Effects of a Concurrent Task on Walking Over Firm and Foam Surfaces in Persons with Transfemoral Amputation

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A dissertation

submitted in partial fulfillment of the

requirements for the degree of

Doctor of Philosophy

University of Washington

2014

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Program Authorized to Offer Degree:

Rehabilitation Science

University of Washington

Abstract

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People with lower limb loss (LLL) experience profound mobility challenges, including a high incidence of falls, low balance confidence, and diminished walking activity. In addition to these mobility restrictions, many people with LLL report the need to concentrate on every step. This need to concentrate on walking may reflect increased reliance on cognitive control to compensate for loss of peripheral afferent feedback and efferent control. Reliance on cognitive control can be inferred using dual-task paradigms, where walking is performed with and without a concurrent task. This aims of this dissertation were to (1) review dual-task stance and walking research in persons with LLL, (2) quantify changes in walking associated with addition of a concurrent task in persons with transfemoral amputation (TFA) using microprocessor knees compared to controls without limb loss, and (3) use a dual-task paradigm to infer the need for cognitive control to walk over simple and

challenging surfaces in participants with TFA using microprocessor knees and controls. Quantitative motion analysis was used to assess walking performance while walking with and without a concurrent cognitive task. People with TFA walked more slowly, with wider steps, and with reduced gait quality compared to controls across all task and surface conditions. However, people with TFA were not differentially affected by addition of a concurrent task in either surface condition. These results may suggest that participants with TFA adopt conservative walking patterns to reduce reliance on cognitive control for mobility.

Future work will assess whole body movements and biomechanical measures of postural stability using estimated center of mass (COM) position. Link-segment models based on markers and participant mass distributions are used to estimate whole-body COM position. However, modeling guidelines are not established for people with LLL who use prostheses. Thus, the following aim was also examined: (4) assess the equivalency of two modeling approaches used to estimate COM position- an anatomical approach, based on the mass distribution properties of the intact side; and a prosthetic-specific approach, based on prosthetic component masses. The anatomical and prosthetic-specific models from two participants with TFA produced small, but potentially meaningful differences in calculated COM parameters.

This research was conducted with the approval of the Human Subjects Division
of the
University of Washington.
Application Number: 41711
Date of Approval: 10/04/2011

Plain Language Summary

People often do other things when walking. Sometimes people talk with friends, tend to children, and make mental lists while they are walking. Most people can easily pay attention to multiple tasks. However, doing one or more tasks when walking can be hard for many people with lower limb loss. People with lower limb loss often say they need to pay attention to walking. Giving full attention to walking may keep them from doing other important things at the same time. Also, people with lower limb loss cannot feel the surface of the ground on their prosthetic side. This can make walking over soft surfaces difficult and may require more attention.

The need to pay attention to walking can be studied by measuring walking with and without a thinking task. This is called dual-task walking. Studying dual-task walking allows researchers learn how walking with a thinking task may differ between people with and without lower limb loss. The purpose of this research was to study whether or not a thinking task changed walking in people with lower limb loss who use computerized prosthetic knees. We studied people using computerized knees since they may lessen the need to pay attention to walking. Walking with and without the thinking task was measured while people walked over a firm surface and a soft surface. We measured walking on firm and soft surfaces because we wanted to see how walking on soft surface might change their need to pay attention. Walking in people with lower limb loss was compared to walking in people without lower limb loss.

Fourteen people with lower limb loss and fourteen people without limb loss were in our study. People with limb loss walked more slowly and with wider steps than people without limb loss. In addition, people with lower limb loss walked more slowly and with wider steps on the soft surface compared to the firm surface. In contrast, people without limb loss often walked the same or better over the soft surface. However, the thinking task did not greatly change walking on the soft or firm surfaces in either group. The result that the thinking task did not differentiate walking between groups may mean that people with lower limb loss do not pay more attention to walking than people without limb loss. This result could also mean that people with lower limb use a way of walking that decreases the need to pay attention.

This study had another part. We compared two methods for measuring body movements in people with lower limb loss. These results will also be used to help us learn how the thinking task affected the body's movements during walking in people with and without lower limb loss. Small differences were found in the methods for measuring body movements. This result suggests we should carefully pick the method to measure body movement in future studies of people with lower limb loss.

Acknowledgements

I would like to first acknowledge my advisor and mentor, Dr. Valerie Kelly. She is the scientist, teacher, and mentor that I hope to someday become and I am fortunate to have worked so closely with her for the past four years. Many thanks to her for the time, knowledge, compassion, and patience that she so freely shared- I plan to pay it forward.

I would also like to thank my mentor, Dr. Brian Hafner. I have immensely benefitted from the time and energy that he put into my academic development. His words of wisdom are frequently in the front of my mind and will inform my research and writing for the rest of my career.

Thank you to my committee members, Drs. Deborah Kartin, Patricia Kramer, and David Morgenroth, for their wisdom and guidance.

Thank you to Dr. Dagmar Amtmann, who has be instrumental in my development as a scientist. Also, thank you to my teammates at UWCORR.

I would like to acknowledge and thank Dr. Marcia Ciol for providing statistical advice and Rebecca Archer for her help with data collection and analysis.

I would like to extend many thanks to Victoria Corrin, Ann Yamane, and Susan Spaulding for their support and encouragement over the past four years and to my PhD cohort, Namrata Grampurohit, Torey Gilbertson, Lin-Ya Hsu, and Cristine Agresta, who were always there for me.

Thank you to my family and friends, who have been so patient with and supportive of me throughout this process, and to Mae, who made me laugh even on my toughest days. Most of all, I would like to thank my husband, John, who has been my rock, my biggest cheerleader, and the love of my life for over a decade. He prioritized this goal of mine and worked with me to make it happen- I could not ask for anything more from a life partner.

Funding: The projects described in this dissertation were supported by a Center for Sensorimotor Neural Engineering Seed Grant, a subaward of award number EEC- 1028725 from the National Science Foundation. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Science Foundation.

For John and Mae

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Foreword

People with lower limb loss (LLL) experience profound mobility challenges due, in part, to physical loss of limb structures and disruption in peripheral systems that provide sensory input and motor control. Movement limitations experienced in this population often include impaired postural stability (Vrieling et al., 2008a; Buckley, O'Driscoll, & Bennett, 2002; Geurts & Mulder, 1994; Fernie & Holliday, 1978), increased metabolic energy expenditure while walking (Genin, Bastien, Franck, Detrembleur, Willems, 2008; Chin, Sawamura, Shiba, Oyabu, Nagakura, Takase, et al., 2003; Boonstra, Schrama, Fidler, Eisma, 1994; Waters & Mulroy, 1999; Traugh, Corcoran, Reyes, 1975), decreased gait speed (Boonstra, 1994; Waters, 1999; Jaegers, Arendzen, de Jongh, 1995; Genin, Bastien, Franck, Detrembleur, Willems, 2008), and pronounced gait asymmetries (Donker & Beek, 2002; Jaegers, 1995; Hof, van Bockel, Schoppen, Postema, 2007; Nolan, Wit, Dudzinski, Lees, Lake, Wychowanski, 2003). Such limitations may result in difficulties negotiating common barriers within the community like uneven terrain (Lamoth, Ainsworth, Polomski, & Houdijk, 2010), hills (Vrieling et al., 2008b), and stairs (Ramstrand & Nilsson, 2009; Jones, Twigg, Scally, Buckley, 2006). It is conceivable that these mobility challenges might contribute to adverse experiences reported in limb loss research, such as restrictions in walking activity (Halsne, Waddingham, & Hafner, 2013; Stepien, Cavenett, Taylor, & Crotty, 2007) and a high incidence of reported falls (Gauthier-Gagnon, Grisé, & Potvin, 1999; Miller, Deathe, Speechley, & Koval, 2001a).

In addition to the above mobility limitations, many people with LLL report the need to "concentrate on every step" (Miller, 2001a; Gauthier-Gagnon, 1999). This need to concentrate on walking may reflect increased reliance on cognitive resources to compensate for loss of peripheral afferent feedback and efferent control. An increased use of cognitive resources for ambulation may limit those resources available for other cognitive tasks, such as interacting socially or observing the environment. Further, the need to concentrate on walking has been correlated with an increase in falls and an elevated fear of falling in persons with LLL (Miller, Speechley, & Deathe, 2001b). Thus, reduction in the need to concentrate on walking may serve to both improve quality of life and promote safety in this population. Novel prosthetic interventions have the potential to reduce the need for persons with LLL to concentrate on walking (Childress & Weir, 2004), although the actual impact of such interventions on heightened concentration are often equivocal (Williams et al., 2006; Hafner & Smith, 2009; Hafner, Willingham, Buell, Allyn, & Smith, 2007).

Dual-task paradigms can be used to study how higher cognitive functions, including concentration, might interact with postural tasks, such as standing and walking. Research using dual-task paradigms assesses the simultaneous performance of a postural task and a concurrent cognitive or motor task. Declines in performance on one or both tasks (i.e., dual-task interference), is then used to infer relative contributions of cognitive resources to postural control (Abernethy, 1988). An underpinning assumption in dual-task research is that dual-task interference is caused by limited cognitive resources or processing. Two main theories explain dual-task interference: the capacity theory and the bottleneck theory.

The capacity theory hypothesizes a limited amount of cognitive resources available. In circumstances when simultaneous performance of one or more tasks requires cognitive processing that exceeds the available capacity, performance quality of one or more tasks declines (Tombu & Jolicœur, 2003). The bottleneck theory postulates that simultaneous performance of multiple tasks can lead to processing interference in a "structural central bottleneck." In this case, the neural system prioritizes one of the tasks and temporarily postpones action on the other, leading to performance decline on the non-prioritized task (Ruthruff, Pashler, Klaassen, 2001). Both theories assert that when increased cognitive resources or processes are required for performance of a task, remaining resources or processing channels available for the performance of a concurrent task may be insufficient. When there are insufficient resources or processing channels, it is hypothesized that concurrent performance of these tasks will result in decline in performance of one or both of the tasks.

Dual-task research is widely used in rehabilitation science to infer reliance on cognitive control during motor task performance (Woollacott & Shumway-Cook, 2002). Because dual-task paradigms are a non-invasive means to infer the extent to which cognition is employed in the control of standing and walking, it has been an attractive research paradigm for researchers interested in postural control. However, dual-task research can be methodologically challenging, requiring those who employ it to understand the implications of methodological choices to appropriately and meaningfully interpret results (Abernethy, 1988; Fraizer & Mitra, 2008; Al-Yahya, Dawes, Smith, Dennis, Howells, & Cockburn, 2011). In dual-task research, the choice of postural and cognitive tasks, use of directions for task prioritization, and inclusion of baseline (or single-task) conditions are all methodological choices that need to be carefully considered based on the research question. Accordingly, these methodological decisions affect interpretations and inferences made based on results of the corresponding dual-task studies.

Dual-task paradigms have also been used to assess concurrent performance of postural and cognitive tasks in persons with LLL. Overall, these studies provide inconclusive objective support for dual-task differences in balance and walking performance between people with and without LLL. Since there is little definitive evidence of differential dual-task decline in previous research, one might speculate that people with LLL do not require heightened cognitive control for postural tasks, such as standing and walking. However, methodological considerations such as small, heterogeneous samples, inter-study variation in choice of concurrent tasks, and critical limitations in application of dual-task methods may limit the ability to infer such conclusions.

