A Gradual vs. Sudden Introduction to Novel Locomotor Task Requirements: Consequences for Motor Learning, Balance Control and Cognitive Demand

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Abstract

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The physical rehabilitation of individuals with lower limb loss has traditionally been guided by a device driven paradigm, with much less attention, if any, allocated to the manner in which established motor learning strategies may be used to learn prosthetic locomotor skills. Much of this gap is attributable to the fact that the efficacy of most motor learning strategies has been derived from constrained upper extremity motor skills. Motor learning strategies that increase practice difficulty and the size of movement errors are thought to facilitate motor learning. In contrast to this, gradual training minimizes movement errors and reduces practice difficulty by incrementally introducing task requirements, yet remains as effective as sudden training and its large movement errors for learning novel reaching tasks. While attractive as a locomotor rehabilitation strategy, it remains unknown whether the efficacy of gradual training extends to learning locomotor tasks and their unique functional requirements. Therefore, a series of experiments were designed to examine whether gradual versus sudden training influenced the acquisition of task specific dynamics, the maintenance of lateral balance control and the cognitive demand required among unimpaired adults during training as well as 24 hour retention and transfer performance of a novel locomotor task, asymmetric split belt treadmill walking. The potential clinical application of this work was then examined by studying the ability of individuals with transtibial limb loss to use a novel powered prosthetic foot based upon either a gradual or sudden restoration of propulsive ankle power. Despite more specific and difficult practice for the sudden cohort, gradual training preserved motor learning of the novel locomotor task, reduced the challenge to lateral balance control and altered the whole-body kinematic strategy selected to regulate lateral balance while reducing the cognitive demand required during training. This suggests that large movement errors and increased practice difficulty may not be necessary for learning locomotor tasks, and that gradual training may present a viable locomotor rehabilitation strategy. Indeed, among a small cohort of individuals with unilateral transtibial limb loss, a gradual restoration of propulsive ankle power was found to promote more consistent elicitation of prosthetic peak ankle power.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Number Page

LIST OF TABLES

Table Number Page

Table 5.2. Self-selected overground walking speeds 96

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Chapter 1. GENERAL INTRODUCTION

1.1 BACKGROUND AND SIGNIFICANCE

There is an increasing level of technology emerging to provide potential therapies and interventions for individuals with locomotor impairments. This trend is particularly evident in the field of prosthetics and orthotics with the development and commercialization of powered prosthetic feet (Herr and Grabowski, 2012), knees (Sup et al., 2011), and exoskeletons (Herr, 2009) that are capable of replacing or augmenting muscle function lost or damaged as a result of neuromuscular or musculoskeletal impairments.

Coinciding with this increase in locomotor rehabilitation technology is a concurrent increase in the proportion of individuals with locomotor impairments who have additional co-morbidities and lower mobility levels. In the field of prosthetics this is exemplified by the rising incidence of dysvascular amputations (Adams et al., 1999; Dillingham et al., 2002), and the growing incidence of health conditions such as obesity and diabetes which are expected to raise the prevalence of lower limb loss in the United States to more than 3.6 million persons by the year 2050 (Ziegler-Graham et al., 2008).

Current prescription criteria and traditionally held viewpoints suggest that only the most active individuals are capable of learning to use and benefit from advanced prosthetic technology (Friel, 2005; Kaufman et al., 2007). Such a position eliminates a growing percentage of individuals with lower limb loss (LLL) from consideration for use of these emerging devices. Therefore, at a time when advanced rehabilitation technology is increasing, the size of the customary target population may actually be decreasing.

In addition to the increasing level of advanced prosthetic technology and the decreasing size of the target population, is the realization that advances in technology alone are likely insufficient. Several recently published studies have reported that in spite of the ability to restore many characteristics of normative locomotor function, advanced prosthetic technology does not eliminate all functional limitations, and in fact may create additional locomotor compensations (Aldridge et al., 2012; Ferris et al., 2012; Herr and Grabowski, 2012). While this may be attributed to a number of causes, it has been suggested that one of the primary reasons could be the lack of an established systematic training strategy for learning to use powered prostheses (Aldridge et al., 2012; Ferris et al., 2012).

It is well established that becoming proficient in a motor skill requires a tremendous amount of training (Snoody, 1926; Crossman, 1959; Ericsson et al., 1993). All things being equal, the degree of performance improvement depends on the amount of deliberate practice that is performed (Schmidt and Lee, 2005). However, the amount of practice during locomotor rehabilitation is typically limited by time, financial, personnel, and safety considerations, as well as equipment availability and physical limitations due to co-morbidities. Therefore, it is critical that practice be designed and structured to maximize training efficiency and effectiveness, particularly given the aforementioned changes in the population of individuals with lower limb loss. This can be accomplished by implementing a range of established motor learning strategies prior to, during and after deliberate physical practice (Schmidt and Lee, 2005). However, a majority of the research examining the efficacy of these motor learning strategies has been performed using constrained upper extremity or sport-related motor skills. Therefore our understanding as to the ability of these motor learning strategies to improve or restore locomotor function remains unknown. As a result, in addition to the need to develop effective locomotor rehabilitation training protocols for individuals with lower limb loss learning to use powered prostheses, there is a pressing need to first examine the influence of established motor learning strategies on the acquisition of locomotor tasks among unimpaired adults.

Research in this area will: 1) increase our understanding of whether the efficacy of established motor learning strategies generalizes to locomotor tasks and their unique functional requirements, and 2) lead to the development of locomotor rehabilitation protocols that may help alleviate locomotor impairments and activity limitations that persist in spite of advances in technology, while expanding the pool of candidates for powered prosthetic devices beyond the small percentage who make up the most active portion of the patient population.

1.2 GOALS AND SPECIFIC AIMS

It is hoped that this work will increase our understanding of motor learning principles and their application to locomotor tasks, leading to an expansion of the physical rehabilitation of individuals with lower limb loss beyond the customary device-driven paradigm to include evidence-based motor learning strategies. While there are a number of established motor learning strategies which may be used to enhance the acquisition of motor skills, this work focused on the rate at which the difficulty of a motor skill should be introduced during practice, gradually or suddenly, and how it affects whole body locomotor performance. Within the context of these overall objectives, four specific aims were proposed:

1. *Determine whether a gradual versus sudden training strategy influences how well a novel locomotor task is learned among unimpaired adults.*

    Hypothesis: Gradual training will lead to equivalent short-term learning of a novel locomotor task despite less difficult practice during initial training.

2. *Determine whether a gradual versus sudden training strategy influences lateral balance control during training and subsequent performance of a novel locomotor task among unimpaired adults.*

    Hypothesis: Compared to sudden training, gradual training will reduce the challenge to lateral balance control, and alter the whole-body frontal plane kinematic pattern selected to maintain lateral balance during training retention and transfer performance.

3. *Determine whether a gradual versus sudden training strategy influences the cognitive demand required while learning a novel locomotor task among unimpaired adults.*

   Hypothesis: The cognitive demand required while learning the novel locomotor task will be reduced by using a gradual versus a sudden training strategy.

4. *Determine whether a gradual versus sudden restoration of propulsive ankle power influences how well individuals with unilateral transtibial limb loss learn to walk with a powered prosthetic foot.*

   Hypothesis: A gradual restoration of propulsive ankle power during training will enable individuals with unilateral transtibial limb loss to elicit peak propulsive ankle power closer to physiological values and with greater consistency.

The long-term goals of this work are to:

1. Examine whether the effectiveness of established motor learning strategies generalize from upper extremity to locomotor tasks and their unique requirements,
2. Ensure efficient and effective use of emerging powered rehabilitation devices,
3. Broaden patient access to emerging powered rehabilitation devices,
4. Minimize locomotor impairments that persist in spite of advances in rehabilitation technology,
5. Drive technological innovation of powered rehabilitation devices.

1.3 SUMMARY

This dissertation was pursued in an effort to begin addressing the use of established motor learning strategies in regards to training individuals to use advanced rehabilitation technology. Of particular interest was the manner in which individuals with lower limb loss should be trained to use emerging powered prosthetic components. In accordance with these interests, this work was designed with two primary purposes. First, this work examines whether a motor learning strategy, gradual training, is able to generalize to the performance of locomotor tasks and their unique functional requirements. This involved a series of three experiments. In the first two, whole-body kinematic data were collected in order to examine task-specific motor skill acquisition and the control of lateral balance throughout training and 24 hour retention or transfer performance of a novel locomotor task. In a third experiment, the cognitive demand imposed by each training strategy was examined by comparing reaction times during a dual-task protocol.

The second purpose of this work was to explore the clinical application of gradual versus sudden training among a small sample of individuals with unilateral transtibial limb loss (TTLL) learning to use a powered prosthetic foot. In this pilot study kinetic data from the powered foot were collected and compared to physiological norms in order to explore the potential utility of a gradual or sudden restoration of powered ankle function as a viable training strategy during the physical rehabilitation of individuals with TTLL.

The knowledge gained from this research will enhance our understanding of how various characteristics of locomotor performance respond to motor learning strategies historically reserved for the acquisition of upper extremity skills. This will provide a basis with which to develop further locomotor rehabilitation protocols using additional motor learning strategies in order to enhance locomotor performance among a host of patient populations, and in particular individuals with neuromuscular or musculoskeletal impairments who are learning to use emerging powered rehabilitation technologies.

1.4 FLOW OF DISSERTATION

This dissertation is structured using a manuscript style format. Following a brief introduction and overview in the present chapter, chapters two through five represent individual manuscripts that are in various stages of preparation or submission to peer-reviewed scientific journals. Each experiment is then summarized in the final chapter.

Chapter Two investigates how a gradual versus sudden training strategy influences the acquisition, retention, and transfer of a novel locomotor task, asymmetric split belt treadmill walking. This is accomplished by comparing task-specific whole-body sagittal plane kinematics between the two training cohorts.

Using the same experimental protocol, Chapter Three reports on the challenge to lateral balance control as a function of gradual versus sudden training. The challenge to lateral balance control is assessed by examining whole-body frontal plane kinematics.

In the fourth chapter, the cognitive demand required while learning a novel locomotor task using gradual or sudden training is reported. Probe reaction times elicited during a dual-task experiment are used to infer differences in cognitive demand.

Chapter Five provides an initial assessment of gradual versus sudden training as locomotor rehabilitation strategies. In this chapter, a pilot study explores the gradual versus sudden restoration of powered ankle movement among a small cohort of individuals with transtibial limb loss.

A summary of each experiment and their major findings is presented in Chapter Six. Lastly, study limitations and suggestions for future research are presented and discussed.

Chapter 2. GRADUAL TRAINING REDUCES PRACTICE DIFFICULTY WHILE PRESERVING MOTOR LEARNING OF A NOVEL LOCOMOTOR TASK

2.1 INTRODUCTION

There exists an abundance of motor learning strategies (Schmidt and Lee, 2005) that can be used to make practice more difficult. Such an approach to training has been consistently shown to improve motor learning despite decrements in initial performance (Christina and Bjork, 1991; Schmidt and Bjork, 1992; Schmidt and Lee, 2005). Practice difficulty can also be manipulated by controlling the rate at which the task requirements of a motor skill are introduced during training. Specifically, practice difficulty can be increased by using a sudden training strategy whereby task requirements are abruptly introduced and then maintained throughout practice, an approach which results in large movement errors (Criscimagna-Hemminger et al., 2010). Alternatively, practice difficulty can be reduced by using a gradual training strategy which incrementally introduces task requirements over the course of a practice session, resulting in small movement errors which often go unnoticed by the learner (Criscimagna-Hemminger et al., 2010).

The detection of large movement errors by the cerebellum (Morton and Bastian, 2006; Shadmehr et al., 2010), and subsequent correction by the motor system is thought to be critical to sensorimotor motor learning as it drives the adaptation of movement strategies and the acquisition of motor skills (Rumelhart et al., 1986; Lisberger, 1988; Tseng et al., 2007) by updating an internal model of the interaction between the limb and the environment (Wolpert and Ghahramani, 2000). Thus, the more challenging sudden training and its large movement errors has been proposed as a means to increase practice difficulty and enhance motor learning by cueing the nervous system to make movement corrections in response to large movement errors (Reisman et al., 2010). However, a number of studies in which participants practiced visually distorted or physically perturbed reaching tasks have demonstrated that upon removal of the perturbation, individuals who received gradual training exhibited a slower rate of decay of the adapted reaching pattern, taking longer to reestablish unperturbed reaching movements; an indication that these individuals adapted to the novel reaching tasks more thoroughly than those who received sudden training (Kagerer et al., 1997; Buch et al., 2003; Huang and Shadmehr, 2009; Criscimagna-Hemminger et al., 2010; Taylor et al., 2011).

Beyond short term adaptive responses, novel reaching skills practiced using gradual training are retained as well or better than those using sudden training (Klassen et al., 2005), and appear to generalize to conditions that differ from those of original practice better than after sudden training (Malfait and Ostry, 2004). This suggests that gradual rather than sudden training results in superior motor learning. Thus it would appear that sudden training and large movement errors may not be necessary for motor learning. Therefore, gradual training may be an effective rehabilitation strategy for retraining populations where large movement errors could present substantial challenges, altering what movement strategies are selected to perform the task and how well they are learned. Additionally, not all individuals are responsive to sudden training (Criscimagna-Hemminger et al., 2010; Reisman et al., 2010; Musselman et al., 2011).

To date only one study has examined the influence of gradual versus sudden training on locomotor tasks (Torres-Oviedo and Bastian, 2012). In this study of short term adaptations, gradual training resulted in a slower rate of decay of an adapted locomotor pattern, while sudden training induced greater initial adaptation to the novel locomotor task (Torres-Oviedo and Bastian, 2012). It remains unknown whether the efficacy of gradual training demonstrated for the delayed retention and transfer of novel upper extremity reaching tasks (Malfait and Ostry, 2004; Klassen et al., 2005) generalizes to the delayed retention and transfer of locomotor skills and their unique requirements. A better understanding of how or if gradual versus sudden training influences the acquisition of locomotor skills may be particularly important to locomotor rehabilitation, especially considering the emergence of powered prosthetic and exoskeleton technology. Given the rapid rate of technological advancement in the field of prosthetics and orthotics (Grill, 2007), the development of appropriate training strategies will be essential to ensure the most effective and widespread application of these devices among individuals with locomotor impairments.

The objective of this study was to determine whether gradual versus sudden training influenced how well a novel locomotor task was learned. This was accomplished by examining whole body sagittal plane kinematics during training and 24 hour retention or transfer performance of a novel locomotor task, asymmetric split belt treadmill walking (Dietz et al., 1994). We hypothesized that despite reduced practice difficulty, gradual training would result in equivalent or superior motor learning as assessed by 24 hour retention or transfer performance of the novel locomotor task.

2.2 METHODS

2.2.1 *Recruitment*

Participants were recruited from the general population of adults without impairment. Inclusion criteria were age between 18 and 50, and the ability to walk continuously for 20 minutes on a treadmill without assistance. Exclusion criteria were medical conditions, assessed by self report, which could result in impaired gait or sensory loss, including significant musculoskeletal, neurologic, or cardiopulmonary conditions and any previous split belt walking experience. Testing of this population allows for a controlled assessment of gradual versus sudden training for learning locomotor tasks prior to their implementation in rehabilitation protocols for individuals with locomotor impairments. All protocols were approved by local Institutional Review Boards. Informed consent was obtained from each participant prior to enrollment. Demographic factors including age, height, mass, gender, self-selected walking speed (SSWS) and limb dominance was recorded. SSWS was calculated from the average time over four trials required to walk a known distance of 19.63 meters, while limb dominance were assessed by self report of preferred kicking leg (Kramer and Balsor, 1990).

2.2.2 *Experimental Protocol*

A 15-minute treadmill acclimation phase, during which participants walked at a velocity of 0.7 m/s on a Bertec split belt instrumented treadmill (Bertec, Columbus, OH), was used to promote gait consistency (Zeni and Higginson, 2010). The same controlled walking speed was used for each participant to ensure that identical velocity changes were used during subsequent phases of the experiment for all participants. This provided each participant with the same training experience, strengthening the internal validity of our protocol. Following treadmill acclimation, an additional 20 strides were performed to characterize baseline walking performance. Participants were then randomly allocated to one of four cohorts: 1) gradual training and retention testing, 2) sudden training and retention testing, 3) gradual training and transfer testing, or 4) sudden training and transfer testing. Noise cancelling earphones and custom eyewear were worn throughout the experiment to control acoustic feedback from treadmill motors and visual feedback from treadmill belts.

During training all participants were asked to practice the same novel locomotor task, asymmetric split belt treadmill walking, where one leg is driven at a faster velocity than the other leg (Dietz et al., 1994). This task was chosen because it is a novel locomotor task that provides an established experimental paradigm for examining sensorimotor learning (Bastian, 2008), a process that is inherent to locomotor rehabilitation. For those participants allocated to the sudden training cohort the novel locomotor task (split belt treadmill walking) was introduced via a single abrupt change in belt velocity. The belt under the dominant leg was accelerated at 5.0 m/s^2 to reach a velocity of 1.4 m/s (2:1 walking) between heel strikes. 2:1 walking was then maintained for the remainder of the training phase, 720 consecutive strides. Similar to protocols using perturbed reaching tasks (Malfait and Ostry, 2004; Klassen et al., 2005), the gradual training cohort was introduced to split belt treadmill walking using incremental steps. Each of these steps consisted of 20 strides, over which the dominant leg belt speed was increased by 0.02 m/s using an acceleration of 0.001 m/s^2. This continued until the dominant leg belt velocity reached 1.4 m/s (2:1 walking), a transition which took 700 strides (35 blocks of 20 strides). Twenty additional 2:1 walking strides were then performed by the gradual training cohort. The magnitude of the velocity changes and the acceleration were chosen to minimize the detection of each incremental change and represent the lower limits of the treadmill controls. The number of strides taken over the course of training were the same for each cohort, 720. All participants were given the same instructions; maintain or restore a comfortable, rhythmic walking pattern. Participants were naïve to the novel locomotor task, split belt treadmill walking, as well as their allocation to gradual or sudden training. A handrail in front of the treadmill was made available, although participants were encouraged to use it only as needed.

Retention and transfer tests were performed 24 hours post training to allow sufficient time for stabilization and consolidation of motor memories created during training (Muellbacher et al., 2002; Luft et al., 2004). Prior to retention or transfer testing all participants were given 5 minutes to reacclimatize to the treadmill at 1:1 walking. The retention test consisted of the same 2:1 walking task performed during training, with the exception that all participants experienced a sudden reintroduction during retention testing. Retention testing allowed us to assess how the durability or recall of the locomotor strategy practiced the previous day was affected by gradual versus sudden training. Transfer testing consisted of a modification of the original locomotor task practiced during training, wherein the dominant leg belt speed was three times that of the non dominant leg belt, 2.1 m/s (3:1 walking). Similar to retention, a sudden reintroduction of the novel locomotor task was used during transfer testing. This branch of the experiment allowed us to assess the flexibility of the locomotor strategy, the degree to which it could be produced in a different environment from which it was originally practiced. Retention and transfer tests consisted of 400 strides. All participants were naïve regarding their allocation to the retention or transfer groups.

2.2.3 *Data Collection*

Fifty-seven reflective markers, 14 mm in diameter were placed bilaterally on the participants' bony landmarks, using an accepted whole-body marker set (Sawers and Hahn, 2012). Throughout all phases of the protocol, three-dimensional marker coordinate data were collected at 120Hz using a 12 camera Vicon MX motion capture system (Vicon, Oxford, UK) and synchronized with ground reaction force (GRF) data collected from the treadmill force platforms (Bertec, Columbus, OH) at 1200Hz for gait event detection.

2.2.4 *Data Analysis*

Raw three dimensional marker coordinate data were filtered (4th order Butterworth filter with 5 Hz low pass cutoff frequency) (Winter, 2009) and combined with participant specific anthropometric data adapted from the initial work of Dempster (Winter, 2009) to build a 15 segment whole body model in Visual 3D (C Motion, Germantown, MD)(Sawers and Hahn, 2012). Whole body center of mass (COM) position was calculated using the weighted sum of all body segments, with 15 segments representing the whole body; head neck, trunk, pelvis, upper arms, forearms, hands, thighs, shanks, and feet.

The Sagittal Inclination Angle (SIA) (Figure 2.1), a measure of limb endpoint control relative to the whole body COM, was chosen as the metric of locomotor performance.

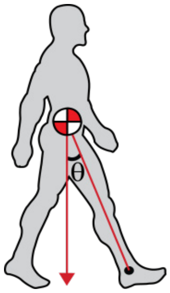

Figure 2.1 Sagittal Inclination Angle (SIA). The SIA is formed by a vector from the whole-body COM to the lateral malleolus with respect to the vertical.

It was be defined as the angle formed by a vector from the COM to the lateral malleolus with respect to the vertical in the sagittal plane (Chen and Chou, 2010),

$$\theta = \sin^{-1}\left(\frac{\vec{J}_{\text{ankle to COM}} \times \vec{J}_{\text{vertical}}}{|\vec{J}_{\text{ankle to COM}}|}\right)$$

where $\vec{J}_{\text{ankle } to \text{ COM}}$ is the vector from the ankle (lateral malleolus) to the whole body COM in the sagittal plane, and $\vec{J}_{\text{vertical}}$ is the unit vector of the vertical. The SIA was chosen as the metric for locomotor performance on the basis of previous biomechanical (McMahon and Cheng, 1990; Griffin et al., 2004), neurophysiological (Bosco et al., 1996; Bosco et al., 2000; Bosco et al., 2005), and behavioral (Lacquaniti et al., 1990; Chang et al., 2009) studies which have shown that whole limb function is an important characteristic of locomotion, specifically with respect to the whole body COM (Winter et al., 1991; Redfern and Schumann, 1994; Balasubramanian et al., 2010). Furthermore, the SIA excludes any effects of body height, making it suitable for inter-individual comparisons (Lee and Chou, 2006). A similar metric has also been shown to demonstrate adaptive qualities during split belt treadmill walking (Reisman et al., 2005). Using custom MATLAB^{TM} (MathWorks, Natick, MA) code, discrete values for the SIA were calculated on a stride by stride basis at ipsilateral heel strike for the fast (dominant) and slow (non dominant) legs. The standard deviation (SD) of the SIA was then calculated for each 20 stride bin during baseline walking, training, retention and transfer phases of the experiment. The SD reflects the amount of uncertainty in the movement pattern (Stergiou, 2004). The amount of uncertainty in a movement pattern is a useful metric for assessing recovery of sensorimotor control (Bauby and Kuo, 2000) as it reflects the challenge or difficulty of a locomotor task (Bauby and Kuo, 2000; Donelan et al., 2004; Owings and Grabiner, 2004b). A reduction in uncertainty is thought to result from efficient execution of that movement pattern (Stergiou and Decker, 2011) and be indicative of the amount of learning that has occurred (Marteniuk, 1976). A measure of movement uncertainty also provides a more universal and less biased approach to the assessment of motor learning as it does not presume that there is an ideal kinematic movement strategy that all individuals should conform to, nor does it penalize individuals who later elect to perform the motor skill with a movement strategy that differs from initial training, a scenario likely to present itself during transfer testing. Therefore, in this study, motor learning was operationally defined as the extent to which the amount of uncertainty in the SIA during retention (2:1 walking) or transfer (3:1 walking) was restored to baseline 1:1 walking levels.

