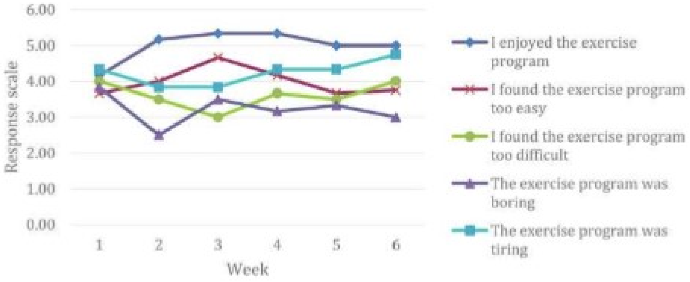

Figure 5. AVG-only group mean responses to weekly questions.

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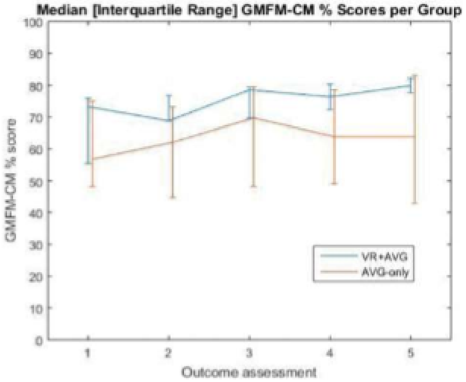

Figure 6. Gross Motor Function Measure Challenge Module % median (interquartile range) scores per group at each outcome assessment.

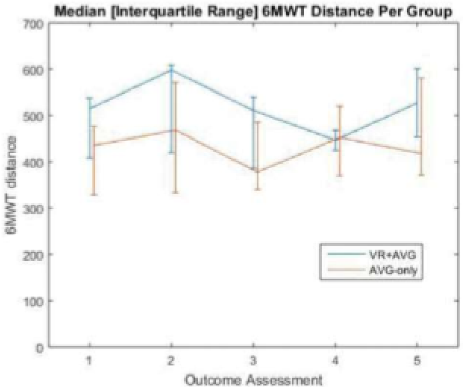

Figure 7. Six-Minute Walk Test median (interquartile range) scores per group at each outcome assessment.

Visual inspection shows that participants in both groups did not indicate that games were too easy nor too hard or that they were bored or fatigued.

GMFM-CM and 6MWT

Figure 6 illustrates the median GMFM-CM scores (expressed as percentages) for each group at each outcome assessment. The AVG-only group demonstrated a statistically significant improvement in GMFM-CM score following the 6-week intervention (Time 2 to Time 3; median difference 4.5 points, interquartile range [IQR] 4.75, $z = -2.032$, $p = 0.042$). This improvement is greater than the minimum detectable change at a 90% confidence interval (MDC 90) of 4.4 points (Wright FV. personal communication). Figure 7 illustrates the median 6MWT scores for each group at each outcome assessment. The VR + AVG group demonstrated a significant decrease in 6MWT distance following the intervention, greater than the minimal detectable change (MDC) of 61.9 m for children at GMFCS Level I (Thompson et al., 2008) (Time 2 to Time 3; median decrease 68.2 m, IQR 39.7 m, $z = -2.023$, $p = 0.043$), although 6MWT times returned to baseline at 2 months post-intervention (Time 5). There were no significant between group differences at any time point.

Discussion

Contrary to our hypothesis, children who began a 6-week AVG home exercise program with a 1-week intensive VR intervention did not demonstrate enhanced gross motor skills or functional mobility as compared to those who undertook a 6-week AVG exercise program alone. Instead, the AVG-only group showed a statistically and clinically significant improvement on the GMFM-CM after the 6-week program. Results may be explained by differences in the dosage received by the two groups. The AVG-only group played an average of 14.7 more minutes daily than did the VR + AVG group. In addition, the VR + AVG group was less consistent: 2 participants had a 1-week interruption during the study intervention, and 1 participant only completed 5 of the 6 weeks of training. As such, the intervention frequency for these participants was lower. In addition, while differences in baseline GMFM-CM or 6MWT scores between the two groups were not statistically significant, Figures 6 and 7 illustrate that the VR + AVG group had higher median scores on both outcome measures at baseline. The VR + AVG group may have had less potential to improve their functioning as a result of the intervention.

Both groups decreased their 6MWT distances immediately following the 6-week AVG program, with the VR + AVG group demonstrating a clinically and statistically significant decrease. These findings cannot be explained by test administration factors, as we followed testing recommendations and standardized testing for time of day, test order and examiner. Notes for these testing sessions do not indicate that any participants reported being unduly fatigued.

Two possible explanations for the decrease in 6MWT distances may be suggested. First, the time spent playing Kinect each day may have detracted from participants' ability to participate in other physical activities, which may have decreased their cardiovascular endurance. However, children in the VR + AVG group played less than did the AVG-only group, improved their GMFM-CM scores, and reported that they were participating in other physical activities throughout the 6-week program, so this rationale seems unlikely. 6MWT distances at baseline for the VR + AVG group were higher than reported in other studies (e.g., Nsenga Leunkeu et al., 2012; Thompson et al., 2008), yet this group had a mean GMFM-CM percentage score of 59% (SD 31.8%, range 6.3% to 86.6%), indicating wide variability in terms of advanced gross motor skills. A qualitative assessment of parents and families would help to understand whether the time spent playing the Kinect games took away from time the child would have otherwise been physically active in another capacity.

Secondly, the Kinect exercise program may not have been sufficiently challenging or focused appropriately on specific areas of muscle weakness that would improve functional mobility or gross motor skills in order to be captured by the chosen outcome measures, such as the hip abductors, knee extensors or ankle dorsiflexors. The games were chosen to challenge balance, strength and endurance, and progressions were suggested to maximize challenge throughout the 6 weeks. However, previous research has demonstrated considerable inter-individual variability in AVG game play among children with CP (Berry et al., 2011), and we can't be sure whether participants played games at recommended intensity. Participants reported playing an average of 34.76 (SD 8.44) minutes per day. A 30-minute game play

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session, with games lasting 90-120 seconds, interrupted by frequent breaks to change discs, likely did not have sufficient duration, dosage or intensity to elicit functional change.

Therapists were asked to achieve a "just-right challenge" in this study using information from participants' responses to the 5 weekly questions. For example, they were encouraged to progress the program challenge if participants reported that it was too easy. Participants and families were encouraged to elaborate on difficulties over email. However, only 26% of the emails written by children/families pertained to program clarification. As such, therapists did not have additional information from the emails that would have helped them to build on children's responses to progress the intervention challenge, implying that programs were likely not sufficiently individualized.

Although we evaluated an AVG system with prior evidence of effectiveness in this population (Luna-Oliva et al., 2013) and a VR system with established evidence (Glegg et al., 2014), developed exercise programs with experienced pediatric physical therapists, and used reliable and valid outcome measures, our study had several limitations. The sample size was small and not powered to detect change. Multiple outcome measures in a short time period may have led to fatigue, influencing test performance. A balance-specific outcome measure may have captured more specific training effects related to the intervention; analysis of this measure is currently underway and will be reported in a subsequent publication. We did not measure motivation over the 6 weeks using a standardized outcome measure. Participants only logged in to the website once per week on average, which might have led to recall bias. Self-report means that actual adherence to the AVG program is unknown. Email content analysis showed less frequent discussion of exercise challenge or progression between participants and therapists than anticipated. Therapists could have checked in with families more frequently and could have asked more questions to help further individualize and progress the exercise programs.

Future studies could increase individualization of exercise programs using off-the-shelf AVGs. Participant report may be enhanced by use of a smartphone app rather than website interaction, which would be more feasible for daily reporting. Low-cost rehabilitation-specific AVG systems with tele-rehabilitation monitoring, such as Jintronix (www.jintronix.com) or Mitii (http://elsassfonden.dk/mitii/english)/ offer individualized parameter settings and allow therapists to remotely monitor adherence and performance. The effectiveness of these systems as home exercise programs could be compared to the Xbox360 in a clinical trial. Finally, subsequent studies will better incorporate principles of the self-determination theory of motivation, which emphasizes competence, autonomy and relatedness (D'Arrigo, Ziviani, Poulsen, Copley, & King, 2016). Although we valued autonomy by letting participants choose games and frequency, subsequent studies could better emphasize competence by providing children with more detailed feedback about their success (such as graphs showing scores increasing over time), and relatedness by pairing participants with age and condition similar peers to focus on competition or teamwork.

Conclusions

Kinect for Xbox 360 AVG home exercise, supervised remotely by a physiotherapist, did not lead to changes in gross motor skills or functional mobility in this pilot study. There was a significant decrease in 6MWT distance following a 6-week intervention for participants who began with a 1-week VR "jump-start." This finding may be related to insufficient AVG intensity or dosage. All participants who showed a decrease in 6MWT distances post-AVG training returned to baseline scores at 2 months post-exercise program completion. Subsequent

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research will enhance intervention features to measure motivation and explore mechanisms to individualize commercially-available AVG exercise programs.

Declarations of Interest

The authors report no declarations of interest.

Acknowledgments

The authors would like to thank participating children and families, physiotherapists Kerri Burgess and Melissa Cormier for their assistance in delivering the interventions, physiotherapy assistants Sandy Schafer and Shannon Theriault for assisting with home Kinect setup, and Patrick Vienneau for designing the website.

Funding

This study was funded by the Ontario Federation for Cerebral Palsy and the Ottawa Children's Treatment Center. Dr. Levac's postdoctoral studies were supported by a fellowship from the Canadian Institutes of Health Research and NeuroDevNet and a career enhancement award from the Canadian Child Health Clinician Scientist Program.

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APPENDIX B

Consent forms and recruitment texts

How do children and adolescents maintain their balance?

Our research lab at the University of Ottawa is interested in how children and adolescents are able to maintain their balance while standing on a moving platform.

What we will ask you to do: If you choose to participate, you will attend a one hour session at our Motor Control Laboratory. During this session, we will use markers to record your body movements, and discs to record muscle activity. For best recordings, we may need to lightly shave the hair on your legs where the disks will be placed. You will then be asked to step onto a platform which will move back and forth, increasing in speed 3 times.

For your time and effort, you will receive a gift certificate for Tim Hortons. Costs associated with parking will be covered by the research group

If you are interested and would like more information, please contact us:

Richard Mills, Research Assistant
Motor Control Laboratory
Faculty of Health Sciences
University of Ottawa
200 Lees Ave, Ottawa, ON, K1S 5S9
[redacted]

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Sciences

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Information and Youth Consent Form (16-17yrs)

Title of the study: How do children and adolescents maintain their balance?

Heidi Sveistrup, PhD
Motor Control Laboratory
200 Lees Ave, Ottawa ON, K1S 5S9
Tel. [redacted]

Invitation to Participate: I am invited to participate in the abovementioned research study conducted by Dr Sveistrup.

Purpose of the Study: The purpose of the study is to use a movable platform to challenge and record the performance of an individual while they stay balanced on a moving platform. This study will provide information on how children and adolescents ages 7-17 are able to maintain their balance through expected and unexpected disturbances.

Participation: My participation will consist essentially of 1 one-hour session. During the session, my date of birth, gender, height, and weight will be recorded onto a data sheet and small reflective markers will be placed on my body to record movements. Small disks will be placed on my skin over 6 muscles of the leg and back to record muscle activity. For best recordings, a light shaving of the hair on my legs where the disks will be placed may be needed. I will then be asked to step onto a platform and a safety harness will be attached. I will also be required to wear form fitting shorts and a t-shirt to ensure accurate recordings.

I will then be asked to maintain my balance as the platform is moved back and forth. Movements will start at a slow speed, and increase suddenly three times at intervals of between 80-100 seconds.

Risks: My participation in this study will entail that I stand for periods of time on the platform and this may cause me to feel tired. I have received assurance from the researcher that every effort will be made to minimize these risks; I may notify the researches should I require a rest.

Benefits: I will not get a personal benefit from being part of the study.