The following literature review (Chapter 1) aimed to critically appraise results of previous dual-task research and discuss how the methods applied may, in part, explain discrepancies between self-report of "concentration on every step" and objective measurement of dual-task performance in people with LLL. The study of how dual-task paradigms have been applied in previous research is was a crucial first step for subsequent research (Chapters 2 and 3), which aimed to build upon previous dual-task research to better understand cognitive control of simple and challenging walking tasks in people with LLL using microprocessor knees compared to people without LLL. Future analyses of the data described in Chapters 2 and 3 will be used to assess whole-body center of mass (COM) kinematic parameters as biomechanical measures of postural stability. To conduct these analyses, biomechanical models will need to be created to estimate COM position in participants with and without LLL. Thus, the aim of Chapter 4 was to compare whole-body kinematic parameters calculated from two different approaches to modeling people with LLL to assess if model type affects COM-related parameters in this population. Chapter 5 provides a summary of the overall results of this dissertation, identifies the primary implications for rehabilitation science, and suggests directions for future research.

Chapter 1. Dual-task research in people with lower limb loss:

A review of the literature

Abstract

Dual-task methods have been used to infer reliance on cognitive control for postural tasks in people with lower limb loss (LLL), but results of studies that employ these methods often contradict self-reported outcomes regarding the perceived need to concentrate on walking. The aim of this review is to summarize and appraise the current state of dual-task standing and walking research in persons with LLL and discuss implications for future research. A comprehensive search of PubMed, CINAHL, and Web of Science for relevant literature published between January 1965 and August 2014 was performed using multiple combinations of the following keywords: attention, cognitive, dual task, multitasking, reaction time, mental load, amputation, limb prosthesis, C-leg, microprocessor knee, microprocessor-controlled, balance, walking, and posture. Eligibility criteria for studies were: availability in English, inclusion of participants with lower extremity limb loss, and assessment of standing or walking under dual-task conditions. Eleven publications were identified that met inclusion criteria. Six examined differences in dual-task standing or walking between people with and without LLL and five assessed dual-task walking across prosthetic knee conditions. Definitive conclusions about the role of cognitive resources to compensate during standing and walking in people with LLL could not be drawn from the existing dual-task research due to heterogeneity in methods across studies. Further research assessing the cognitive control of walking in people with LLL is needed.

Introduction

People with lower limb loss (LLL) must adopt atypical postural control strategies due to loss of critical sensorimotor structures following amputation. Because these sensorimotor substrates play crucial roles in the maintenance of postural stability for standing and walking, people with LLL may compensate by allocating visual and other cognitive resources to these tasks. In fact, Gauthier-Gagnon et al. (1999) found that 46% of respondents with transtibial amputation (TTA) and 59% of respondents with transfemoral amputation (TFA) reported the need to "concentrate on every step," perhaps reflecting a disproportionate reliance on cognitive resources for walking in these populations. Furthermore, the need to concentrate on walking reported by people with LLL has been correlated with falling and fear of falling (Miller, Speechley, & Deathe, 2001b). The relationship between reporting the need to concentrate on walking and falls has important implications for practitioners in rehabilitation medicine, who have the potential to improve safety and quality of life in people with LLL through prosthetic and therapeutic interventions.

The interaction between cognition and postural control in people with LLL can be studied using a dual-task paradigm. In this research paradigm, a postural task, like standing or walking, is performed with and without a concurrent cognitive or motor task. Decline in performance on one or both tasks provides insight into the relative contributions of cognitive resources for postural control (Abernethy, 1988).

A growing body of research using dual-task methods has been conducted in people with LLL, but results of these studies often contradict self-reported outcomes regarding the perceived need to concentrate on walking (Gauthier-Gagnon, 1999; Miller, 2001a). Thus, the goal of this review was to synthesize and appraise the available studies that used dual-task methods to study postural control tasks in people with LLL. This review was structured to address the following questions:

(1) Do people with LLL differ from people without LLL in objective measures of dual-task standing?

(2) Do people with LLL differ from people without LLL in objective measures of dual-task walking?

(3) Is dual-task walking in people with LLL modified with use of microprocessor-controlled prosthetic technologies?

Methods

Literature Search and Inclusion Criteria

A comprehensive search of the literature was performed using three electronic databases: PubMed (1966 – August, 2014), CINAHL (1982 – August, 2014), and Web of Science (1965 – August, 2014). The search strategy included the following combinations of keywords: [attention* OR cognitive OR "dual task" OR multitasking OR "reaction time" OR (mental AND load*)] AND [amput* OR "limb prosthesis" OR C-leg OR "microprocessor knee" or "microprocessor-controlled"] AND [balance OR walking OR posture]. In addition, references of identified articles were reviewed.

Eligibility criteria for publications included in this review were as follows: articles must be available in English, participants must be adults with lower extremity limb loss of any etiology, participants must currently use a prosthesis, and the primary or secondary outcome measures must objectively assess standing or walking under dual-task conditions. Excluded studies were those available only in abstract form, unpublished theses or dissertations, and review articles.

Study Selection and Data Extraction

One reviewer evaluated titles and abstracts to determine the eligibility of articles identified by the literature search. Articles that were potentially eligible for inclusion in the review were read in full and assessed based on the eligibility criteria stated above. Pertinent information from eligible articles, including sample size, sample characteristics (age, level of amputation), standing or walking task description, cognitive task description, and results, was then extracted from each article into an evidence table that allowed for comparisons between similar articles. The articles were classified by their ability to address one or more of the following questions: (1) Do people with LLL differ from controls in objective measures of dual-task standing?, (2) Do people with LLL differ from controls in objective measures of dual-task walking?, and (3) Is dual-task walking in people with LLL modified by microprocessor-controlled prosthetic technologies? Meta-analysis of existing data was not possible because of the variety of study designs, methodologies, and outcomes measured. Summary measures of interest were reported as performance outcomes associated with the postural (i.e., standing or walking) task and the concurrent cognitive task.

Results

Database searches yielded 106 unique publications for consideration. Review of abstracts identified 18 publications that were read in full. Of those, 10 articles fit the eligibility criteria and were fully reviewed. One additional article (Hof, 2007) was identified through an unrelated literature search by the author. This article used dual-task methods to validate an outcome of walking stability, but did not discuss the addition of a dual task in the study title or abstract and did not cite, nor was cited by, previous dual-task studies in people with LLL. Thus, although this study fit inclusion criteria, it was not discoverable in searches associated with this topic. This article was also included in this review (Figure 1.1, Table 1.1).

Results of the reviewed publications are presented in the following three subgroups: (1) standing-cognition dual-tasking in people with LLL compared to controls, (2) walking-cognition dual-tasking in people with LLL compared to controls, and (3) impact of microprocessor technology on walking-cognition dual-tasking in people with LLL.

Standing-cognition dual-tasking in people with LLL compared to controls

Three observational studies examined the impact of a concurrent cognitive task on quiet and perturbed standing postural control in persons with LLL. Two studies by Geurts and colleagues (1991; 1994) examined longitudinal changes in the automaticity of standing postural control throughout the rehabilitation process in persons with recent LLL and controls without amputation. Vrieling and colleagues (2008a) used a cross-sectional approach to assess differences in standing postural control under single- and dual-task conditions between persons with and without LLL.

Participants. Sample characteristics varied greatly both within each study and across the three studies. All three standing-cognition studies had small samples of 8-12 persons with LLL. Within each study, the samples varied in age, amputation level, time since amputation, prosthetic componentry, and etiology of amputation. One study included an age- and gender-matched control group (Geurts, 1991), one study included a non-matched control group (Vrieling, 2008), and one study included both matched- and non-matched controls (Geurts, 1994). While cognitive status of participants was not described in any of the three studies, two studies excluded participants with significant memory and attention deficits (Geurts, 1991; Geurts, 1994).

Methods. Studies varied in terms of the selected postural control and cognitive tasks. Standing postural control tasks included quiet standing on a stable surface, weight shifts to visually-guided targets, and standing on a surface that swayed in a rhythmic, predictable manner. Standing postural control was quantified using measures of postural sway (e.g., root mean square of the center of pressure displacement and velocity) (Geurts, 1991; Geurts, 1994; Vrieling, 2008) and weight-bearing symmetry (Vrieling, 2008). Cognitive tasks chosen for these studies were either mathematical (Geurts, 1991; Geurts, 1994) or choice reaction time tests using visual (Geurts, 1991) and acoustic (Vrieling, 2008) stimuli. One study (Geurts, 1991) used two different cognitive tasks – the visual Stroop was used for the majority of participants, but serial subtractions were used for participants that were unable to discern colors. All three studies assessed standing postural control under both single- and dual-task conditions. Two of the three studies (Geurts, 1991; Geurts, 1994) assessed cognitive performance under both single- and dual-task conditions and one study (Vrieling, 2008) did not report the results of cognitive task performance. Instructions for focus in dual-task conditions were not clearly stated in these three studies.

Results. Two of the three studies investigated the effects of a concurrent cognitive task on postural sway in quiet standing in people with LLL and controls (Geurts, 1994; Geurts, 1991). Both of these studies found significantly greater postural sway during dual- relative to single-task conditions in people with LLL at the start of rehabilitation compared to controls (Geurts, 1991; Geurts, 1994). Additionally, these studies examined the effects of the rehabilitation process on dual-task standing in persons with LLL. Although both studies reported significant improvements in postural sway in either the sagittal (Geurts 1991; Geurts, 1994) or coronal (Geurts, 1991) directions in the dual-task condition, significant changes in dual-task interference (defined as a differential effect, dual-task minus single-task performance) were only reported in coronal postural sway in one study (Geurts, 1991). No significant between- or within-group differences Geurts (1991) or group by task interactions (Geurts, 1994) were observed for cognitive task performance.

Two studies (Vrieling, 2008; Geurts, 1994) investigated the effect of a concurrent cognitive task on postural control in perturbed standing, such as visually-guided weight shifting (Geurts, 1994) and standing on a rhythmically moving surface (Vrieling, 2008). Although these studies did not report significant differences in single-task relative to dual-task standing between persons with amputation and controls, Geurts and colleagues (1994) described fewer weight shifts and more errors on the cognitive task in persons with LLL compared to non-matched controls. Vrieling et al. (2008) did not report significant group differences in dual- relative to single-task performance in the postural task. All three studies reported significant group differences in standing postural control performance, regardless of single-task or dual-task condition.

Walking-cognition dual-tasking in people with LLL compared to controls

Three cross-sectional, observational studies examined dual-task walking in persons with LLL compared to controls. Nakamura and colleagues (1984) studied the impact of walking on the performance of a concurrent cognitive task to assess the cognitive demand required for control of prosthetic limbs. Lamoth et al. (2010) investigated the variability and stability of walking in simple and challenging conditions, including the impact of a concurrent cognitive task on level, indoor walking. Hof (2007) also investigated the effect of a concurrent cognitive task on walking performance, but assessment of dual-task walking was not a primary outcome of interest for this study.

Participants. The samples in these studies were small and participant characteristics differed between the three walking studies. Nakamura et al. (1984) recruited eleven participants with LLL, who varied in their level of amputation, and nine controls. No other participant characteristics were described nor did the authors note whether the controls were matched. Lamoth (2010) and Hof (2007) included between six and eight participants with TFA along with matched-controls. The participants with LLL varied in the time following their amputation (range of 3 months to 43 years) and age. Etiology of limb loss and prosthesis characteristics varied in one study (Lamoth, 2010) and were not reported in the other (Hof, 2007). Cognitive status of participants was not characterized in the three studies.