To determine whether gradual versus sudden training influenced how well the novel locomotor task was learned, we calculated the Average Uncertainty Residual (AuR) of the SIA for the fast (dominant) and slow (non dominant) legs during training, retention and transfer. The AuR was defined as the mean difference in the SIA uncertainty (SD) between baseline 1:1 walking (20 strides) and each of the training, retention and transfer bins (20 strides). The lower the AuR, the closer the amount of uncertainty in the movement pattern to that of baseline 1:1 walking. During training, a lower AuR indicates less difficulty or challenge presented by the locomotor task. During retention or transfer, a lower AuR can be further interpreted as greater learning of the novel locomotor task.

2.2.5 *Statistical Analysis*

To evaluate the effect of gradual versus sudden training on the difficulty of practice and the degree of motor learning, we compared the Average Uncertainty Residual (AuR) between the gradual and sudden cohorts for the fast and slow legs during training, retention and transfer using a multivariate analysis of variance (MANOVA) (*1-tailed test, $\alpha=0.05$*). To determine whether the difficulty of practice and degree of motor learning varied by leg within each training strategy, paired t-tests (*2-tailed, $\alpha=0.05$*) were performed to compare the AuR between the fast and slow legs within each training strategy during training, retention and transfer. Differences in uncertainty between training (2:1 walking) and baseline 1:1 walking were also assessed with paired t-tests (*1-tailed test, $\alpha=0.05$*). All statistical tests were conducted using SPSS (V.19; SPSS, Inc., Chicago IL).

2.3 RESULTS

Thirty-two adults without impairment were recruited and participated in the study (Table 2.1). During training, the Average Uncertainty Residual (AuR) of the Sagittal Inclination Angle (SIA) for fast and slow legs was found to be significantly larger for the sudden versus the gradual training cohort (fast leg $p < 0.0001$; slow leg $p = 0.015$) (Figure 2.2 and Figure 2.3; Table 2.2). Within each training strategy (i.e. gradual and sudden), the AuR of the fast leg was found to be significantly lower than that slow leg during training (gradual training, $p = 0.04$; sudden training, $p = 0.049$) (Table 2.2). Additionally, the amount of uncertainty in the SIA during training was found to be significantly larger than during baseline 1:1 walking for both the fast ($p < 0.0001$) and slow ($p < 0.0001$) legs during sudden training, but only for the slow leg ($p = 0.04$) during gradual training. During retention and transfer, the AuR was not significantly different between the gradual and sudden training cohorts, for either the fast or slow leg (Figure 2.2 and Figure 2.3; Table 2.2). Within both training strategies, the AuR of the fast leg was found to be significantly lower than the slow leg during sudden retention and gradual transfer (Table 2.2).

Table 2.1. Participant demographics

Cohort		Height (m)	Mass (kg)	Age (years)	Gender[a]	SSWS (m/s)	Dominant Leg[b]
Gradual Retention (n=8)	Mean (*SD*)	1.73 (*0.10*)	67 (*12*)	33 (*8*)	4M, 4F	1.44 (*0.13*)	8R, 0L
	Range	1.60-1.85	54-89	24-50		1.23-1.67	
Sudden Retention (n=8)	Mean (*SD*)	1.71 (*0.13*)	74 (*17*)	31 (*6*)	5M, 3F	1.41 (*0.16*)	8R, 0L
	Range	1.51-1.85	49-103	25-43		1.13-1.63	
Gradual Transfer (n=8)	Mean (*SD*)	1.79 (*0.07*)	76 (*12*)	28 (*5*)	7M, 1F	1.42 (*0.10*)	7R, 1L
	Range	1.65-1.88	56-91	23-36		1.25-1.51	
Sudden Transfer (n=8)	Mean (*SD*)	1.67 (*0.12*)	67 (*9*)	28 (*4*)	2M, 6F	1.43 (*0.17*)	7R, 1L
	Range	1.52-1.85	55-83	24-36		1.12-1.70	

[a] M = Male; F = Female
[b] R = Right; L = Left

Table 2.2. The Sagittal Inclination Angle Average Uncertainty Residual (AuR) of the slow and fast legs.

Phase	Sudden Training Cohort		Gradual Training Cohort	
	Fast Leg AuR (*SD*)	Slow Leg AuR (*SD*)	Fast Leg AuR (*SD*)	Slow Leg AuR (*SD*)
Training	0.1676 (*0.07*)$^{\S, \infty, *}$	0.2556 (*0.17*)$^{\alpha, \infty, *}$	0.0371 (*0.10*)$^{\S, \blacklozenge}$	0.1138 (*0.13*)$^{\alpha, \infty, \blacklozenge}$
24 hr Retention	0.0326 (*0.08*)*	0.1542 (*0.08*)*	0.0830 (*0.14*)	0.1405 (*0.06*)
24 hr Transfer	0.2960 (*0.21*)	0.3022 (*0.16*)	0.2276 (*0.25*)$^{\blacklozenge}$	0.4685 (*0.25*)$^{\blacklozenge}$

§ = comparison of the fast leg AuR between gradual and sudden training cohorts with $p < 0.05$ during training
α = comparison of the slow leg AuR between gradual and sudden training cohorts with $p < 0.05$ during training
∞ = comparison of training uncertainty and baseline walking uncertainty with $p < 0.05$
* = comparison of fast and slow leg AuR within sudden training with $p < 0.05$
◆ = comparison of fast and slow leg AuR within gradual training with $p < 0.05$

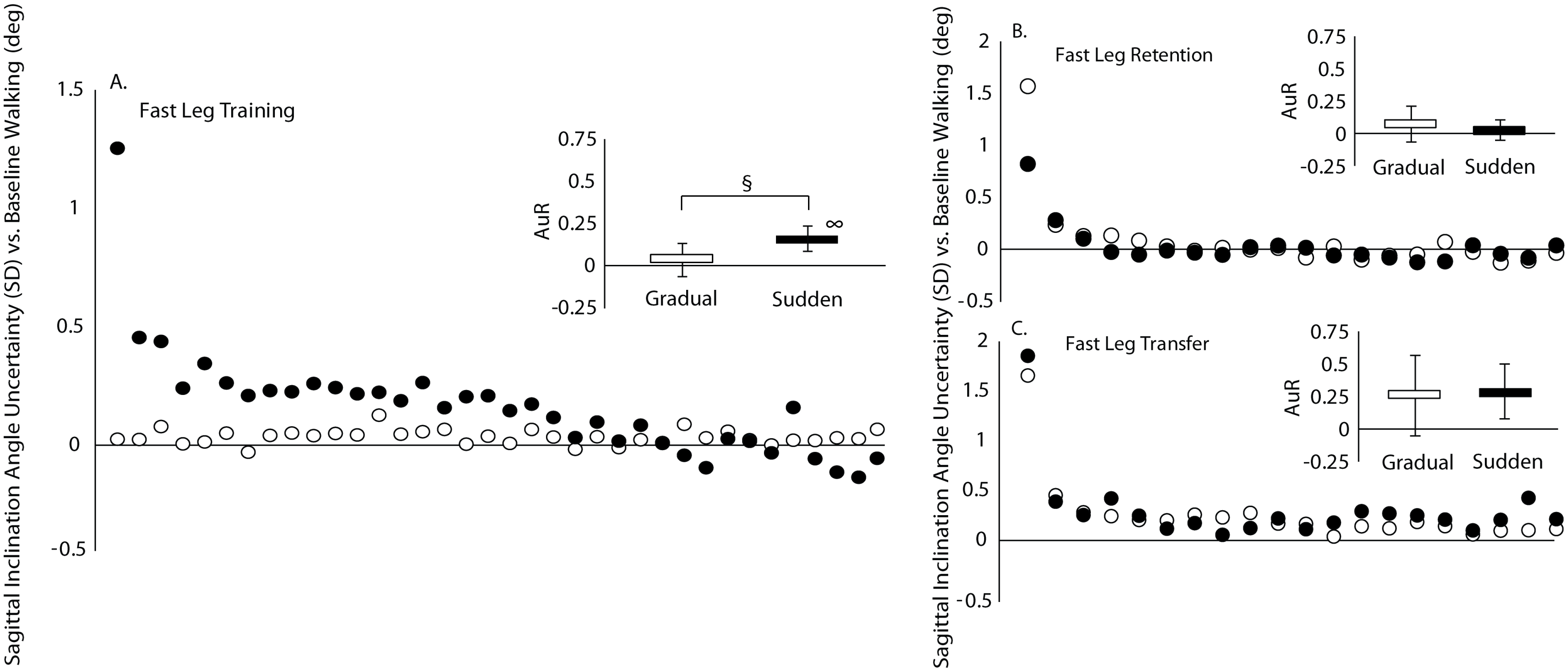

Figure 2.2. Sagittal Inclination Angle (SIA) uncertainty (SD) of the fast leg with respect to baseline walking for the gradual (○) and sudden (●) cohorts during (A) training, (B) retention, and (C) transfer. Each data point represents the average uncertainty over 20 strides with respect to baseline walking. Inset is the resulting Average Uncertainty Residual (AuR) with error bars equal to ±1SD. (A) The AuR of the fast leg during training was significantly larger during sudden vs. gradual training ($p < 0.0001$)§. The amount of uncertainty in the fast leg SIA during training was significantly greater than during baseline walking for sudden ($p < 0.0001$)$^{\infty}$, but not gradual training. No significant differences in the AuR of the fast leg were found between gradual and sudden training during (B) retention or (C) transfer.

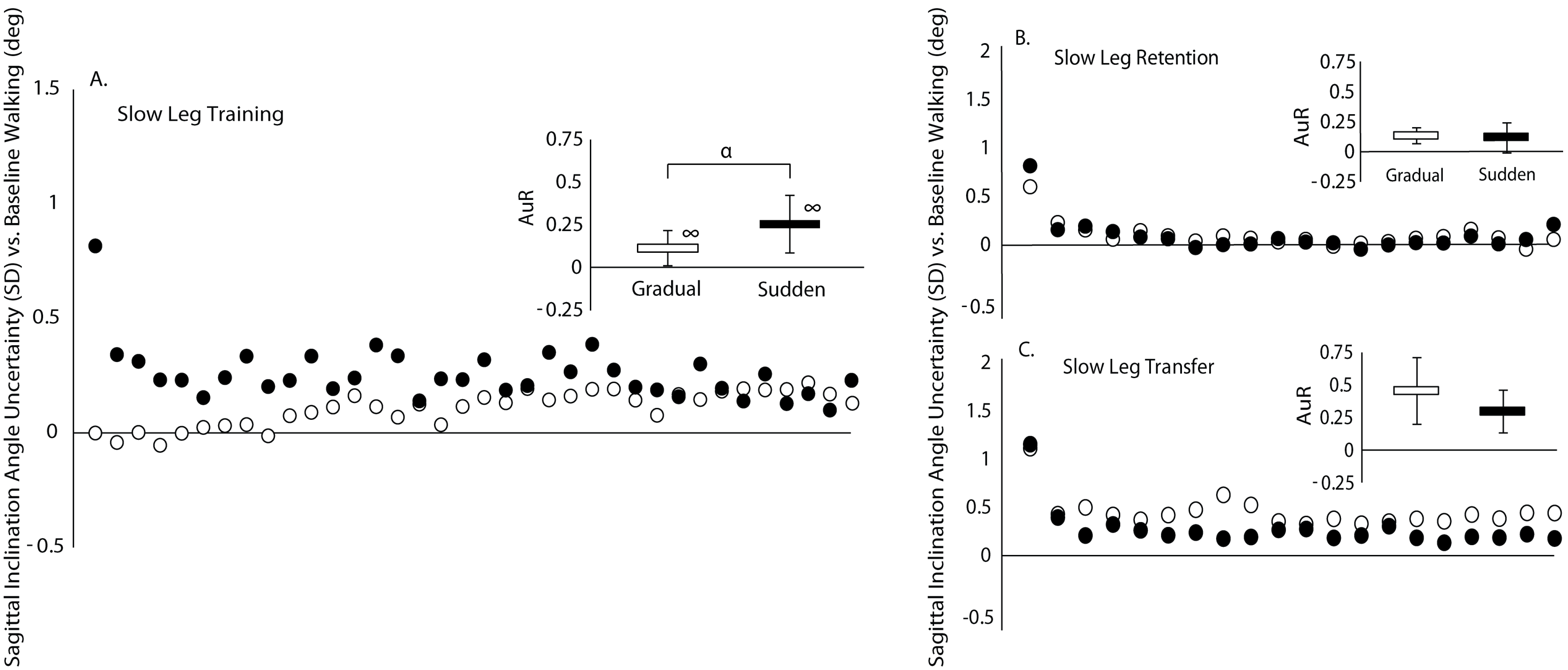

Figure 2.3. Sagittal Inclination Angle (SIA) uncertainty (SD) of the slow leg with respect to baseline walking for the gradual (○) and sudden (●) cohorts during (A) training, (B) retention, and (C) transfer. Each data point represents the average uncertainty over 20 strides with respect to baseline walking. Inset is the resulting Average Uncertainty Residual (AuR) with error bars equal to ±1SD. (A) The AuR of the fast leg during training was significantly larger during sudden vs. gradual training ($p = 0.015$)$^{\alpha}$. The amount of uncertainty in the slow leg SIA during training was significantly greater than baseline walking for both sudden ($p < 0.0001$)$^{\infty}$, and gradual training ($p = 0.04$)$^{\infty}$. No significant differences in the AuR of the fast leg were found between the gradual and sudden cohorts during (B) retention or (C) transfer.

2.4 DISCUSSION

This study sought to determine whether gradual versus sudden training influenced how well a novel locomotor task was learned. The Average Uncertainty Residual (AuR) of the Sagittal Inclination Angle (SIA) was calculated to quantify the amount of uncertainty in the whole-body sagittal plane movement pattern during training, retention or transfer with respect to baseline walking, and infer the difficulty of training and the degree of motor learning. During sudden training the AuR of the fast and slow legs were significantly larger than during gradual training, while the AuR of the slow leg was significantly larger than that of the fast leg within each training strategy (Figure 2.2 and Figure 2.3; Table 2.2). This suggests that sudden training was significantly more difficult than gradual training and that regardless of training strategy, acquisition of the slow leg whole-body sagittal plane kinematic pattern was more difficult than that of the fast leg. During sudden training the slow and fast legs were found to have a significantly greater amount of uncertainty than baseline walking, while during gradual training only the slow leg was found to have a significantly greater amount of uncertainty than baseline walking. This suggests that during sudden training both legs presented significantly more difficulty than baseline walking, while during gradual training, only the slow leg presented more difficulty than baseline walking.

During retention and transfer testing, the AuR of the fast and slow legs were found to be equivalent between the gradual and sudden cohorts (Figure 2.2 and Figure 2.3; Table 2.2). This suggests that despite more specific and challenging training for the sudden cohort on day one, both training strategies resulted in equivalent motor learning of the complex locomotor task when assessed by delayed retention and transfer.

Additionally, the gradual and sudden cohorts both exhibited a lower AuR for the fast than the slow leg during retention and transfer testing. However, this difference was only statistically significant during transfer testing of the gradual cohort and retention testing of the sudden cohort. This suggests that whole-body sagittal plane kinematic patterns of the fast leg were learned better than those of the slow leg, but only significantly so during transfer testing for the gradual cohort, and retention testing of the sudden cohort.

These results corroborate previous findings (Kagerer et al., 1997; Malfait and Ostry, 2004; Klassen et al., 2005; Kluzik et al., 2008; Criscimagna-Hemminger et al., 2010; Torres-Oviedo and Bastian, 2012) that gradual training is significantly less difficult than sudden training. Thus despite the additional performance requirements associated with a locomotor task (i.e. balance control, whole body support, maintenance of forward progression), gradual training appears equally capable of reducing the difficulty associated with practicing novel reaching or locomotor tasks. Given that a fundamental trait of gradual training is its ability to reduce movement errors and task difficulty during practice; this is an important step when considering whether gradual training may apply to locomotor rehabilitation.

To date, the only other study that has examined the influence of gradual versus sudden training on practice difficulty of a novel locomotor task focused on measures of locomotor symmetry (Torres-Oviedo and Bastian, 2012). While yielding valuable insight, the assessment of symmetry, where values for each leg are combined, may overlook important functional differences between each leg. Specifically, the present study found that regardless of whether gradual or sudden training was used, the difficulty of the novel locomotor task during training was significantly greater for the slow than the fast leg

(Table 2.2). These findings may be particularly relevant to locomotor rehabilitation as the changes experienced by the fast and slow legs during split belt treadmill walking may model those of unilateral locomotor impairments such as lower limb loss or stroke. For example, the fast leg on the treadmill during 2:1 walking and the paretic or amputated leg undergo changes to their state or condition (i.e. increased belt velocity; limb loss or paresis) as well as changes in performance requirements. Conversely, the slow leg during 2:1 walking and the unimpaired contralateral leg of an individual who has suffered a lower limb loss or stroke only undergoes a change in performance requirements, not state or condition (i.e. belt velocity does not change and the leg has no level of impairment). Based on this analogy and our results, it can be inferred that during locomotor rehabilitation, individuals with unilateral locomotor impairments may experience significant difficulty not only with re-learning the dynamics of the impaired leg, but perhaps more so with the contralateral unimpaired leg. This hypothesis may have clinical relevance for the staging and focus of locomotor rehabilitation for common unilateral locomotor impairments such as lower limb loss or stroke survivors.

To date, the influence of gradual versus sudden training on delayed retention and transfer performance has been limited to the assessment of novel upper extremity reaching tasks (Klassen et al., 2005). Klassen, et al., (2005) examined the influence of gradual versus sudden training on the retention of two novel reaching tasks. In both, participants were asked to make a reaching movement from a constant starting position to targets located 15cm radially from the start position in the horizontal plane. In one task, participants had to adapt their reaching behavior to a visuomotor rotation of their hand position, while in a second, participants had to adapt their reaching behavior to a perturbing force that was directed perpendicular to the direction of the hand velocity vector during each reaching trial. Upon re-testing participants a day later, they found that for the visuomotor reaching task, gradual and sudden training resulted in equivalent levels of performance, while for the perturbed reaching task, gradual training resulted in superior performance compared to sudden training (Klassen et al., 2005). From these results the authors concluded that gradual training is capable of producing equivalent or superior retention and thus learning of novel reaching tasks. Our results support those of equivalent retention found by Klassen, et al., (2005), but not those of superior retention, suggesting that the ability of gradual training to produce equivalent retention generalizes from upper extremity to locomotor tasks, but not the ability to produce superior retention.

Using a similar force perturbation reaching task, Malfait and Ostry (2004) examined the degree to which a gradual versus sudden introduction of the perturbing force during training influenced how well participants could transfer the acquired reaching pattern across different configurations of the same arm. In the present study we found that gradual and sudden training resulted in equivalent transfer of the novel locomotor pattern, however Malfait and Ostry (2004) reported that transfer of the novel reaching task to a different arm configuration (i.e. a different shoulder position) was greater following gradual than sudden training (Malfait and Ostry, 2004). While this discrepancy could be due to inherent differences between constrained reaching tasks and complex locomotor tasks, it is more likely due to methodological differences. Where we had gradual and sudden cohorts perform an equivalent number of trials (i.e. strides), participants in Malfait and Ostry (2004) who were allocated to the sudden cohort performed 30 reaching trials, while those allocated to the gradual training cohort performed over five times as many, 160 reaching trials. This difference in the volume of training likely favored transfer in the gradual cohort, regardless of any underlying differences between gradual and sudden training. Additionally, the transfer of the novel reaching pattern was only assessed over the first few trials of transfer testing, potentially only capturing the initial response to the perturbing force, and missing the true dynamics of the learned reaching pattern. Given these methodological differences, it would seem likely that the true influence of gradual versus sudden training on the delayed transfer of novel motor skills is one of equivalent transfer performance, rather than superior transfer performance.

While gradual training appears to make locomotor performance during practice less difficult, results from the present study indicate that the ability of gradual training to produce superior delayed retention or transfer does not appear to generalize from upper extremity to locomotor tasks. This may be due to the greater difficulty and degrees of freedom associated with locomotor versus constrained reaching tasks. However, the capacity of gradual training to produce an equivalent degree of motor learning as sudden training, while significantly reducing the difficulty of practice, should be favorably considered when weighing its potential utility to locomotor rehabilitation.