Confidentiality and anonymity: I have received assurance from the researcher that the information I will share will remain strictly confidential. I understand that the contents will be used only for generalized data (i.e. not participant-specific) and that my confidentiality and anonymity will be protected *through the use of participant codes*.

Conservation of data: The data collected (hard copies and electronic data) will be kept in a secure manner. All hardcopies will be kept in a locked file cabinet in a locked office (Lees A123). The master list of codes and signed informed consent forms will be stored separately in a locked file cabinet in the laboratory (Lees A121). All electronic data will be stored on a laboratory computer and will be password protected.

Compensation: I will receive a gift certificate for Tim Hortons, valued at $5.00. Costs associated with parking will also be covered by the research group.

Voluntary Participation: I am under no obligation to participate and if I choose to participate, I can withdraw from the study at any time and/or refuse to answer any questions, without suffering any negative. If I choose to withdraw, all data gathered until the time of withdrawal will be destroyed.

Acceptance: I, ____________________ agree to participate in the above research study conducted by *Dr Sveistrup* of the *School of Human Kinetics, Faculty of Health Sciences.*

I give my permission to use photographs and/or video recordings of my participation in this study for publication and/or presentation purposes (circle one)

Photographs :	YES	NO
Video Recordings:	YES	NO
I want identifying features (i.e. face) censored:	YES	NO

If I have any questions about the study, I may contact the researcher or the project research assistant, Mr Richard Mills, at [redacted].

If I have any questions regarding the ethical conduct of this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON K1N 6N5
Tel.: (613) 562-5387
Email: ethics@uottawa.ca

There are two copies of the consent form, one of which is mine to keep.

Participant's signature: *(Signature)* Date: *(Date)*

Researcher's signature: *(Signature)* Date: *(Date)*

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Faculty of Health Sciences
School of Rehabilitation Sciences

Information and Parent Consent Form

Title of the study: How do children and adolescents maintain their balance?

Heidi Sveistrup, PhD
Motor Control Laboratory
200 Lees Ave, Ottawa ON, K1S 5S9
Tel. [redacted]

Invitation to Participate: My child is invited to participate in the abovementioned research study conducted by Dr Sveistrup.

Purpose of the Study: The purpose of the study is to use a movable platform to challenge and record the performance of an individual while they stay balanced on a moving platform. This study will provide information on how children and adolescents ages 7-17 are able to maintain their balance through expected and unexpected disturbances.

Participation: My child's participation will consist essentially of 1 one-hour session. His/her date of birth, gender, height, and weight will be recorded onto a data sheet . During the session, small reflective markers will be placed on his/her body to record movements. Small disks will be placed on my child's skin over 6 muscles of the leg and back to record muscle activity. For best recordings, a light shaving of the hair on the legs where the disks will be placed may be needed. He/she will then be asked to step onto a platform and a safety harness will be attached. He/she will also be required to wear form fitting shorts and a t-shirt to ensure accurate recordings.

My child will then be asked to maintain my balance as the platform is moved back and forth. Movements will start at a slow speed, and increase suddenly three times at intervals of between 80-100 seconds.

Risks: My child's participation in this study will entail that he/she stand for periods of time on the platform and this may cause me to feel tired. My child has received assurance from the researcher that every effort will be made to minimize these risks; he/she may notify the researches should he/she require a rest.

Benefits: My child will not get a personal benefit from being part of the study.

Confidentiality and anonymity: My child has received assurance from the researcher that the information he/she will share will remain strictly confidential. He/she understands that the contents will be used only for generalized data (i.e. not participant-specific) and that my child's confidentiality and anonymity will be protected *through the use of participant codes*.

Conservation of data: The data collected (hard copies and electronic data) will be kept in a secure manner. All hardcopies will be kept in a locked file cabinet in a locked office (Lees A123). The master list of codes and signed informed consent forms will be stored separately in a locked file cabinet in the laboratory (Lees A121). All electronic data will be stored on a laboratory computer and will be password protected.

Compensation: My child will receive a gift certificate for Tim Hortons, valued at $5.00. Costs associated with parking will also be covered by the research group.

Voluntary Participation: My child is under no obligation to participate and if he/she chooses to participate, he/she can withdraw from the study at any time and/or refuse to answer any questions, without suffering any negative. If my child chooses to withdraw, all data gathered until the time of withdrawal will be destroyed.

Acceptance: I, ____________________ agree to allow my child _______________ participate in the above research study conducted by *Dr Sveistrup* of the *School of Human Kinetics, Faculty of Health Sciences.*

I give my permission to use photographs and/or video recordings of my child's participation in this study for publication and/or presentation purposes (circle one)

Photographs :	YES	NO
Video Recordings:	YES	NO
I want identifying features (i.e. face) censored:	YES	NO

If I or my child have any questions about the study, I may contact the researcher or the project research assistant, Mr Richard Mills, at [redacted].

If I have any questions regarding the ethical conduct of this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON K1N 6N5
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How do children keep their balance?

Our testing lab at the University of Ottawa wants to know how children can hold their balance.

We have a large platform that can move up and down and side to side. But don't worry! There is a safety strap that holds you so you don't fall.

We want to find out how you can stay standing while we move the platform.

<u>What you will do</u>:
You will stand in the middle of the platform.
It will then begin to move back and forth for about 1 minute.
Then we will add a bit more speed.
We will do this 3 more times.
Your goal is to keep standing. You can rest whenever you want.

We will also ask you if we can make a video and take pictures to help us show others our work. You can say yes or no - it's up to you!

It's OK if you change your mind and you don't want to take part anymore. At any time, just let your mom or dad or one of the workers know. Or if you have any questions, just ask!

If you or your parents have any questions, your parents can call:
Richard Mills at the University of Ottawa
[redacted]

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Information and Youth Consent Form (16-17yrs)

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Tel. [redacted]

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Purpose of the Study: The purpose of the study is to use a movable platform to challenge and record the performance of an individual while they stay balanced on a moving platform. This study will provide information on how children and adolescents ages 7-17 are able to maintain their balance through expected and unexpected disturbances.

Participation: My participation will consist essentially of 3 one-hour sessions over two weeks. My date of birth, gender, height, and weight will be recorded onto a data sheet . During each session, small reflective markers will be placed on my body to record movements. Small disks will be placed on my skin over 6 muscles of the leg and back to record muscle activity. For best recordings, a light shaving of the hair on my legs where the disks will be placed may be needed. I will then be asked to step onto a platform and a safety harness will be attached. I will also be required to wear form fitting shorts and a t-shirt to ensure accurate recordings.

I will then be asked to maintain my balance as the platform is moved back and forth. Movements will start at a slow speed, and increase suddenly three times at intervals of between 80-100 seconds.

Risks: My participation in this study will entail that I stand for periods of time on the platform and this may cause me to feel tired. I have received assurance from the researcher that every effort will be made to minimize these risks; I may notify the researches should I require a rest.

Benefits: I will not get a personal benefit from being part of the study.

Confidentiality and anonymity: I have received assurance from the researcher that the information I will share will remain strictly confidential. I understand that the contents will be used only for generalized data (i.e. not participant-specific) and that my confidentiality and anonymity will be protected *through the use of participant codes*.

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If I have any questions about the study, I may contact the researcher or the project research assistant, Mr Richard Mills, at [redacted].

If I have any questions regarding the ethical conduct of this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON K1N 6N5
Tel.: (613) 562-5387
Email: ethics@uottawa.ca

There are two copies of the consent form, one of which is mine to keep.

Participant's signature: *(Signature)* Date: *(Date)*

Researcher's signature: *(Signature)* Date: *(Date)*

uOttawa
L'Université canadienne
Canada's university

Université d'Ottawa
Faculté des sciences de la santé
École des sciences de la réadaptation

University of Ottawa
Faculty of Health Sciences
School of Rehabilitation Sciences

Information and Parent Consent Form

Title of the study: How do children and adolescents maintain their balance?

Heidi Sveistrup, PhD
Motor Control Laboratory
200 Lees Ave, Ottawa ON, K1S 5S9
Tel. [redacted]

Invitation to Participate: My child is invited to participate in the abovementioned research study conducted by Dr Sveistrup.

Purpose of the Study: The purpose of the study is to use a movable platform to challenge and record the performance of an individual while they stay balanced on a moving platform. This study will provide information on how children and adolescents ages 7-17 are able to maintain their balance through expected and unexpected disturbances.

Participation: My child's participation will consist essentially of 3 one-hour sessions over two weeks. His/her date of birth, gender, height, and weight will be recorded onto a data sheet . During each session, small reflective markers will be placed on his/her body to record movements. Small disks will be placed on my child's skin over 6 muscles of the leg and back to record muscle activity. For best recordings, a light shaving of the hair on the legs where the disks will be placed may be needed. He/she will then be asked to step onto a platform and a safety harness will be attached. He/she will also be required to wear form fitting shorts and a t-shirt to ensure accurate recordings.

My child will then be asked to maintain my balance as the platform is moved back and forth. Movements will start at a slow speed, and increase suddenly three times at intervals of between 80-100 seconds.

Risks: My child's participation in this study will entail that he/she stand for periods of time on the platform and this may cause me to feel tired. My child has received assurance from the researcher that every effort will be made to minimize these risks; he/she may notify the researches should he/she require a rest.

Benefits: My child will not get a personal benefit from being part of the study.

Confidentiality and anonymity: My child has received assurance from the researcher that the information he/she will share will remain strictly confidential. He/she understands that the contents will be used only for generalized data (i.e. not participant-specific) and that my child's confidentiality and anonymity will be protected *through the use of participant codes*.

Conservation of data: The data collected (hard copies and electronic data) will be kept in a secure manner. All hardcopies will be kept in a locked file cabinet in a locked office (Lees A123). The master list of codes and signed informed consent forms will be stored separately in a locked file cabinet in the laboratory (Lees A121). All electronic data will be stored on a laboratory computer and will be password protected.

Compensation: My child will receive a gift certificate for Tim Hortons, valued at $15.00. Costs associated with parking will also be covered by the research group.

Voluntary Participation: My child is under no obligation to participate and if he/she chooses to participate, he/she can withdraw from the study at any time and/or refuse to answer any questions, without suffering any negative. If my child chooses to withdraw, all data gathered until the time of withdrawal will be destroyed.

Acceptance: I, ____________________ agree to allow my child _______________ participate in the above research study conducted by *Dr Sveistrup* of the *School of Human Kinetics, Faculty of Health Sciences.*

I give my permission to use photographs and/or video recordings of my child's participation in this study for publication and/or presentation purposes (circle one)

Photographs :	YES	NO
Video Recordings:	YES	NO
I want identifying features (i.e. face) censored:	YES	NO

If I or my child have any questions about the study, I may contact the researcher or the project research assistant, Mr Richard Mills, at [redacted].

If I have any questions regarding the ethical conduct of this study, I may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON K1N 6N5
Tel.: (613) 562-5387
Email: ethics@uottawa.ca

There are two copies of the consent form, one of which is mine to keep.

Participant's signature: *(Signature)* Date: *(Date)*

Researcher's signature: *(Signature)* Date: *(Date)*

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de la santé

École des sciences de la réadaptation

University of Ottawa

Faculty of Health

Sciences

School of Rehabilitation Sciences

How do children keep their balance?

Our testing lab at the University of Ottawa wants to know how children can hold their balance.

We have a large platform that can move up and down and side to side. But don't worry! There is a safety strap that holds you so you don't fall.

We want to find out how you can stay standing while we move the platform.

What you will do:
You will stand in the middle of the platform.
It will then begin to move back and forth for about 1 minute.
Then we will add a bit more speed.
We will do this 3 more times.
Your goal is to keep standing.
You can rest whenever you want.
We would like you to come back and do this again 2 more times.

We will also ask you if we can make a video and take pictures to help us show others our work. You can say yes or no - it's up to you!

It's OK if you change your mind and you don't want to take part anymore. At any time, just let your mom or dad or one of the workers know. Or if you have any questions, just ask!