Methods. These studies varied in their methodological approach to studying dual-tasking while walking. The goal of one study (Nakamura, 1984) was to use a simple reaction time task to understand the relative cognitive demand of walking in persons with LLL. Unlike the other 10 articles included in this review, the investigators did not quantify walking task outcomes. In addition, they did not conduct statistical analyses to compare dual-task outcomes between controls and participants with LLL. Instead, the investigators focused on differences in reaction time between single- and double-limb support in order to better understand how the different phases in the gait cycle affected cognitive demand in persons with and without LLL. In contrast, Lamoth and colleagues used an unspecified serial subtraction task to study the differential effect of a cognitive task on the stability and variability of walking between participants with LLL and controls. Walking outcomes included walking speed, stride time, stride time variability (calculated as the coefficient of variation [COV]), the root mean square of anterior-posterior (AP) and medial-lateral (ML) trunk acceleration, and evaluations of stability using local stability exponents and sample entropy in the AP and ML planes. All walking outcomes were measured with a triaxial ambulant accelerometer fixed near the participant's center of mass. The study investigators also analyzed performance on the cognitive task by counting the number of subtractions made during the six minute trial as well as the absolute and relative amount of errors made by participants. Hof and colleagues (2007) asked participants to walk on a treadmill at standardized speeds with and without performance of a concurrent visual Stroop test. Cognitive task outcomes were not described in this study. Details on directions for focus in dual-task conditions were not provided in any of the three walking-cognition dual-tasking studies.

Results. The results of these walking studies cannot be synthesized due to their differing objectives. Nakamura et al. (1984) reported a significant increase in reaction times in walking compared to standing in both persons with LLL and controls. Differences in the relative cognitive demand associated with walking between persons with LLL and controls were not described by study investigators. Lamoth et al. (2010) found that persons with LLL walked significantly slower and with less stability (i.e., higher ML and AP root mean square trunk acceleration, local stability exponent, and mediolateral sample entropy) than controls in all conditions (single-task, dual-task, indoors, outdoors even, outdoors uneven).

However, mean stride time and stride time COV were not significantly different between groups. They also found that walking in dual-task conditions was significantly slower, had longer stride times, and increased the ML root mean square trunk acceleration compared to single-task indoor walking for both groups (participants with LLL and controls). They did not find that participants with LLL were differentially impacted in dual- relative to single-task conditions when compared to controls (no interaction of group by condition in ANOVA analyses). No significant differences were reported for the cognitive task outcomes. The results described by Lamoth et al. (2010) were consistent with those of Hof (2007), who also did not find differences between single-task and dual-task walking performance.

Nakamura and colleagues (1984) also reported reaction time in persons with LLL by level of amputation. They found that reaction times differed between levels of amputation, finding generally longer reaction times in persons with higher levels of amputation in standing and all phases of stepping. However, the investigators did not statistically compare reaction times by group and they noted that there was very high interpersonal variability in performance among participants with LLL.

Impact of microprocessor technology on walking-cognition dual-tasking in people with LLL

Five experimental studies assessed differences in dual-task walking associated with use of a microprocessor knee (MPK) compared to a non-microprocessor knee (NMPK). Each of these studies used within-participant designs, meaning that participants were exposed to all experimental conditions and served as their own controls. These studies were longitudinal, ranging between three months to over a year in length and used repeated measures (2 to 6 data collection time points). Three of the five studies were AB or ABC crossover studies (Heller, 2000; Williams, 2006; Meier, 2012), meaning that there was only one data collection point for each experimental condition. In contrast, two (Hafner, 2007; Hafner, 2009) of the five studies were before and after reversal designs (ABAB), meaning that experimental conditions were repeated.

Participants. Sample sizes for these studies ranged from 8 to 17 participants. Three of the five studies reported attrition (Hafner, 2007; Hafner, 2009; Williams, 2006) and one study (Williams, 2006) reported a large attrition rate, with 56% of study participants withdrawing from the study prior to completion of study protocols. All of the studies were homogeneous with respect to the level of amputation of the participants studied, with all participants having amputations at or above the knee and below the hip. Study participants were heterogeneous with respect to age and etiology, with the majority of participants experiencing amputation secondary to trauma.

Methods. Each study compared dual-task performance of MPKs to one or more NMPKs to determine if microprocessor technology improved dual-task walking performance in participants with TFA. Four of the five studies (Williams, 2006; Hafner, 2007; Hafner, 2009; and Meier, 2012) assessed performance of the Otto Bock C-Leg (Ottobock, Duderstadt, Germany), a single axis hydraulic knee with microprocessor control of swing and stance phases (Berry, 2006). One article evaluated the Intelligent Prosthesis, a single axis hydraulic knee with microprocessor control of swing phase only (Michael, 1999).

The types of NMPKs used for comparisons were controlled in three of the five studies. Comparison knees included a single-axis knee with pneumatic swing control (Heller, 2000), a polycentric knee with hydraulic swing control (Meier, 2012), and a single axis knee with hydraulic control of both stance and swing phases (Williams, 2007; Meier, 2012). In addition to standardization of NMPKs, these studies standardized the prosthetic feet used in both non-microprocessor and microprocessor knee conditions. The remaining two studies (Hafner, 2007; Hafner, 2009) used the participant's current non-microprocessor knee and foot as a comparison condition. The prosthetic foot was standardized in the microprocessor knee condition across participants for all five studies. In addition, all studies standardized the prosthetic socket between knee conditions, randomized the order of knee allocation, and provided accommodation periods for each prosthetic knee condition.

Walking conditions and outcomes associated with walking performance varied across these studies. The five reviewed studies assessed the following walking tasks in dual-task conditions: walking over a treadmill (Heller, 2000), indoor walking in a hallway (Williams, 2006), walking the length of two city blocks on an outdoor sidewalk (Hafner, 2007; Hafner, 2009), and traversing an obstacle course with different terrain qualities (Meier, 2012). Three of the five studies used self-selected walking speed as a measure of walking performance (Williams, 2006; Hafner, 2007; Hafner, 2009). One study used a retroreflective marker placed on the participant's head to measure sway and draw conclusions about walking quality between conditions (Heller, 2000). Another used time to complete a standardized obstacle course to compare walking performance between knees

(Meier, 2012). Four (Hafner, 2009; Hafner, 2007; Williams, 2006; Heller, 2000) of the five studies did not report measurement of single-task performance on the walking tasks. One study (Meier, 2012) measured walking in both single- and dual-task conditions. However, this study did not vary the order of task conditions. In this study, all participants were presented with a novel and challenging obstacle course in the single-task condition and then were asked to repeat the course with the addition of a concurrent cognitive task.

The choice of cognitive task also varied between studies. Cognitive tasks chosen for these five studies included the visual Stroop test (Heller, 2000), visual counting tasks (Heller, 2000), verbal fluency tests (Williams, 2006), serial subtraction of 3s or 7s (Williams, 2006; Meier, 2012), and repeating numbers in the backwards order (Hafner, 2007; Hafner, 2009). None of the studies reviewed measured single-task performance on the cognitive task or provided instructions for focus in the dual-task condition. In addition, one study (Meier, 2012) did not report dual-task cognitive performance.

Results. Of the five studies, only one (Hafner, 2009) concluded that performance of a concurrent task differentially impacted walking performance while using a MPK compared to use of a NMPK. Hafner et al. (2009) found that walking speed was significantly increased while walking in dual-task conditions using the MPK compared to NMPKs and that this increase was most evident in people who were categorized as limited community ambulators (i.e., those classified as K-level 2). The other four studies concluded that there was no difference in the impact of a concurrent cognitive task on walking between MPKs and NMPKs based on self-selected walking speed (Williams, 2006; Hafner, 2007), cognitive task performance (Williams, 2006; Hafner, 2007; Hafner, 2007; Heller, 2000), time to complete an obstacle course (Meier, 2012), or whole-body sway velocity (Heller, 2000). In addition, one study (Meier, 2012) found that use of the C-Leg resulted in lower movement efficiency, measured with the Total Heart Beat Index (THBI), in dual-task relative to single-task walking than in the non-microprocessor knee conditions.

Self-report. Three of the five studies (Williams, 2006; Hafner, 2007; Hafner, 2009) assessed participant self-report of perceived walking-cognition interactions between knee conditions using investigator-designed survey questions. Williams et al. (2006) asked participants about attention given to the walking task in the study and administered a five-item survey assessing average cognitive burden. Hafner et al. (2007; 2009) designed a 14-question self-report survey of which three questions assessed mental energy, difficulty of dual-tasking, and required concentration on walking. Of the three studies that assessed participant perspectives, significant reductions were observed in attention given to walking during study protocols (Williams, 2006), difficulty of dual-tasking while walking (Hafner, 2007), and average cognitive burden (Williams, 2006) in the microprocessor knee condition compared to the non-microprocessor knee condition.

Discussion

The primary aim of this review was to assess studies that used a dual-task paradigm to assess posture-cognition and walking-cognition interactions in people with LLL. Eleven publications were identified that examined standing postural control or walking using a dual-task methodology in people with LLL. Of these, three assessed standing-cognition dual-tasking in people with and without LLL, three assessed walking-cognition dual-tasking in people with and without LLL, and five assessed walking-cognition dual-tasking in people with TFA across MPK and NMPK conditions. Overall, variation in study methods limits synthesis of results and may have contributed to inconsistent outcomes. In addition, methodological considerations such as small, heterogeneous samples, heterogeneity in tasks, and order effects complicated the synthesis of results. Similarly, dual-task-specific considerations, such as failure to report performance in single-task conditions, no assessment of cognitive task outcomes, and lack of instructions for focus made interpretation of results from individual studies challenging. However, trends in identified studies indicated the following:

Standing-cognition dual-tasking in people with LLL compared to controls. Of the three studies that assessed standing-cognition dual-tasking, two studies assessed control of quiet standing in participants with recent LLL, one study assessed control of perturbed standing in participants with recent LLL, and one study assessed control of perturbed standing in experienced participants with LLL. Differences in dual-task standing postural control between persons with and without LLL were found in two (Geurts, 1991; Geurts, 1994) of the three articles. Thus, there is some evidence for disproportionate deficits in dual-task standing postural control for persons with LLL compared to control participants, though this was not consistent in all three articles (Vrieling, 2008). While these studies are a promising start for understanding differences in dual-task standing postural control in people with LLL, additional research is needed that explores characteristics of participants that may require additional cognitive control of standing. For example, participants with vascular LLL may be additionally challenged in postural control tasks due to impaired sensory feedback on the non-prosthetic side (Shumway-Cook & Woollacott, 2000). Additionally, further research is needed that explores the effects of a concurrent task on unpredictably perturbed standing tasks between people with LLL and controls, which may reflect reactive postural control challenges experienced in daily life (e.g., standing on a bus as it begins moving).

Walking-cognition dual-tasking in people with LLL compared to controls. Of the three studies that assessed walking-cognition dual-tasking, one study assessed cognitive demand by measuring reaction time during a stepping task and two studies assessed the effect of a concurrent cognitive task on walking performance. None of the studies provided conclusive evidence of greater cognitive demand (Nakamura, 1984) or that the addition of a concurrent cognitive task differentially impacts walking (Lamoth, 2010; Hof, 2007) in participants with LLL compared to controls. As seen in the previous articles on postural control, these studies used very small samples that had varying levels of heterogeneity in important characteristics such as amputation level (Nakamura, 1984), etiology of amputation (Nakamura, 1984; Hof, 2007; Lamoth, 2010), and prosthesis type (Nakamura, 1984; Hof, 2007; Lamoth, 2010). Thus, future research should assess dual-task walking in subgroups defined by etiology, level, and prosthesis type to better understand characteristics of participants who may be more negatively impacted by the addition of a concurrent task. In addition, it is possible that flat, level walking is not sufficiently challenging to reveal differences in postural control capabilities between persons with LLL and controls. Persons with LLL do not have reliable sensory inputs or motor outputs on their prosthetic side, which are crucial for adapting to challenging or unpredictable surfaces commonly seen in community ambulation (Shumway-Cook & Woollacott, 2012). Thus, future research should consider assessing dual-task walking over challenging or unpredictable surfaces that may more closely reflect daily walking tasks.