One possible explanation for how gradual and sudden training result in equivalent motor learning of a novel locomotor task despite such disparate training experiences is that during gradual training, participants may have re-weighted the available feedback used to modify their locomotor pattern during training. For every motor command two forms of consequences are produced, a sensory consequence, and a reward consequence (Izawa and Shadmehr, 2011). The sensory consequence is based upon feedback from our sensory organs regarding the sensory outcome of the movement, and forms the basis of the sensory prediction error, a critical component of motor skill adaptation (Tseng et al., 2007). The reward consequence provides a subjective measure of the utility or usefulness of the motor commands, and forms the basis of the reward prediction error (Izawa and Shadmehr, 2011). Both sensory and reward prediction errors contribute to the acquisition of a motor skill, however, the weight they are assigned can vary. When sensory prediction errors are minimized, a greater reliance may be placed on reward prediction error to drive the modification of the movement pattern during practice (Izawa and Shadmehr, 2011). Given that gradual training reduced practice difficulty in the present study, and has been previously shown to reduce movement errors and thus the size of sensory prediction errors (Criscimagna-Hemminger et al., 2010), the gradual training cohort may have relied more on the reward prediction error, compensating for any discrepancy in the availability of sensory prediction errors (Izawa and Shadmehr, 2011). Such a strategy would allow the gradual cohort to maintain a level of motor learning equivalent to the sudden cohort despite the absence of any appreciable sensory prediction error.

Alternatively, the gradual and sudden training cohorts may have acquired the novel locomotor task using different mechanisms, implicit and explicit learning respectively. While we did not set out to test whether gradual or sudden training promoted motor learning through implicit or explicit processes, anecdotal reports from the participants suggested that gradual training did support motor learning through implicit processes. Specifically, the majority of the participants receiving gradual training were unable to accurately describe the number of velocity changes that occurred in the fast belt, and frequently mischaracterized the increase in the dominant leg belt velocity as "the non-dominant leg slowing down", or "the treadmill inclining". This demonstrates an inability to accumulate explicit rules regarding task performance despite acquisition of the motor skill, a characteristic of implicit learning (Masters, 1992). This was in direct opposition to the sudden training cohort who accurately described the locomotor task, "dominant leg faster than the non-dominant leg". Additionally, another motor learning strategy, 'errorless learning' (Maxwell et al., 2001), which shares many features with gradual training, has been reported to promote implicit over explicit learning for a variety of motor skills (Masters et al., 2004; Poolton et al., 2005; Orrell et al., 2006a). While implicit and explicit processes may be used in parallel to learn a motor skill (Gentile, 1998), it seems likely that the gradual training cohort relied more on implicit processes.

These findings may have implications for future clinical research and treatment strategies. As prosthetic and orthotic technology evolves to include devices which restore physiological levels of joint power (Herr, 2009; Herr and Grabowski, 2012), effective motor learning strategies should be developed in parallel to ensure the safe and efficient application of this technology (Grill, 2007). As a starting point, consideration ought to be given to how powered movements generated by emerging powered prosthetic and exoskeleton technology should be "turned on" or restored during training. Given the ability of gradual training to promote equivalent learning of a locomotor task with much less difficulty than sudden training, a gradual restoration of powered movement may afford patients who would otherwise not be considered candidates for advanced prosthetic and orthotic technology (due to multiple co-morbidities or mobility restrictions) the opportunity to learn to use and benefit from such devices. Additionally, as gradual training avoids major perturbations and thus the need to produce an immediate response, a gradual restoration of powered movement may allow individuals to determine the most efficient way to integrate these external sources of joint power into their neuromuscular pattern, minimizing proximal and contralateral compensations.

While the use of a treadmill was essential to conducting this study, several aspects of its use may have influenced the results. The lack of optic flow associated with walking on a treadmill may have increased variability of the foot trajectories. However, the amount of variability has been reported to be equivalent between treadmill and overground walking (Owings and Grabiner, 2004a), therefore the lack of optic flow may not influence gait variability. While the use of a slower baseline walking speed was justified to prevent 2:1 and 3:1 walking speeds from becoming excessive, the slower walking speed may have increased medial lateral COM motion (Orendurff et al., 2004) during baseline walking. The 15 minute acclimation period was intended to reduce the influence of both of these concerns. We chose to calculate the amount of uncertainty in the sagittal plane movement pattern over 20 stride bins. While some debate exists as to whether this is a sufficient number of strides to capture the amount of uncertainty during locomotion (Owings and Grabiner, 2003), 20 stride bins were used because those were the increments over which the velocity of the fast treadmill belt was increased during gradual training. Extending the length of those bins would have made training longer, possibly inducing fatigue and confounding the results.

This work examined whether gradual versus sudden training influenced how well a novel locomotor task was learned by assessing one aspect of locomotor behavior, variability of whole-body sagittal plane kinematics. Additional research is required to examine whether segment angle contributions to whole-body sagittal plane kinematics are affected by training strategy, and whether different kinetic strategies are used to perform the task as a function of training strategy. Additionally, the ability of gradual versus sudden training to influence other critical features of successful locomotion such as lateral balance control, cognitive demand and movement efficiency deserve further examination.

2.5 CONCLUSION

This study found that despite more specific and difficult practice for the sudden cohort on day one, gradual and sudden training resulted in equivalent motor learning of the novel locomotor task when assessed by delayed retention and transfer. In light of these results it would appear that gradual training provides a means to learn locomotor tasks with greater ease than sudden training, a characteristic that may directly benefit locomotor rehabilitation.

2.6 BRIDGE

This first study described the ability of gradual training to reduce practice difficulty without sacrificing how well sagittal plane kinematics specific to a novel locomotor task were learned. Beyond task specific requirements, controlling lateral balance is critical for the performance of any locomotor task. To determine the effect of gradual versus sudden training on lateral balance control, a second experiment was performed where whole-body frontal plane kinematics were examined under the same experimental conditions described in this chapter. Understanding how different motor learning strategies affect lateral balance control will facilitate the development of effective locomotor rehabilitation protocols. Chapter Three presents the differences in lateral balance control that emerge from the use of gradual versus sudden training.

Chapter 3. GRADUAL TRAINING REDUCES THE CHALLENGE TO LATERAL BALANCE CONTROL DURING TRAINING AND SUBSEQENT PERFORMANCE OF A NOVEL LOCOMOTOR TASK

3.1 INTRODUCTION

The ability to maintain or restore walking balance by controlling one's center of mass with respect to one's base of support in response to continually changing environmental conditions and task requirements is a critical component of safe and purposeful bipedal locomotion (Patla, 1991; Patla and Shumway-Cook, 1999). Compared to the emphasis placed on identifying locomotor balance control mechanisms (MacKinnon and Winter, 1993; Winter, 1995; Pai and Patton, 1997; Hof et al., 2005) and impairments (Miller et al., 2001; Chou et al., 2003; Simpson et al., 2011), little attention has been paid to the potential role that common motor learning strategies implemented prior to, during, or after physical practice (Schmidt and Lee, 2005) may play in the acquisition and maintenance of locomotor balance control (Bhatt and Pai, 2008; Domingo and Ferris, 2009, 2010). This gap may be attributed to the fact that a majority of the research examining the efficacy of common motor learning strategies has been performed using constrained upper extremity or sport-related motor skills, minimizing the need or interest in assessing their influence on locomotor balance control. Therefore, the ability of common motor learning strategies to improve or restore locomotor balance control remains largely unknown. A better understanding of this area may prove essential to the development of effective locomotor rehabilitation protocols.

Among the host of available motor learning strategies, gradual training (Kagerer et al., 1997; Malfait and Ostry, 2004) presents a potentially attractive approach to improving or restoring locomotor balance control during rehabilitation. Compared to sudden training, where large movement errors are produced in response to an abrupt introduction of performance requirements, gradual training avoids the large movement errors traditionally thought to drive motor learning (Wolpert and Ghahramani, 2000) by incrementally introducing performance requirements throughout practice, effectively reducing practice difficulty (Criscimagna-Hemminger et al., 2010). In spite of this reduction in movement errors and practice difficulty, gradual training is able to maintain or improve performance on adaptive reaching tasks (Kagerer et al., 1997; Buch et al., 2003; Malfait and Ostry, 2004; Klassen et al., 2005; Michel et al., 2007; Kluzik et al., 2008; Criscimagna-Hemminger et al., 2010), and strengthen the adaptation to novel locomotor tasks (Torres-Oviedo and Bastian, 2012) when compared to sudden training. However, it remains unknown whether the efficacy of gradual training generalizes to the restoration or recovery of locomotor balance control, and specifically lateral balance control which is considered more challenging to the central nervous system (Kuo, 1999; Bauby and Kuo, 2000) and critical to successful bipedal locomotion (MacKinnon and Winter, 1993).

The objective of this study was to determine whether gradual versus sudden training influences lateral balance control during training and subsequent performance of a novel locomotor task. This was accomplished by examining whole-body frontal plane kinematics throughout training, retention, and transfer performance of a novel locomotor task; asymmetric split belt treadmill walking (Dietz et al., 1994). It was hypothesized that compared to sudden training, gradual training would reduce the challenge associated with controlling lateral balance, and result in the selection of a different whole-body frontal plane inclination angle to maintain lateral balance control during training, retention and transfer.

3.2 METHODS

3.2.1 *Recruitment*

Participants were recruited from a population of adults without impairment. Inclusion criteria were age between 18 and 50, and the ability to walk continuously for 20 minutes on a treadmill without assistance. Exclusion criteria were self-reported conditions that could impair gait, including musculoskeletal, neurologic or cardiopulmonary conditions and any previous split belt walking experience. All protocols were approved by Institutional Review Boards. Written informed consent was obtained prior to enrollment. Demographics including age, height, mass, gender, self-selected walking speed (SSWS) and limb dominance (Kramer and Balsor, 1990) were recorded.

3.2.2 *Experimental Protocol*

A 15 minute treadmill acclimation phase, during which participants walked at a velocity of 0.7 m/s on a Bertec split-belt instrumented treadmill (Bertec, Columbus, OH), was used to promote gait consistency (Zeni and Higginson, 2010). An additional 20 strides were then performed to characterize baseline walking performance. Next, participants were randomly allocated to one of four cohorts; 1) gradual training and retention testing, 2) sudden training and retention testing, 3) gradual training and transfer testing, or 4) sudden training and transfer testing. Noise cancelling earphones and custom eyewear, which blocks the lower visual field, were worn throughout the experiment to minimize acoustic feedback from treadmill motors and visual feedback from treadmill belts.

During training all participants practiced the same novel locomotor task, asymmetric split belt treadmill walking, where one leg is driven at a faster velocity than the other (Dietz et al., 1994). For participants allocated to sudden training, the novel locomotor task (split-belt treadmill walking) was introduced via a single abrupt change in belt velocity. The belt under the dominant leg was accelerated at 10.0 m/s^2 to reach a velocity of 1.4 m/s (2:1 walking) between heel-strikes. 2:1 walking was then maintained for the remainder of training, 720 consecutive strides. The gradual training cohort was introduced to 2:1 walking by incrementally increasing the belt speed. Each incremental increase occurred during a period of 20 strides, over which the dominant leg belt velocity was increased by 0.02 m/s using an acceleration of 0.001 m/s^2. This continued until the dominant leg belt velocity reached 1.4 m/s (2:1 walking), a transition which took 700 strides (35 blocks of 20 strides). Twenty additional 2:1 walking strides were then performed by the gradual cohort, for a total of 720 strides during training. The magnitude of the velocity changes and the acceleration were chosen to minimize detection of the incremental changes and represent the lower limits of treadmill motor control. Participants were given the same instructions; maintain or restore a comfortable, rhythmic walking pattern. Participants were naïve to the novel locomotor task, 2:1 walking, as well as their allocation to gradual or sudden training.

Retention and transfer tests were performed 24 hours post-training to allow sufficient time for stabilization and consolidation of motor memories created during training (Muellbacher et al., 2002; Luft et al., 2004). Prior to retention or transfer testing all participants were given 5 minutes to re-acclimate to the treadmill at 1:1 walking. The retention test consisted of the same 2:1 walking task performed during training. The transfer test consisted of a modification of the original locomotor task, wherein the velocity of the dominant leg belt was three times that of the non-dominant leg belt, 2.1 m/s (3:1 walking). Retention and transfer tests were performed with a sudden re-introduction. They provided an examination of how well lateral balance control strategies were retained and generalized following gradual or sudden training. Retention and transfer tests consisted of 400 strides.

3.2.3 *Data Collection*

Fifty-seven reflective markers were placed on participants' bony landmarks (Sawers and Hahn, 2012). Throughout all phases of the experimental protocol, three-dimensional marker coordinate data were collected at 120Hz using a 12 camera Vicon MX motion capture system (Vicon, Oxford, UK) and synchronized with ground reaction force (GRF) data collected from the treadmill force platforms at 1200Hz.

3.2.4 *Data Analysis*

Marker coordinate data were filtered (4th order Butterworth with 5 Hz low-pass cut-off) and combined with participant specific anthropometric data adapted from Dempster (Winter, 2009) to build a 15 segment whole-body model in Visual 3D (C-Motion, Germantown, MD) (Sawers and Hahn, 2012). Whole-body center of mass (COM) position was calculated using a weighted-sum approach.

The Frontal Inclination Angle (FIA) (Fig. 1), a measure of limb endpoint control relative to the COM, was chosen as the metric of lateral balance control. It was defined as the angle formed by a vector from the COM to the lateral malleolus with respect to the vertical in the frontal plane (Chen and Chou, 2010),

$$\theta = \sin^{-1}\left(\frac{\vec{\mathrm{J}}_{\text{ankle to COM}} \times \vec{\mathrm{J}}_{\text{vertical}}}{|\vec{\mathrm{J}}_{\text{ankle to COM}}|}\right)$$

where $\vec{\mathrm{J}}_{\text{ankle } to \text{ COM}}$ is the vector from the ankle (lateral malleolus) to the COM in the frontal plane, and $\vec{\mathrm{J}}_{\text{vertical}}$ is the unit vector of the vertical.

The FIA was selected as the metric for lateral balance control because lateral foot placement relative to the COM is a critical factor affecting frontal plane whole-body balance (Townsend, 1985; MacKinnon and Winter, 1993; Hof et al., 2007; Marigold and Misiaszek, 2009), and the primary means of altering COM deviations in the frontal plane (MacKinnon and Winter, 1993; Winter, 1995). The FIA is also sensitive to gait imbalance (Chen and Chou, 2010), removes the effect of stature and is not affected by walking velocity (Lee and Chou, 2006).

Using custom MATLAB$^{\text{TM}}$ (MathWorks, Natick, MA) code, discrete values for the FIA were calculated on a stride-by-stride basis at ipsilateral heel-strike for the fast (dominant) and slow (non-dominant) legs. This event in the gait cycle was chosen because of the importance it presents to maintaining frontal plane balance control during locomotion (MacKinnon and Winter, 1993; Sawers and Hahn, 2012). The mean and standard deviation (SD) of the FIA were then calculated for every 20 strides during baseline 1:1 walking, training (2:1 walking), retention (2:1 walking) and transfer (3:1 walking). The mean describes the whole-body frontal plane kinematic strategy selected to manage lateral balance control, while the SD reflects the amount of uncertainty in that movement pattern (Stergiou, 2004). The amount of uncertainty in the frontal plane movement pattern is a useful metric for assessing the acquisition or recovery of sensorimotor control of lateral balance (Bauby and Kuo, 2000) as it quantifies the challenge or difficulty presented to lateral balance control by a locomotor task (Bauby and Kuo, 2000; Donelan et al., 2004; Owings and Grabiner, 2004b; Richardson et al., 2004; Arellano and Kram, 2011).

To determine whether gradual versus sudden training influenced the challenge associated with maintaining lateral balance control, we calculated the Average Uncertainty Residual (AuR) of the FIA for the fast (dominant) and slow (non-dominant) legs during training, retention and transfer. The AuR was defined as the mean difference in FIA uncertainty (SD) between baseline 1:1 walking (20 strides) and each block of 20 strides during training, retention and transfer. The lower the AuR, the closer the amount of uncertainty in the movement pattern to that of baseline 1:1 walking, and the lower the challenge to lateral balance control. To determine whether different whole-body frontal plane kinematic strategies emerged from gradual versus sudden training we calculated the Average Angular Residual (AAR) of the FIA for the fast (dominant) and slow (non-dominant) legs. For training the AAR was defined as the mean difference in the FIA between baseline 1:1 walking (20 strides) and the last 20 strides of training. For retention and transfer, the AAR was defined as the mean difference in FIA between baseline 1:1 walking (20 strides) and each block of 20 strides during retention and transfer. The larger the AAR, the greater is the change in the whole-body frontal plane kinematic strategy from baseline 1:1 walking.

3.2.5 *Statistical Analysis*

To evaluate the effect of gradual versus sudden training on the challenge to lateral balance control during training, retention, and transfer, a multivariate analysis of variance

(MANOVA) was performed to compare the Average Uncertainty Residual (AuR) between the gradual and sudden cohorts for both the fast and slow legs during training, retention and transfer testing (*1-tailed test, $\alpha=0.05$*). Differences in lateral movement uncertainty between 2:1 training and baseline 1:1 walking were assessed with paired t-tests (*1-tailed test, $\alpha=0.05$*). The same analyses were performed for the Average Angular Residual (AAR) to examine the effect of gradual versus sudden training on the frontal plane kinematic movement strategies selected to maintain lateral balance control. All statistical tests were conducted using SPSS (V.19; SPSS, Inc., Chicago IL).

3.3 RESULTS

Thirty-two adults without impairment were recruited and participated in the study (Table 3.1). During 2:1 training, the Average Uncertainty Residual (AuR) of the Frontal Inclination Angle (FIA) for the fast and slow legs was found to be significantly larger for the sudden versus the gradual training cohort (fast leg, $p < 0.001$; slow leg, $p = 0.042$) (Figure 3.1 and Figure 3.2; Table 3.2). Additionally, the amount of uncertainty in the FIA during 2:1 training was found to be significantly larger than during baseline 1:1 walking for the fast and slow legs during sudden (fast-leg, $p < 0.001$; slow-leg, $p < 0.001$), but not during gradual training (fast-leg, $p = 0.060$; slow-leg, $p < 0.101$) (Figure 3.1 and Figure 3.2; Table 3.2). During retention and transfer testing the AuR of the fast leg was significantly larger for the sudden than the gradual training cohort (fast-leg retention, $p = 0.003$; fast-leg transfer, $p = 0.005$), while the AuR of the slow leg was significantly larger for the sudden than the gradual training cohort during transfer, but not retention (slow-leg retention, $p = 0.432$; slow-leg transfer, $p = 0.035$) (Figure 3.1 and Figure 3.2; Table 3.2).

Despite a notable difference throughout training, the Average Angular Residual (AAR) of the FIA over the last 20 strides of training was not significantly different between the gradual or sudden cohorts for either the fast or slow leg (fast leg, $p = 0.071$; slow leg, $p = 0.651$) (Figure 3.3 and Figure 3.4; Table 3.3). Over the last 20 strides of training the FIA of the fast leg was significantly larger than during baseline 1:1 walking among the sudden but not the gradual training cohort (gradual, $p = 0.234$; sudden, $p = 0.001$) (Figure 3.3 and Figure 3.4; Table 3.3), while the FIA of the slow leg was significantly smaller compared to baseline 1:1 walking for both the sudden and gradual training cohorts (gradual, $p = 0.044$; sudden, $p < 0.001$) (Figure 3.3 and Figure 3.4; Table

3.3). During retention testing, the AAR of the FIA for the fast but not the slow leg was significantly larger among the sudden training cohort (fast-leg retention, p = 0.023; slow-leg retention, p = 0.904) (Figure 3.3 and Figure 3.4; Table 3.3). During transfer testing, the AAR of the FIA for the slow but not the fast leg was significantly larger among the sudden training cohort (fast-leg transfer, p = 0.772; slow-leg transfer, p = 0.041) (Figure 3.3 and Figure 3.4; Table 3.3).

Table 3.1. Participant demographics

Cohort		Height (m)	Mass (kg)	Age (years)	Gender[a]	SSWS (m/s)	Dominant Leg[b]
Gradual Retention (n=8)	Mean (*SD*)	1.73 (*0.10*)	67 (*12*)	33 (*8*)	4M, 4F	1.44 (*0.13*)	8R, 0L
	Range	1.60-1.85	54-89	24-50		1.23-1.67	
Sudden Retention (n=8)	Mean (*SD*)	1.71 (*0.13*)	74 (*17*)	31 (*6*)	5M, 3F	1.41 (*0.16*)	8R, 0L
	Range	1.51-1.85	49-103	25-43		1.13-1.63	
Gradual Transfer (n=8)	Mean (*SD*)	1.79 (*0.07*)	76 (*12*)	28 (*5*)	7M, 1F	1.42 (*0.10*)	7R, 1L
	Range	1.65-1.88	56-91	23-36		1.25-1.51	
Sudden Transfer (n=8)	Mean (*SD*)	1.67 (*0.12*)	67 (*9*)	28 (*4*)	2M, 6F	1.43 (*0.17*)	7R, 1L
	Range	1.52-1.85	55-83	24-36		1.12-1.70	

[a] M = Male; F = Female
[b] R = Right; L = Left

Table 3.2. The Frontal Inclination Angle Average Uncertainty Residual (AuR) of the slow and fast legs.

Phase	Sudden Training Cohort		Gradual Training Cohort	
	Fast Leg AuR (*SD*)	Slow Leg AuR (*SD*)	Fast Leg AuR (*SD*)	Slow Leg AuR (*SD*)
Training	0.20 (*0.07*)$^{\S, \infty}$	0.11 (*0.10*) $^{\alpha, \infty}$	0.04 (*0.10*)§	0.04 (*0.12*)$^{\alpha}$
24 hr Retention	0.14 (*0.05*)$^{\Omega}$	0.01 (*0.14*)	0.01 (*0.13*)$^{\Omega}$	0.001 (*0.06*)
24 hr Transfer	0.26 (*0.11*)$^{\Psi}$	0.22 (*0.04*) $^{\Phi}$	0.10 (*0.10*)$^{\Psi}$	0.09 (*0.18*)$^{\Phi}$

§ = represents a comparison of the fast leg AuR between gradual and sudden cohorts during 2:1 training, $p < 0.05$
α = represents a comparison of the slow leg AuR between gradual and sudden cohorts during 2:1 training, $p < 0.05$
∞ = represents a comparison of 2:1 training uncertainty and baseline 1:1 walking uncertainty, $p < 0.05$
Ω = represents a comparison of the fast leg AuR between gradual and sudden cohorts during retention, $p < 0.05$
Ψ = represents a comparison of the fast leg AuR between gradual and sudden cohorts during transfer, $p < 0.05$
Φ = represents a comparison of the slow leg AuR between gradual and sudden cohorts during transfer, $p < 0.05$

Table 3.3. The Frontal Inclination Angle Average Angular Residual (AAR) of the slow and fast legs during training, retention and transfer.