If you or your parents have any questions, your parents can call:
Richard Mills at the University of Ottawa
[redacted]

Virtual Reality Jump-Start Study

Investigators: [redacted]; [redacted]; [redacted]; [redacted]; [redacted]; [redacted]

Dear Parents/Guardians:

We would like to invite your child to take part in a research study to evaluate the effect of a home-based VR exercise program on improving balance, walking skills and participation in physical activities in children, adolescents and young adults with cerebral palsy (CP).

This study is funded by the Ontario Federation for Cerebral Palsy and by a research grant from the Ottawa Children's Treatment Centre.

WHY ARE WE DOING THIS STUDY?

Many children and youth with CP have balance impairments that interfere with functional mobility and participation in physical activities. Using VR systems as part of physiotherapy exercise programs for children and youth with CP is an emerging area of research and clinical practice. We have developed an exercise program using the Kinect for Xbox 360 (Microsoft), a common VR system that is used in rehabilitation to help children practice balance and movement skills. Children can do this exercise program at home. We would like to understand whether this exercise program is effective at improving children's balance, walking skills and participation in physical activities.

In addition, we want to see whether starting this Kinect exercise program with a short, intense week of therapy using a different VR system (the Interactive Rehabilitation Exercise System (IREX; GestureTek) can improve the results from the Kinect exercise program. Unlike the Kinect, the IREX is used at the Ottawa Children's Treatment Centre and supervised by a physiotherapist.

WHAT DOES THE STUDY INVOLVE?

- Your child will be given an individualized Kinect exercise program.
- 2 members of the research team will come to your home to set up the Kinect and help you and your child learn the website.
- Your child will do the Kinect exercises for 30 min/day, 5 days/week for 6 weeks, supervised by you.
- You and your child will log in to the website at least 2X/week to record your Kinect activities and connect with the physiotherapist who will monitor whether to make the activities harder or easier for your child.
- There is a 50% chance that your child will be placed in the group of the study where they will first take part in the short, intense week of therapy at OCTC. This would be for 1hr/day for 5 days. The therapist would then give the individualized Kinect exercise program and your child would play at home for 6 weeks and use the website, as described above.
- You and your child will come to the University of Ottawa for tests to measure balance, walking ability and participation on 5 occasions during the study.

We will pay for your parking during the study visits. Your child will receive the Kinect and Xbox 360 as well as the 4 study games.

HOW CAN I GET MORE INFORMATION OR SIGN UP FOR THE STUDY?

Please contact Rick Mills by phone at [redacted] or by email at [redacted].

THANK YOU

TELEPHONE RECRUITMENT SCRIPT
Virtual Reality Jump-Start Study
University of Ottawa

Telephone Script for obtaining verbal consent from parents/guardians

N.B: For young adults, pronouns will be changed when speaking directly to the participant, and location of interventions will be changed to the Motor Control Laboratory

Part A

Hello, my name is XX and I am calling from the University of Ottawa. I'm returning your phone call/email **[select one]** about the Virtual Reality Jump-Start study. Thank you for your interest in/asking for more information about **[select one]** having your child take part in this study. Let me tell you about the study and what it involves.

We are doing this study to compare the effect of 2 VR exercise programs on improving balance, walking skills and participation in physical activities in children, adolescents and young adults with cerebral palsy (CP). The VR systems that we are interested in are the Kinect, which can be used at home, and the IREX, which can be used in the clinic. The IREX and the Kinect have some differences, but both require children to move and balance during game play. Previous studies have shown the IREX to be effective in a short-term physiotherapy exercise program for children and youth with CP, but this study is the first to explore the use of the Kinect in this way.

Each exercise program will last 7 weeks. Your child will be assigned at random, that is by a method of chance (like a flip of a coin), to one of the two exercise groups. In the first group, your child would use both VR systems. For the first week, he/she would come in to the Ottawa Children's Treatment Centre every day for a one-hour exercise session delivered by a physiotherapist using the IREX. At the end of the last session, your child would have a chance to practice the Kinect so that the therapist can decide which Kinect activities are best for him/her. We will visit your home to introduce you and your child to our study website and to set up the Kinect. For the next six weeks, your child would use the Kinect at home for at least 30min per day, 5X/week. The Kinect exercise program would be supervised by the physiotherapist through our study website website. Using the website will allow you and your child to report what Kinect games he/she is playing and the therapist will respond to make suggestions for how to make the games harder or easier. We will ask you and your child to log in to the website at least twice a week to record the kinds of activities that he/she is involved in.

The second group is only the six weeks Kinect exercise program at home. We would ask you and your child to come to OCTC on one occasion to meet the therapist and your child would have a chance to practice the Kinect so that the therapist can decide which Kinect activities are best for him/her. We would then visit your home to help you set up the Kinect system on your TV and to introduce you and your child to our study website. The activities would be supervised by the physiotherapist and you and your child would log in to the website at least twice a week.

No matter which exercise group your child is assigned to, we will ask you and your child to come in to the Motor Control Laboratory at the University of Ottawa on 5 occasions so that we can measure your child's balance, walking skills, and participation throughout the study. Each visit would last about 1.5 to 2 hours. These assessments would be at the beginning of the study, 1 week into the study, at the end of the 7-week exercise program, one month after finishing the exercise program, and three months after finishing the exercise program. On the first visit, we will ask you to fill out a short questionnaire asking about your child's age, grade level, CP diagnosis, experience with the Kinect and involvement in recreational and organized sports activities. Depending on your child's age, you and/or your child will also fill out three short questionnaires asking about your child's participation, physical activity and feelings about his/her physical activity levels. If you have any trouble with these forms, we would be glad to help.

At each outcome assessment visit, your child will also participate in 3 supervised tests. The first is a balance test that involves wearing a harness and standing on a moving platform. The second is a movement and strength skills test that involves tasks such as walking backwards, bouncing a basketball, and doing jumping jacks. The third is a walking test. Finally, when your child finishes the exercise program, we will ask you and your child to answer some questions about what you liked or didn't like about the VR exercises.

The overall time that you would be participating in the study is 5 months, but the exercise program and the use of the website is only 6 or 7 weeks, depending on which exercise group your child is assigned to. We will reimburse you for parking at all study visits. No matter what group your child is assigned to, he/she will receive a Kinect and Xbox 360 as well as the 4 study games. You and your child may choose at any time not to participate in this study. If you or your child chooses to withdraw, this is not a problem in any way.

Do you have any questions?

Are you and your child interested in participating in this study?

☐Yes ☐ No ➔ Thank you for your time!
🡻
If Yes…

Part B

What is your child's name? _____________

I would like to get some contact information for you, ask you some questions about **[insert child's name]** to make sure that he/she is eligible for the study, and schedule a time for you and **[insert child's name]** to come in for the first study visit. Do you have time right now to answer some questions or would you prefer that I call back?

☐Yes ☐ No ➔ Alternative Date and Time:____________________________
🡻

Name: ______________________________ Telephone: __________________________

Address: ____

CHECK THAT ADDRESS IS WITHIN 50 KM RADIUS OF EITHER [redacted] [OTTAWA] OR [redacted] [KANATA]

IF OUTSIDE OF THIS RADIUS, EXPLAIN: Because one part of this study involves a home visit to set up the Kinect, we can only travel so far. Unfortunately you live outside of our study area. Thank you for your interest in the study!

Email Address (optional; explain it is so that we can send information forms and parking directions): ______________________________________

How would you like to receive information about the study?

☐ Email ☐ Mail

What language is spoken most often in your home?

☐ English ☐ French ☐ Other (specify): ____________________

Do you feel comfortable completing questionnaires in English?

☐ Yes ☐ No

Do you have a TV?

☐ Yes ☐ No

In the room where the TV is located, is there at least a 6 ft by 4ft space in front of the TV where your child could play the Kinect games safely, without encountering any safety obstacles (like a slippery rug or a coffee table?)

☐ Yes ☐ No

IF NOT, ASK IF FURNITURE ETC COULD BE REARRANGED TO MAKE THIS POSSIBLE. IF THIS IS NOT POSSIBLE, EXPLAIN THAT SAFE SPACE FOR GAME PLAY IS REQUIRED FOR STUDY PARTICIPATION AND THANK THEM FOR THEIR INTEREST IN THE STUDY.

Does your child have a Kinect at home?

☐ Yes ☐ No

If yes, how long has he/she had the Kinect? _____________

Does your child play the Kinect more than 1hr/week?

☐ Yes ☐ No

If yes, explain that we are looking for children who have only minimal experience playing the Kinect for this study and thank them for their interest and time.

Do you have a computer with internet access in your home?

☐ Yes ☐ No

If not, will explain that an internet connection is required for study participation and thank parent for their time/interest in the study.

I'd like to ask you a couple of questions about **[insert child's name]**.

How old is **[insert child's name]**? ______________

What grade is **[insert child's name]** in at school? _____________

What is **[insert child's name]** diagnosis? ______________

Do you know **[insert child's name]** Gross Motor Function Classification System Level? _____________

It's OK if not, the following questions will elicit the level.

Is your child able to walk independently without a gait aid (walker, crutches)?

☐ Yes ☐ No

If not, explain that eligibility for this study is only for children who can walk without a gait aid.

Is your child able to run?

☐ Yes ☐ No

Is your child able to jump?

☐ Yes ☐ No

If able to run and jump, they are GMFCS Level I; if not able to run or jump, they are GMFCS Level II.

Does your child have normal hearing and vision, or wear glasses/hearing aids to correct their vision?

☐ Yes ☐ No

If abnormal, explain that normal/corrected hearing/vision is required for interaction with the Kinect and for participation in study outcome measures and thank parent for their time/interest in the study.

Does your child have asthma attacks or other respiratory issues while undertaking mild or moderate physical activity?

☐ Yes ☐ No

Is your child's asthma or respiratory issue controlled through the use of inhalers or other medication during exercise sessions?

☐ Yes ☐ No

If not, explain that we are focusing on rehabilitation of motor function and require participants to perform fairly strenuous activity, it is possible that your child may not be safe to participate in the training program. Thank parent for time/interest in the study.

Does your child have a history of a seizure disorder?

☐ Yes ☐ No

If yes, explain that since there is a very small chance that Kinect game play can elicit a seizure in those predisposed to seizures, we can't accept the child into the study from a safety perspective and thank parent for time/interest in the study.

Does your child have any cognitive, communication or learning challenges?

☐ Yes ☐ No

If yes, ask parents if they believe their child could play Kinect video games independently and if they could interact with study investigators and respond to instructions for the outcome measures, such as jump on one foot, walk backwards down the hallway, etc. If they can't, explain that this is required for participation in the study and thank parent for their time/interest in the study.

Thank you for providing us with this information! The first step is to read over and sign the consent form that I will mail/email to you. The consent form gives you information about the study. Please bring the forms with you to the study visit and you can sign after you have had the chance to ask us any questions you might have. If you receive the consent form, read it over and decide not to participate, please just let us know. This is not a problem! I will also mail an assent form for you to read with your child. This is a form that explains the study to your child. At the study visit we will ask your child to sign the form indicating that they understand and agree to participate in the study.

I would like to schedule a first study visit for you and **[insert child's name]**. When is a convenient time for you?

Time/date:___________________

I will mail instructions to University of Ottawa, parking instructions and instructions to get to the laboratory with the consent forms.

Do you have any questions at this time about anything I have just talked about? If ever you have any questions about the project you may contact me at any time. Again, my name is XXX. I can be reached at XXX. This information will also be clearly written on the consent form.

Thank you for your time – see you on ____________________!

LETTER OF INFORMATION
Virtual Reality Jump-Start Study
University of Ottawa

Title of Study: A Rehabilitation 'Jump-Start': Does an intensive clinic-based virtual reality (VR) experience enhance the effectiveness of a home-based VR therapy program in children with CP?