Impact of microprocessor technology on walking-cognition dual-tasking in people with LLL. Of the five studies that assessed walking-cognition dual-tasking associated with prosthetic knee type in people with TFA, one study assessed the use of a knee with microprocessor-control of swing only (Heller, 2000), which does not affect stability in stance phases of gait when knee stability is most crucial. The remaining four studies (Williams, 2006; Hafner, 2007; Hafner, 2009; Meier, 2012) assessed use of the C-Leg, a prosthetic knee with microprocessor-control of stance and swing, which uses sensors in the knee and pylon to inform rapid changes to the knee flexion and extension resistance (Berry, 2006). Of the studies that assessed differences in dual-tasking between the C-Leg and NMPKs, only one (Hafner, 2009) provided evidence of improved dual-task walking performance between microprocessor and non-microprocessor knee conditions. This study also provided evidence that use of this technology may be most beneficial to people with LLL who are limited community ambulators. Additionally, only one of the studies (Meier, 2012) assessed walking over challenging terrain conditions, a condition that may reflect walking challenges encountered in daily mobility and which may be most impacted by the features of a microprocessor knee with stance control (Sawers & Hafner, 2013). The Meier et al. study (2012) found trends toward dual-task improvements in walking across all knee conditions, suggesting an arousal effect for all participants in the study. However, order effects may also explain these results, as single-task walking through the obstacle course always preceded dual-task walking. Thus, further research is needed that assesses dual-task walking over challenging terrain between microprocessor and non-microprocessor knees. In addition, future research is needed that assesses the impact of other innovative technology, such as powered prostheses or prostheses that incorporate direct neural control, on dual-task walking in people with LLL.

Of the 47 participants in these five studies, only three had amputation secondary to vascular causes and none of the participants required assistive devices for data collection sessions. In contrast, epidemiological studies report that the majority of amputations at the transfemoral level are due to vascular complications (Dillingham, 2002) and that 84.7% of people with TFA use assistive devices for walking outside of their home (Gauthier-Gagnon, 1999). Thus, participants in this group may not be similar in etiology or functional ability to the general population of people with TFA. Future research should assess the effects of a concurrent task in people with dysvascular TFA and those who require assistive devices for community ambulation.

Self-report. All of the three studies that assessed self-report found that use of a microprocessor knee was associated with reports of significant reductions in the difficulty of dual-tasking (Williams, 2006; Hafner, 1007; Hafner, 2009) or cognitive burden (Williams, 2006) from the participants' perspective. These results suggest an important role for self-reported assessment of cognitive control of postural tasks in people with LLL.

Future research should consider incorporating self-report into objective dual-task studies. In addition, development of psychometrically-sound self-report items that assess cognitive control in walking tasks may assist with understanding the role of cognition for postural tasks in people with LLL.

Limitations of this review

This review was limited to peer-reviewed manuscripts indexed in the three databases searched and available in English. These criteria excluded studies that have been disseminated in abstract form, but not yet made available in peer-reviewed journals (Howard, 2013; Morgan, 2014). Further, there may have been articles that included a dual-task, but did not discuss this work in their abstract or keywords, as was seen in the Hof (2007) article. Finally, few studies were identified and, generally, results could not be compared due to heterogeneity in research aims and sample characteristics.

Conclusion

The relatively small number of studies assessing dual-task standing postural control and walking in people with LLL suggests that research assessing interactions between postural control and cognition in this population is in its infancy. Further research is needed that assesses both standing postural control and walking between people with and without LLL to establish objective differences between groups. In addition, results from the identified dual-task studies in this review indicate that dual-task control of standing and walking may be challenging for some, but not all people with LLL. Future research should assess how different population characteristics (e.g., level of amputation, time since limb loss, etiology) affect dual-task balance and walking performance. Research by Nakamura (1984) indicated that more proximal amputation levels were associated with greater cognitive demand for stepping tasks and work by Geurts (1991; 1994) provided evidence that people with recent LLL are able to improve dual-task postural control throughout the rehabilitation process. Additional work in this area should solidify these initial findings in larger, more homogenous groups. Further, it is likely that not all standing and walking postural control tasks require people with LLL to "concentrate". Future research should examine how dual-task standing and walking deficits are affected by the complexity of the postural control task and the cognitive task to better understand differential use of cognitive resources experienced by persons with LLL in daily life. And finally, little is known about rehabilitation interventions that mitigate the need for cognitive control in people with LLL. Hafner (2009) demonstrated that microprocessor knees may improve dual-task walking in people with TFA who are limited community ambulators. Future research should assess other therapeutic and prosthetic interventions that have the potential to reduce the need for cognitive control of postural tasks in people with LLL.

Table 1.1. Extracted research evidence for dual-task studies in people with LLL

Study Characteristics		Sample Characteristics						Task Characteristics				Dual-Task Results	
Author (year)	Design	n	Mean Age (SD)	Sex	Level	Etiology	Control	Postural task	Cognitive task	Baseline	Focus	Postural task	Concurrent task
Geurts (1991)	Obs. Cohort	8	67.7 (18.1)	F: 3 M: 5	TF: 2 KD: 2 TT: 4	Vascular: 5 Infection: 2 Trauma: 1	10 age-, gender-matched	Quiet standing	Visual Stroop (n=5); Serial sub. (n=3)	Both	Postural task	AP & ML RMS COP velocity (sway): significantly higher in DT relative to ST conditions for people with LLL (compared to controls) at both the start and end of rehabilitation. In addition, people with LLL significantly decreased DT AP and ML sway from start to end of rehabilitation. Differential (DT-ST) and quotient (DT/ST) descriptions of sway were significantly different between people with LLL and controls at the start and end of rehabilitation in ML sway only.	No significant differences in performance between groups or conditions.

Geurts (1994)	Obs. Cohort	12	59.4 (18.3)	F: 3 M: 9	TF: 3 KD: 5 TT: 4	Vascular: 9 Other: 3	12 age-, gender-matched8 NM (av. age: 24.9)	Quiet and perturbed standing	Arithmetic task (assess math equations)	Both	-	Quiet standing: AP & ML RMS COP velocity (sway): significant group x condition interaction indicating more DT interference in the participants with LLL compared to matched and NM controls; significant condition x time interaction in AP sway for people with LLL indicated an improvement in DT AP sway with rehabilitation. Perturbed standing: AP & ML RMS COP velocity (sway) & weight shifting: no significant group x condition interaction, indicating that DT interference did not differ between groups consisting of people with LLL and both matched and NM controls.	Quiet standing: no significant differences in performance between people with LLL and matched controls, but a significant group x condition interaction between people with LLL and NM controls, indicating in increase in number of errors in people with LLL in DT conditions, while there is no change in performance in NM controls. Perturbed standing: no significant interactions between people with LLL and matched or NM controls.

Vrieling (2008)	Obs. Cohort	8	51.8 (12.7)	F: 2 M: 6	TF: 3 TT: 5	Trauma: 5 Tumor: 2 Vascular: 1	9 NM	Perturbed standing	Auditory Stroop	Postural only	-	No significant differences in DT relative to ST conditions for either group in AP GRF or AP COP displacement	-
Nakamura (1984)	Cross-sect.	11	-	-	HD: 1 TF: 5 TT:5	-	9 NM	Stepping	Simple reaction -time task	Cog-nitive only	-	-	RT: significant different in RT between standing and stepping in all groups; controls and TF groups had significantly longer RTs in double limb support compared to single limb support (bilaterally for controls and prosthetic side only for TF).
Hof (2007)	Cross-sect.	6	40.5 (6.6)	F: 2 M: 4	TF	-	6 leg length-, gender-matched	Walking (treadmill, 3 set speeds)	Visual Stroop	Postural only	-	Significant differences in DT walking between people with LLL and controls in % stance, stride width, and margin of stability, but similar results were seen between groups in normal walking conditions.	-

Lamoth (2010)	Cross-sect.	8	43.8 (14.8)	F: 3 M: 5	TF	Trauma: 5 Tumor: 2 Vascular: 1	8 age-, gender-matched	Walking (indoor, SSWS)	Serial sub.	Postural only	-	Speed: significantly slower in DT relative to ST conditions for both groups, but no group x task interactions. Stride time COV: no significant findings. Trunk acceleration: RMS ML decreased in DT relative to ST conditions, but no group x task interactions; AP SEn increased in the control group in DT relative to ST conditions, but was maintained in the TF group (significant group x task interaction).	No differences between groups in number of subtractions, number of errors, or relative number of errors
Heller (2000)	Cross-over	10	38 (-)	F: 3 M: 7	TF	Trauma: 8 Tumor: 2	MPK: Intelligent Prosthesis NMPK: Endolite Stabilized Knee	Walking (treadmill, 60s of varying speeds)	Simple: visual counting task Complex: visual Stroop	Walking with simple cog-nitive task as baseline	-	Ratio of sway velocity: No significant differences observed between ratios of sway velocity between knee conditions	Accuracy: no significant differences reported in accuracy on the cognitive task
Williams (2006)	Cross-over	8	48.5 (10.2)	F: 1 M: 7	TF	-	MPK: C-Leg NMPK: Mauch SNS	Walking (indoor, SSWS and controlled walking speed)	Verbal fluency, serial subtractions	-	-	Speed: no significant differences in walking speed between knee conditions	No significant differences in cognitive performance between knee conditions

Hafner (2007)	Cross-over	17	48.4 (17.2)	F: 4 M: 13	TF	Trauma: 10 Tumor: 3 Infection: 2 Vascular: 1 Other: 1	MPK: C-Leg NMPK: current prosthesis	Walking (outdoor, two city blocks)	Verbal reverse numbers	-	-	Speed: no significant differences in walking speed between knee conditions	No significant differences in % accuracy between knee conditions
Hafner (2009)	Cross-over	17	48.4 (17.2)	F: 4 M: 13	TF	Trauma: 10 Tumor: 3 Infection: 2 Vascular: 1 Other: 1	MPK: C-Leg NMPK: current prosthesis	Walking (outdoor, two city blocks)	Verbal reverse numbers	-	-	Speed: significant difference in walking speed between knee conditions for K2 group only	No significant differences in % accuracy between knee conditions in either group (K2 or K3)
Meier (2012)	Cross-over	12	46 (8.6)	F:2 M: 10	TF	Trauma: 7 Infection: 2 Congenital: 2 Vascular: 1	MPK: C-Leg NMPK: Otto Bock 3R60, Mauch SNS	Walking (indoor, obstacle course, SSWS)	Serial sub.	Postural task only	-	OC completion time: significant difference between knee conditions, significantly reduced time to complete course between ST and DT conditions for Mauch SNS only. THBI: significant decrease in movement efficiency with C-Leg, no differences in movement efficiency in comparison knees.	-

Abbreviations in this table- %: percent, AP: anterior-posterior, COP: center of pressure, COV: coefficient of variation, Cross-sect.: cross-sectional, DT: dual-task, F: female, GRF: ground reaction force, HD: hip disarticulation, K2: Medicare Classification Level 2 (limited community ambulator), K3: Medicare Classification Level 3 (unlimited community ambulator), KD: knee disarticulation, LLL: lower limb loss, M: male, ML: mediolateral, MPK: microprocessor knee, NM: non-matched, NMPK: non-microprocessor knee, Obs.: observational, OC: obstacle course, RMS: root mean square, RT: reaction time, SEn: sample entropy, SNS: stance and swing, ST: single-task, sub.: subtraction, SSWS: self-selected walking speed, Sub.: subtraction, TF: transfemoral, THBI: total heart beat index, TT: transtibial.