Phase	Sudden Training Cohort		Gradual Training Cohort	
	Fast Leg AAR (*SD*)	Slow Leg AAR (*SD*)	Fast Leg AAR (*SD*)	Slow Leg AAR (*SD*)
Training	0.68 (*0.63*)$^{\infty}$	- 0.57 (*0.50*)$^{\infty}$	0.23 (*0.74*)	- 0.46 (*0.84*)$^{\infty}$
24 hr Retention	1.4 (*1.09*)§	- 0.45 (*0.50*)	0.11 (*0.90*)§	- 0.51 (*1.26*)
24 hr Transfer	0.94 (*0.79*)	- 2.02 (*0.74*)$^{\alpha}$	1.07 (*0.89*)	- 0.94 (*1.13*)$^{\alpha}$

∞ = represents a comparison of 2:1training and baseline 1:1 walking uncertainty with $p < 0.05$
§ = represents a comparison of the fast leg AAR between gradual and sudden cohorts during retention, $p < 0.05$
α = represents a comparison of the slow leg AAR between Gradual and Sudden cohorts during transfer, $p < 0.05$

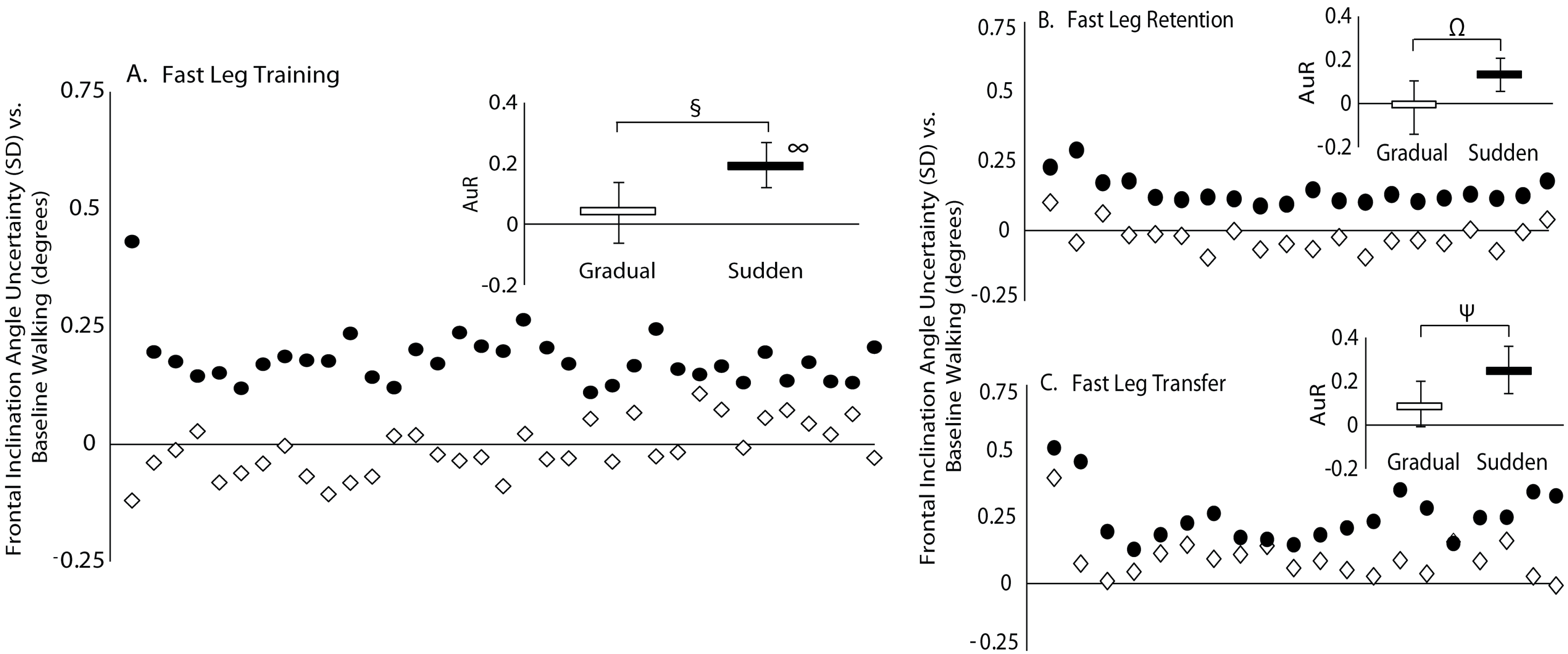

Figure 3.1. Frontal Inclination Angle (FIA) uncertainty (SD) of the fast leg with respect to baseline walking for the gradual (◇) and sudden (●) cohorts during training (A), retention (B), and transfer (C). Each data point represents the average uncertainty over 20 strides with respect to baseline walking. Inset is the resulting Average Uncertainty Residual (AuR) with error bars equal to ±1SD. (A) The AuR of the fast leg during training was significantly larger during sudden vs. gradual training (fast leg, $p < 0.001)^{\S}$. The amount of uncertainty in the fast leg FIA during training was significantly greater than during baseline walking for sudden and gradual Training $(p < 0.001)^{\infty}$. The AuR of the fast leg was significantly larger for the sudden than the gradual training cohort during retention (B) and transfer (C) testing, (fast leg retention, $p = 0.003)^{\Omega}$, (fast leg transfer, $p = 0.005)^{\Psi}$.

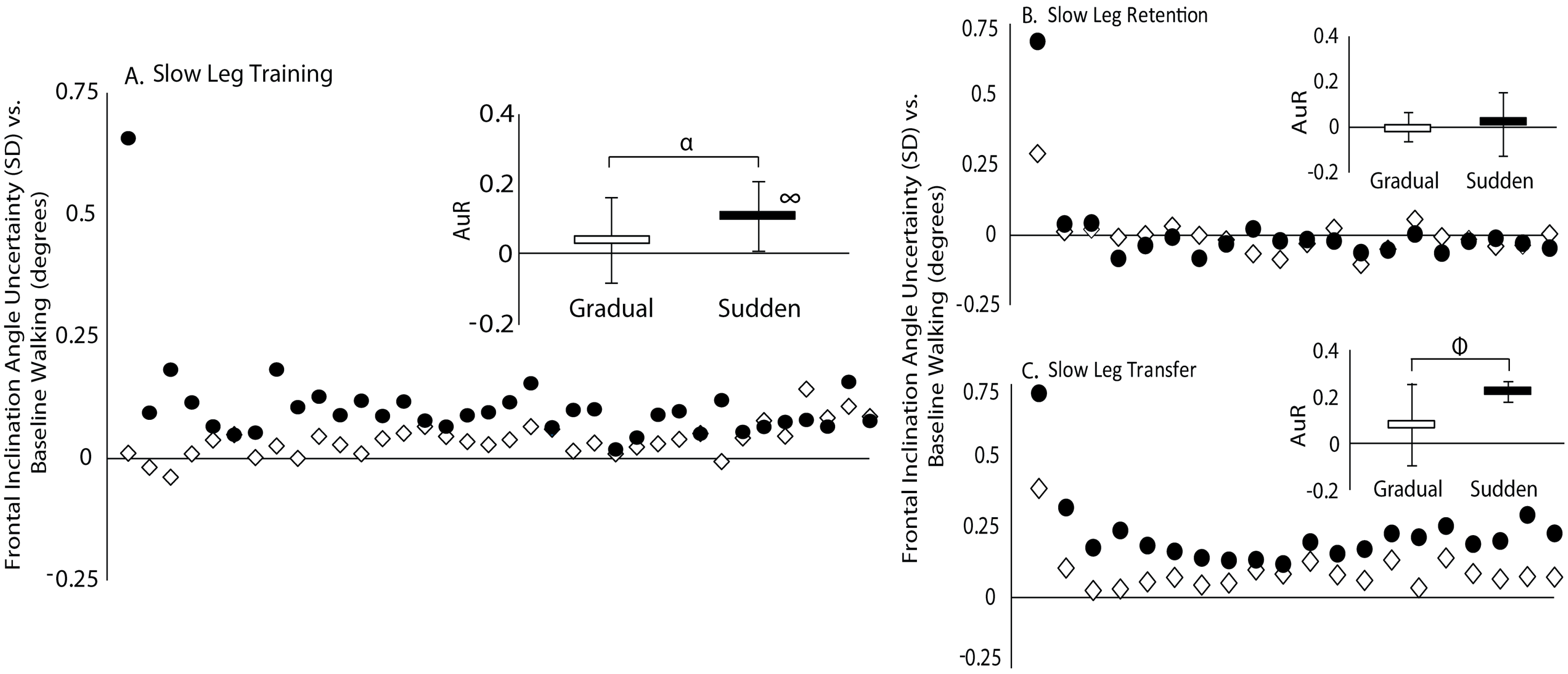

Figure 3.2. Frontal Inclination Angle (FIA) uncertainty (SD) of the slow leg with respect to baseline walking for the gradual (◇) and sudden (●) cohorts during training (A), retention (B), and transfer (C). Each data point represents the average uncertainty over 20 strides with respect to baseline walking. Inset is the resulting Average Uncertainty Residual (AuR) with error bars equal to ±1SD. (A and B) The AuR of the slow leg during training was significantly larger during sudden vs. gradual training (slow leg, $p = 0.042)^{\alpha}$. The amount of uncertainty in the slow leg FIA during training was significantly greater than during baseline walking for sudden and gradual Training $(p < 0.001)^{\infty}$. The AuR of the slow leg was significantly larger for the sudden than the gradual training cohort during transfer (F), but not retention (E) (slow leg retention, p = 0.432), (slow leg transfer, $p = 0.035)^{\Phi}$.

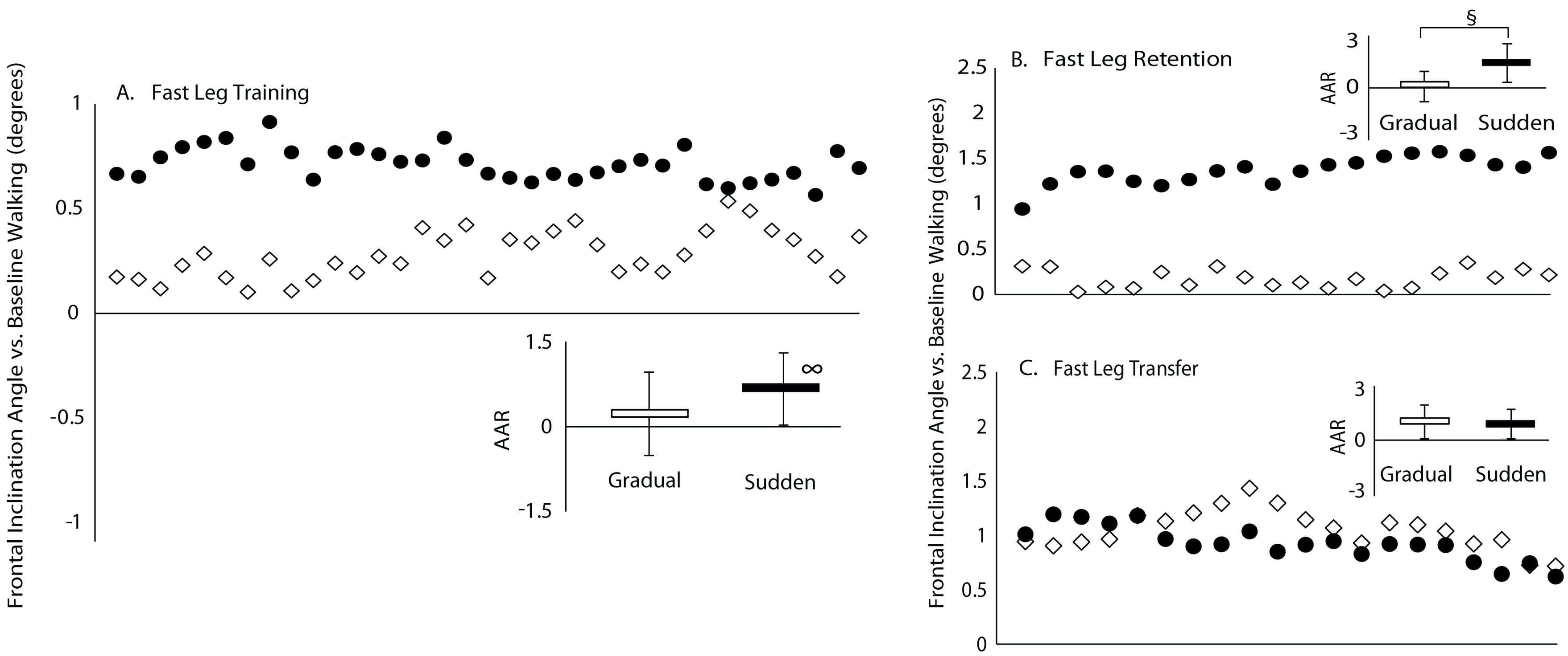

Figure 3.3. Frontal Inclination Angle (FIA) (degrees) of the fast leg with respect to baseline walking for the gradual (◇) and sudden (●) cohorts during training (A), retention (B), and transfer (C). Each data point represents the average angle over 20 strides with respect to baseline walking. Inset is the resulting Average Angular Residual (AAR) with error bars equal to ± 1SD. (A) The AAR of the fast leg over the last 20 strides of training was significantly larger than baseline walking during sudden ($p = 0.001$)$^{\infty}$ but not gradual training ($p = 0.234$). (B, C) The AAR of the fast leg was significantly larger for the sudden than the gradual training cohort during retention ($p = 0.023$), but not transfer ($p = 0.772$).

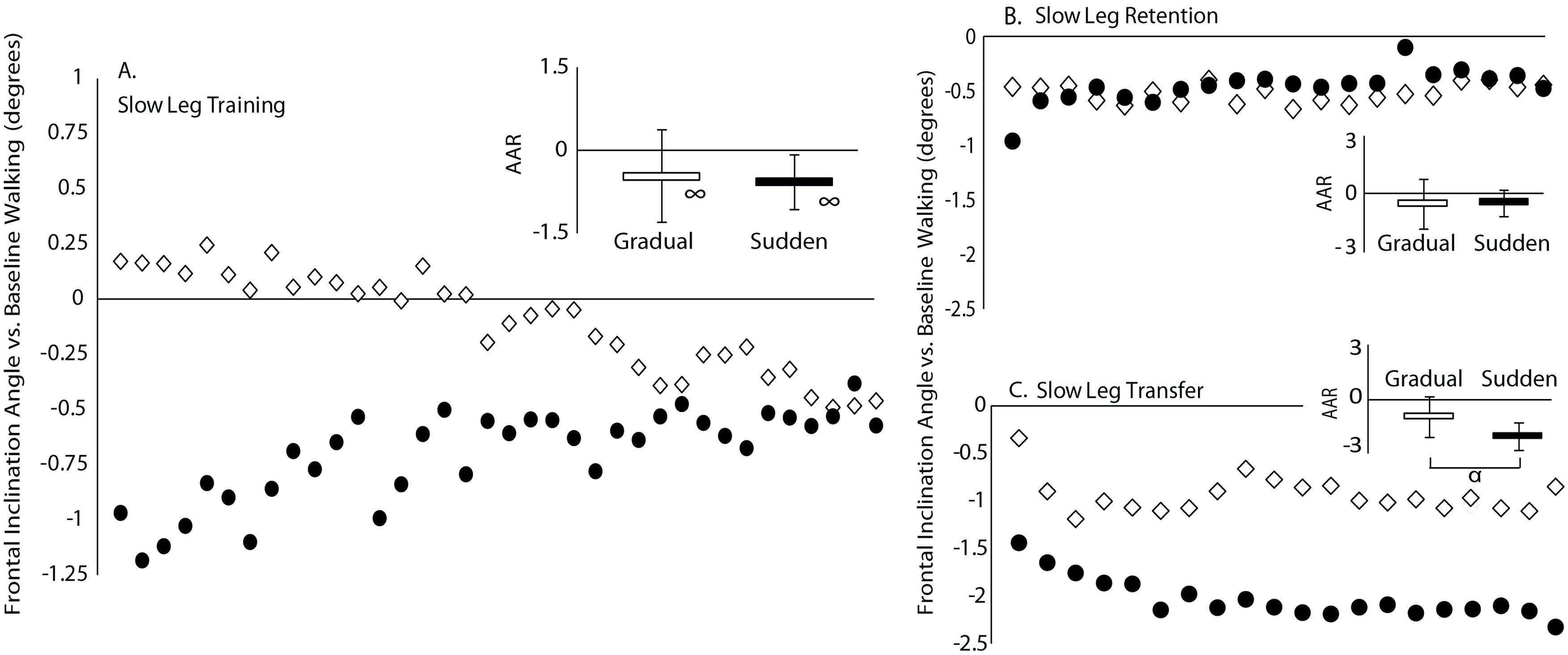

Figure 3.4. Frontal Inclination Angle (FIA) (degrees) of the slow leg with respect to baseline walking for the gradual (◇) and sudden (●) cohorts during training (A), retention (B), and transfer (C). Each data point represents the average angle over 20 strides with respect to baseline walking. Inset is the resulting Average Angular Residual (AAR) with error bars equal to ± 1SD. (A) The AAR of the slow leg over the last 20 strides of training was significantly smaller than baseline walking during sudden $(p < 0.001)^{\infty}$ and gradual training (p = 0.044). (B, C) The AAR of the slow leg was significantly larger for the sudden than the gradual training cohort during transfer (p = 0.041), but not retention (p = 0.904).

3.4 DISCUSSION

This study sought to determine whether gradual versus sudden training influences lateral balance control during training and subsequent performance of a novel locomotor task. The Average Uncertainty Residual (AuR) and the Average Angular Residual (AAR) of the Frontal Inclination Angle (FIA) were calculated to infer the challenge presented to lateral balance control and describe the whole-body frontal plane kinematic strategy selected to maintain lateral balance control during training, retention and transfer. The significantly smaller AuR of the fast and slow legs during gradual training (Figure 3.1 and Figure 3.2; Table 3.2) suggests that the gradual cohort experienced significantly less challenge to lateral balance control during training than the sudden cohort. Furthermore, the lack of any significant difference in the amount of uncertainty in the lateral movement pattern between baseline 1:1 walking and the gradual cohort during 2:1 training implies that the challenge of controlling lateral balance during 2:1 gradual training was no greater than during baseline 1:1 walking.

During retention testing, the AuR of the fast but not the slow leg was significantly greater among those individuals who had received sudden rather than gradual training the previous day (Figure 3.1 and Figure 3.2; Table 3.2). During transfer testing, the AuR of the fast and the slow leg were both significantly greater among those individuals who had received sudden training the previous day (Figure 3.1 and Figure 3.2; Table 3.2). This suggests that those individuals who received gradual training had less difficulty controlling lateral balance when re-tested the following day. These results imply that the manner by which participants were initially trained influenced the challenge to lateral balance control during training, and perhaps more importantly, the challenge of controlling lateral balance during subsequent performance of the same or a similar locomotor task. Therefore, gradual training appears to promote the learning of a more durable and flexible strategy for the control of lateral balance. It is also worth noting that when expressed as a percent difference, the reduction in the uncertainty of the lateral movement pattern (i.e. AuR) observed between the gradual and sudden cohorts across all phases of the experiment (Figure 3.1) was found to be larger (59-92%) than that reported for other measures of lateral variability in previous studies (12%) which examined the impact of simple mechanical interventions on the challenge to lateral balance control (Richardson et al., 2004). This suggests that the choice of training strategies may play a larger role than the provision of mechanical aids in the restoration or recovery of lateral balance control.

The results of this study build upon the previous work of Domingo et al., (2009; 2010) and Bhatt (2008) by describing the impact of two different motor learning strategies on the selection of whole-body frontal plane kinematic movement patterns to control lateral balance. Despite similar values at the end of training, sudden and gradual training were found to result in the selection of unique whole-body frontal plane movement patterns as described by the difference in AAR (Figure 3.3 and Figure 3.4; Table 3.3) throughout retention and transfer. This suggests that gradual and sudden training promote the learning of different whole-body frontal plane kinematic movement strategies to regulate lateral balance control. Specifically, participants who received sudden training the previous day had a significantly greater increase in the fast leg Frontal Inclination Angle (FIA) with respect to baseline 1:1 walking during retention and a significantly greater decrease in the slow leg FIA with respect to baseline 1:1 walking during transfer than those participants who received gradual training (Figure 3.3 and Figure 3.4).

These results confirm those of previous studies that postural (Orrell et al., 2006b; Chiviacowsky et al., 2010) and locomotor (Bhatt and Pai, 2008; Domingo and Ferris, 2009, 2010) balance control can be influenced by the selection of specific motor learning strategies. Similar to the results presented in this study, Domingo et al., (2009; 2010) found that control of lateral balance could be improved by reducing the challenge to locomotor balance control during training rather than augmenting it, provided that this did not involve physical guidance (Domingo and Ferris, 2009). The results of the current study and those of Domingo et al., (2009; 2010), suggest that training strategies aimed at improving lateral balance control should avoid practice conditions which introduce considerable challenge to locomotor balance control or rely on physical guidance. Rather, they should be designed to provide a degree of difficulty or challenge that learners are able to manage independently. The finding that 2:1 gradual training did not pose significantly more challenge to lateral balance control than baseline 1:1 walking, yet led to superior control of lateral balance the next day suggests that the ideal level of practice difficulty may be closer to that experienced within one’s normal repertoire. Specifically, a gradual training strategy may allow individuals to explore and develop a balance control strategy over time without the risk of loss of balance. The use of a sudden training strategy, particularly for a complex task such as lateral balance control, may force individuals to respond immediately to address the threat to balance control presented by the abrupt introduction of task demands. This may prevent individuals from thoroughly exploring all of the possible solutions and experiencing the true nature of the task, thus selecting a balance control strategy that while successful (i.e. prevents falls), may not be the most effective (Sanger, 2004). Gradual training may also promote the development of greater self-efficacy regarding balance control and thus balance confidence (Maki et al., 1991). This may in turn promote superior lateral balance control the next day.