Principal Investigator:

[redacted]
Physiotherapist and Postdoctoral Fellow, School of Rehabilitation Science

Co-Investigator(s), Department/Hospital/Institution:

[redacted], School of Rehabilitation Science, University of Ottawa
, School of Physical Therapy and Occupational Therapy, McGill University
, Physiotherapist, Ottawa Children's Treatment Centre
, Physiatrist, Children's Hospital of Eastern Ontario
, Faculty of Medicine, University of Ottawa
Richard Mills, PhD student, School of Human Kinetics, University of Ottawa

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Dear Parents/Guardians:

Your child is being invited to participate in a research study to evaluate the effect of two different Virtual Reality (VR) exercise program on balance, physical activity and participation in children and youth with cerebral palsy (CP). In order to decide whether or not you want your child to be a part of this research study, you should understand what is involved and the potential risks and benefits. This form gives detailed information about the research study, which will be discussed with you. Once you understand the study, you will be asked to sign this form if you would like your child to participate. Please take your time to make your decision. Feel free to discuss it with your friends and family.

This study is funded by research grants from the Ontario Federation for Cerebral Palsy and the Ottawa Children's Treatment Centre. Part of the information from this study will be used as part of Richard Mills' PhD student project.

WHY ARE WE DOING THIS STUDY?

Many children and youth with CP have balance impairments that interfere with functional mobility and participation in physical activities. Using VR systems as part of physiotherapy exercise programs for children and youth with CP is an emerging area of research and clinical practice. We have developed exercise programs using the Kinect for Xbox 360 (Microsoft) and the Interactive Rehabilitation Exercise System (IREX;

GestureTek), common VR systems that can be used in rehabilitation to help children practice balance and movement skills. We would like to understand whether these exercise programs are effective at improving children's balance, walking skills and participation in physical activities..Both systems involve games with which children interact using body movements, but the IREX can only be used at a rehabilitation centre, while the Kinect can be used at home.

The purpose of this study is to compare the effect of a 6-week Kinect home-based exercise program alone to the same program that begins with an intense *'jump-start'* 1-week IREX exercise program on improving balance, walking skills and participation in physical activities in children and young adults with CP. Previous research studies have shown that a 1-week IREX exercise program has a positive impact on balance and functional mobility in adolescents with CP. There is no evidence for use of the Kinect. This study is unique and important because it will help to provide this evidence for the Kinect and give us information about whether the clinic-based '*jump-start'* is necessary.

WHAT WILL BE MY CHILD'S RESPONSIBILITIES IF HE/SHE TAKES PART IN THE STUDY?

If you and your child volunteer to participate in this study, he/she will be participating in one of two different VR exercise programs. Both programs are aimed at improving your child's balance, walking ability and self-confidence to participate in physical activities.

One program occurs at home using the Kinect for 6 weeks. You and your child will come to OCTC on one occasion at the beginning of the study so that your child can experience playing the Kinect games and the therapist can set up the exercise program. Your child will then be asked to use the Kinect at least 30 min/day for 5 days/week.

The second program has 2 parts: Firstly, your child would come to OCTC for 1hr/day for 5 days in a row to use the IREX in an exercise program delivered by a physiotherapist. Your child will then exercise using the Kinect at home, for at least 30 min/day for 5 days/week for the next 6 weeks.

In both programs, your child will also be asked to log on at least twice per week to an interactive website to record his/her physical activities and VR exercises, discuss progression of the VR exercises with the physiotherapist, and to take part in fun informational activities to promote awareness about the importance of keeping active.

In both programs, your child will also participate in 5 assessment sessions, each approximately 1.5 to 2 hours in length: 1) At the beginning of the study, 2) at the end of the IREX exercise program week (children in the Kinect group will not have received any exercise during that week), 3) at the end of the 6-week Kinect exercise program, 4) Four weeks after the end of the exercise program, and 5) Eight weeks after the end of the exercise program.

The total time involvement will be:

Kinect practice:

- 1 hr at OCTC to set up the Kinect home program with the physiotherapist (not including travel time to/from OCTC)
- 2 hrs during the Kinect and website set-up home visit
- 2.5 hrs/wk at home for six weeks to participate in Kinect exercise program
- 1 hr/wk on website for 6 weeks of Kinect exercise program
- 3 hrs at the Motor Control Laboratory on 5 occasions throughout the study (not including travel time to/from the laboratory)

TOTAL: 39 hours (not including travel time)

IREX + Kinect practice:

- 1 hr/day for 5 days in a row at OCTC; plus an extra 1 hour on the last day to set up Kinect home program (not including travel time to/from OCTC)
- 2 hrs during the Kinect and website set-up home visit
- 2.5 hrs/wk at home for six weeks to participate in Kinect exercise program
- 1 hr/wk on website for 6 weeks of Kinect exercise program
- 3 hrs at the Motor Control Laboratory on 5 occasions throughout the study (not including travel time to/from the laboratory)

TOTAL: 44 hours (not including travel time)

Which VR exercise program will my child receive?

Your child will be assigned at random, that is by a method of chance (like a flip of a coin), to one of two VR Exercise Groups – Exercise A, or Exercise B. Your child will have a one in two chance of being in the group that receives Exercise A – IREX practice; and a one in two chance of being in the group that receives Exercise B – IREX + Kinect practice.

VR Exercise Programs: Description

Exercise A: Kinect practice

- The physiotherapist develops a personalized Kinect exercise home program for your child.
- A study team member visits your home to set up the Kinect system. Kinect games elicit movements that challenge balance, strength and coordination such as weight-shifting, standing on one leg, reaching to the side, squatting and jumping.
- Participants exercise using the Kinect at home at least 30 min/day, 5 days per week for 6 weeks. Participants must keep track of the length of each exercise session.
- **WEBSITE:** Participants use the website to keep track of their Kinect activities and to interact with the physiotherapist about how to progress Kinect activities. For example, therapists might recommend that children adapt the games in some way, such as by holding a weight or standing on one leg.

Exercise B: IREX + Kinect practice

- Week 1: The physiotherapist will develop a personalized IREX exercise program for the participant.
- Participants exercise for 1 hour every day for 5 days using the IREX system at OCTC.
- The therapist may provide verbal feedback and physical guidance
- IREX games elicit movements that challenge balance, strength and coordination such as weight-shifting, standing on one leg, reaching to the side, squatting and jumping.
- Difficulty levels of games can be progressed as performance improves.
- The physiotherapist will develop a personalized Kinect exercise home program for the participant
- Weeks 2 -7:
- A study team member visits your home to set up the Kinect system. Kinect games elicit movements that challenge balance, strength and coordination such as weight-shifting, standing on one leg, reaching to the side, squatting and jumping
- Participants exercise using the Kinect at home at least 30 min/day, 5 days per week for 6 weeks. Participants must keep track of the length of each exercise session.
- **WEBSITE:** Participants use the website to keep track of their Kinect activities and to interact with the physiotherapist about how to progress Kinect activities. For example, therapists might recommend that children adapt the games in some way, such as by holding a weight or standing on one leg.

Who will provide the VR exercise programs?

The IREX exercise will be provided by a physiotherapist.

The Kinect exercise will be selected by the physiotherapist. The Kinect exercises will be done at home and should be supervised by you, the child's parent. You and your child can interact frequently with the physiotherapist via the website or telephone to progress Kinect activities or discuss any problems that you are having.

Where will the study activities take place?

IREX exercise will take place at the Ottawa Children's Treatment Centre (Ottawa or Kanata site). Kinect exercise will take place at your home. All of the outcome assessments will take place at the Motor Control

Laboratory at the University of Ottawa, Lees Campus at 200 Lees Avenue. Evening and weekend sessions are possible and anticipated given school schedules.

Outcome Assessment

The results of the two different VR exercise programs will be compared to see if one program is better than the other. In order to compare the effect of these two programs, your child will be assessed at five different times

- 1) Before beginning the exercise program,
- 2) At the end of the IREX exercise week (no exercise that week for the Kinect group)
- 3) At the end of the 6 week exercise program,
- 4) 4 weeks after the exercise program is finished, and
- 5) 12 weeks after the exercise program is finished.

On all five occasions, study investigators and a trained physiotherapist will assess your child. This therapist will be unaware of which therapy group to which your child has been assigned.

Your child's assessment will include the following tests and questionnaires:

1. **Demographic information:** On the first assessment we will ask you to fill out a short questionnaire asking about your child's age, grade level, CP diagnosis, experience with the Kinect and involvement in recreational and organized sports activities.
2. **Balance test:** Your child will stand on a platform that is moved using a hydraulic motor. We will measure your child's balance using a force plate that he/she stands on while the platform moves forwards and backwards. Small reflective markers will be placed on his/her body to record movements. Small disks will be placed on your child's skin over 6 muscles of the leg and back to record muscle activity. For best recordings, a light shaving of the hair on the legs where the disks will be placed may be needed. He/she will then be asked to step onto a platform and a safety harness will be attached. He/she will also be required to wear form fitting shorts and a t-shirt to ensure accurate recordings.
3. **Gross Motor Function Measure Challenge Module**: This test is administered by a physiotherapist and evaluates coordination, agility, balance, speed and strength. It involves tasks like doing jumping jacks, walking backwards, and dribbling a basketball.
4. **Six Minute Walk Test**: Your child will be asked to walk indoors at a comfortable speed for a period of six minutes. The assessor will measure how far your child was able to walk in this time period.
5. **Participation and Environment Measure for Children and Youth (PEM-CY):** A paper questionnaire that asks questions about your child's participation in home, school, and community settings.
6. **Physical Activity Questionnaire (Child and Adolescent versions)***:* You and/or your child can fill out this paper questionnaire asking about the amount of participation in regular physical activities performed in the past 7 days.
7. **Athletic Competence Subscale of the Self-Perception Profile (SPP) for Children/Adolescents:** Children fill out this questionnaire asking how they feel about participating in athletic activities.

WHAT BENEFIT IS THIS TO YOUR CHILD?

We cannot promise any personal benefits to your child from his/her participation in this study. Potential benefits may include changes in your child's balance and walking ability and confidence in his/her ability to participate in physical activities. Your child's participation in this study may help other children and youth with CP in the future. There is a good chance that the results of studies such as this will help therapists choose the best available VR exercise program for children and youth with CP.

WHAT RISKS ARE INVOLVED IN THIS STUDY?

Although rare, there are some risks involved in participating in this study.

Muscle soreness: As with any exercise activity, some participants may experience some post exercise muscle soreness. This discomfort is usually mild and temporary. Warm up and cool down activities during each session will help reduce the risk of muscle discomfort or injury.

Falls: During this study, your child will be practicing balance activities that he or she might find challenging. Your child may have balance problems as a result of his or her CP and therefore be at risk of falling during these activities. Falls can result in minor injury or even more severe injuries like a fracture. In order to reduce the risk of falls, your child will receive one to one close supervision by the therapist during all IREX exercise activities and outcome assessment tests. However, Kinect activities will take place in your own home, without supervision from study personnel. The researcher will give you advice on how to make Kinect play safe in your home and the home program will be individually designed based on your child's balance and walking abilities. However, it is your responsibility to supervise your child's Kinect activities.

Emotional and psychological discomfort: Many children are familiar with the concept of movement-based video games, but the physiotherapist will introduce the child to the games and provide instructions about the movements that are required. IREX and Kinect games do not provide negative feedback, but the physiotherapist will remind children that their performance on the games is not being monitored. IREX and Kinect programs will be individualized to children's capabilities.

WHAT DO YOU NEED TO DO?

If you choose to have your child take part in this study, please sign this form when you come for the study visit, after asking the study investigators any questions you might have. We will explain the study to your child and give him/her the opportunity to ask questions as well. We will ask your child to read and sign an assent form which indicates their understanding of what is involved in order to participate in the study.

WHAT ELSE DO YOU NEED TO KNOW?

All personal data will be kept strictly confidential. Only the researchers will have access to the data. This information will be kept for a period of five years. No personal information regarding your child will be identified in the publication of the results of this study. We hope to have 20 children and young adults participating in this study.

Even if you agree for your child to participate in the study, your child's participation is voluntary and you or he/she may decide to withdraw from the study at any time. There is no obligation to participate in any aspect of this project. Participating in study does not prevent your child from receiving other therapy outside the study exercise programs. You will be asked to keep a record of your child's attendance at therapy outside of the study sessions.

WHAT HAPPENS IF MY CHILD HAS A RESEARCH-RELATED INJURY?