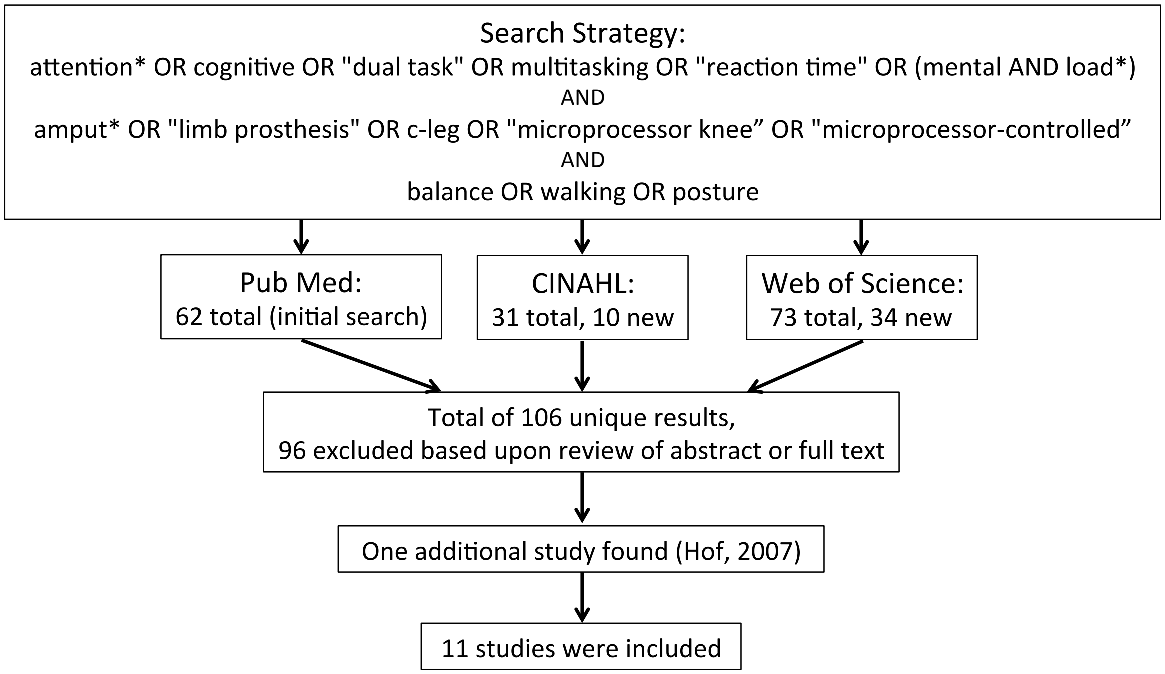

Figure 1.1. Schematic of search strategy and results.

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Chapter 2. The impact of a concurrent task on walking in persons with transfemoral amputation compared to controls

Abstract

Many people with lower limb loss report the need to concentrate on walking, which may be indicative of increased reliance on cognitive control that is not typical among non-amputee peers. The goal of this study was to quantify changes in walking associated with addition of a concurrent task in persons with transfemoral amputation (TFA) using microprocessor knees compared to age- and sex-matched controls. Walking was assessed using quantitative motion analysis in both single-task (walking alone) and dual-task (walking while performing a cognitive task) conditions over a firm surface. The cognitive task was also performed as a single-task while seated. Primary outcome measures were walking speed, step width, and step time asymmetry, as well as cognitive task response latency and accuracy. A repeated-measures analysis of variance was used to examine the effects of task (single-task, dual-task) and group (TFA, control) for each outcome measure. No significant interactions between task and group were observed (all $p > 0.11$) indicating that the addition of a concurrent cognitive task did not differentially affect walking between participants with TFA using microprocessor-controlled knees and matched controls.

Introduction

Limb amputation is a major life event that can profoundly impact an individual's health, quality of life, and physical function. Changes in walking and mobility commonly observed in persons with lower limb loss (LLL) include decreased postural stability (Lamoth, Ainsworth, Polomski, & Houdijk, 2010; Vrieling et al., 2008a; Miller & Deathe, 2004; Buckley, O'Driscoll, & Bennett, 2002; Geurts & Mulder, 1994; Fernie & Holliday, 1978), slower gait speed (Boonstra, Schrama, Fidler, & Eisma, 1994; Waters & Mulroy, 1999; Donker & Beek, 2002; Jaegers, Arendzen, de Jongh, 1995), spatial or temporal gait asymmetries (Donker & Beek, 2002; Jaegers, 1995; Hof, van Bockel, Schoppen, Postema, 2007; Nolan, Wit, Dudzinski, Lees, Lake, Wychowanski, 2003), reduced activity level (Halsne, Waddingham, Hafner, 2013), and difficulty negotiating uneven terrain, hills, and stairs (Ramstrand & Nilsson, 2009; Vrieling et al., 2007; Vrieling et al., 2008b; Jones, Twigg, Scally, Buckley, 2006). These limitations and restrictions may contribute to unsafe events, such as falling, in this population. For example, a study of 435 persons with lower limb loss found that over 66% of people with transfemoral amputation (TFA) fell in the past year, and of those that fell, 40% experienced an injury (Miller, Speechley, & Deathe, 2001a). Another study of 396 persons with limb loss reported that more than 60% of individuals with TFA experienced falls in the prior month (Gauthier-Gagnon, Grisé, & Potvin, 1999). Together, these studies suggest that the frequency of falls in people with TFA is higher than other fall-risk populations, such as the elderly (Tinetti & Williams, 1997).

In addition to notable challenges with walking and mobility, many people with LLL report the need to “concentrate on every step” (Miller, Deathe, Speechley, & Koval, 2001b) Gauthier-Gagnon, 1999). This need to concentrate is correlated with a heightened risk of falling and fear of falling in this population (Miller, 2001a). Although modern prostheses are able to replace limb structures to restore ambulatory mobility, prosthetic users do not have direct motor control of, or receive sensory feedback from, the prosthetic limb. This neural disconnect likely requires people with LLL to rely on cognitive control and visual input when walking as compensations for impaired prosthetic limb motor control and sensory feedback (Shumway-Cook & Woollacott, 2000).

The reliance on cognitive control for walking can be explored with a dual-task paradigm. Studies using dual-task paradigms measure walking with and without performance of a concurrent task as a means to study interactions between cognition and walking in different groups and under various conditions. Although the heightened need to concentrate on walking has been identified as a concern by people with LLL, few articles have used dual-task paradigms to study interactions between cognition and walking in people with LLL compared to non-amputee peers (Lamoth, 2010; Hof, 2007; Nakamura, 1984). Comparing people with LLL to peers without amputation is important to understand if, and subsequently how, the need to concentrate on walking differentially impacts mobility between groups. Previous researchers concluded that the addition of a cognitive task did not significantly impact walking in persons with LLL compared to non-amputee controls (Lamoth, 2010; Hof, 2007). However, methodological issues present in prior studies, such as small, heterogeneous sample sizes, may limit statistical power and lead to erroneous conclusions (Portney & Watkins, 2009).

In addition, previous work has not explored this comparison between controls without LLL and people using state-of-the-art componentry, such as microprocessor knee technology. Such prosthetic technology has the potential to improve walking performance and reduce falls in people with LLL (Hafner, 2007; Hafner, 2009; Kahle, Highsmith, & Hubbard, 2008; Berry, Olson, & Larntz, 2009; Blumentritt, Schmalz, & Jarasch, 2009) and has qualitatively been associated with a reduced need to concentrate on walking in this population (Hafner, 2007; Hafner, 2009; Williams et al., 2006). Thus, there remains a need to examine interactions between cognition and walking in people with LLL using microprocessor technology compared to matched controls.

The aim of this study was therefore to quantify changes in walking associated with the addition of a concurrent cognitive task in persons with TFA using microprocessor knees compared to age- and sex-matched controls. Walking performance over a flat, level surface was assessed by three critical aspects of walking: progression (measured as self-selected walking speed), postural stability (measured as step width), and gait quality (measured as step-time asymmetry). Associated spatiotemporal measures (e.g., step length, cadence, step time) were also examined to further characterize gait in both groups. We hypothesized that performance of a concurrent cognitive task while walking would cause declines in gait speed, postural stability while walking, and gait quality in people with LLL, but would not affect walking performance in control participants.

Methods

In this observational, cross-sectional study, participants with and without transfemoral amputation were asked to attend the University of Washington Human Motion Analysis Laboratory for a single, 2-hour test session.

Participants

Participants were recruited using posted flyers at local prosthetic clinics. Eligibility criteria common to all participants were: (1) age of 18 years or older; (2) the ability to walk continuously and independently (i.e., without the physical assistance of another person or the use of an assistive device) for 15 minutes; (3) the ability to independently ascend and descend ramps and stairs; and (4) no diagnosis of medical conditions that affect walking, cognition, or the ability to complete the protocol, such as a history of severe musculoskeletal, cardiovascular, or respiratory disease; vestibular or neurological dysfunction; or visual impairment that was not corrected with use of glasses or contacts. Additional eligibility criteria for the TFA group were: (5) unilateral involvement; (6) most recent amputation surgery more than one year ago; (7) use of a stable, comfortable prosthesis for at least three months; and (8) daily use of a prosthesis with a knee that includes microprocessor control of stance phase. Participants in the control group were matched to members in the TFA group in both age (within 5 years) and sex. This study was conducted with approval from the University of Washington Institutional Review Board. All participants provided informed consent prior to beginning the study.

Procedure

A clinical evaluation was performed to characterize study participants and included collection of self-reported demographic and health information such as age, sex, education, assistive device use, history of falls, and presence of other health conditions. Balance confidence was assessed with the Activities-specific Balance Confidence (ABC) Scale, a self-report measure of perceived confidence in performing 16 daily activities (Powell & Myers, 1995). Cognition was tested using the Montreal Cognitive Assessment (MoCA), a short screening exam that assists in the detection of mild cognitive impairment (Nasreddine et al., 2005). Participants with TFA were also queried about their date of amputation, design and age of their current prosthesis, and etiology of amputation during the clinical evaluation. Participants with TFA were also asked to comment on whether they had to pay extra attention to walking and to note situations or activities that require additional attention.

Cognitive task. The cognitive task performed in this study was an auditory analog of the Stroop test, a choice reaction time test. In this task, participants wore a wireless headset (Plantronics, Inc., Santa Cruz, USA; Jabra Corporation, Nasua, USA) that transmitted stimuli consisting of the words “high” and “low” said in either a high or a low pitch. Participants were instructed to respond by naming the pitch as quickly as possible. Stimuli were presented every three seconds with a random delay of 0-1 second prior to each stimulus. Four different kinds of stimuli (i.e., the word “high” said in a high pitch, the word “low” said in a low pitch, the word “high” said in a low pitch, and the word “low” said in a high pitch) were presented in blocks of eight stimuli per block. Two presentations of each stimulus were randomly presented within each block. A multichannel stereo sound mixer (RadioShack, Fort Worth, USA) with customized cables and custom software (coded in LabVIEW, National Instruments Corporation, Austin, USA) were used to collect the stimuli and responses for later processing of response latency and accuracy. Cognitive task performance was assessed in single-task (while participants were seated) and dual-task (while participants were walking) conditions. Participants were oriented to this task and completed 60 practice stimuli prior to collection of single-task and dual-task conditions. Outcome measures used to characterize cognitive task performance were response latency, the time between the onset of the stimulus and the onset of the response, and response accuracy, calculated as the total number of correct responses divided by the total number of stimuli, expressed as a percentage.