The results of this work may have implications for the physical rehabilitation of individuals with lower limb loss, or other locomotor balance control impairments. Recent technological advances in the field of prosthetics have led to the development of prosthetic feet and knees that are capable of restoring physiological levels of joint power (Sup et al., 2008; Herr and Grabowski, 2012). While technology has made great gains in restoring aspects of locomotor performance (i.e. metabolics), balance control impairments persist among individuals with lower limb loss despite technological advancements. The results of the present study suggest that when introducing such a device, a gradual restoration of powered movement may induce less challenge to balance control and result in the restoration of superior lateral balance control while simultaneously allowing a broader range of patients to access this technology.

As it relates to balance control interventions, perturbation training involves the repeated introduction of balance threats; with the goal of improving responses to perturbations and thus locomotor balance control. While recently established as a successful means to reduce falls (Bhatt and Pai, 2008; Wang et al., 2011), to date, perturbation training has only made use of a single perturbation magnitude that has been abruptly introduced. The results of the present study suggest that perturbation training may benefit from the use of a gradual introduction of the magnitude of the perturbation during training, particularly among individuals prone to or with a history of falls.

While necessary to perform this study, the use of a treadmill may have affected the results. The lack of visual flow and slow walking speed during baseline 1:1 walking may have altered the kinematic movement strategies, their variability and the challenge to lateral balance control. However, the 15 minute acclimation period was intended to minimize these concerns. The use of a split belt treadmill may have increased step width (Altman et al., 2012); however, the comparison of all conditions to baseline walking minimizes this potential limitation. Additionally, a greater number of strides may be necessary to fully capture the uncertainty of the lateral movement pattern (Owings and Grabiner, 2003).

Additional research is necessary to determine whether the differences in kinematic movement strategies observed in this study are accompanied by differences in kinetic strategies and whether the ability of gradual training to reduce the challenge to lateral balance control can be retained over an extended period of time.

3.5 CONCLUSION

This study found that the use of a gradual versus sudden training strategy reduced the challenge to lateral balance control during initial practice of a novel locomotor task. Additionally, participants who received gradual versus sudden training had less difficulty controlling lateral balance upon re-testing the next day, and selected different whole-body frontal plane kinematic movement strategies to regulate lateral balance control. These results suggest that motor learning strategies are capable of altering aspects of locomotor balance control and there selection should receive greater attention during the development of locomotor balance control rehabilitation protocols.

3.6 BRIDGE

The study reported in this chapter described how gradual versus sudden training reduced the challenge to lateral balance control and altered the selection of whole-body frontal plane kinematic movement strategies during the performance of a novel locomotor task. Learning or re-learning locomotor skills can be cognitively demanding. Furthermore, excessive cognitive demand may impair the acquisition of motor skills. Therefore, a third study was designed to examine whether the cognitive demand associated with learning a novel locomotor task is influenced by the use of a gradual or sudden training strategy. Chapter Four details the differences in cognitive demand that arise while practicing a novel locomotor task when using gradual or sudden training.

Chapter 4. EFFECTS OF GRADUAL VERSUS SUDDEN TRAINING ON THE COGNITIVE DEMAND REQUIRED WHILE LEARNING A NOVEL LOCOMOTOR TASK

4.1 INTRODUCTION

Dual-task methodologies (Abernethy, 1988; Fraizer and Mitra, 2008) are frequently used to assess the cognitive demand required to perform locomotor tasks (Lajoie et al., 1993; Abernethy et al., 2002; Brown et al., 2005; Ojha et al., 2009), examine the effect of a secondary task on locomotor performance (Ebersbach et al., 1995; Weerdesteyn et al., 2003; Beauchet et al., 2005; Grabiner and Troy, 2005), and determine how the relationship between cognitive demand and physical performance is influenced by a variety of factors including age (Lajoie et al., 1996; Marsh and Geel, 2000; Brown et al., 2005), and physical impairment (Parker et al., 2005; Lamoth et al., 2008; Smulders et al., 2012). In contrast, dual-task methodologies are rarely used to assess how the cognitive demand required while learning a novel motor skill is influenced by common practice conditions or training strategies (Wulf et al., 2001; Lam et al., 2010b). While their efficacy for learning motor skills has been well documented (Wulf et al., 2010), the cognitive demand associated with the use of different training strategies remains largely unknown. It stands to reason that if two training strategies lead to equivalent motor learning, yet one requires less cognitive demand, it may represent a preferable rehabilitation strategy for retraining motor skills among individuals with cognitive impairments or those without cognitive impairments relearning a cognitively demanding locomotor task.

Gradual training incrementally introduces task requirements over the course of a practice session. This results in the production of small movement errors which often go unnoticed by the learner (Criscimagna-Hemminger et al., 2010). In spite of the supposed need for large movement errors and increased practice difficulty (Christina and Bjork, 1991; Schmidt and Bjork, 1992; Wolpert and Ghahramani, 2000) to facilitate motor learning, gradual training has been shown to improve or preserve the adaptation to and retention or transfer of novel motor skills when compared to sudden training with its abrupt introduction of task requirements (Kagerer et al., 1997; Malfait and Ostry, 2004; Klassen et al., 2005; Kluzik et al., 2008; Criscimagna-Hemminger et al., 2010; Torres-Oviedo and Bastian, 2012). Several studies have suggested that the efficacy of gradual training may be due to the sub-threshold increments reducing awareness of the changes and subsequently the contribution of conscious strategic adjustments during training (Hatada et al., 2006; Criscimagna-Hemminger et al., 2010). This lack of conscious adjustments may engage an implicit rather than explicit learning mechanism, and a concurrent reduction in cognitive demand (Buch et al., 2003). Conversely, sudden training is thought to require explicit cognitive strategies to deal with the larger movement errors and increased practice difficulty. However, the cognitive demand required while learning a motor skill using either gradual or sudden training has not yet been examined and therefore remains unknown. A better understanding of whether gradual versus sudden training influences the cognitive demand required while learning a novel locomotor skill may facilitate the selection of motor learning strategies during physical rehabilitation, and provide additional insight into whether gradual versus sudden training engages implicit rather than explicit learning mechanisms.

The objective of this study was to determine whether gradual versus sudden training influenced the cognitive demand required while practicing a novel locomotor task. This was accomplished by examining probe reaction times to a visual stimulus on a simple reaction time task and whole-body sagittal plane kinematics while practicing a novel locomotor task, asymmetric split belt treadmill walking (Dietz et al., 1994). It was hypothesized that the cognitive demand required while learning the novel locomotor task would be reduced by using a gradual versus a sudden training strategy.

4.2 METHODS

4.2.1 *Recruitment*

Participants were recruited from a population of adults without impairment. Inclusion criteria were age between 18 and 50, the ability to walk continuously for 20 minutes on a treadmill without assistance, and no prior split belt treadmill experience. Exclusion criteria were self-reported conditions that could impair gait, including musculoskeletal, neurologic or cardiopulmonary conditions. All protocols were approved by Institutional Review Boards. Written informed consent was obtained prior to enrollment. Demographics including age, height, mass, gender, self-selected walking speed (SSWS) and limb dominance (Kramer and Balsor, 1990) were recorded.

4.2.2 *Experimental Protocols*

4.2.2.1 Cognitive Task (secondary task)

The cognitive task consisted of a simple reaction time (RT) task. This was selected over more demanding tests, (i.e. choice RT task or Stroop test) to prevent the cognitive task from becoming so demanding as to induce attention switching. Simple RT tasks have also proven to be sufficiently sensitive to detect differences in the cognitive demand for both simple and challenging motor tasks (Lajoie et al., 1996; Abernethy et al., 2002; Gage et al., 2003; Ojha et al., 2009). The simple RT task consisted of a series of visual cues “+” followed by stimuli “**O**” presented on the center of a 32 inch LCD screen four feet from the participants using SuperLab (V. 4.5; Cedrus, San Pedro, CA). Participants were asked to respond as quickly as possible following stimulus onset by depressing a hand-held trigger (Microsoft Corp., Redmond, WA). The cue and stimulus combination were selected to reduce perceptual content of the secondary task relevant to postural control that could help anchor balance and attenuate any influence of the dual task component (Fraizer and Mitra, 2008). To minimize stimulus predictability, anticipatory strategies and the possibility that response measures were walking phase specific, the visual stimuli were presented in an unpredictable fashion at various points throughout the gait cycle (Hirschfeld and Forssberg, 1991). This was accomplished by randomly selecting time intervals between each visual cue and stimulus onset from a list of six possible times (500, 1500, 2000, 3500, 4500, and 5000 ms). The frequency of stimulus presentations was set to 12 stimuli per 20 strides as recommended by Salmoni (1976), (Salmoni et al., 1976) and any responses less than 100 milliseconds were rejected as anticipatory responses (Gage et al., 2003). To reduce competition between the primary task of walking and the secondary RT task for common physical or neural effectors, differing response modalities (lower versus upper extremity) and sensory modalities (proprioceptive versus visual) were chosen for the primary (2:1 walking) and secondary (RT) tasks. RTs were defined as the time (msec) between onset of visual stimulus and onset of the motor response (Maki and McIlroy, 1996). Absolute RTs were selected over relative RTs as there was no difference expected between cohorts in baseline RT values, and the success of previous studies in identifying differences in cognitive demand across a variety of motor tasks using absolute RTs (Lajoie et al., 1993, 1996; Abernethy et al., 2002; Gage et al., 2003; Ojha et al., 2009). Reaction times were recorded on a PC using SuperLab (V. 4.5; Cedrus, San Pedro, CA).

4.2.2.2 Walking Task (primary task)

Participants walked on a Bertec split belt treadmill (Bertec, Columbus, OH) under two conditions: *1:1 walking*, where both leg are driven at the same velocity (0.7 m/s), and novel *2:1 walking*, where the dominant leg is driven at a velocity that is two times that of the non-dominant leg (Dietz et al., 1994). Half of the participants practiced the novel 2:1 walking task using a sudden training strategy, while the other half received gradual training. For participants allocated to sudden training, the novel locomotor task (2:1 walking) was introduced via a single abrupt change in belt velocity. The belt under the dominant leg was accelerated at 10.0 m/s^2 to reach a velocity of 1.4 m/s (2:1 walking) between heel-strikes. 2:1 walking was then maintained for the remainder of training, 720 consecutive strides. The gradual training cohort was introduced to 2:1 walking by incrementally increasing the belt speed. Each incremental increase occurred during a period of 20 strides, over which the dominant leg belt velocity was increased by 0.02 m/s using an acceleration of 0.001 m/s^2. This continued until the dominant leg belt velocity reached 1.4 m/s (2:1 walking), a transition which took 700 strides (35 blocks of 20 strides). Twenty additional 2:1 walking strides were then performed by the gradual cohort, for a total of 720 strides during training. The magnitude of the velocity changes and the acceleration were chosen to minimize the detection of each incremental change and represent the lower limits of treadmill control. All participants were given the same instructions; maintain or restore a comfortable, rhythmic walking pattern. Participants were naïve to the novel locomotor task, 2:1 walking, as well as their allocation to gradual or sudden training. Because the 2:1 walking task had to remain novel under dual-task conditions, single task 2:1 walking was performed by a separate yet comparable cohort (n

= 10) as part of a different study and presented in Chapter 2 (Sawers and Hahn, Submitted).

4.2.2.3 Dual-Task Conditions

Following 20 seated practice trials of the cognitive task to ensure familiarity with the RT procedure, baseline processing speed was assessed as the average of 20 seated trials on the simple RT task. These data were used to confirm equivalent processing speeds between cohorts to ensure fair comparisons during subsequent phases of the experiment. Following 15 minutes of single-task 1:1 walking to allow for treadmill acclimation (Zeni and Higginson, 2010), and an additional 20 strides to characterize baseline 1:1 walking performance, participants continued 1:1 walking at 0.7 m/s for another 180 strides while performing the RT task, in order to determine 1:1 walking RTs. Over the course of the 180 1:1 walking strides, 108 visual stimuli were presented. These data provided a record of the cognitive demand required for 1:1 walking prior to the introduction of 2:1 walking. Participants were then randomly allocated to either gradual or sudden training for 2:1 walking.

During dual-task 2:1 walking, the gradual and sudden cohorts were presented with the same number of stimuli and the same time intervals between the visual cue and stimulus onset. This was done to help ensure that any differences in RTs between the two protocols were comparable. Over the duration of the training protocol (~720 strides), 432 visual stimuli were presented. In an effort to reduce interpretive difficulties that could arise due to attentional switching from the primary locomotor task to the secondary cognitive task when the secondary task is introduced, participants were instructed to maintain focus on and afford priority to the primary locomotor task (Siu et al., 2008), 2:1

walking. The likelihood of attentional switching with the introduction of the secondary cognitive task was further reduced by the substantial challenge of the primary locomotor task (2:1 walking) (Kelly et al., 2010).

4.2.3 *Data Collection*

Fifty-seven reflective markers were placed on participants' bony landmarks (Sawers and Hahn, 2012). Throughout all walking conditions, three-dimensional marker coordinate data were collected at 120Hz using a 12 camera Vicon MX motion capture system (Vicon, Oxford, UK) and synchronized with ground reaction force (GRF) data collected from the treadmill force platforms at 1200Hz..

4.2.4 *Data Analysis*

Following the principles of the dual-task paradigm as described by Kahneman (1973), performance on the cognitive task (absolute RTs), while performing either of the primary locomotor tasks (1:1 or 2:1 walking) was compared and any differences in RTs between the tasks was interpreted as a difference in the required cognitive demand (Kahneman, 1973). To examine whether gradual or sudden training influenced the cognitive demand required while learning the novel locomotor task (2:1 walking), the 432 RT responses during dual-task 2:1 walking were separated into four sequential and equal bins of 108 RTs (Q_1, Q_2, Q_3, Q_4). For each of the four dual-task 2:1 walking RT bins, the mean RT for the gradual and sudden training cohorts were compared.

To examine whether participants shifted their focus of attention away from the primary locomotor tasks (2:1 walking) and towards the secondary cognitive task (simple RT task) during dual-task conditions, we compared the amount of uncertainty in the whole-body sagittal plane movement pattern during single and dual-task locomotor performance of 2:1 walking. The whole-body sagittal plane movement pattern was described by the Sagittal Inclination Angle (SIA). The SIA is a measure of limb endpoint control relative to the whole body center of mass (COM) (Chen and Chou, 2010). It was chosen as the metric of locomotor performance on the basis of previous biomechanical (McMahon and Cheng, 1990; Griffin et al., 2004), neurophysiological (Bosco et al., 1996; Bosco et al., 2000; Bosco et al., 2005), and behavioral (Lacquaniti et al., 1990; Chang et al., 2009) evidence for the importance of whole limb function to locomotion, specifically with respect to the whole body COM (Redfern and Schumann, 1994; Balasubramanian et al., 2010). Marker coordinate data were filtered with a 4th order Butterworth 5 Hz low-pass cut-off frequency and combined with participant-specific anthropometric data adapted from Dempster (Winter, 2009) to build a 15 segment whole-body model in Visual 3D (C-Motion, Germantown, MD) (Sawers and Hahn, 2012). Whole-body center of mass (COM) position was calculated using the weighted sum approach.

Using custom MATLAB™ (MathWorks, Natick, MA) code, discrete values for the SIA were calculated on a stride by stride basis at ipsilateral heel strike for the fast (dominant) and slow (non dominant) legs. To quantify the amount of uncertainty in the sagittal plane movement pattern during single and dual-task 2:1 walking, the standard deviation (SD) of the SIA was calculated for every 20 strides. During 2:1 walking this resulted in 36 values (i.e. from 720 strides). The residual between each of these 36 values and the uncertainty (SD) of baseline 1:1 walking, similarly calculated over 20 strides, was then computed. The mean of these 36 residual values was then calculated to quantify the average uncertainty in the sagittal plane movement pattern during training, the Average Uncertainty Residual (AuR). The AuR was then compared between the single and dual-task 2:1 walking conditions. A lack of significant difference between them was taken to indicate that the uncertainty in the sagittal plane movement pattern was not significantly different between single and dual-task conditions, suggesting that no shift in attentional focus away from the primary locomotor task occurred under dual-task conditions, ensuring an accurate assessment of cognitive demand. The SD was used to assess locomotor performance because it reflects the amount of uncertainty in a movement pattern (Stergiou, 2004), which in turn reflects the challenge or difficulty of a locomotor task (Bauby and Kuo, 2000; Donelan et al., 2004; Owings and Grabiner, 2004b).

4.2.5 *Statistical Analysis*

To evaluate the effect of gradual versus sudden training on the cognitive demand required to learn a novel locomotor task (2:1 walking), an independent t-test (*1-tailed, $\alpha=0.05$*) was performed to compare the average reaction time (RT) during 2:1 walking between the gradual and sudden cohorts. To examine whether differences in RT, and thus cognitive demand, between the Gradual and Sudden cohorts were consistent throughout training or only present during portions of training, additional independent t-tests (*1-tailed, $\alpha=0.05$*) were performed between the gradual and sudden training cohorts for each of the four sequential RT bins (Q_1, Q_2, Q_3, Q_4) during training. Necessary corrections for multiple comparisons were made (four comparisons, $\alpha=0.0125$). To ensure that priority was afforded to the primary locomotor task (2:1 walking) during dual-task conditions a MANOVA was used to compare motor performance between single and dual-task conditions using the Average Uncertainty Residual (AuR) of the Sagittal Inclination Angle (SIA) for the fast and slow legs. All statistical tests were conducted using SPSS (V.19; SPSS, Inc., Chicago IL).

4.3 RESULTS

Twenty adults without impairment were recruited and participated in the study (Table 4.1). Sample locomotor and reaction time data for a participant in the gradual and a participant in the sudden training cohorts is provided in Figure 4.1. There was no significant difference in either the average seated or 1:1 walking reaction times (RT) between the gradual and sudden training cohorts (seated, $p = 0.435$; 1:1 walking, $p = 0.398$) (Table 4.1). The Average Uncertainty Residual (AuR) during dual-task 2:1 walking was found to be equivalent to that during single-task 2:1 walking for the fast and slow legs during both gradual (fast leg, $p = 0.469$; slow leg, $p = 0.278$) and sudden (fast leg, $p < 0.355$; slow leg, $p = 0.307$) training (Figure 4.2). The average RT during 2:1 walking was significantly greater for the sudden than the gradual training cohort ($p = 0.010$) (Table 4.1). While consistently greater than during gradual training across all four bins (Q_1, Q_2, Q_3, Q_4), the difference in RT between the gradual and sudden training cohorts was only significant during Q_1 ($p = 0.005$) (Figure 4.3).

Table 4.1. Participant demographics and probe reaction times.

Cohort		Height (m)	Mass (kg)	Age (years)	Gender[a]	SSWS (m/s)	Dominant Leg[b]	Seated RT	1:1 Walking RT	2:1 Walking RT
Gradual Training (n=10)	Mean (*SD*)	1.70 (*0.10*)	62.09 (*9.11*)	33.6 (*8.03*)	4M, 4F	1.56 (*0.11*)	9R, 1L	329 (*23*)	368 (*20*)	403 (*25*)$^{\infty}$
	Range	1.60-1.85	54.25-89.61	24-50		1.23-1.67		296-359	338-405	368-452
Sudden Training (n=10)	Mean (*SD*)	1.72 (*0.13*)	69.45 (*11.20*)	31.4 (*6.91*)	5M, 3F	1.50 (*0.20*)	9R, 1L	332 (*57*)	372 (*44*)	460 (*59*)$^{\infty}$
	Range	1.55-1.91	60.33-88.9	23-44		1.19-1.83		246-433	300-464	371-558

[a] M = Male; F = Female

[b] R = Right; L = Left

RT = Reaction time

∞ = represents a comparison of reaction times between the gradual and sudden training cohorts with ($p = 0.0095$) during 2:1 walking

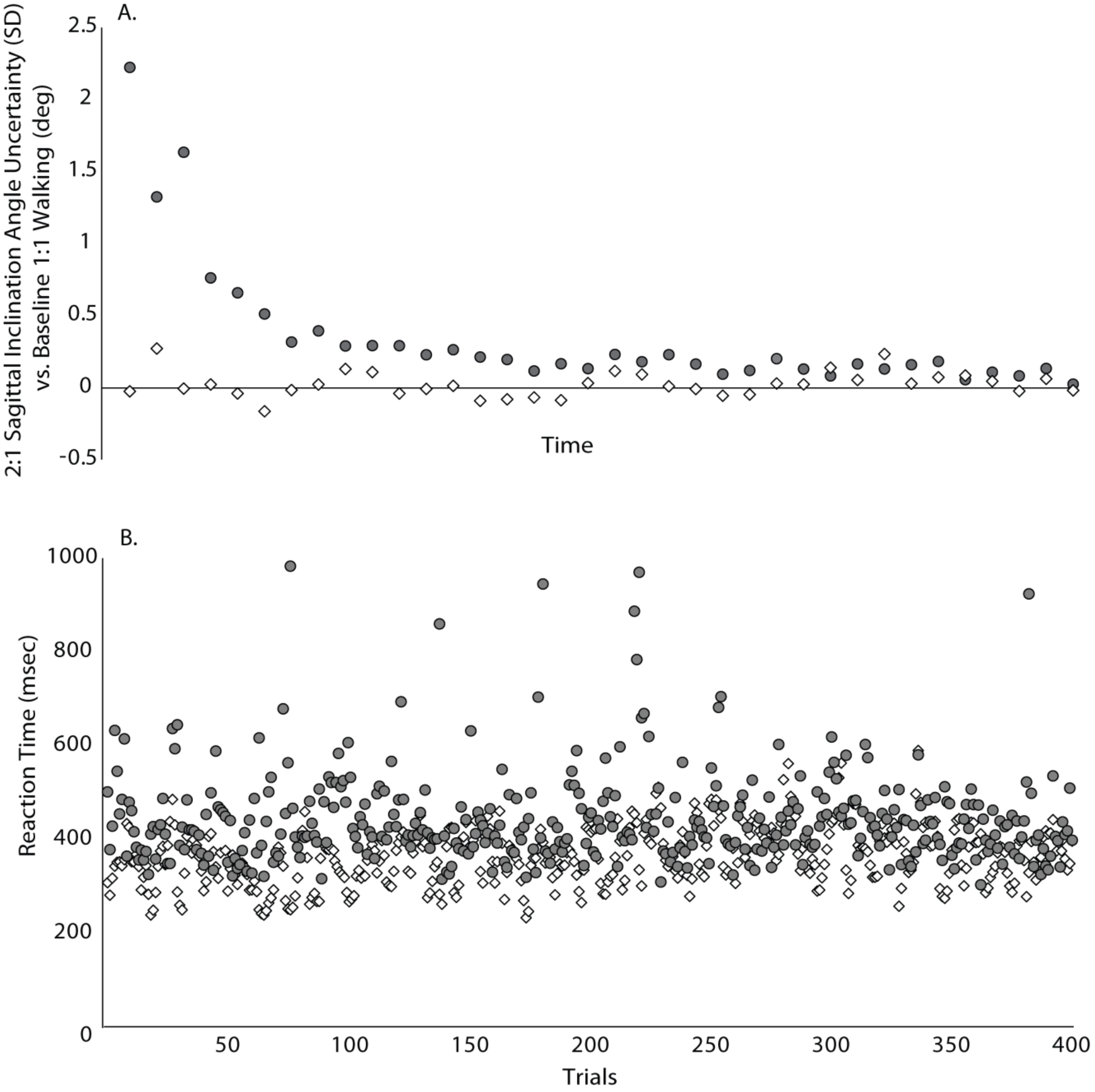

Figure 4.1. Representative locomotor and reaction time data from one gradual (◇) and one sudden (●) participant during 2:1 walking training