If your child is injured as a direct result of taking part in this study, all necessary medical treatment will be made available to him/her at no cost. Financial compensation for such things as lost wages, disability or discomfort due to this type of injury is not routinely available. However, if you sign this consent form it does not mean that you waive any legal rights you may have under the law, nor does it mean that you are releasing the investigator(s), institution(s) and/or sponsor(s) from their legal and professional responsibilities.

WILL THERE BE ANY COSTS?

Other than the cost of parking for study visits, there are no direct costs to participating in this research project. The study will reimburse you for the costs related to parking for your study visits.

WILL MY CHILD BE PAID TO PARTICIPATE IN THIS STUDY?

No, your child will not be paid to participate in this study. However, no matter what group your child is assigned to, and regardless of whether he/she completes the study, he/she will receive a Kinect and Xbox as well as four Kinect games to keep at home.

IF I HAVE ANY QUESTIONS OR PROBLEMS, WHOM CAN I CALL?

This study has been reviewed and approved by the University of Ottawa Faculty of Health Sciences Research Ethics Board. If you have any questions regarding the ethical conduct of this study, you may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON K1N 6N5; Tel.: (613) 562-5387; Email: ethics@uottawa.ca.

If you would like to receive more information about the study at any time, please contact the researcher, [redacted] by phone [redacted] or by email [redacted]. We would be pleased to provide you with a summary of study results at the conclusion of the study or invite you to an information session.

Thank you for your help!

[redacted]
Postdoctoral Fellow
Rehabilitation Science
University of Ottawa

INFORMED CONSENT
Virtual Reality Jump-Start Study
University of Ottawa

Parental/Guardian Statement:

I am the parent or legal guardian of the child named below, who is under the age of 18 years.

Parent's Consent and Signature

I have read the preceding information thoroughly. I have had the opportunity to ask questions, and all of my questions have been answered to my satisfaction. I give my personal consent and give consent for my child, __________________________, to take part in a study where he/she will be assigned to one of two VR exercise programs and participate in a 6 or 7-week exercise program. He/she will log in to a website 2X/week during the 6 week exercise program. He/she will also visit the University of Ottawa on 5 occasions over a 20-week study period to assess his/her balance, walking skills and participation. I understand that I will receive a signed copy of this form.

I agree that it is my responsibility to supervise my child during the VR exercise program at home.

Signature of Parent/Guardian: __________________________Date: ________________

Print name: ____

Parent's Consent and Signature: Gross Motor Function Measure Challenge Module Score

I understand that the Gross Motor Function Measure Challenge Module is a new outcome assessment being developed at the Bloorview Research Institute (Toronto, ON) and that the development of normative data for children with cerebral palsy is underway. I agree to allow my child's score on the Gross Motor Function Measure Challenge Module at the pre-study outcome assessment, age, sex, and Gross Motor Function Classification System Level to be shared with researchers at the Bloorview Research Institute in order to help build the norms for this assessment tool. No other identifiers about my child will be shared with the researchers.

Signature of Parent/Guardian: __________________________Date: ________________

Print name: ____

Consent form administered and explained in person by:

____
Name and Role in the study

_______________________________________ _______________
Signature Date

LETTER OF INFORMATION FOR CHILDREN AGE 7-12
Virtual Reality Jump-Start Study
University of Ottawa

Title of Study: A Rehabilitation ‘Jump-Start’: Does an intensive clinic-based virtual reality (VR) experience enhance the effectiveness of a home-based VR therapy program in children with CP?

Principal Investigator:

[redacted]
Physiotherapist and Postdoctoral Fellow, School of Rehabilitation Science

Dear Children,

WHY ARE WE DOING THIS STUDY?

We are doing a research study about how playing virtual reality video games might help balance and walking skills in children with cerebral palsy (CP). A research study is a way to learn more about people. Virtual reality video games involve using your body to play games on the TV screen. We are interested in the Kinect, which is a video game that you can use at home. We are also interested in another game called the IREX, which you can play at the Ottawa Children’s Treatment Centre.

WHY AM I BEING ASKED TO BE IN THE STUDY?

We are inviting kids with CP to be in the study.

WHAT IF I HAVE QUESTIONS?

You can ask questions at any time if something is difficult to understand. You or your parents can call [redacted] at [redacted].

IF I AM IN THE STUDY WHAT WILL HAPPEN TO ME?

If you want to be in this study, you will be in 1 of 2 groups.

The first group will use the Kinect at home, supervised by your parent. We will ask you to play the Kinect games for 30 minutes every day, five days each week, for six weeks. The Kinect games will be set to the right level for you. We will come to your home to set up the Kinect. We will ask you and your parent to go on to the internet to this website to type in what VR exercises you are doing on our study website. You can use the website to ask the physiotherapist questions about how to make the VR exercises harder or easier.

> The second group will exercise for an extra week at the start of the study. You will come to the Children’s Treatment Centre each day for five days to play the IREX with the physiotherapist. The physiotherapist will decide how to make the games harder or easier for you. Then, kids in this group will do the Kinect exercises at home for six weeks, and use the website to tell the physiotherapist if the exercises are too hard or too easy.

We will also ask you and your parent to come to our office at the University of Ottawa where you will do a few tests of your balance, movement and walking skills. You can help your parent answer some questions about the kinds of activities you are doing and how you feel about those activities. These tests include standing on a safe moving table so we can measure your balance. We will also ask you to do some movements like jumping jacks and walking indoors for six minutes. You will do these tests five different times. After the exercise program is over, we will ask you some questions about what you liked or didn’t like about the VR exercises.

WILL I BE HURT IF I AM IN THE STUDY?

We are asking you to take part in VR exercises that involve a lot of moving, bending, and reaching. If you haven't played the games before, the physiotherapist will help you understand what to do. If you aren't used to these kinds of movements you may feel some muscle soreness. There is also a small chance that you might fall when you are doing the VR exercises. A therapist will help you with the VR exercises at the Children's Treatment Centre, but when you are doing your VR exercises at home, you and your parents will need to make sure that you are doing the exercises safely. We will make sure that the games are at the right level for you, and if they are too hard or too easy, you can tell the physiotherapist and she will change them.

WHAT WILL I GET OUT OF BEING IN THE STUDY?

We can't promise that you will get anything out of being in the study, but we hope that you will have fun playing the games. The study will also help other therapists understand how best to use these VR games with other kids with CP. You will receive a Kinect and Xbox 360 and a few games to keep at your home for you to play once the study is done.

DO I HAVE TO BE IN THE STUDY?

You do not have to be in this study, if you do not want to be. If you decide that you don't want to be in the study after we begin, that's OK too. Nobody will be angry or upset. We talked to your parents about the study and it is okay for you to talk to them about it too.

WHAT HAPPENS AFTER THE STUDY?

When we are finished with this study we will write a report about what was learned. This report will not include your name or that you were in the study.

Thank you for your help!

[redacted]
Postdoctoral Fellow
Rehabilitation Science
University of Ottawa

ASSENT FORM FOR CHILDREN AGE 7-12
Virtual Reality Jump-Start Study
University of Ottawa

<u>If you decide you want to be in this study</u>, please print/write your name. If you decide that you don't want to be in the study, then all you have to do is ask your parents to call Danielle.

I, ________________________________ (Print your name) would like to be in this research study.

__________________________________(Date of assent)

__________________________________ (Name of person who obtained assent)

__________________________________ (Signature of person who obtained assent and Date)

__________________________________ (Principal Investigator name)

__________________________________ (PI signature and Date)

LETTER OF INFORMATION FOR YOUTH/YOUNG ADULTS AGE 13-21
Virtual Reality Jump-Start Study
University of Ottawa

Title of Study: A Rehabilitation 'Jump-Start': Does an intensive clinic-based virtual reality (VR) experience enhance the effectiveness of a home-based VR therapy program in children with CP?

Principal Investigator:

[redacted]
Physiotherapist and Postdoctoral Fellow, School of Rehabilitation Science

Co-Investigator(s), Department/Hospital/Institution:

[redacted], School of Rehabilitation Science, University of Ottawa
, School of Physical Therapy and Occupational Therapy, McGill University
, Physiotherapist, Ottawa Children's Treatment Centre
, Physiatrist, Children's Hospital of Eastern Ontario
, Faculty of Medicine, University of Ottawa
Richard Mills, PhD Student, School of Human Kinects, University of Ottawa

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Dear Youth/Young Adult,

You are being invited to participate in a research study to evaluate the effect of two different Virtual Reality (VR) exercise programs on balance, physical activity and participation in children, youth and young adults with cerebral palsy (CP). In order to decide whether or not you want to be a part of this research study, you should understand what is involved and the potential risks and benefits. This form gives detailed information about the research study, which will be discussed with you. Once you understand the study, you will be asked to sign this form if you would like to participate. Please take your time to make your decision. Feel free to discuss it with your friends and family.

This study is funded by research grants from the Ontario Federation for Cerebral Palsy and the Ottawa Children's Treatment Centre. Part of the information from this study will be used as part of Richard Mills' PhD student project.

WHY ARE WE DOING THIS STUDY?

Many youth and young adults with CP have balance impairments that interfere with functional mobility and participation in physical activities. Using VR systems as part of physiotherapy exercise programs for children and youth with CP is a new area of research and clinical practice. We have developed exercise programs using the Kinect for Xbox 360 (Microsoft) and the Interactive Rehabilitation Exercise System (IREX; GestureTek), common VR systems that can be used in rehabilitation to help children and youth practice balance and movement skills. We would like to understand whether these exercise programs are effective at improving balance, walking skills and participation in physical activities. Both systems involve games with which you interact using body movements, but the IREX can only be used at a rehabilitation centre, while the Kinect can be used at home.

The purpose of this study is to compare the effect of a 6-week Kinect home-based exercise program alone to the same program that begins with an intense *'jump-start'* 1-week IREX exercise program on improving balance, walking skills and participation in physical activities in children and young adults with CP. Other research studies have shown that a 1-week IREX exercise program has a positive impact on balance and functional mobility in adolescents with CP. We don't yet know whether the Kinect works to improve balance and walking skills. This study is unique and important because it will help to provide this evidence for the Kinect and give us information about whether the clinic-based '*jump-start'* is necessary.

WHY AM I BEING ASKED TO BE IN THE STUDY?

We are inviting children, adolescents and young adults with CP to be in the study.

WHAT IF I HAVE QUESTIONS?

You can ask questions if you do not understand any part of the study. If you have questions later that you don't think of now, you or your parents can call [redacted], the study investigator, again at [redacted].

WHAT WILL BE MY RESPONSIBILITIES IF I TAKE PART IN THE STUDY?

If you volunteer to participate in this study, you will be participating in one of two different VR exercise programs. Both programs are aimed at improving your balance, walking ability and self-confidence to participate in physical activities. One program occurs at home using the Kinect for 6 weeks. You will come into OCTC or the Motor Control Laboratory on one occasion at the beginning of the study so that you can experience playing the Kinect games and the therapist can set up the exercise program. You will be asked to use the Kinect at least 30 min/day for 5 days/week.

The second program occurs 5 times a week for the first week using the IREX delivered by a physiotherapist at OCTC or the Motor Control Laboratory (depending on your age). Then, you will exercise using the Kinect at home, for at least 30 min/day for 5 days/week.

In both programs, you will also be asked to log on at least twice per week to a website to record your physical activities and VR exercises and discuss with the physiotherapist how to make the VR exercises harder or easier.

In either program, you will also participate in 5 assessment sessions each approximately 1.5-2 hours in length: 1) At the beginning of the study, 2) at the end of the IREX exercise program (If you are in the Kinect group you will not have done any exercise during that week), 3) at the end of the 7-week exercise program, 4) 4 weeks after the end of the exercise program, and 5) 12 weeks after the end of the exercise program.