Walking task. To assess the effect of a concurrent cognitive task on walking, participants were asked to walk at their self-selected walking speed on an 8.8-meter pathway over a firm, flat surface in a laboratory setting. Walking was recorded in the middle four meters of the pathway to minimize the impact of acceleration and deceleration in each trial. Walking performance was assessed in single-task (walking alone) and dual-task (walking while performing the cognitive task) conditions. Participants performed two 24-second walking trials in each condition. In the dual-task condition, participants were asked to focus on the cognitive task in an effort to standardize task prioritization.

Retroreflective markers were placed on the participants' trunk (sternum and thorax), pelvis (anterior and posterior superior iliac spines, iliac crests), bilateral arms (acromions, lateral epicondyles, wrists, mid-upper and mid-lower arms), and bilateral legs (trochanters, thighs, patellae, lateral knee joints, tibial tubercles, lateral malleoli, posterior heels, and metatarsal phalangeal joints). For the prosthetic side of participants with TFA, markers were placed over prosthetic socket (trochanter, distal end, and anterolateral socket), knee (prosthetic knee joint, anterior knee, and knee/pylon junction), pylon (pylon/foot junction), and foot (lateral, posterior, and dorsal aspects). Three-dimensional marker position data was collected at 120 Hz using an 8-camera Qualisys Motion Capture System (Gothenburg, Sweden). Qualisys Track Manager was used to identify markers, interpolate gaps in marker position data (generally <0.25 second long), and truncate trials to data collected in the center of the capture volume, where data quality was optimized. Visual 3D motion analysis software (C-Motion, Inc., Rockville, MD) was used to filter marker position data using a fourth order, bidirectional, lowpass Butterworth filter with a cutoff of 6 Hz, build three degree-of-freedom linked-segment models, and label heel strike and toe off events.

Stride and step characteristics were subsequently calculated for each participant in Visual 3D. Walking speed, step width, and step time asymmetry were the primary outcomes for this study. Walking speed is a valid, reliable, and sensitive measure of gait (Middleton, Fritz, & Lusardi, 2014) and has been noted to decrease in people with LLL under dual-task conditions (Lamoth, 2010). Walking speed was calculated for each stride as the distance between heel strikes on the same side divided by the time between heel strike events. Step width is an outcome associated with postural stability in older adults (Lord et al., 2012) and people with LLL have increased step width in response to challenging walking conditions (Hak et al., 2013). Step width was calculated for each step as the mediolateral distance between the calculated ankle joint center at the ipsilateral heel strike and the opposite heel strikes. Step time asymmetry has been used to assess temporal differences in gait patterns between the prosthetic and non-prosthetic sides (Nolan et al., 2003). Step time asymmetry is often higher in people with TFA compared to controls (Nolan, 2003), and increased asymmetry may reflect, in part, worsening of gait compensations common in this population (e.g., vaulting, lateral trunk lean). Step time asymmetry was calculated as the absolute value of the difference between the right and left step times. Right step time was calculated as the time between left and right heel strikes and left step time was calculated as the time between right and left heel strikes. The following additional spatiotemporal gait characteristics were calculated and reported to further characterize gait quality in both groups: stride length (the distance traveled between one heel strike to the next on the same side), cadence (the number of steps taken per minute), step time (described above), and two measures of step time variability. The first is the coefficient of variation (COV, Eq. 1) has been assessed previously in dual-task research in this population (Lamoth, 2010).

$$\mathrm{COV} = \frac{SD}{Mean} x \ 100\% \qquad (1)$$

The second, based on work by Galna and colleagues (Eq. 2), is meant to isolate the construct of variability from associated asymmetry and preserve the original units to improve interpretability (Galna, Lord, & Rochester, 2013).

$$\text{Variability} = \sqrt{\frac{Step\ Time\ Variance_{Left} + Step\ Time\ Variance_{Right}}{2}} \qquad (2)$$

Statistical Analysis

Descriptive analyses were performed for all variables (IBM SPSS Statistics version 19.0, Armonk, USA). Differences between groups with respect to participant characteristics (e.g., age, cognitive function, balance confidence) were assessed using paired t-tests. The effect of dual-task performance was examined for each walking and cognitive outcome measure using repeated-measures analysis of variance (ANOVA) with one within-subject factor (task: single-task, dual-task) and one between-subject factor (group: TFA, control). The level of significance for all tests was set at $\alpha = 0.05$.

Results

Participants

Participants with TFA (n=14) and matched controls (n=14) were similar with respect to age ($p = 1.0$), height ($p = 0.61$), weight ($p = 0.71$), and number of comorbid conditions ($p =$

1.0). People with LLL had significantly lower MoCA scores ($t(26) = -3.31$, $p = 0.006$), ABC scores ($t(26) = -3.72$, $p = 0.003$), and a significantly greater number of falls per year ($t(26) = 3.07$, $p = 0.009$) (Table 2.1). All 14 participants with TFA reported that they paid "more attention to walking than people without amputation," and the most common situations and activities requiring attention included walking on icy or slippery surfaces (n=14, 100%), over uneven terrain (n=13, 92.9%), down stairs (n=12, 85.7%), and walking in sand or snow (n=12, 85,7%).

Cognitive task performance

A significant main effect of task ($F(1, 26) = 8.24$, $p = 0.008$) for response latency indicated that both groups had longer response latencies in dual-task compared to single-task conditions. No other significant main effects or interactions were observed for either response latency or response accuracy (all $p > 0.025$, Table 2.2).

Walking performance

An average of 23.1 steps per condition was analyzed for each participant. The number of steps per participant did not significantly differ by group ($p = 0.45$) or task ($p = 0.08$). A main effect of group was observed for walking speed ($F(1,26) = 13.65$, $p = 0.001$), step width ($F(1,26) = 27.37$, $p < 0.001$), and step time asymmetry ($F(1,26) = 24.89$, $p < 0.001$), indicating that participants with TFA walked more slowly, with wider steps, and with more asymmetry than controls under both single- and dual-task conditions. A main effect of task was observed for step width ($F(1,26) = 19.09$, $p < 0.001$), indicating that both groups adopted wider step widths when performing a concurrent task. No significant interactions were observed (all $p > 0.11$), indicating that the addition of a concurrent cognitive task did not differentially affect walking speed, step width, or step time asymmetry between participants with TFA and controls (Table 2.2, Figure 2.1). Step time asymmetry was more variable among participants with TFA than controls (Table 2.2 and Figure 2.2).

Secondary walking measures

A main effect of group was observed for most secondary outcomes, including stride length ($F(1,26) = 8.77$, $p = 0.006$), step time ($F(1,26) = 4.52$, $p < 0.043$), step time COV ($F(1,26) = 22.74$, $p < 0.001$), and step time variability ($F(1,26) = 9.77$, $p = 0.004$) indicating that under both single- and dual-task conditions, participants with TFA walked with smaller stride lengths, shorter step times, and greater variability than controls. In addition, a main effect of task was found for step time ($F(1,26) = 4.26$, $p = 0.049$) and cadence ($F(1,26) = 4.91$, $p = 0.036$) indicating that both groups had shorter average step times and took more steps per minute in dual-task relative to single-task conditions. No other main effects or significant interactions were observed (all $p > 0.05$), indicating that the addition of a concurrent cognitive task did not differentially affect step length, cadence, step time, or variability measures between participants with TFA and controls. Step width and step time asymmetry, variability, and COV had high between-subject variability in participants with TFA compared to controls (Table 2.3).

Discussion

The purpose of this study was to compare single-task and dual-task walking in people with TFA using microprocessor knee technology compared to age- and sex-matched controls. Results of this study suggest that people with TFA walk with slower gait speeds, larger step widths, and greater asymmetry when compared to people without amputation, regardless of whether or not a concurrent cognitive task is performed. Gait differences between people with and without LLL have been reported in previous literature (Lamoth, 2010; Hof, 2007) and reflect a gap in walking performance between non-amputee controls and people with LLL, even those using state-of-the-art prosthetic technology. However, contrary to our hypothesis, the addition of a concurrent cognitive task did not differentially affect walking over a firm, level surface between groups. Research by Lamoth & colleagues also demonstrated that the addition of a concurrent cognitive task did not differentially affect spatiotemporal gait parameters in eight people with TFA using non-standardized prosthetic components compared to matched controls. Together, these studies indicate that walking over a level surface does not require additional cognitive control for people with TFA compared to people without LLL, but importantly, people with TFA appear to adopt a gait pattern that is slower and reduces postural stability demands compared to controls.

Although results of this study are consistent with those reported by Lamoth et al. (2010), these results lead to the following question: why is there an inconsistency between these objective findings and the high incidence of people with TFA who report the need to “concentrate on every step” (Gauthier-Gagnon, 1999; Miller, 2001)? While approximately 60% of people with TFA reported “concentrating on every step”, the remaining 40% reported that “walking has become automatic” (Gauthier-Gagnon, 1999). Therefore, though a large majority of people with TFA report the need to concentrate on walking, this does not encompass the experience of all people with TFA. Furthermore, participants in this study may have been more active and physically capable sample due to eligibility criteria that included the ability to walk for 15 minutes without assistive devices. Indeed, previous research (Gauthier-Gagnon, 1999) reports that over 70% of people with TFA use canes, crutches, or a walker for locomotion indoors. While the use of assistive devices may be less common among people using microprocessor knee technology, this data suggests a high reliance on assistive devices among people with TFA. Thus, our study may have disproportionately represented people with TFA who were among the most physically capable and who may be less reliant on cognition for walking over level surfaces.

In the current study, all participants with TFA reported that they “pay more attention to walking than those without amputation” and that tasks such as walking on slippery surfaces, uneven terrain, stairs, sand, and snow were most often reported as requiring attention. Walking on unpredictable or uneven surfaces relies more on reactive postural control strategies than walking on a flat, predictable surface. When walking on unpredictable surfaces, people with LLL may increase reliance on cognitive resources to compensate for impaired reactive postural control that results from damage to the peripheral sensorimotor structures (Smith, Michael, & Bowker, 2004). Future studies should explore the effect of a concurrent task on challenging walking situations, such as uneven surfaces, that require reactive postural responses to unanticipated perturbations (Shumway-Cook & Woollacott, 2012).

Previous research examined participants using heterogeneous knee types, with the majority using non-microprocessor controlled knees (Lamoth, 2010). In contrast, the current study limited participation to persons using knees with microprocessor control of stance and swing phases. Such knees have the potential to improve stability while walking through use of sensors that continuously monitor and modify hydraulic resistance to knee flexion to prevent or ameliorate falls (Berry, 2006). Further, it has been demonstrated that dual-task walking is improved with microprocessor knees compared to non-microprocessor knees in persons with TFA who are limited community ambulators (Hafner, 2009). In this study, the finding that a concurrent task impacted walking similarly in participants with TFA and controls suggests that the use of advanced prosthetic technology may reduce reliance on cognitive resources when walking over a firm, predictable surface. However, this conclusion is not fully supported by these data, as statistically significant group differences were observed for all primary and most secondary gait measures, even in single-task conditions. Thus, there remains a large gap in speed, postural stability, and gait quality between control participants and people with LLL, even those using advanced prosthetic technology. The observed gap in walking performance suggests that participants with TFA may adopt a conservative walking pattern, characterized by slow walking and a wide base of support (Tsai & Lin, 2013), in order to reduce reliance on cognitive control in dual-task conditions.