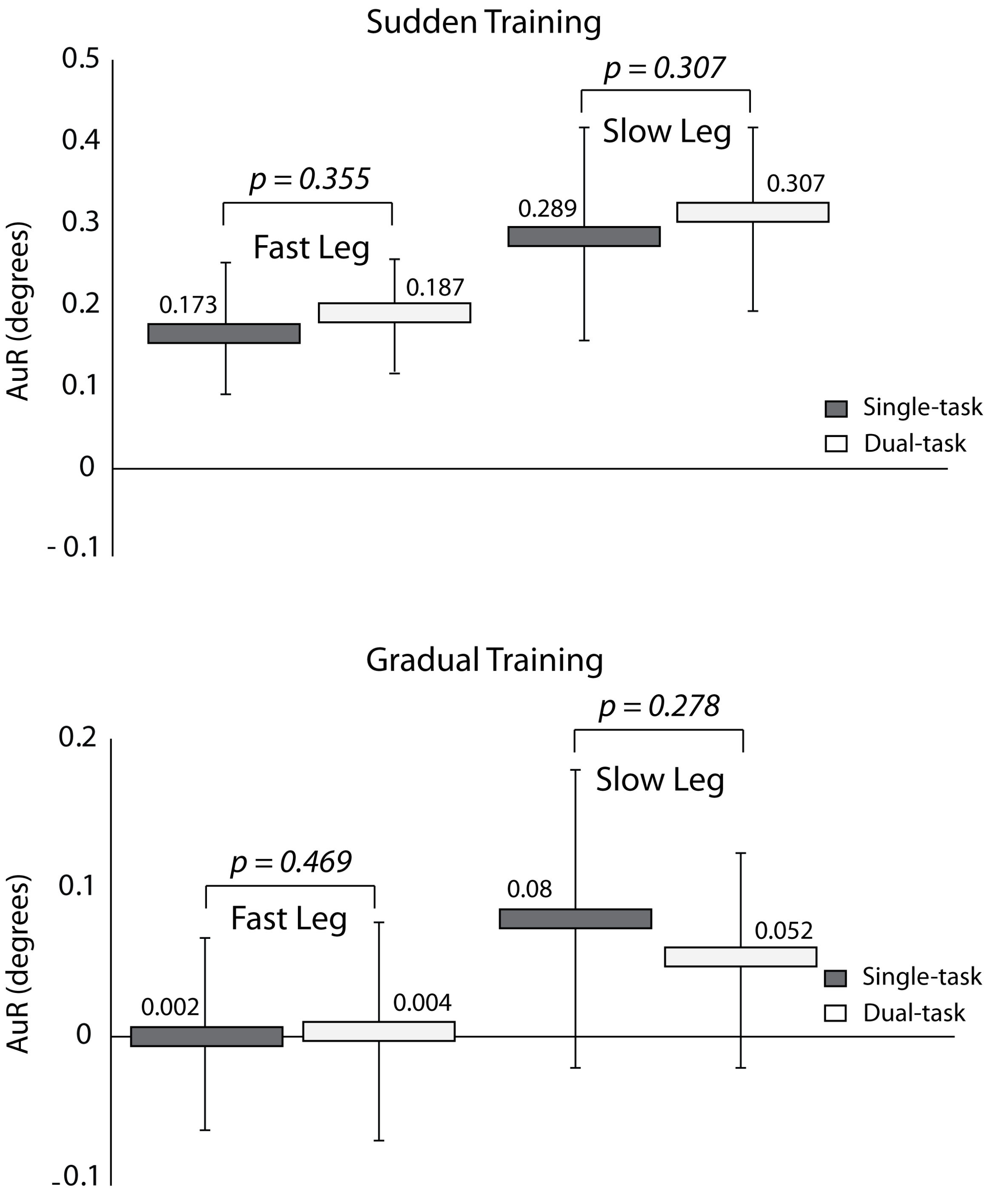

Figure 4.2. Average Uncertainty Residual (AuR) of the sagittal inclination angle for the fast and slow legs during gradual and sudden training under single and dual-task conditions. Error bars equal ±1SD. For both the gradual and sudden training cohorts, the AuR of the fast and slow legs were equivalent between single and dual-task conditions ($p > 0.05$), indicating that there was no decrement in locomotor performance with the addition of the secondary cognitive task. Given the need to preserve the novelty of 2:1 walking, single-task walking was performed by a separate but equivalent sample of participants (Sawers and Hahn, Submitted).

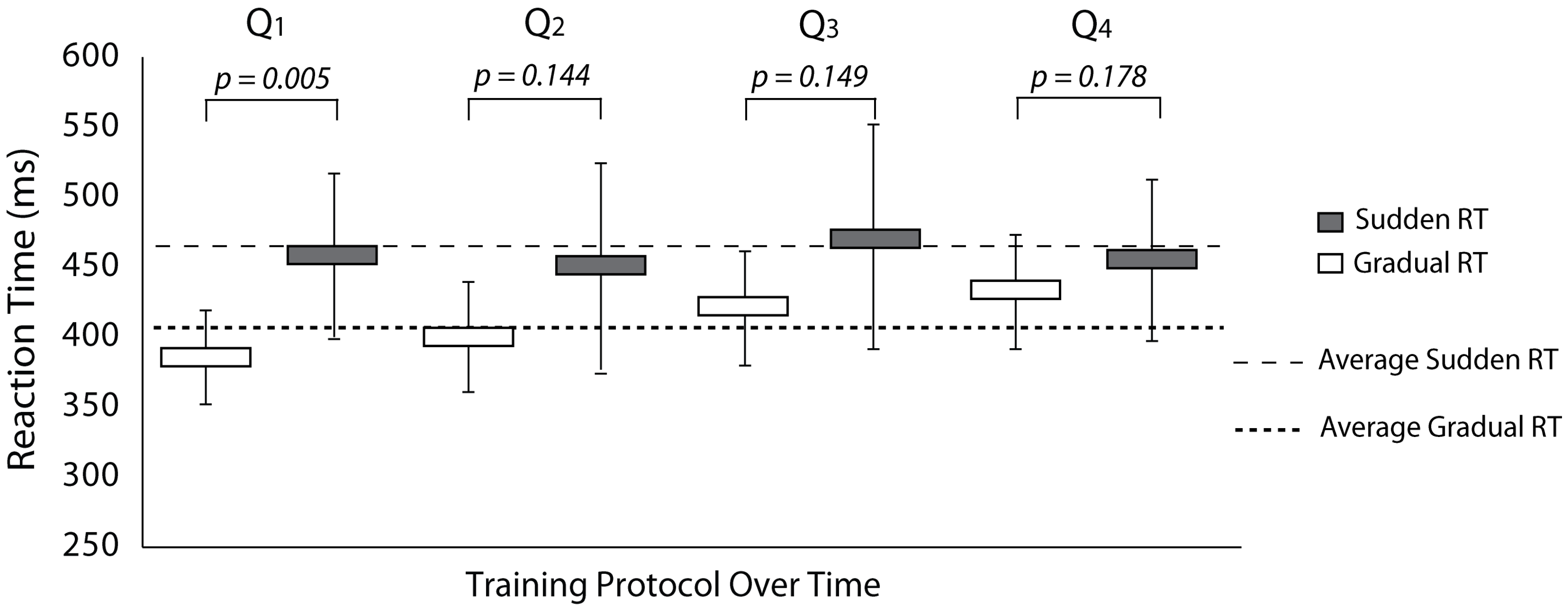

Figure 4.3. Probe reaction times (RT) during dual-task 2:1 walking. Data points (white box = gradual training, grey box = sudden training) for each quarter (Q_1-Q_4) were derived from the average of 108 RT. Error bars equal ±1SD. While the average reaction time for the sudden cohort (– – –) was higher than that of the gradual cohort (▪▪▪▪▪) during 2:1 training ($p = 0.010$), the differences between quarters was only significant during Q_1 ($p = 0.005$).

4.4 DISCUSSION

This study sought to determine whether gradual versus sudden training influences the cognitive demand required while learning a novel locomotor task. This was accomplished by examining reaction times (RT) on a simple RT task and whole-body sagittal plane kinematics during single and dual-task conditions. During both seated and 1:1 walking, each of the training cohorts had similar average RTs (Table 4.1), indicating that the cognitive performance of the two groups was comparable at baseline. Furthermore, 2:1 walking performance, as assessed by the Average Uncertainty Residual (AuR) of the fast and slow legs, was not significantly different between single and dual-task conditions for either the gradual or sudden training cohorts. This indicates that the addition of the secondary cognitive task did not degrade locomotor performance and that attentional switching away from the primary locomotor task, 2:1 walking, did not occur, ensuring that the primary locomotor task was afforded priority. This is further corroborated by the observed increase in the average RT during 2:1 walking with respect to 1:1 walking for the gradual (35 msec) and sudden (88 msec) cohorts. Together these results suggest that the addition of the simple RT task did not affect locomotor performance and as such any changes in RT reflect changes in the cognitive demand required by the primary motor task (Abernethy, 1988).

During dual-task 2:1 walking, the average RT was significantly greater among participants who received sudden (460 msec) rather than gradual (403 msec) training (Table 4.1). This suggests that the cognitive demand required during practice was modulated by the training strategy. The difference in average RT between the two training strategies, 57 msec, is greater than differences reported between level ground walking and ascending (43 msec) or descending (34 msec) stairs (Ojha et al., 2009) as well as crossing obstacles (~ 40 msec) (Brown et al., 2005) among unimpaired young adults.

Upon further inspection the difference in average RT between the gradual and sudden training cohorts was found to vary over the course of training (Figure 4.3). While the RT for the sudden cohort was consistently larger than that of the gradual cohort over each interval of training (Q1, Q2, Q3, Q4) (Figure 4.3), this difference was only statistically significant during the first interval of training (Q1). This suggests that the overall increase in cognitive demand while practicing the novel locomotor task under sudden conditions was due in large part to the difference over the initial training period. Even though the greater RT for the sudden versus the gradual training cohort was only significant for the first interval of training (Q1), the difference in RT between gradual and sudden training over the first three intervals (Q1= 82 msec, Q2 = 54 msec, Q3 = 57 msec) were all greater than the increases in cognitive demand observed for walking versus ascending or descending stairs (43 and 34 msec respectively) (Ojha et al., 2009), as well as overground locomotion versus obstacle crossing (~ 40 msec) (Brown et al., 2005). This suggests that although these differences were not found to be statistically significant they may nonetheless represent meaningful differences in cognitive demand between the two training strategies.

Interestingly, while the cognitive demand associated with practicing 2:1 walking increased during the course of gradual training (Figure 4.3), cognitive demand during sudden training remained elevated, failing to diminish over the course of training. This may suggest that for both cohorts, the participants were still in the early, cognitive phase of learning rather than the associated or automatic phases of learning. While it remains unknown whether similar differences in cognitive demand would be seen during subsequent performance of the novel locomotor task hours or days later, the lack of change in the cognitive demand among the sudden cohort throughout practice suggests that selection of the training strategy used during practice may play a role in determining the cognitive resources that are allocated to performance of a motor skill beyond practice. A similar hypothesis has been tested for a golf putting task learned under two practice conditions similar to those used in this study, "errorless learning" and "errorful learning" (Lam et al., 2010b). In that study, individuals who learned the putting task under errorless conditions were found to perform equally well on a variation of the original putting task a short time later but with reduced cognitive demand (Lam et al., 2010b). This suggests that the decrease in practice difficulty during training may have caused cognitive resources to be allocated more efficiently by the errorless learners when task demands were changed. Similarly, Wulf (2001) found that practicing a novel balance control task using an external rather than internal focus reduced the cognitive demand during training as well as subsequent performance of the same task 24 hours later. These results lend support to the idea that the choice of training strategy used during practice may influence more than just how well a motor skill is learned. Training strategies may also modulate the cognitive demand required during initial training as well as during subsequent performance.

A number of studies have suggested that the outcomes related to the use of gradual versus sudden training may be due to a reduced awareness of ongoing changes and subsequently a reduction in the contribution of cognitive effort and the use of different learning mechanisms (Buch et al., 2003; Criscimagna-Hemminger et al., 2003; Malfait and Ostry, 2004; Hatada et al., 2006; Criscimagna-Hemminger et al., 2010). Specifically, the transfer of reaching tasks between arms following sudden but not gradual training has been attributed to an increased cognitive effort due to the sudden introduction and related movement errors, (Malfait and Ostry, 2004). Greater adaptation, retention and within-limb transfer of the same reaching tasks following gradual training has been attributed to the removal or minimization of cognitive strategies (Buch et al., 2003; Malfait and Ostry, 2004; Hatada et al., 2006; Criscimagna-Hemminger et al., 2010). This suggests that sudden training requires explicit cognitive strategies to deal with the larger movement errors and increased practice difficulty, while gradual training engages implicit learning mechanisms, reducing cognitive demand (Buch et al., 2003). The results of this study support the idea proposed in previous studies that gradual training reduces the cognitive demand required during training to perform a novel motor task. Whether this indicates that gradual training drives motor learning through an implicit rather than explicit mechanism remains unknown. However, considering the reduction in cognitive demand and the inability of many of the gradually trained participants to demonstrate an explicit understanding of the changes in treadmill conditions that occurred during practice, it would appear that gradual training may promote motor learning though implicit rather than explicit mechanisms.

The differences in cognitive demand between the two training strategies, specifically over the first quarter of training (Q1), may be related to the idea that processing error feedback is more cognitively demanding than processing feedback indicating success (Koehn et al., 2008; Lam et al., 2010a). Greater movement errors and increased practice difficulty define sudden training (Criscimagna-Hemminger et al., 2010; Torres-Oviedo and Bastian, 2012). Greater practice difficulty for the sudden training cohort in this study was apparent from the greater uncertainty observed in the sagittal movement pattern during training, particularly over the first half of training (Figure 4.1), when the difference in cognitive demand was also greatest between the two training strategies (Figure 4.3). Given the increase in practice difficulty, the sudden training cohort likely had to process more error feedback than the gradual training cohort, potentially contributing to the increased cognitive demand observed with sudden training. Additionally, greater cognitive demand is thought to be required during movement preparation versus execution (Ells, 1973; Fisher, 1997; Lam et al., 2010a). Considering the need of participants in the sudden training cohort to respond to the abrupt introduction of task demands, it would stand to reason that while both cohorts must execute similar movements, the sudden training cohort may have required additional movement planning or preparation in order to adapt to the sudden changes in walking conditions, necessitating an increase in cognitive demand to make these adjustments.

Learning or re-learning motor skills with a cognitive component, such as walking (Woollacott and Shumway-Cook, 2002), may be limited when the cognitive demand of training is too high. A motor learning or re-learning strategy that minimizes cognitive demands may be particularly advantageous during physical rehabilitation for individuals that experience challenges with cognitive demand or when the skill being practiced is particularly cognitively demanding. One specific example of this may be the use of powered exoskeletons (Herr, 2009), or prostheses (Herr and Grabowski, 2012). A unique feature of these devices is that the level of assistance which they provide must be "turned on”. Based on the results of the current study, it is plausible that by gradually rather than suddenly restoring powered function with these rehabilitation devices, the attentional demand required during training and subsequent use may be reduced.

This study used a simple RT task to assess cognitive demand. It is plausible that the use of a more challenging cognitive task such as a choice RT task or a Stroop task may have provided a more sensitive measure, enabling a more precise assessment of cognitive demand (i.e. not just RT, but also correct or incorrect responses). The simple RT task made use of a visual stimulus and physical response. The presentation of a visual stimulus and the lack of optic flow while walking on a treadmill may have affected locomotor performance, while the use of a common mechanical effector to generate the response (i.e. arms are also used in locomotion) may have influenced the results. To limit these influences all participants were given time to acclimate to the treadmill, the secondary cognitive task and dual-task conditions. The use of an auditory stimulus and verbal response along with the addition of virtual reality environment would further serve to address these issues. The delivery of the stimulus was not paired to specific gait events. Therefore it is possible that the stimulus may have been presented more frequently at certain points in the gait cycle for some participants than others. In future work the presentation of the stimulus should be linked to specific gait events to ensure consistency in the timing of stimulus presentation across participants. The variability of whole-body sagittal plane dynamics were used to assess motor performance and ultimately the degree of attention switching. Future work may be well served by also including an assessment of whole-body frontal plane kinematics as well as sagittal plane kinematics in assessing motor performance and by extension the extent of attention switching. Additionally, uncertainty in the sagittal plane movement pattern was assessed over 20 stride increments. While debate exists regarding the number of strides required to capture the uncertainty of a locomotor pattern (Owings and Grabiner, 2003), 20 stride increments were selected because that was the range over which the velocity of the fast treadmill belt was increased during gradual training. Extending the length of those increments would have increased the length of training, possibly inducing fatigue and confounding the results.

This study was limited to the examination of the cognitive demand required during training as a function of practice conditions, gradual versus sudden. Future work will employ dual-task approaches to assess whether practice conditions such as gradual versus sudden training influence the automaticity of the learned motor pattern and whether the addition of a secondary task influences how well locomotor skills are learned. Additionally, future work should include the use of non-invasive imaging techniques such as functional near-infrared spectroscopy (Suzuki et al., 2008) to confirm the results of traditional dual-task methodologies.

4.5 CONCLUSION

This study found that the use of a gradual versus sudden training strategy reduced the cognitive demand required while learning a novel locomotor task, particularly during initial practice. This difference in cognitive demand may have arisen due to an increase in error processing and/or movement planning during sudden training, thereby requiring the use of an explicit rather than implicit learning mechanism. Future work is required to examine the interaction between other motor learning strategies and cognitive demand during training and subsequent performance among unimpaired and impaired individuals.

4.6 BRIDGE

The experiment reported in Chapter Four described how gradual training reduces the cognitive demand associated with practicing a novel locomotor task. Having examined the influence of gradual versus sudden training on the acquisition of task-specific requirements, lateral balance control and cognitive demand among unimpaired adults, a fourth experiment was developed to explore the application of gradual versus sudden training as locomotor rehabilitation strategies. Chapter Five describes the results of a pilot study where propulsive ankle power was restored in either a gradual or sudden fashion among a small sample of individuals with transtibial limb loss using a powered prosthetic foot.

Chapter 5. RESTORATION OF PROPULSIVE ANKLE POWER AMONG INDIVIDUALS WITH UNILATERAL TRANSTIBIAL LIMB LOSS: A CASE SERIES

5.1 INTRODUCTION

The physical rehabilitation of individuals with lower limb loss (LLL) has traditionally been guided by a device driven paradigm (Sawers et al., In press). As a result, clinical practice and research priorities have historically focused on the design and function of the prosthesis, rather than how established motor learning strategies may be used to learn prosthetic locomotor skills. From this device-driven paradigm considerable advances in prosthetic technology have emerged. Recently this has included a biomimetic powered prosthetic foot, the BiOM™ Ankle, (iWalk, Inc., Bedford, MA) that is capable of generating physiological levels of propulsive ankle power and work (Au et al., 2007; Eilenberg et al., 2010). These features are critical to safe and purposeful locomotion (Patla, 1991; Meinders et al., 1998; Winter, 1998) yet lost following lower limb amputation and absent from all other commercially available prosthetic feet (Hofstad et al., 2004). To date, use of the BiOM™ Ankle among highly active individuals with transtibial limb loss (TTLL) has led to increases in walking speed, (Ferris et al., 2012; Herr and Grabowski, 2012) improvements in prosthetic ankle range of motion (Ferris et al., 2011; Mancinelli et al., 2011; Ferris et al., 2012; Herr and Grabowski, 2012) and most temporal-spatial parameters, (Ferris et al., 2012) as well as the normalization of the metabolic cost of walking in some, (Herr and Grabowski, 2012) but not all individuals with unilateral (TTLL). (Mancinelli et al., 2011).

Despite this advance in prosthetic technology and improvements in locomotor performance, several challenges remain unaddressed when considering the restoration of biomimetic ankle function among individuals with TTLL. Kinematic and kinetic compensations at proximal and contralateral joints common to the locomotor patterns of individuals with TTLL (Winter and Sienko, 1988; Soares et al., 2009; Prinsen et al., 2011) persist despite prolonged use of the BiOM™ Ankle (Aldridge et al., 2012; Ferris et al., 2012; Herr and Grabowski, 2012) or similar devices (Segal et al., 2011). Additionally, a growing percentage of individuals with TTLL are contraindicated for advanced prosthetic technology such as the BiOM™ Ankle based on current prescription criteria and traditionally held viewpoints that only the most active individuals are capable of learning to use and benefiting from advanced prosthetic technology (Friel, 2005; Kaufman et al., 2007). The continued presence of locomotor compensations and a diminishing target population may be due to the lack of any systematic approach with which to train individuals with TTLL how to use powered prostheses (Aldridge et al., 2012; Ferris et al., 2012). Training strategies based on established motor learning principles may assist in resolving these challenges.