The total time involvement will be:

IREX + Kinect group:

- 1 hr/day for 5 days in a row at OCTC or the Motor Control Laboratory, plus an extra 1 hr on the last day to set up Kinect home program (not including travel time to/from OCTC)
- 2 hrs during the Kinect and website set-up home visit
- 2.5 hrs/wk at home for six weeks to participate in Kinect exercise program
- 1 hr/wk on website for 6 weeks of Kinect exercise program
- 3 hrs at the Motor Control Laboratory on 5 occasions throughout the study (not including travel time to/from the laboratory)

TOTAL: 44 hours (not including travel time)

Kinect group:

- 1 hr at OCTC or the Motor Control Laboratory to set up the Kinect home program with the physiotherapist (not including travel time to/from OCTC or Lab)
- 2 hrs during the Kinect and website set-up home visit

- 2.5 hrs/wk at home for six weeks to participate in Kinect exercise program
- 1 hr/wk on website for 6 weeks of Kinect exercise program
- 3 hrs at the Motor Control Laboratory on 5 occasions throughout the study (not including travel time to/from the laboratory)

TOTAL: 39 hours (not including travel time)

Which VR exercise program will I receive?

You will be assigned at random, that is by a method of chance (like a flip of a coin), to one of two Exercise Groups – Exercise A, or Exercise B. You will have a one in two chance of being in the group that receives Exercise A – Kinect practice; and a one in two chance of being in the group that receives Exercise B – IREX + Kinect practice.

VR Exercise Programs: Description

Exercise A: Kinect practice
- The physiotherapist will develop a personalized Kinect exercise home program for the participant
- A study team member visits your home to set up the Kinect system. Kinect games elicit movements that challenge balance, strength and coordination such as weight-shifting, standing on one leg, reaching to the side, squatting and jumping
- Participants exercise using the Kinect at home at least 30 min/day, 5 days per week for 6 weeks. Participants must keep track length of each exercise session.
- **WEBSITE:** Participants use the website to keep track of their Kinect activities and to interact with the physiotherapist about how to progress Kinect activities. For example, therapists might recommend that children adapt the games in some way, such as by holding a weight or standing on one leg.

Exercise B: IREX + Kinect practice
- Week 1: Participants exercise for 1 hour every day for 5 days using the IREX system at OCTC.
- The physiotherapist will develop a personalized IREX exercise program for the participant.
- The therapist may provide verbal feedback and physical guidance
- IREX games elicit movements that challenge balance, strength and coordination such as weight-shifting, standing on one leg, reaching to the side, squatting and jumping
- Difficulty levels of games can be progressed as performance improves
- Weeks 2-7:
- The physiotherapist will develop a personalized Kinect exercise home program for the participant
- A study team member visits your home to set up the Kinect system. Kinect games elicit movements that challenge balance, strength and coordination such as weight-shifting, standing on one leg, reaching to the side, squatting and jumping
- Participants exercise using the Kinect at home at least 30 min/day, 5 days per week for 6 weeks. Participants must keep track length of each exercise session.

WEBSITE: Participants use the website to keep track of their Kinect activities and to interact with the physiotherapist about how to progress Kinect activities. For example, therapists might recommend that children adapt the games in some way, such as by holding a weight or standing on one leg.

Who will provide the VR exercise programs?

The IREX exercise program will be provided by a physiotherapist. The physiotherapist will make decisions about which games to use and how to progress the exercise program.

The physiotherapist will make decisions about which Kinect games to use and how to progress the exercise program. The Kinect exercises will be done at home and depending on your age, should be supervised by your parent. You and/or your parent can interact frequently with the physiotherapist via the website or telephone to progress Kinect activities or discuss any problems that you are having.

Where will the study activities take place?

IREX exercise will take place at the Ottawa Children's Treatment Centre or at the Motor Control Laboratory. Kinect exercise will take place at your home. All of the outcome assessments will take place at the Motor Control Laboratory at the University of Ottawa Lees Campus at 200 Lees Avenue.

Outcome Assessment

The results of the two different VR exercise programs will be compared to see if one program is better than the other. In order to compare the effect of these two programs, you will be assessed at five different times –

- 1) Before beginning the exercise program,
- 2) At the end of the IREX exercise program (Kinect group participants will not have received any exercise yet)
- 3) At the end of the 6 week exercise program,
- 4) 4 weeks after the exercise program is finished, and
- 5) 12 weeks after the exercise program is finished.

On all five occasions, study investigators and a trained physiotherapist will assess you. This therapist will be unaware of which therapy group to which you have been assigned.

Your assessment will include the following tests and questionnaires:

1. **Demographic information:** On the first assessment we will ask you to fill out a short questionnaire asking about your age, grade level, CP diagnosis, experience with the Kinect and involvement in recreational and organized sports activities.
2. **Balance test:** You will stand on a platform that is moved using a hydraulic motor. We will measure you balance using a force plate that you stand on while the platform moves forwards and backwards. Small disks will be placed on your skin over 6 muscles of the leg and back to record muscle activity. For best recordings, a light shaving of the hair on your legs where the disks will be placed may be needed. You will then be asked to step onto a platform and a safety harness will be attached. You will also be required to wear form fitting shorts and a t-shirt to ensure accurate recordings.
3. **Gross Motor Function Measure Challenge Module**: This test is administered by a physiotherapist and evaluates coordination, agility, balance, speed and strength. It involves tasks like doing jumping jacks, walking backwards, and dribbling a basketball.
4. **Six Minute Walk Test**: You will be asked to walk indoors at a comfortable speed for a period of six minutes. The assessor will measure how far you were able to walk in this time period.
5. **Participation and Environment Measure for Children and Youth (PEM-CY):** A paper questionnaire that asks questions about your participation in home, school, and community settings.
6. **Physical Activity Questionnaire (Child and Adolescent versions)***:* This questionnaire asks about the amount of participation in regular physical activities performed in the past 7 days.
7. **Athletic Competence Subscale of the Self-Perception Profile (SPP) for Children/Adolescents:** This questionnaire asks how you feel about participating in athletic activities.

WHAT BENEFIT IS THIS TO YOU?

We cannot promise any personal benefits to you from your participation in this study. However, we believe benefits will likely include improvements in your balance and walking ability. You may also find that you have increased confidence in your ability to participate in physical activities. Your participation in this study may help other children and youth with CP in the future. The results of this study will help therapists choose the best available VR exercise program for children and youth with CP.

WHAT RISKS ARE INVOLVED IN THIS STUDY?

Although rare, there are some risks involved in participating in this study.

Muscle soreness: As with any exercise activity, some participants may experience some post exercise muscle soreness. This discomfort is usually mild and temporary. Warm up and cool down activities during each session will help reduce the risk of muscle discomfort or injury.

Falls: During this study, you will be practicing balance activities that you might find challenging. You may have balance problems as a result of your CP and therefore be at risk of falling during these activities. Falls can result in minor injury or even more severe injuries like a fracture. In order to reduce the risk of falls, you will receive one to one close supervision by the therapist during all IREX exercise activities and outcome assessment tests. However, Kinect activities will take place in your own home, without supervision from study personnel. The researcher will give you advice on how to make Kinect play safe in your home and the home program will be individually designed based on your balance and walking abilities. However, it is you and your parents' responsibility to ensure safe Kinect game play.

Emotional and psychological discomfort: Many people are familiar with the concept of movement-based video games, but the physiotherapist will introduce you to the games and provide instructions as to the movements that are required. Your performance on the games is not being monitored. IREX and Kinect programs will be individualized to your skill level.

WHAT DO YOU NEED TO DO?

Please ask me to explain anything you don't understand before signing the consent form. If you choose to take part in this study, please sign this form when you come for the study visit, after asking the study investigators any questions you might have.

WHAT ELSE DO YOU NEED TO KNOW?

All personal data will be kept strictly confidential. Only the researchers will have access to the data. This information will be kept for a period of five years. No personal information regarding you will be identified in the publication of the results of this study. We hope to have 20 children and young adults participating in this study.

Even if you agree to participate in the study, your participation is voluntary and you may decide to withdraw from the study at any time. There is no obligation to participate in any aspect of this project. Participating in study does not prevent you from receiving other therapy outside the study exercise programs. You will be asked to keep a record of your attendance at therapy outside of the study sessions.

WHAT HAPPENS IF I HAVE A RESEARCH-RELATED INJURY?

If you are injured as a direct result of taking part in this study, all necessary medical treatment will be made available to you at no cost. Financial compensation for such things as lost wages, disability or discomfort due to this type of injury is not routinely available. However, if you sign this consent form it does not mean that you waive any legal rights you may have under the law, nor does it mean that you are releasing the investigator(s), institution(s) and/or sponsor(s) from their legal and professional responsibilities.

WILL THERE BE ANY COSTS?

Other than the cost of parking for study visits, there are no direct costs to participating in this research project. The study will reimburse you for the costs related to parking for your study visits.

WILL I BE PAID TO PARTICIPATE IN THIS STUDY?

No, you will not be paid to participate in this study. However, no matter what group you are assigned to, you will receive a Kinect and Xbox as well as four Kinect games.

IF I HAVE ANY QUESTIONS OR PROBLEMS, WHOM CAN I CALL?

This study has been reviewed and approved by the University of Ottawa Faculty of Health Sciences Research Ethics Board. If you have any questions regarding the ethical conduct of this study, you may contact the Protocol Officer for Ethics in Research, University of Ottawa, Tabaret Hall, 550 Cumberland Street, Room 154, Ottawa, ON K1N 6N5; Tel.: (613) 562-5387; Email: ethics@uottawa.ca.

If you would like to receive more information about the study at any time, please contact the researcher, [redacted] at [redacted] or by email at [redacted]

Thank you for your help!

Yours truly,

[redacted]
Postdoctoral Fellow
Rehabilitation Science
University of Ottawa

INFORMED CONSENT FORM FOR YOUTH AND YOUNG ADULTS AGE 13-21
Virtual Reality Jump-Start Study
University of Ottawa

Youth/Young adult consent and signature

I have read the preceding information thoroughly. I have had the opportunity to ask questions, and all of my questions have been answered to my satisfaction. I agree to participate in this study. I understand that I will receive a signed copy of this form. If you decide later on that you don't want to be in the study, then all you have to do is call or ask your parents to call Danielle.

I, ________________________________ (Print your name) would like to be in this research study.

__________________________________(Date of consent)

__________________________________ (Name of person who obtained consent)

__________________________________ (Signature of person who obtained consent and Date)

__________________________________ (Principal Investigator name)

Youth/Young adult Consent and Signature: Gross Motor Function Measure Challenge Module Score

I understand that the Gross Motor Function Measure Challenge Module is a new outcome assessment being developed at the Bloorview Research Institute (Toronto, ON) and that the development of normative data for children with cerebral palsy is underway.I agree to allow my score on the Gross Motor Function Measure Challenge Module at the pre-study outcome assessment, age, sex, and Gross Motor Function Classification System Level to be shared with researchers at the Bloorview Research Institute in order to help build the norms for this assessment tool.No other identifiers about me will be shared with the researchers.

I, ____(Print your name) agree to share my GMFM Challenge Module score.

APPENDIX C

Ethical approval and renewal certificates

Université d'Ottawa University of Ottawa
Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

Health Sciences and Sciences Research Ethics Board

CONDITIONAL ETHICS APPROVAL

April 9, 2013

The University of Ottawa Health Sciences and Sciences Research Ethics Board (REB) has examined the application for ethical approval for the research project entitled "**HOW DO CHILDREN MAINTAIN THEIR BALANCE**" (File #H02-13-10) submitted by Professor Heidi Sveistrup from the Faculty of Health Sciences at the University of Ottawa.

This is to confirm that the REB, which operates in accordance with the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (2nd edition)* and other applicable laws and regulations in Ontario, has granted a conditional ethics approval for the above named research project.

Full approval may be granted upon submission of the following documents: (a) copy of approval from OCTC, (b) French translated documents, and (c) final copies of all consent and assent forms (both French and English) on official uOttawa letterhead. Recruitment and data collection may not begin until full approval has been granted. Please note that any change to the protocol and/or other documents must receive written approval from the REB.