Additionally, there were notable differences in results from a previous study (Lamoth, 2010) in comparison to the current study. For example, participants with TFA in this study walked approximately 0.1 m/s slower than those in the previous study under single-task walking conditions. This difference in walking speed may be because the sample in the current study was 10 years older than the sample in the study by Lamoth and colleagues (Lamoth, 2010), but may also support the aforementioned interpretation that participants in our study chose to adopt a conservative walking pattern. An additional example of this conservative walking strategy was observed in step width. In the current study, participants with TFA adopted step widths in single-task conditions that were approximately seven centimeters wider than the controls. This finding suggests that participants preemptively used conservative, safe walking patterns to reduce the need to rapidly modify walking in response to challenging walking conditions, such as the addition of a concurrent cognitive task. These comparisons between people with and without LLL in the current study and comparisons across studies with LLL may indicate that people with TFA, especially older individuals, may elect to prioritize safety and minimize reliance on cognitive control at the expense of walking speed and quality, even in single-task walking conditions. Thus, people with LLL may be differentially impacted by the addition of a concurrent cognitive task, however, this impact may not have manifested as changes in walking performance.

Limitations

Limitations associated with the present study should be noted. First, this research was conducted in a laboratory setting, which may not accurately reflect experiences in community settings. In addition, methodological choices such as providing instructions for focus or the choice of cognitive task may also limit generalizability to situations presented in daily life. Further, as noted above, it is possible that participants with TFA in this study had higher physical abilities due to certain eligibility criteria (e.g., ability to walk without assistive devices). Thus, it is possible that our sample does not fully reflect the larger population of individuals with TFA.

Conclusion

Results from this study suggest that people with TFA using microprocessor-controlled knees do not differ from controls in the impact of a concurrent cognitive task on walking performance. This is potentially because people with TFA in our sample adopted a conservative walking strategy, with slower gait speed, a wider base of support, and greater asymmetry than controls, even in the single-task walking condition. Further research is needed to examine the impact of a concurrent cognitive task when walking over compliant surfaces to assess the potential use of cognitive resources in situations that rely more heavily on sensory inputs and that approximate more challenging conditions characteristic of community mobility.

Table 2.1. Participant Demographics/Characteristics

Part. #	Age (yr)	M/F	Ht (m)	Wt (kg)	MoCA	ABC	# cond.	Falls/ yr	Yrs since amp	Etiology
TFA-1	42	M	71	172	27	3.7	0	0	29	Tumor
TFA-2	55	M	75	210	26	3.1	0	3	17	Tumor
TFA-3	75	M	72	194	24	3.5	2	0	57	Trauma
TFA-4	39	M	67	155	27	3.5	0	2	12	Trauma
TFA-5	36	F	67	162	27	2.2	0	1	14	Trauma
TFA-6	77	F	67	148	28	2.4	1	2	5	Vascular
TFA-7	65	F	67	135	25	3.0	0	1	15	Trauma
TFA-8	49	M	70	195	29	3.8	0	0	10	Trauma
TFA-9	55	M	70	215	26	2.8	0	3	34	Trauma
TFA-10	39	F	63	103	27	2.6	0	3	25	Tumor
TFA-11	61	M	71	229	26	3.6	0	4	43	Trauma
TFA-12	45	M	70	162	25	3.1	0	12	4	Infection
TFA-13	47	F	66	138	28	3.0	0	4	28	Trauma
TFA-14	68	M	69	205	27	3.1	1	3	9	Infection
TFA mean (SD)	53.8 (13.6)	F: 35.7%	1.75 (0.08)	78.5 (16.4)	26.6 (1.3)	3.1 (0.5)	0.3 (0.6)	2.7 (3.0)	21.6 (15.3)	-
Control mean (SD)	53.8 (13.4)	F: 37.5%	1.76 (0.11)	77.2 (13.7)	28.3 (1.4)	3.7 (0.4)	0.3 (0.7)	0.1 (0.4)	-	-
p-value	1.0	1.0	0.61	0.71	0.006	0.003	1.0	0.009	-	-

Table 2.2. Mean results and *p*-values for walking and cognitive measures

	TFA		Control		p-value		
	ST	DT	ST	DT	Group	Task	Group x Task
WALKING TASK							
Walking Speed (m/s)	1.167 (0.166)	1.150 (0.165)	1.387 (0.177)	1.413 (0.196)	0.001	0.73	0.11
Step Width (m)	0.188 (0.041)	0.197 (0.045)	0.121 (0.025)	0.130 (0.021)	<0.001	<0.001	0.86
Step Time Asymmetry (s)	0.075 (0.042)	0.080 (0.058)	0.010 (0.007)	0.011 (0.006)	<0.001	0.31	0.47
Stride Length (m)	1.355 (0.172)	1.331 (0.177)	1.520 (0.138)	1.518 (0.145)	0.006	0.12	0.16
Cadence (steps/s)	104.0 (7.0)	104.7 (7.8)	109.3 (9.2)	111.5 (8.8)	0.060	0.036	0.27
Step Time (s)	0.583 (0.041)	0.580 (0.046)	0.553 (0.046)	0.542 (0.042)	0.043	0.049	0.19
Step Time Variability (s)	0.018 (0.005)	0.017 (0.006)	0.013 (0.003)	0.012 (0.003)	0.004	0.17	0.89
Step Time COV (%)	7.3 (3.3)	7.8 (4.5)	2.6 (0.6)	2.5 (0.6)	<0.001	0.36	0.21
COGNITIVE TASK							
Response Latency (s)	0.807 (0.161)	0.851 (0.208)	0.690 (0.130)	0.738 (0.129)	0.06	0.008	0.91
Response Accuracy (%)	94.6 (8.8)	96.0 (5.8)	98.2 (3.8)	99.1 (3.3)	0.12	0.14	0.76

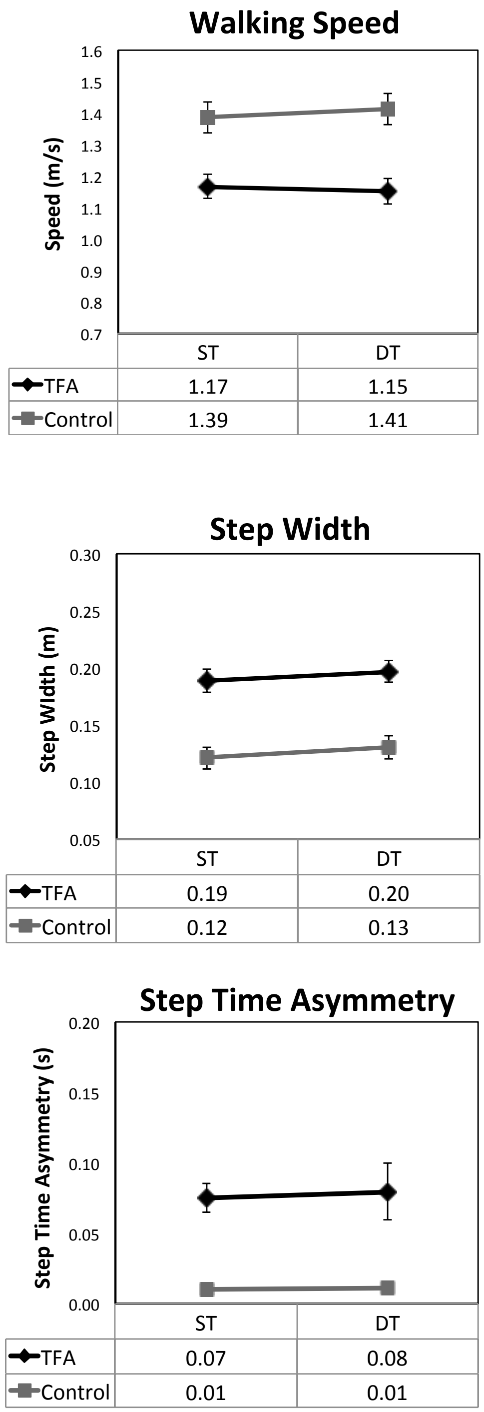

Figure 2.1, a-c. Single- and dual-task walking speed, step width, and step time asymmetry results for both groups. Grey squares represent data for the control group, and black diamonds represent data for the TFA group.

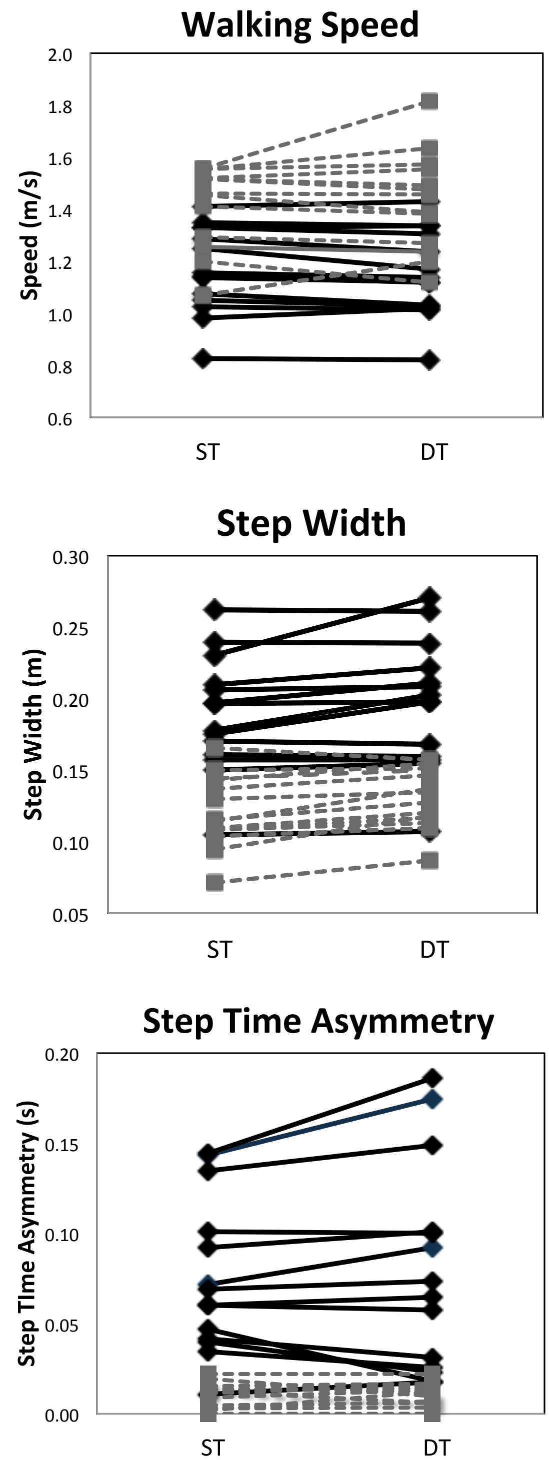

Figure 2.2, a-c. Single- and dual-task walking speed, step width, and step time asymmetry results for individuals in both groups. Grey squares represent data for the control group, and black diamonds represent data for the TFA group.