A unique feature of powered prostheses is that they need to be “turned on”. In the case of a powered prosthetic foot, ankle power can be restored suddenly, where the capability of the foot to generate propulsive ankle power is abruptly re-introduced at full strength, or gradually where power is slowly re-introduced through incremental steps. Current clinical practice lacks any systematic approach, but can be characterized by an abrupt restoration of ankle power followed by a series of adjustments based on subjective patient feedback and observational gait analysis. Therefore, prior to examining the use of other established motor learning strategies as part of a physical rehabilitation protocol for powered prostheses, we must first understand how to “turn on” a powered prosthesis.

Compared to sudden training, where large movement errors and increased practice difficulty are produced in response to an abrupt introduction of task requirements, gradual training avoids the large movement errors traditionally thought to drive motor learning (Wolpert and Ghahramani, 2000) by incrementally introducing task requirements throughout practice, effectively reducing practice difficulty (Criscimagna-Hemminger et al., 2010). In spite of the reduction in movement errors and practice difficulty, gradual training is able to maintain or improve performance on adaptive reaching tasks (Kagerer et al., 1997; Buch et al., 2003; Malfait and Ostry, 2004; Klassen et al., 2005; Michel et al., 2007; Kluzik et al., 2008; Criscimagna-Hemminger et al., 2010), and strengthen the adaptation to novel locomotor tasks (Torres-Oviedo and Bastian, 2012), when compared to sudden training. Recently we found that despite providing more specific and difficult practice, sudden training results in equivalent learning of a novel locomotor task as gradual training. Gradual training was also found to reduce the challenge to lateral balance control and the cognitive demand necessary to perform the locomotor task (Sawers and Hahn, Submitted). This demonstrates that contrary to conventional motor learning principles, large movement errors and increased practice difficulty may not be required for motor learning, and that the gradual introduction of a motor task during training may be an effective locomotor rehabilitation strategy for retraining patient populations where large movement errors and increased practice difficulty may result in selection of ineffective movement strategies. However, it remains unknown whether gradual training can be effectively applied to the locomotor rehabilitation of individuals with lower limb loss learning to use powered prostheses.

The objective of this pilot study was to examine how a gradual versus sudden restoration of ankle power influences the ability of individuals with unilateral TTLL to elicit peak propulsive ankle power from a powered prosthetic foot. This was accomplished by examining the magnitude and consistency of the peak ankle power elicited from a powered prosthetic foot following gradual or sudden training the previous day and comparing it to predicted physiological values. It was hypothesized that a gradual restoration of ankle power during training would enable individuals with unilateral TTLL to elicit peak ankle power closer to physiological values and with greater consistency.

5.2 METHODS

5.2.1 *Recruitment*

Participants were recruited from local amputee support groups. Inclusion criteria were unilateral transtibial limb loss, a well-fitting and comfortable prosthetic socket as assessed by a licensed prosthetist and the ability to walk without an assistive device for a minimum of eight minutes. Exclusion criteria were any previous powered prosthetic foot use, and any additional self-reported conditions that could impair gait, including musculoskeletal, neurologic or cardiopulmonary conditions. All protocols were approved by Institutional Review Boards. Written informed consent was obtained prior to enrollment.

5.2.2 *Experimental Protocol*

Each participant was fit with a powered prosthetic foot, the BiOM™ Ankle (iWalk, Inc., Bedford, MA) which is capable of producing physiological levels of propulsive ankle power (Au et al., 2007; Eilenberg et al., 2010). Using the current clinical standards of patient report and observational gait analysis, the BiOM™ Ankle was aligned to each patient's current prosthetic socket in an unpowered state by a licensed prosthetist. Once acceptable alignment was achieved, 10-20 additional strides were taken with the BiOM™ Ankle in a powered state to set and tune foot parameters. The number of strides was minimized in an effort to ensure that participants gained minimal experience with the device, limiting their exposure to the powered system and ensuring that the intervention remained novel. Using currently available methods, the lower and upper limits of power delivery were set at the minimum perceivable level and 38% above respectively. Timing of power delivery was also set based on patient report and observational gait analysis. Once alignment and fitting were completed, participants were returned to their prescribed prosthetic foot to determine preferred treadmill walking speed and begin treadmill acclimation.

Preferred treadmill walking speed (PWS) was determined for each participant wearing their prescribed prosthetic foot by starting at 0.5 m/s and increasing belt speeds in increments of 0.05 m/s until a comfortable walking speed was identified by the participant. This was repeated three times and an average PWS was recorded and used throughout the remainder of the protocol. All participants were given 10 minutes of treadmill acclimation to promote gait consistency (Zeni and Higginson, 2010). A safety harness was worn by each participant, with slack monitored by a staff member to ensure that body weight was not supported during the protocol.

Five additional minutes of treadmill walking at PWS was then performed with the BiOM™ Ankle in an unpowered state to allow for acclimation to the inertial characteristics of the foot. Fifty consecutive strides with the BiOM™ Ankle in an unpowered state were then collected to characterize baseline walking performance at PWS. Seated rest was given as necessary. Participants were then randomly allocated to either the sudden or gradual training cohorts.

During power foot training, all participants walked for 400 strides at their PWS without explicit knowledge of whether ankle power was to be restored gradually or suddenly. Those in the gradual cohort had ankle power introduced at their lower limit and gradually increased to their upper limit in 2% increments every 20 strides until the upper power limit was reached (~400 strides total). The sudden cohort was introduced to ankle power via a single abrupt onset at their upper limit which was then maintained for all 400 strides of training. The same training protocol was repeated two additional times, for a total of three training bouts, with five minutes of seated rest between each bout. Participants from the two cohorts returned 24 hours later to perform a modification of the original locomotor task, walking on the treadmill at their PWS +25% and -25% for ~400 strides, using their upper power limit throughout. The order of the transfer tasks was randomized.

5.2.3 *Data Collection*

Fifty-seven reflective markers were placed on participants' bony landmarks (Sawers and Hahn, 2012). Throughout all walking conditions, three-dimensional marker coordinate data were collected at 120Hz using a 12 camera Vicon MX motion capture system (Vicon, Oxford, UK) and synchronized with ground reaction force (GRF) data collected from the treadmill force platforms (Bertec, Columbus, OH) at 1200Hz. Preferred and fast self-selected overground walking speeds were collected over four walking trials of a known distance (19.63 meters) with the prescribed prosthetic foot on the first day prior to training and with the BiOM™ Ankle following re-testing the second day in order to identify potential changes as a result of the intervention and/or training strategy. Participant preference was assessed following day-two re-testing.

5.2.4 *Data Analysis*

Marker coordinate and GRF data were filtered using a 4th order Butterworth filter with a 5 Hz and 25 Hz low-pass cut-off frequency respectively. Processed marker coordinate data were combined with participant specific anthropometric data adapted from Dempster (Winter, 2009) to build a 15 segment whole-body model in Visual 3D (C-Motion, Germantown, MD) (Sawers and Hahn, 2012). Kinematic data were combined with processed GRF data in Visual 3D to calculate the rotational ankle joint power using inverse dynamics. The peak propulsive ankle power elicited from the BiOM™ Ankle was chosen as the metric for locomotor performance with the powered foot because of its importance to locomotor function (Kuo, 2002) and the availability of participant-specific normative data (Lelas et al., 2003) to use as a biomimetic target. Additionally, it is reasonable to assume that the benefits of a powered prosthesis such as the BiOM™ Ankle are associated with the ability to consistently elicit physiological values of propulsive ankle power.

Using custom MATLAB^{TM} (MathWorks, Natick, MA) code, the average (mean) and variation (SD) in the peak propulsive ankle power elicited from the BiOM™ Ankle were calculated for each 20-stride window during all three training bouts and both 24-hr transfer tests. The ability to elicit physiological values of peak ankle power from the BiOM™ Ankle was determined by comparing the mean peak propulsive ankle power elicited over every 20-stride window during transfer, to an expected, participant-specific, velocity dependent, physiological value (Lelas et al., 2003). Smaller average absolute differences between the mean peak propulsive ankle power generated from the BiOM™ Ankle and the expected physiological value was considered to represent a superior ability to elicit physiological values of ankle power. The consistency with which peak propulsive ankle power was elicited was determined by examining the average (median) variation in propulsive ankle power across all 20-stride windows during transfer. Lower average variation represented greater consistency in eliciting peak propulsive ankle power from the BiOM™ Ankle. The median was selected due to the skewed distribution of the variability data. For this pilot study quantitative data were analyzed descriptively and compared between participants from the two training cohorts.

5.3 RESULTS

Five individuals with unilateral TTLL were recruited and participated in the study (Table 5.1). In four of the five participants, the peak propulsive ankle power elicited from the BiOM^{TM} Ankle was found to be substantially greater than the expected physiological value (Figure 5.1). As a result, no further analyses were performed comparing the average propulsive ankle power to expected physiological values. The relationship between peak ankle power of the intact limb to predicted physiological values and the BiOM™ Ankle was inconsistent between participants, but generally consistent within participants (Figure 5.1). The average variation in peak ankle power was lower throughout all training bouts, but specifically round one, and during both transfer tasks among the participants who received gradual training the previous day (Figure 5.2). Changes in self-selected preferred overground walking speed were inconsistent following gradual or sudden training, while self-selected fast overground walking speed increased among all participants, more so among those who received gradual training (Table 5.2). Gradually trained participants preferred the BiOM^{TM} Ankle over their prescribed prosthetic foot, while those participants trained with a sudden restoration of ankle power preferred their prescribed prosthetic foot over the BiOM^{TM} Ankle (Table 5.1).

Table 5.1. Participant demographics and foot preference

Participant	Height (m)	Mass (kg)	Age (years)	Gender	Etiology	Time Since Limb Loss (years)	MFCL	Foot Preference
Gradual_1	1.85	89.35	58	Male	Trauma	38	K3	BiOM$^{\text{TM}}$ Ankle
Gradual_2	1.91	118.84	51	Male	Infection	3	K3	BiOM$^{\text{TM}}$ Ankle
Gradual_3	1.75	83.91	31	Male	Infection	2	K3	BiOM$^{\text{TM}}$ Ankle
Sudden_1	1.76	71.67	33	Male	Trauma	9	K4	Prescribed Foot
Sudden_2	1.70	75.75	27	Male	Trauma	2	K4	Prescribed Foot

MFCL: Medicare Functional Classification Level

Table 5.2. Self-selected overground walking speeds (m/sec) with prescribed foot and after training with the BiOM^{TM} Ankle

Participant	Prescribed Foot		BiOM^{TM} Ankle	
	Preferred	Fast	Preferred *(% change*)	Fast *(% change*)
Gradual_1	1.41	1.68	1.35 *(-4%*)	1.87 (+*10%*)
Gradual_2	1.28	1.33	1.24 (-*3%*)	1.45 (+*8%*)
Gradual_3	1.44	1.70	1.44 (*0%*)	1.83 (+*8%*)
Sudden_1	1.50	1.92	1.63 (+*9%*)	2.06 (+*7%*)
Sudden_2	1.54	1.98	1.45 (-*6%*)	2.02 (+*2%*)

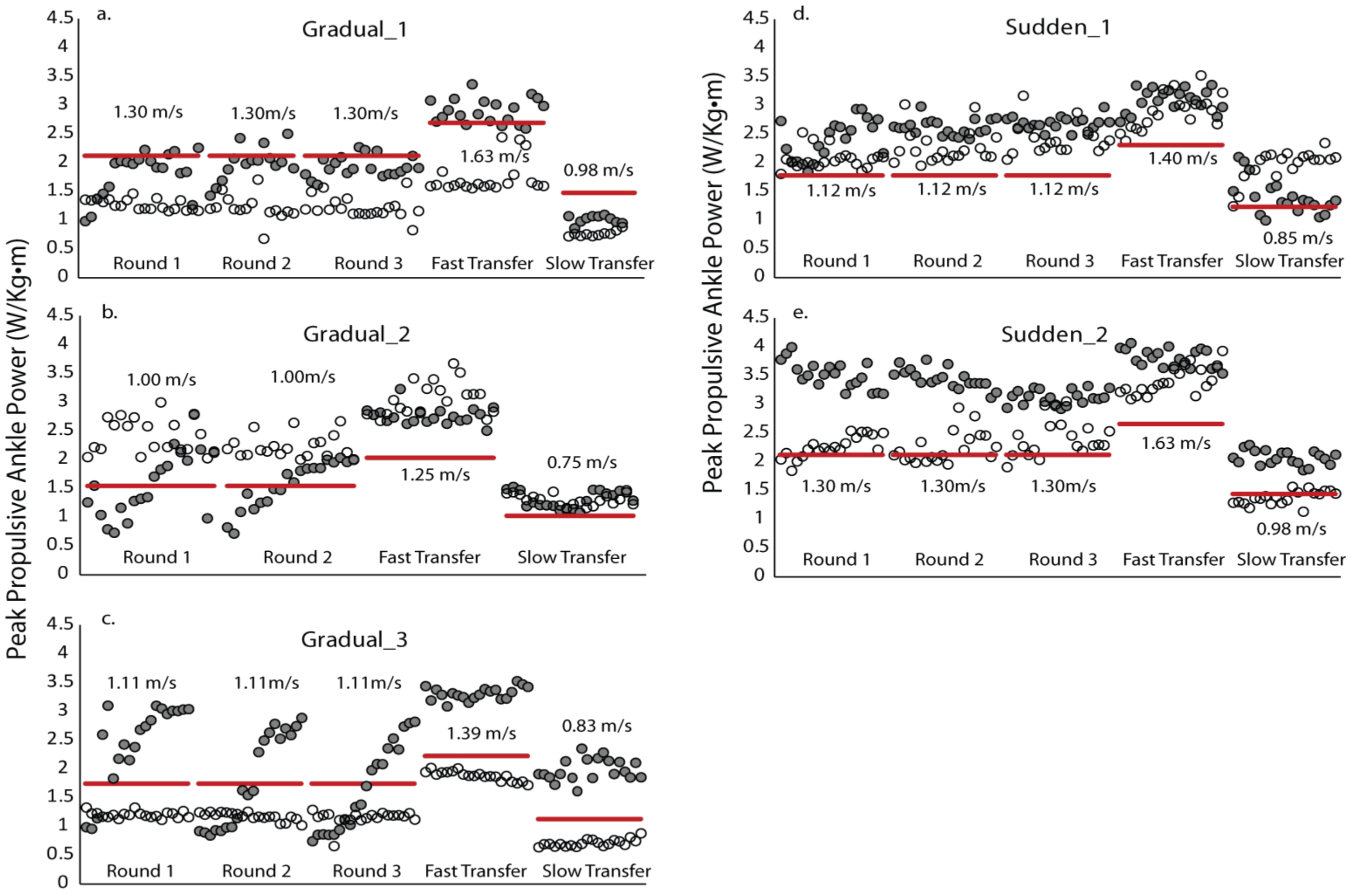

Figure 5.3. Peak propulsive ankle power during training and transfer performance as a function of gradual or sudden training. Each sub-plot corresponds to one participant who was trained with either a gradual (a-c) or sudden (d-e) restoration of propulsive ankle power with the BiOM^{TM} Ankle. Each data point is the mean peak propulsive ankle power elicited over 20 consecutive steps with the BiOM^{TM} Ankle (●) or the intact ankle (○). Each data point was compared to a predicted physiological velocity dependent value (—) based on published regression equations (Lelas, 2003). Two of the three participants who received gradual training (b, c) and both participants who received sudden training elicited peak propulsive ankle power values from the BiOM^{TM} Ankle which exceeded predicted physiological values. This suggests that the BiOM^{TM} Ankle was over-powered for these individuals rendering further comparison to predicted physiological values or the assessment of proximal joint performance inappropriate. Peak propulsive ankle power from the intact ankle did not demonstrate consistent behavior with respect to predicted physiological values or that elicited from the BiOM^{TM} Ankle within or between training strategies, suggesting the wide range of compensations that might occur in the contralateral limb.

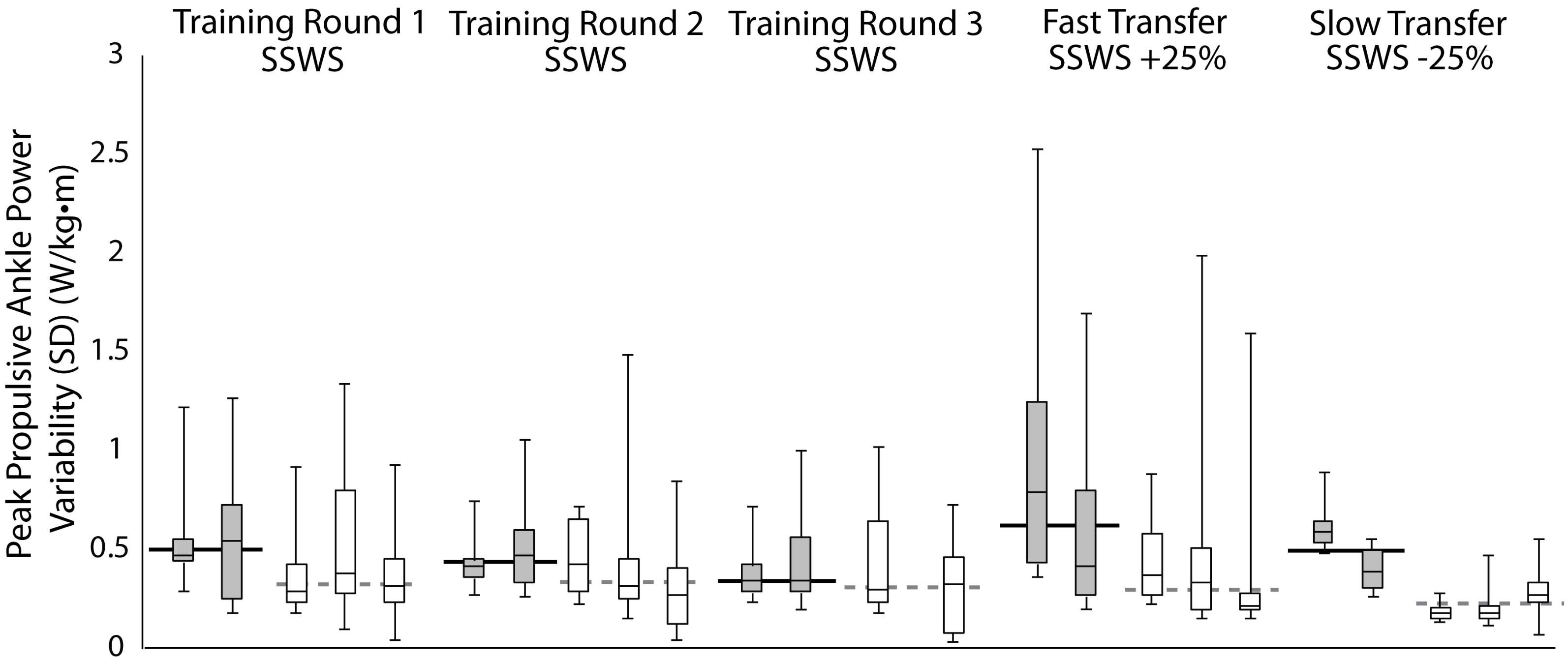

Figure 5.5. Consistency of peak propulsive ankle power elicited from the BiOM^{TM} Ankle during training and transfer task performance as a function of gradual or sudden training. Each box plot corresponds to one participant who was trained with either a gradual (white) or sudden (grey) restoration of propulsive ankle power. The box plots are for the variation (SD) in peak propulsive ankle power, with the average (median) variation describing the consistency with which peak propulsive ankle power was elicited from the BiOM^{TM} Ankle during and following gradual or sudden training. Group averages are denoted by (▬) for the sudden cohort and (┅) for the gradual cohort. During training, the gradual cohort demonstrated slightly greater consistency (lower variation) in peak propulsive ankle power. This difference was greatest during Round 1, and decreased over the remainder of training. During both fast and slow transfer, the gradual cohort demonstrated less uncertainty in the peak propulsive ankle power elicited from the BiOM^{TM} Ankle.

5.4 DISCUSSION

The objective of this pilot study was to examine how a gradual versus sudden restoration of ankle power influences the ability of individuals with unilateral TTLL to elicit peak propulsive ankle power from a powered prosthetic foot. The results of the present study revealed that in four of the five participants the peak ankle power elicited from the BiOM^{TM} Ankle was greater than target physiological values (Figure 5.1). This suggests that the system may have been “over-powered” at its upper limit among these four participants. Similar observations have been reported in recently published studies that examined the use of a powered ankle system among individuals with TTLL. In one study values of peak ankle power were found to be significantly greater than unimpaired adults at self-selected walking speeds (Ferris et al., 2012), while in another values of ankle work exceeded a two standard deviation normative range (Herr and Grabowski, 2012). A third study further demonstrated the challenge in prescribing desired power levels, reporting that peak ankle power exceeded a normative range in some participants, while falling below that same range in other participants (Mancinelli et al., 2011). From these observations and reported findings two concerns present themselves to the application of powered prostheses; knowing what the power level is set to, and determining what that value should be.

The first of these two issues, biomechanically accurate knowledge of the power settings, is principally a software and user interface issue. However, without such knowledge the tendency, as demonstrated in the current study and others (Ferris et al., 2012; Herr and Grabowski, 2012), is to over-power the foot. Restoring excessive or inadequate propulsive ankle power is likely to contribute to the persistence or creation of compensations at proximal and contralateral joints (Segal et al., 2011; Aldridge et al., 2012; Ferris et al., 2012) as excessive or inadequate propulsive ankle power may force the neuromuscular system to adapt and compensate in some fashion proximally so as to supplement inadequate ankle power or absorb excessive power. Similarly, too much ankle power has been shown to increase rather than decrease metabolic costs on an individual level (Zelik et al., 2011). Without the development of more advanced user-interfaces and the availability of biomechanically accurate real-time data, future research and clinical practice will have to rely upon participant feedback and observational gait analysis, both of which are inadequate when assessing joint kinetics.