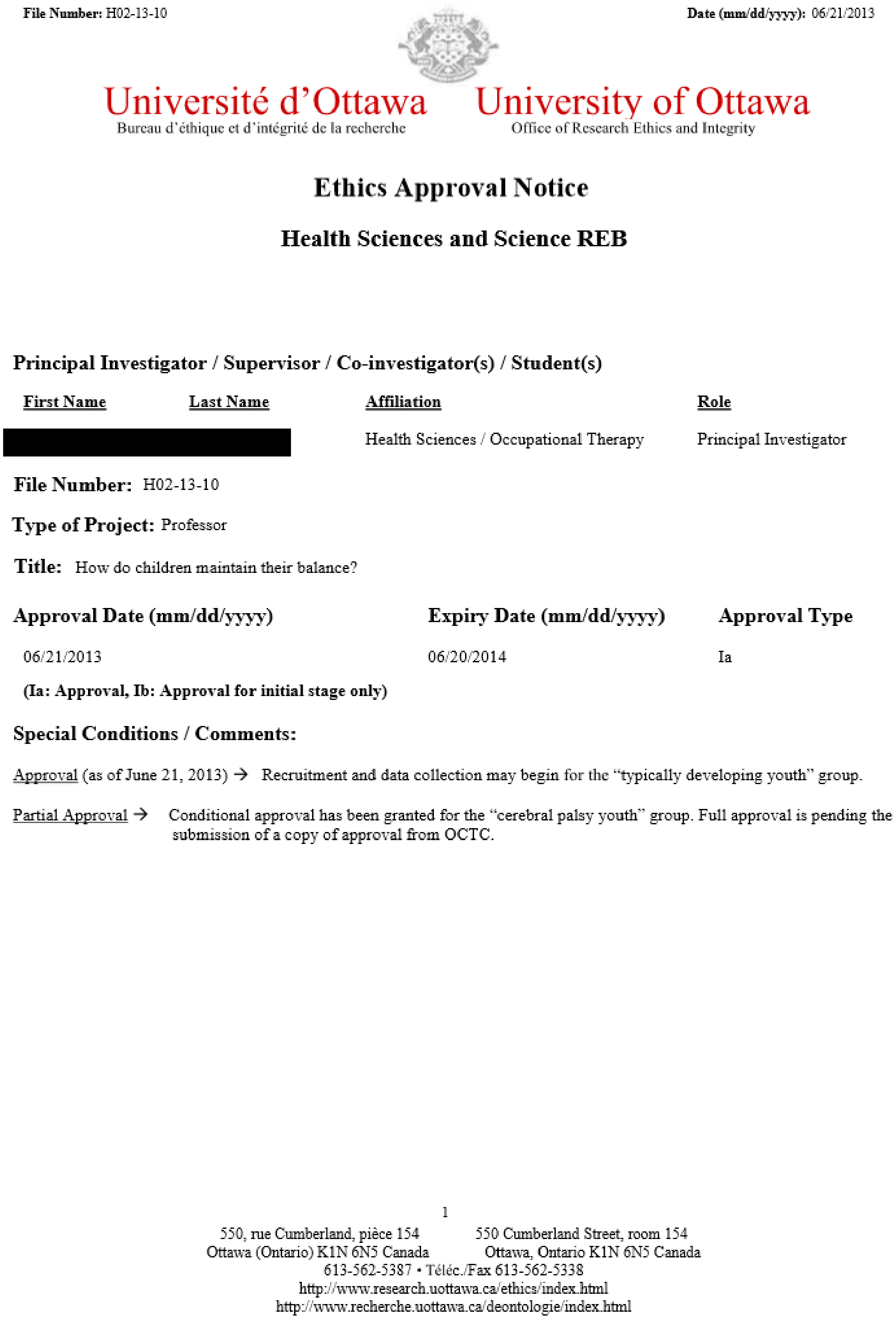
If you have any questions, please do not hesitate to contact the Ethics Office at 613-562-5387 or by e-mail at: ethics@uOttawa.ca.

[redacted]

Protocol Officer for Ethics in Research
For Daniel Lagarec, Chair of the Health Sciences and Sciences REB

550, rue Cumberland 550 Cumberland Street
Ottawa (Ontario) K1N 6N5 Canada Ottawa, Ontario K1N 6N5 Canada

(613) 562-5387 • Téléc./Fax (613) 562-5338
http://www.research.uottawa.ca/ethics/index.html



File Number: H02-13-10 **Date (mm/dd/yyyy):** 06/21/2013

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

Ethics Approval Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
[redacted]	[redacted]	Health Sciences / Occupational Therapy	Principal Investigator

File Number: H02-13-10

Type of Project: Professor

Title: How do children maintain their balance?

Approval Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
06/21/2013	06/20/2014	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:

Approval (as of June 21, 2013) → Recruitment and data collection may begin for the "typically developing youth" group.

Partial Approval → Conditional approval has been granted for the "cerebral palsy youth" group. Full approval is pending the submission of a copy of approval from OCTC.

File Number: H02-13-10 **Date (mm/dd/yyyy):** 06/21/2013

Université d'Ottawa University of Ottawa
Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

This is to confirm that the University of Ottawa Research Ethics Board identified above, which operates in accordance with the Tri-Council Policy Statement and other applicable laws and regulations in Ontario, has examined and approved the application for ethical approval for the above named research project as of the Ethics Approval Date indicated for the period above and subject to the conditions listed the section above entitled "Special Conditions / Comments".

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Please submit an annual status report to the Protocol Officer four weeks before the above-referenced expiry date to either close the file or request a renewal of ethics approval. This document can be found at: http://www.research.uottawa.ca/ethics/forms.html.

If you have any questions, please do not hesitate to contact the Ethics Office at extension 5387 or by e-mail at: ethics@uOttawa.ca.

Signature:

[redacted]

Protocol Officer for Ethics in Research
For Daniel Lagarec, Chair of the Health Sciences and Sciences REB

File Number: H02-13-10 **Date (mm/dd/yyyy):** 11/03/2014

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

Ethics Renewal Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
[redacted]		Health Sciences / Occupational Therapy	Principal Investigator
		Health Sciences / Human Kinetics	Co-investigator

File Number: H02-13-10

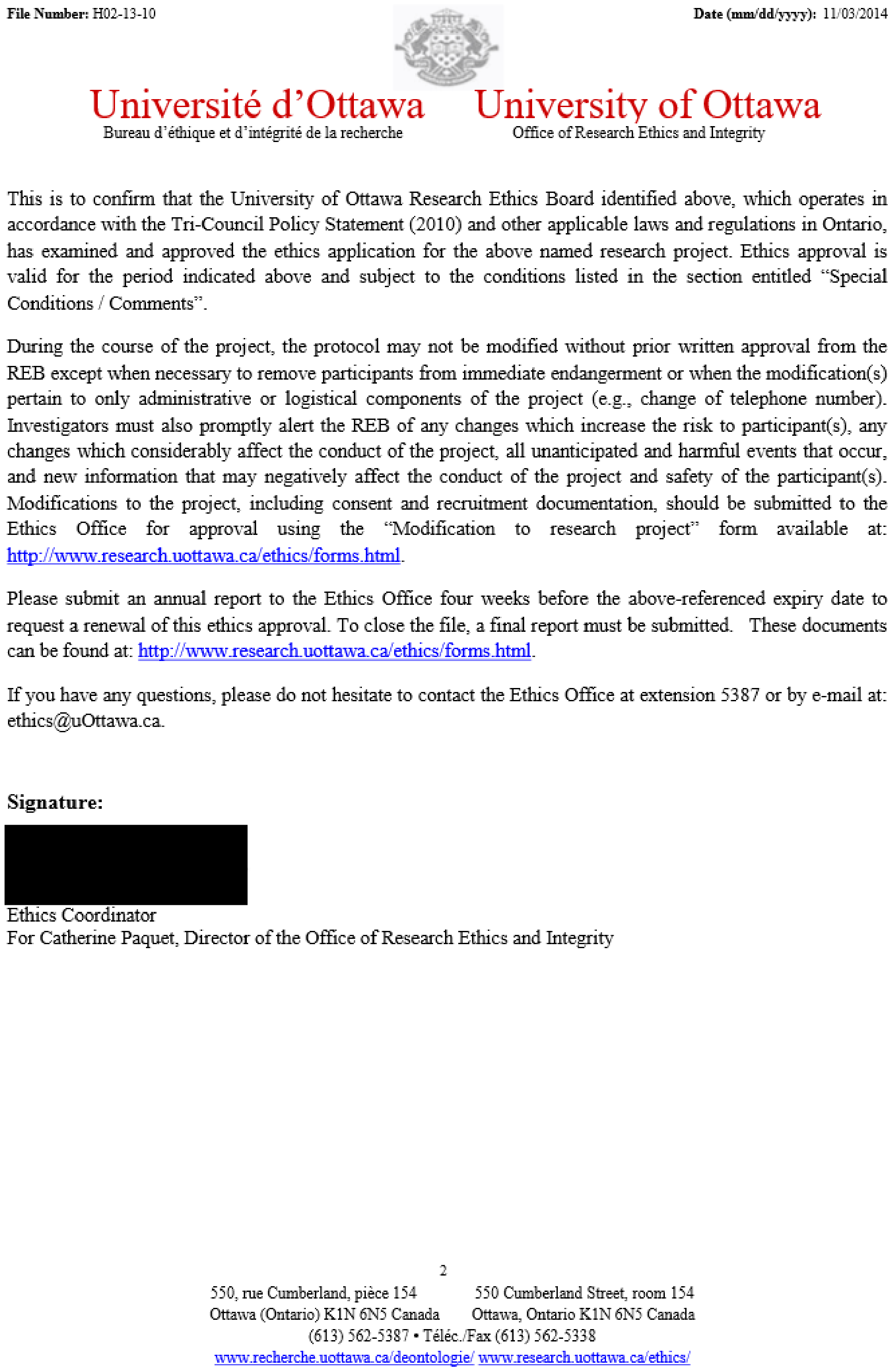
Type of Project: Professor

Title: How do children maintain their balance

Renewal Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
06/21/2014	06/20/2015	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A



File Number: H02-13-10

Date (mm/dd/yyyy): 11/03/2014

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

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Signature:

[redacted]

Ethics Coordinator
For Catherine Paquet, Director of the Office of Research Ethics and Integrity

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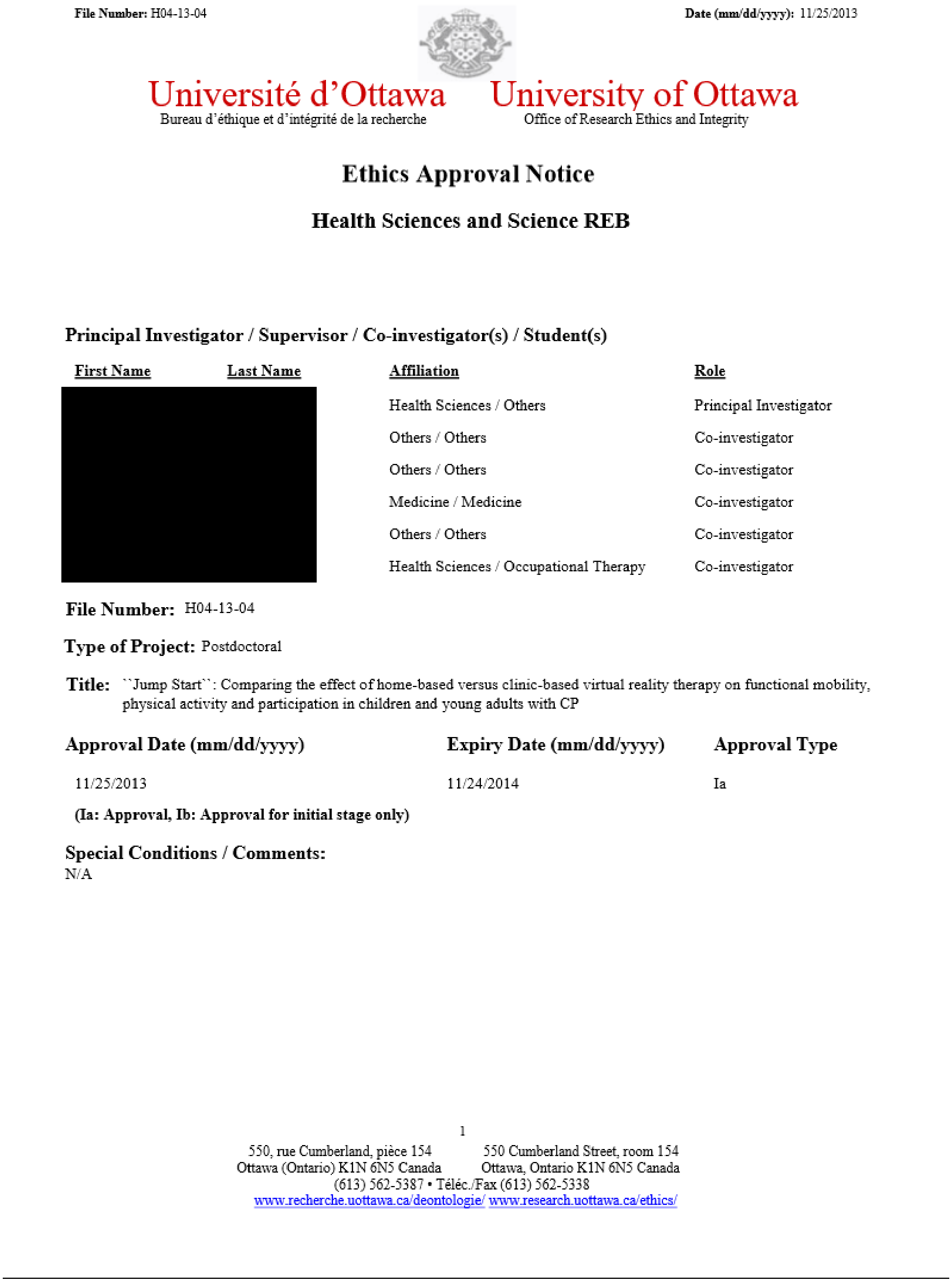
www.recherche.uottawa.ca/deontologie/ www.research.uottawa.ca/ethics/



File Number: H04-13-04 **Date (mm/dd/yyyy):** 11/25/2013

Université d’Ottawa University of Ottawa
Bureau d’éthique et d’intégrité de la recherche Office of Research Ethics and Integrity

Ethics Approval Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
[redacted]	[redacted]	Health Sciences / Others	Principal Investigator
[redacted]	[redacted]	Others / Others	Co-investigator
[redacted]	[redacted]	Others / Others	Co-investigator
[redacted]	[redacted]	Medicine / Medicine	Co-investigator
[redacted]	[redacted]	Others / Others	Co-investigator
[redacted]	[redacted]	Health Sciences / Occupational Therapy	Co-investigator

File Number: H04-13-04

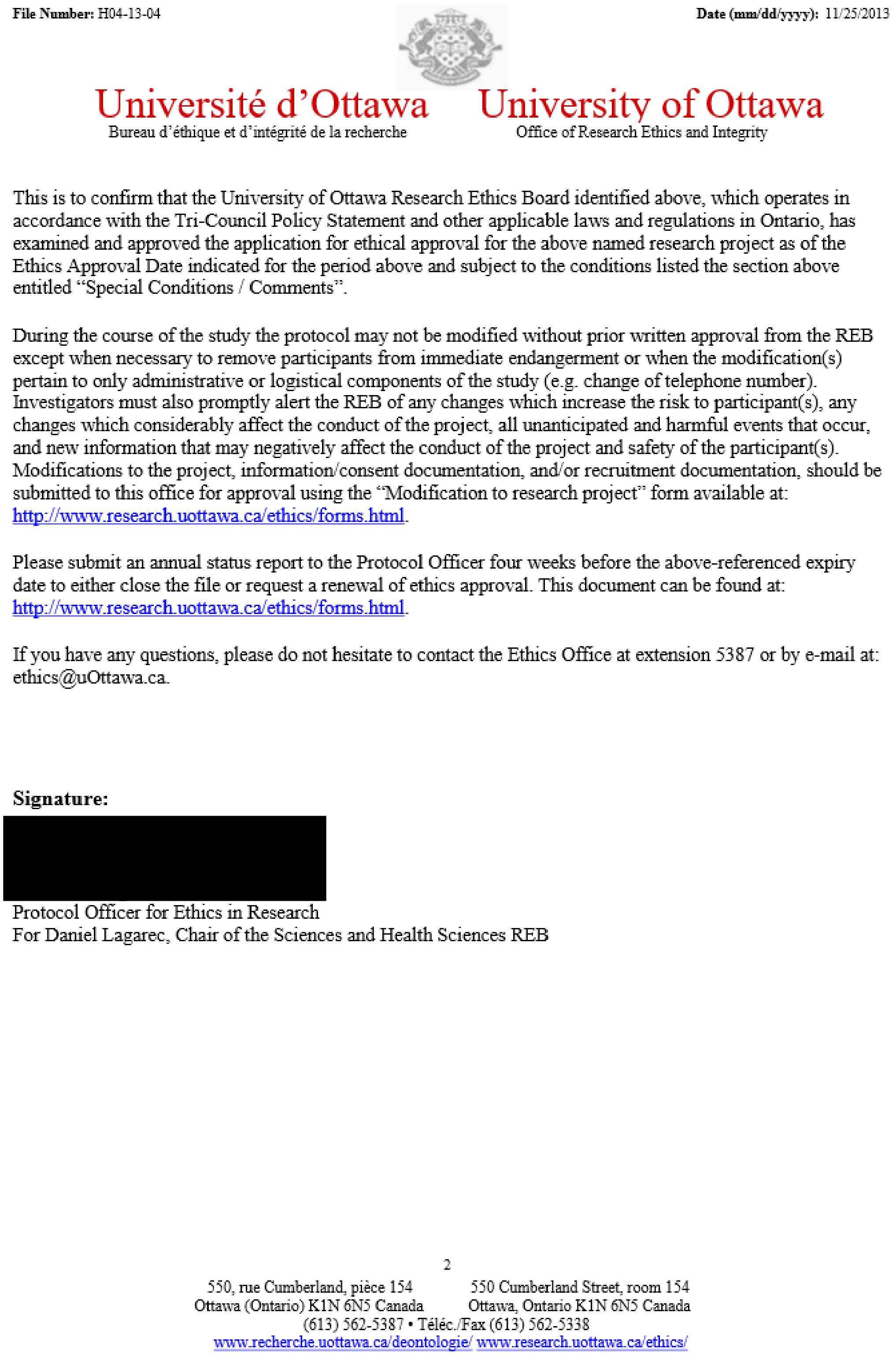
Type of Project: Postdoctoral

Title: ``Jump Start``: Comparing the effect of home-based versus clinic-based virtual reality therapy on functional mobility, physical activity and participation in children and young adults with CP

Approval Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
11/25/2013	11/24/2014	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A



File Number: H04-13-04 **Date (mm/dd/yyyy):** 11/25/2013

Université d'Ottawa
Bureau d'éthique et d'intégrité de la recherche

University of Ottawa
Office of Research Ethics and Integrity

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Signature:

[redacted]

Protocol Officer for Ethics in Research
For Daniel Lagarec, Chair of the Sciences and Health Sciences REB

File Number: H04-13-04 **Date (mm/dd/yyyy):** 11/03/2014

Université d'Ottawa University of Ottawa
Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

Ethics Renewal Notice

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

First Name	Last Name	Affiliation	Role
[redacted]	[redacted]	Health Sciences / Others	Principal Investigator
[redacted]	[redacted]	Others / Others	Co-investigator
[redacted]	[redacted]	Others / Others	Co-investigator
[redacted]	[redacted]	Medicine / Medicine	Co-investigator
[redacted]	[redacted]	Others / Others	Co-investigator
[redacted]	[redacted]	Health Sciences / Human Kinetics	Co-investigator
[redacted]	[redacted]	Health Sciences / Occupational Therapy	Co-investigator

File Number: H04-13-04

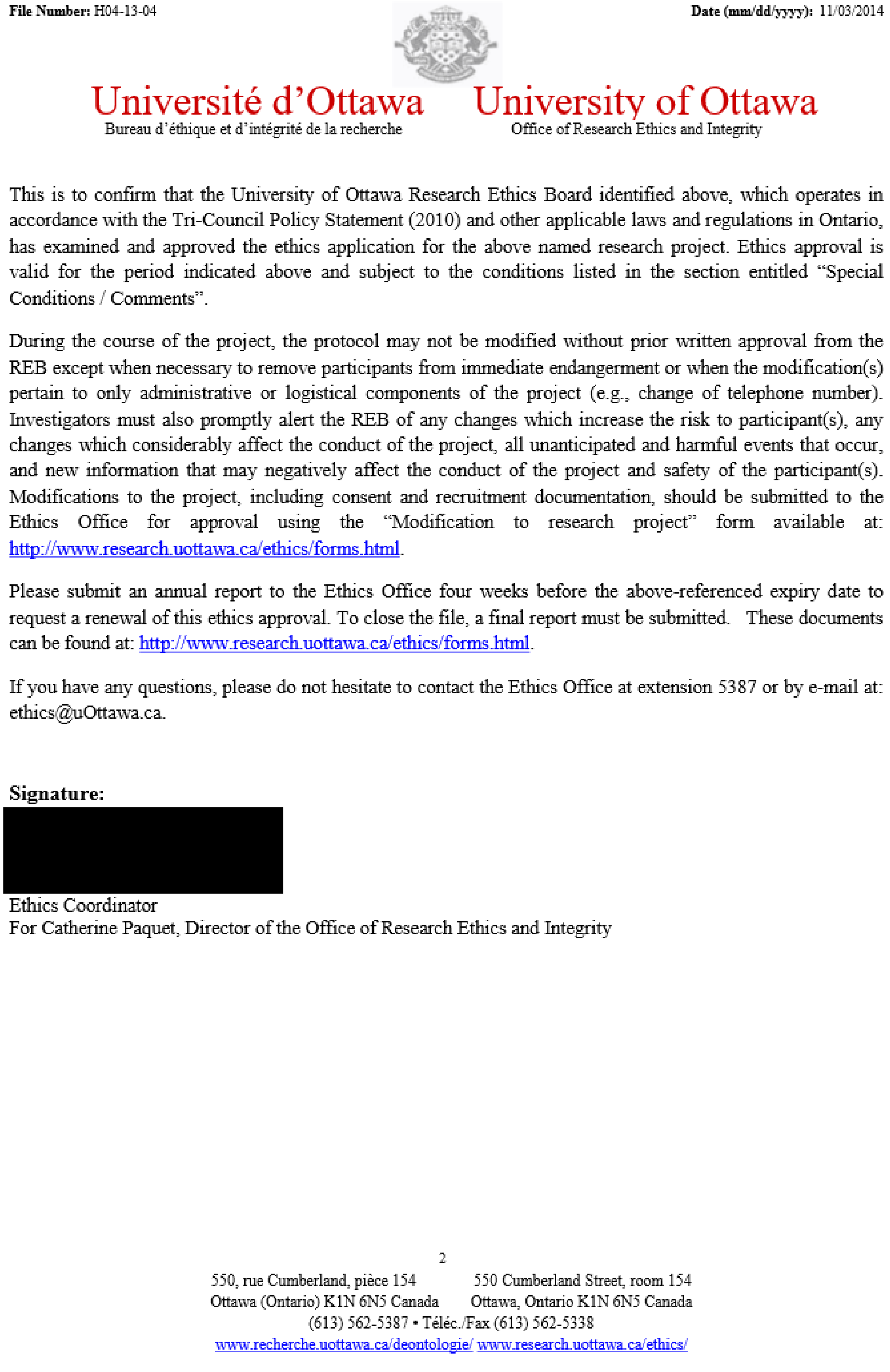
Type of Project: Postdoctoral

Title: ``Jump Start``: Comparing the effect of home-based versus clinic-based virtual reality therapy on functional mobility, physical activity and participation in children and young adults with CP

Renewal Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
11/25/2014	11/24/2015	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A



File Number: H04-13-04 **Date (mm/dd/yyyy):** 11/03/2014

Université d'Ottawa University of Ottawa
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Signature:

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Ethics Coordinator
For Catherine Paquet, Director of the Office of Research Ethics and Integrity