A potentially more challenging and important question is determining what the appropriate power level is when restoring powered ankle function among individuals with TTLL. While previous research has employed a two standard deviation normative physiological range, it remains unknown whether normative values are suitable, what range of values is ideal, and how precise one needs to be in the prescription of "power-levels". As discussed above, the prescription of excessive or inadequate joint power is likely to contribute to the continued presence or creation of additional proximal and contralateral joint compensations despite prolonged use of the BiOM^{TM} Ankle. Despite the tendency to over or under power the BiOM^{TM} Ankle in those studies performed to date (Mancinelli et al., 2011; Ferris et al., 2012; Herr and Grabowski, 2012), this over and under prescription of joint power has been largely ignored and overlooked as a potential cause of the persistent joint compensations. Rather, the preferred explanations for the continued presence of the compensations include design limitations (Ferris et al., 2012; Herr and Grabowski, 2012), the lack of any systematic approach with which to train individuals with LLL how to use powered prostheses (Aldridge et al., 2012; Ferris et al., 2012), and the “pseudo-joint” created at the socket-residual limb interface (Ferris et al., 2012; Herr and Grabowski, 2012). These results suggest the need to increase our understanding of acute and chronic biomechanical and physiological responses to the restoration of powered plantarflexion over a range of values above and below physiological norms (Bigelow et al., 2011) as individuals with TTLL may not use ankle power in a similar fashion to unimpaired individuals (Zelik et al., 2011). In addition to the magnitude of ankle power, the timing with which it is delivered during the gait cycle should also be examined (Kuo, 2002). The objective of this pilot study was to examine the rate at which ankle power is restored; however, the current discussion suggests that future work needs to include an initial assessment of the impact different ankle power levels and their timing have on the locomotor patterns of individuals with TTLL and their use of powered prosthetic components.

Beyond the magnitude of propulsive ankle power, participants who were trained with a gradual restoration demonstrated lower variation in propulsive ankle power during training and both 24 hr transfer tasks (Figure 5.2). This suggests that a gradual restoration of ankle power encourages greater consistency in the production of propulsive ankle power from the BiOM^{TM} Ankle. Greater consistency in propulsive ankle power may assist in the integration of ankle power into whole-body neuromuscular strategies, thereby minimizing proximal joint compensations that persist despite prolonged use of the BiOM^{TM} Ankle (Ferris et al., 2012). Inconsistent performance of a powered prosthetic foot such as the BiOM^{TM} Ankle may encourage greater reliance on the proximal knee and hip joints beyond what is traditionally required in order to ensure safe and effective locomotion. As such, inconsistent performance of a powered prosthetic foot may be another cause of the proximal joint compensations that persist despite the restoration of propulsive ankle power. This possibility is supported by a recent study which reported a standard deviation in peak propulsive ankle power of 1.17 W/kg (0.65 W/kg·m when normalized to average height) with the BiOM^{TM} Ankle among a cohort of highly active individuals with TTLL following three weeks of acclimation to the BiOM^{TM} Ankle (Ferris et al., 2012). This variation in peak power was more than double that of unimpaired adults in the same study and comparable to that reported in this study for the sudden cohort during fast (0.65 W/kg·m) and slow (0.55 W/kg·m) transfer (Figure 5.2). Additionally, the participants in the Ferris (2012) study demonstrated significant locomotor compensations with the restoration of powered ankle function. Whether these compensations are related to the inconsistency with which peak ankle power was elicited or the variation in another function of the BiOM™ Ankle requires further examination. Regardless, given that Ferris (2012) restored ankle power in a manner which could be characterized as sudden, the lower variation (greater consistency) in peak propulsive ankle power demonstrated by the gradually trained cohort in this study may be a direct result of the training strategy.

Each participant's preferred overground walking speed while wearing their prescribed prosthetic foot was greater than that previously reported for individuals with TTLL (Barth et al., 1992; Isakov et al., 2000), but similar to a previous study examining the influence of the BiOM^{TM} Ankle (Ferris et al., 2012). Unlike previous studies (Ferris et al., 2012; Herr and Grabowski, 2012), we found no evidence to suggest that use of the BiOM^{TM} Ankle, regardless of training strategy, increased preferred overground walking speed (Table 5.2). In fact, there was an apparent decrease in preferred walking speed when using the BiOM^{TM} Ankle. This may reflect the limited time participants were provided with the BiOM^{TM} Ankle compared to other studies where increases in preferred walking speed were found. This notion is supported by another study where preferred walking speed decreased despite restoring propulsive ankle power in a cohort of individuals with TTLL. As in the current study, participants had limited time using the novel prosthetic foot (Segal et al., 2011). Therefore, changes in preferred walking speed following the restoration of ankle power may not be immediate, but rather require additional experience with the device.

In contrast with preferred overground walking speed, fast overground walking speed increased among all participants when using the BiOM^{TM} Ankle, with larger increases following gradual (~9%) versus sudden (~5%) training (Table 5.2). This suggests that a gradual rather than sudden restoration of propulsive ankle power may be a more effective approach to increase fast walking speed when introducing a powered prosthetic foot among individuals with TTLL. Additionally, the assessment of fast walking speed rather than preferred walking speed may be a more sensitive measure of change when examining the influence of powered prosthetic feet over a short time period.

In a recent study seven out of ten participants preferred the BiOM^{TM} Ankle over a traditional passive foot (Ferris et al., 2012). In the present study, the three participants who were trained with a gradual restoration of propulsive ankle power indicated a preference for BiOM^{TM} Ankle over their current prosthetic foot, while those who received sudden training preferred their existing prosthetic foot over the BiOM^{TM} Ankle (Table 5.2). Anecdotally, those participants who preferred the BiOM^{TM} Ankle based their preference on the restoration of push-off power. Those who preferred their existing prosthetic foot described "*not needing the push-off assistance*". While this suggests that gradual versus sudden training may alter patient preference, it seems equally likely that these results speak to patient candidacy for powered prosthetic devices. Rather than the most active patients who are currently considered candidates for advance prosthetic technology (Friel, 2005), the BiOM^{TM} Ankle and other devices like it may be well suited for those individuals who are not able to compensate as well for the loss of sensorimotor function of the ankle. In the current study this is supported by the greater age and lower self-selected preferred walking speed of the participants who preferred the BiOM^{TM} Ankle. Similarly, the participants who preferred their existing prosthetic foot were younger and may have retained the ability to compensate for the loss of ankle function, as evidenced by their faster self-selected preferred walking speed (Table 5.2) and greater MFCL (Table 5.1).

While the BiOM^{TM} Ankle was described as over-powered for four of the five participants in the present study, several factors may have influenced this interpretation. The regression equations that were used to calculate the expected physiological values were derived from overground rather than treadmill walking and therefore may not reflect a criterion value for comparison. Additionally, the parameters of the BiOM^{TM} Ankle were set during overground walking while the testing was performed on a treadmill. However, given the minimal differences in joint kinetics between overground and treadmill walking, specifically peak ankle power (Riley et al., 2007), the effect of these two potential limitations may be minimal. During training, each participant selected their preferred walking speed on the treadmill, and in all cases it was lower than their preferred overground walking speed. It is unclear how or if this may have affected the results, but the BiOM^{TM} Ankle was expected to be able to adapt accordingly to walking speed (Markowitz et al., 2011). Lastly, the small sample size in this pilot study limits the external validity of the results.

The results of this pilot study and their interpretation suggest that one of the most critical needs moving forward with research and clinical use of powered prosthetic components is a greater understanding of the acute and chronic biomechanical and physiological impact that a range of restored joint power values and their timing have on the locomotor pattern of individuals with TTLL and their use of powered prosthetic components such as the BiOM^{TM} Ankle. Such endeavors will provide answers that will allow for more individualized delivery of powered prosthetic feet and the pursuit of additional research questions. This may include a continued examination of the rate at which joint power is restored when using powered prostheses, the impact of future design modifications, the manner in which powered prosthetic joint kinetics are used and contribute to body weight support and forward propulsion compared to their biological counterparts, the validity of current prescription criteria for advanced prosthetic technology, the examination of training strategies based upon sound motor learning principles, and the translation of successful training strategies into algorithms that can be installed in future design iterations to extend training from the clinic into the home and community. Regarding the persistence of proximal and contralateral joint compensations following the restoration of biomimetic ankle function, it remains unknown whether these locomotor compensations occur in response to the loss of motor function, sensory function, or some other factors. Therefore, future work should examine how the loss of a range of sensorimotor functions, in isolation and as a whole, contributes to locomotor compensations, in order to help direct the development of future interventions and rehabilitation protocols.

5.5 CONCLUSION

This pilot study highlighted some of the current challenges concerning the implementation of powered prostheses, particularly regarding parameter settings and the biomechanical and physiological response to such settings. Despite these limitations the observations of this pilot study suggest that a gradual restoration of ankle power may facilitate a more consistent elicitation of peak power from the BiOM^{TM} Ankle, which in turn may act to reduce proximal and contralateral joint compensations that have been reported to persist following the restoration of ankle power. Additionally, gradual training may improve acceptance of powered prostheses, while increasing self-selected fast walking speeds.

Chapter 6. SUMMARY OF FINDINGS AND CONCLUSIONS

6.1 MAJOR FINDINGS

The first study described how two different motor learning strategies can influence the ability of unimpaired adults to learn a novel locomotor task, asymmetric split belt treadmill walking. The purpose of this study was to determine whether gradual versus sudden training influenced how well the whole-body sagittal plane kinematics required to perform a novel locomotor task were learned. The results indicated that despite more specific and difficult practice for the sudden cohort on day one, gradual and sudden training resulted in equivalent motor learning of the locomotor task, as assessed by retention and transfer performance. This suggests that gradual training promotes the learning of locomotor tasks with greater ease than sudden training, a characteristic that may directly benefit locomotor rehabilitation. Additionally, whole-body sagittal plane kinematics of the slow leg were found to present a greater challenge during training, as well as during retention and transfer the following day than those of the fast leg. This may have particular relevance for the staging and focus of locomotor rehabilitation of common unilateral locomotor impairments.

The second study discussed the challenge to lateral balance control presented by two different motor learning strategies. The purpose of this study was to determine whether gradual versus sudden training influenced lateral balance control during training and subsequent performance of a novel locomotor task, asymmetric split belt treadmill walking. Findings from this study showed that the use of a gradual versus sudden training strategy reduced the challenge to lateral balance control during training of a novel locomotor task. Additionally, participants who received gradual versus sudden training had less difficulty controlling lateral balance upon re-testing the next day, and used different whole-body frontal plane kinematic strategies to regulate lateral balance control. These results suggest that motor learning strategies are capable of influencing aspects of locomotor balance control, and that selection of appropriate motor learning strategies should receive greater attention during locomotor balance control rehabilitation.

The third study described the cognitive demand required when using two different motor learning strategies to learn a novel locomotor task. The purpose of this study was to determine whether gradual versus sudden training influenced the cognitive demand required while practicing a novel locomotor task. Findings of this study indicated that the use of a gradual versus sudden training strategy reduced the cognitive demand required while learning a novel locomotor task, particularly during training. These results suggest that the choice of training strategy used during practice may influence more than just how well a motor skill is learned. Training strategies may also modulate the cognitive demand required during training, and possibly during subsequent performance of motor skills.

The final study sought to explore the clinical application of gradual and sudden training as potential locomotor rehabilitation protocols among individuals with unilateral transtibial limb loss (TTLL). The purpose of this pilot study was to examine whether a gradual versus sudden restoration of ankle power influenced the ability of individuals with unilateral TTLL to elicit physiological values of peak propulsive ankle power from a powered prosthetic foot, the BiOM^{TM} Ankle. The results indicated that a gradual restoration of ankle power may facilitate a more consistent elicitation of peak power from the BiOM^{TM} Ankle. This may in turn act to reduce proximal and contralateral joint compensations that have been reported to persist following the restoration of ankle power. Further research is recommended to better understand how a range of restored joint power values and their timing affect the locomotor pattern of individuals with TTLL, and their use of powered prosthetic components.

6.2 LIMITATIONS

The first set of potential limitation regarding these experiments involves the use of a treadmill. While ample time was provided for acclimation, the loss of optic flow (Warren et al., 2001) may have influenced our assessment of locomotor performance. However, previous research has demonstrated that the amount of variability in foot placement during treadmill walking is comparable to that of overground walking in both the sagittal and frontal plane (Owings and Grabiner, 2004a). As such, the lack of optic flow may have had minimal influence on the uncertainty of the sagittal and frontal plane movement patterns and thus the results and conclusions presented herein. The addition of a virtual reality environment would further minimize any concerns regarding the loss of optic flow.

The selection of treadmill walking speeds could also be viewed as a potential limitation of these studies. In Chapters Two through Four, (i.e. split belt treadmill experiments) baseline walking speed was limited to 0.7 m/s in order to prevent 2:1 and 3:1 walking speeds from becoming extreme. In doing so the slower walking speed may have increased medial lateral COM motion (Orendurff et al., 2004) during baseline walking, thereby influencing our assessment of whole-body frontal plane kinematics. However, the 15 minutes acclimation period was intended to minimize this possibility.

The regression equations that were used to calculate the expected physiological values of peak propulsive ankle power in chapter five were derived from overground walking while the testing with the BiOM^{TM} Ankle was performed on a treadmill. Concern regarding the validity of using these regression equations for predicting ankle function on a treadmill can be assuaged by recent work demonstrating that no significant difference exists in peak propulsive ankle power during overground and treadmill walking (Riley et al., 2007).

During training with the BiOM^{TM} Ankle, each participant selected their preferred walking speed on the treadmill. In all cases it was lower than their preferred overground walking speed which was used to establish the device parameters. It is unclear whether this may have influenced the results, however, it was anticipated that the BiOM^{TM} Ankle would be able to adapt to different walking speeds (Markowitz et al., 2011).

A second source of potential limitations for these experiments concerns the experimental protocols that were used. All participants in the split belt experiments were afforded the same training experience and used the same walking speeds during 2:1 and 3:1 walking. Given the range of self-selected walking speeds (SSWS) and heights (i.e. leg lengths) among the participants, 2.1 m/s during 3:1 walking may have approached the walk-to-run transition for some participants but not others (Segers et al., 2007), possibly influencing the results. In future work this could be alleviated by using participant-specific protocols in which SSWS or a percentage of SSWS acts as the baseline walking speed. Subsequent increases in walking speed to reach 2:1 or 3:1 walking could then be made as a percentage of that participant specific baseline walking speed rather than as an absolute value.

The use of a simple reaction time (RT) task in Chapter Four may not have provided sufficient challenge to truly probe the differences in cognitive demand between gradual versus sudden training. Despite the justification for the use of a simple RT task, future work may be served by using a more demanding task, such as choice or Stroop RT, to provide a more in-depth assessment of cognitive demand. Additionally, the use of a visual cue and stimulus may have provided perceptual content that assisted in postural control during the locomotor task. While this could have acted to reduce the challenge of the locomotor task, the similarity of locomotor performance under single and dual-task conditions would suggest that the use of a visual cue and stimulus did not improve locomotor performance. Regardless, use of an auditory stimulus may reduce this limitation in future work.

A third group of potential limitations for this set of experiments involves the analysis methods. In many cases the conclusions drawn from the results were based upon significant yet small changes in the dependent variables. While this is not uncommon when examining locomotor performance, it suggests the need for additional measures of change for the variables of interest such as the minimal detectable difference (Portney and Watkins, 2009). This would allow for additional analysis and confirmation that observed differences were in fact “real differences” beyond the expected measurement error.

The amount of uncertainty in the frontal and sagittal plane movement patterns in Chapters Two through Four were calculated over 20 stride increments. While debate exists as to whether this is a sufficient number of strides to capture the amount of uncertainty in a locomotor pattern (Owings and Grabiner, 2003), 20 stride increments were used because those were the increments over which the velocity of the fast treadmill belt was increased during gradual training. Extending the length of those increments would have made training longer, possibly inducing fatigue and confounding the results. Future work may benefit from increasing the number of strides to 50 (Owings and

Grabiner, 2003) and decreasing the number of incremental changes during gradual training.

In this set of experiments the standard deviation was used to quantify the amount of uncertainty in the sagittal and frontal plane movement patterns, as well as in the peak propulsive ankle power in Chapter Five. Additional insight into how different motor learning strategies influence locomotor performance could be derived using other measures of variability such as approximate or sample entropy in order to quantify the structure of the movement variability (Stergiou and Decker, 2011).

It is also possible that by quantifying the average amount of uncertainty in the sagittal and frontal plane movement patterns using the Average Uncertainty Residual (AuR) some resolution may have been lost. In future work it may be of value to examine changes in the average amount of uncertainty over shorter time periods rather over the entire training, retention or transfer session. Such an approach may also yield information regarding how and when to manage practice difficulty (i.e. when to increase or decrease practice difficulty and by how much).

The assessment of motor learning and lateral balance control in Chapters Two, Three and Four were dependent on the accurate estimation of whole-body center-of-mass (COM) position. While several methods exist for estimating COM position, the weighted-sum or kinematic approach is considered to be among the most accurate (Gard et al., 2004).

6.3 SUGGESTIONS FOR FUTURE STUDIES

The studies presented in this dissertation have demonstrated how two different motor learning strategies can influence a number of features critical to locomotor rehabilitation. They have also highlighted the need for additional research in a number of areas.

The present work examined how gradual versus sudden training influenced the acquisition of task-specific whole-body sagittal plane kinematics. Given the possibility that the same whole-body sagittal plane kinematic movement pattern could be produced though a number of different individual segment angle combinations, it may be important to study how the whole-body kinematic pattern was accomplished. Specifically, future research should examine whether the magnitude or timing of joint or segment angle contributions to whole-body sagittal plane kinematics are affected by training strategy, and whether different kinetic or neuromuscular patterns are used to perform locomotor tasks as a function of training strategy. This may provide insight into whether different motor learning strategies encourage compensation or recovery of motor function.

Additionally, it has recently been reported that motor learning can reduce the metabolic cost of movement (Huang et al., 2012). Therefore, future work should examine the ability of gradual versus sudden training and other motor learning strategies to influence metabolic and mechanical movement efficiency. Similar to the assessment of balance control in Chapter Three, movement efficiency should be examined during training and over a period of delayed retention or transfer.

When examining the ability of motor learning strategies to influence locomotor balance control it will be increasingly important to do so over longer periods of time then presented here or in previous studies (Bhatt and Pai, 2008; Domingo and Ferris, 2009, 2010). Therefore, future research should examine whether the ability of gradual training and other motor learning strategies to reduce the challenge to lateral balance control can be retained over an extended period of time. Examining the retention of balance control strategies over an extended period of time with multiple points of measurement may provide insight as to when performance begins to deteriorate and brief "tune-up" training sessions are required. This may also inform upon dosage requirements for locomotor rehabilitation protocols.

Developing clinically relevant balance control interventions using gradual versus sudden training should also be pursued. Specifically, gradual training may be of potential value in the development of perturbation training protocols. Perturbation training involves the repeated introduction of balance threats; with the goal of improving responses to perturbations and thus locomotor balance control. While recently established as a successful means to reduce falls (Bhatt and Pai, 2008; Wang et al., 2011), to date, perturbation training has only made use of a single perturbation magnitude that has been abruptly introduced. The work presented in this dissertation suggests that perturbation training may benefit from the use of a gradual introduction of the perturbation magnitude during training, particularly among individuals prone to or with a history of falls.

While the current work demonstrated the efficacy of gradual versus sudden training to reduce the cognitive demand while practicing a novel locomotor task, it did not examine how the addition of a secondary task influenced motor learning, or whether either training strategy affected the automaticity of the novel locomotor pattern. Therefore, using dual-task methodologies, future research should examine whether practice conditions such as gradual versus sudden training influence the reaction time not just during training, but during subsequent performance in order to examine the automaticity of the acquired locomotor pattern. Furthermore, the assessment of cognitive demand in this dissertation was limited to unimpaired individuals. Future studies may choose to examine how the ability to dual-task and manage cognitive demand is influenced by the use of powered rehabilitation technology and the manner in which individuals are trained to use that technology. As in the work presented here, much of the research examining the cognitive demand of locomotor activities does so through inference of reaction times on secondary tasks and/or alterations in locomotor performance. Future work should include the use of non-invasive imaging techniques such as functional near-infrared spectroscopy (Suzuki et al., 2008) to confirm the results of traditional dual-task methodologies.

The results of the pilot study in Chapter Five suggest that one of the most critical needs moving forward with research and clinical use of powered prosthetic components is a greater understanding of the acute and chronic biomechanical and physiological impact that a range of restored joint power values and their timing have on the locomotor pattern of individuals with TTLL and their use of powered prosthetic components. Such research will allow for more individualized delivery of powered prosthetic components and the pursuit of additional research questions. These questions may include: a continued examination of the rate at which joint power is restored when using powered prostheses, the impact of future design modifications, the manner in which powered prosthetic joint torques contribute to body weight support and forward propulsion compared to their biological counterparts, the validity of current prescription criteria for advanced prosthetic technology, the examination of training strategies based upon sound motor learning principles, and the translation of successful training strategies into algorithms that can be installed in future design iterations to extend training from the clinical setting into the home and community.

While the persistence of proximal and contralateral joint compensations following the restoration of biomimetic ankle function has been reported previously, little has been done to study the possible causes. The prevailing theory is that limitations in the design are responsible for the continued presence of the aforementioned compensations (Ferris et al., 2012; Herr and Grabowski, 2012), however it has also been suggested that the lack of any systematic approach with which to train individuals with LLL how to use powered prostheses may contribute to these compensations (Aldridge et al., 2012; Ferris et al., 2012), as may the “pseudo-joint” created at the socket-limb interface . Overlooked as potential causes for these compensations is the prescription of excessive or inadequate ankle power that has been common in most studies to date, as well as the consistency with which ankle powered is elicited. Each of these potential sources of compensation are testable, therefore future studies should be developed to elucidate their contribution to the persistence of gait compensations, thereby aiding in the design of future prosthetic modifications and locomotor rehabilitation protocols.

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VITA

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