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Chapter 3. The effects of concurrent task on simple and complex walking tasks in persons with transfemoral amputation compared to controls

Abstract

People with lower limb loss (LLL) are not able to reliably sense important ground characteristics due to compromised sensory inputs from their amputated limb. Thus, people with LLL likely rely on cognitive resources to compensate for diminished sensory inputs. The purpose of this study is to use a dual-task paradigm to infer the need for cognitive control to walk over simple and challenging surfaces in participants with transfemoral amputation (TFA) and control participants. Walking performance was assessed with quantitative motion analysis in both single-task (walking alone) and dual-task (walking while performing a cognitive task) conditions over firm and compliant foam surfaces. Primary outcome measures were walking speed, step width, step time asymmetry, and cognitive task performance. A repeated-measures analysis of variance was used to examine effects of task (single-task, dual-task), group (TFA, control), and surface (firm, foam) for each outcome. No significant interactions between task and group or task, group, and surface were observed, indicating that the addition of a concurrent cognitive task did not differentially affect walking performance between groups across either surface. However, significant group by surface interactions for speed, step width, and measures of gait quality indicated that walking in people with LLL was differentially impacted by a challenging walking surface.

Introduction

Lower limb loss (LLL) profoundly alters physical structures and neural systems that enable smooth and efficient control of walking. Prostheses are necessary for the restoration of walking in people with LLL, but even state-of-the-art prosthetic technology does not adequately restore peripheral sensory and motor functions. Sensory feedback and motor control pathways are critical to the neural control of walking, particularly in challenging environments that require quick adaptations of the gait pattern to maintain postural control (Shumway-Cook & Woollacott, 2012). In the absence of sensory inputs from and motor outputs to the prosthetic limb, it is likely that persons with LLL depend on additional compensatory strategies, such as the use of cognitive resources, compared to persons without LLL. Use of cognitive resources by people with LLL may further increase during complex walking tasks, like walking over uneven or compliant surfaces, where peripheral sensory and motor structures are critical for safe and stable mobility.

Indeed, the need to concentrate on walking is commonly reported by persons with LLL (Miller, Speechley, & Deathe, 2001a; Gauthier-Gagnon, Grisé, & Potvin, 1999), including those with transfemoral amputation (TFA). However, objective studies assessing differences in the need to concentrate on walking between people with and without TFA have not substantiated these reports (Lamoth, 2010; Hof, 2007; Chapter 2). The lack of supporting objective evidence may be because previous studies have studied effects of a concurrent task on simple walking, such as walking over a firm surface (Lamoth, 2010; Chapter 2) or on a treadmill (Hof, 2007). To date, no identified studies have assessed differences in dual-task walking between people with and without TFA in challenging environmental conditions that reflect walking surfaces encountered in daily life. Further, walking on complex surfaces, such as ice, sand, and snow, have been identified by people with TFA as scenarios that require additional concentration (Chapter 2).

Thus, the purpose of this research was to examine the effects of a concurrent cognitive task on walking performance over both simple and challenging surface conditions in people with TFA compared to age- and sex-matched controls. We hypothesized that a concurrent cognitive task would disproportionately impact walking on a challenging compliant surface in people with LLL compared to matched controls.

Methods

Participants

Participants were recruited through flyers and posters at prosthetic clinics in the Seattle area. Interested and eligible participants attended the University of Washington Human Motion Analysis Laboratory for a single, 2-hour testing session. The following eligibility criteria were used: (1) 18 years of age or older, (2) able to walk independently without use of an assistive device for 15 minutes, (3) able to negotiate ramps and stairs, and (4) no comorbidities impacting walking, cognition, or the ability to complete the protocol. For people with TFA, additional eligibility criteria were: (5) unilateral limb loss, (6) most recent amputation surgery at least one year prior to study participation, (7) prosthesis that was unchanged and comfortable for at least three months, and (8) primary prosthesis that incorporates a microprocessor-controlled knee. Participants in the control group were selected to match the age (within 5 years) and sex of those in the TFA group. This study was reviewed and approved by the University of Washington Human Subjects Institutional Review Board and informed consent was obtained from all participants prior to the start of any study procedures.

Procedure

Self-reported demographic and health information (e.g., age, sex, education, assistive device use, history of falls, and presence of other health conditions) was collected to characterize study participants. Participants also completed the Activities-specific Balance Confidence (ABC) Scale, a self-report measure of perceived balance confidence during 16 daily activities (Powell & Myers, 1995), and the Montreal Cognitive Assessment (MoCA), a brief tool for screening global cognition (Nasreddine et al., 2005). Participants with TFA were asked to provide details about their amputation and prosthetic history (e.g., date and etiology of amputation, design and age of current prosthesis).

Walking Task. Participants were asked to walk on an 8.8 m pathway at their self-selected speeds. Walking was performed under single-task (walking without performing a cognitive task) and dual-task (walking while performing a cognitive task) over both firm and foam surfaces, resulting in four walking conditions. The firm surface was a level, tiled surface. The foam surface was a 6.1 m long by 0.6 m wide walkway consisting of a 3.8 cm thick marine low density closed cell foam (density of 3-4.5 pounds per cubic foot). The foam surface was constructed with a 0.5 m long ramp of at either end outside of the capture volume to provide a gradual transition between the floor and the foam walkway. Foam surfaces are commonly used in clinical assessments to distort somatosensory input and challenge the sensorimotor system (Shumway-Cook & Horak, 1986). For the single-task and dual-task foam conditions, participants performed at least one practice trial to become familiar with the foam surface and mitigate learning effects. For each of the four walking conditions, participants performed two 24-second walking trials. Participants were asked to focus on the cognitive task to reduce variability in task prioritization between participants. A gait belt was worn by all participants and a physical therapist or prosthetist walked with participants as needed to guard against falls.

Retroreflective markers were placed on the participants' trunk, pelvis, bilateral arms, and bilateral legs. For the prosthetic side of participants with TFA, markers were placed on the prosthetic socket, knee, pylon, and foot (Figure 3.1). An 8-camera Qualisys Motion Capture System (Gothenburg, Sweden) was used to collect three-dimensional marker position data with a capture rate of 120 Hz. Qualisys Track Manager and Visual 3D motion analysis software (C-Motion, Inc., Rockville, MD) were used to process, filter, and calculate stride and step characteristics for each participant from position data (see Chapter 2).

Primary outcomes for this study were walking speed, step width, and step time asymmetry. Walking speed is a valid, reliable, and sensitive measure of progression (Middleton, Fritz, & Lusardi, 2014); step width is a measure of postural stability (Lord et al., 2012); step time asymmetry is a measure of gait quality. In addition, the following secondary spatiotemporal gait characteristics were calculated to further characterize gait quality in both groups: stride length, cadence, step time, step time variability, and step time coefficient of variation (COV). Calculation details for all primary and secondary outcomes are described in Chapter 2.

Cognitive task. Participants performed an auditory analogue of the Stroop test under single-task (while seated) and dual-task (while walking over both firm and foam surfaces) conditions. For this task, participants listened to blocks of auditory stimuli that consisted of the words "high" and "low" said in a high or low pitch and responded by naming the pitch. Stimuli were presented in blocks (20 stimuli per block for practice, eight stimuli per block for single-task and dual-task conditions). Stimuli were presented every 3 seconds with a 0-1 second random delay prior to the presentation of each stimulus to prevent time entrainment of steps with cognitive task presentation during dual-task conditions. Participants were asked to respond as quickly and as accurately as possible. Participants were first oriented to the task and provided a series of 3 practice blocks (60 total practice trials) to mitigate potential learning effects. Two-blocks were performed in the single-task and each dual-task condition. Stimuli and responses were collected for later processing using customized hardware and software (see details in Chapter 2). Cognitive task performance was assessed using response latency, defined as the time between stimulus onset and response onset, and response accuracy, defined as the percent of correct responses.

Statistical Analysis

Means and standard deviations were calculated for all variables (IBM SPSS Statistics version 19.0, Armonk, USA). Paired *t*-tests were used to assess potential between-group differences in participant demographic and health characteristics. Effects of a concurrent cognitive task on walking were examined statistically for primary and secondary walking outcomes using repeated-measures analysis of variance (ANOVA) with two within-subject factors (task: single-task, dual-task; surface: firm, foam) and one between-subject factor (group: TFA, control). Cognitive task performance across conditions was examined using repeated-measures ANOVA with one within-subject factor (task: single-task, dual-task firm, dual-task foam) and one between-subject factor (group: TFA, control). An alpha of 0.05 was the designated level of significance for all statistical tests.

Results

Participants

Participants with TFA (n=14) and age- and sex-matched controls (n=14) were similar in most characteristics, including height (p = 0.61), weight (p = 0.71), and number of comorbid conditions (p = 1.0). However, participants with TFA had significantly lower MoCA scores ($t(26) = -3.31$, p = 0.006), worse ABC scores ($t(26) = -3.72$, p = 0.003), and more self-reported falls per year ($t(26) = 3.07$, p = 0.009) compared to control participants (Table 3.1).

Cognitive task performance

A main effect of task ($F(1,26) = 5.60$, $p = 0.006$) for response latency indicated that both TFA and control groups had longer response latencies in both the firm and foam dual-task conditions compared to the single-task condition. In addition, a main effect of group ($F(1,26) = 4.63$, $p = 0.04$) indicated that people with TFA had longer response latencies across all three conditions (i.e., single-task, dual-task firm, dual-task foam) compared to controls. There was no interaction between task and group for response latency ($p = 0.39$). No significant main effects or interactions were observed for response accuracy (all $p > 0.09$), with average accuracies of 95.1% in the TFA group and 98.8% in the control group (Table 3.2).

Walking performance

On average, 23 steps per condition were analyzed for each participant. Contrary to our hypothesis, there were no significant group by task or group by task by surface interactions for primary measures of walking performance (all $p > 0.05$). A main effect of group ($F(1,26) = 19.15$, $p < 0.001$) and a group by surface interaction ($F(1,26) = 17.62$, $p < 0.001$) were observed for walking speed. Participants with TFA walked more slowly than controls and these between-group differences in speed were larger on the foam than on the firm surface. Significant main effects of group ($F(1,26) = 31.65$, $p < 0.001$), surface ($F(1,26) = 18.98$, $p < 0.001$), and a group by surface interaction ($F(1,26) = 5.25$, $p = 0.026$) were observed for step width. Participants with TFA had wider step widths than controls in both conditions.

For participants with TFA, steps were wider on the foam surface than on the firm surface, however, for control participants, steps were narrower on the foam surface than on the firm surface. A significant main effect of task was also observed for step width ($F(1,26) = 22.52$, $p < 0.001$), indicating that both groups increased step width when a concurrent cognitive task was added in both surface conditions. A significant main effect of group was observed for step time asymmetry ($F(1,26) = 22.56$, $p < 0.001$). People with TFA walked with more asymmetry in all task and surface conditions compared to controls. No other main effects or interactions were observed (all $p > 0.05$, Figure 3.1, Table 3.2).

Secondary walking measures

Similar to the primary walking outcomes, there were no significant group by task or group by task by surface interactions for secondary measures of walking performance (all $p > 0.05$). Significant main effects for group were observed for all secondary walking outcomes, including stride length ($F(1,26) = 10.67$, $p = 0.003$), cadence ($F(1,26) = 8.87$, $p = 0.006$), step time ($F(1,26) = 10.12$, $p < 0.004$), step time variability ($F(1,26) = 24.60$, $p < 0.001$), and step time COV ($F(1,26) = 25.09$, $p < 0.001$). Across all task and surface conditions, participants with TFA walked with smaller stride lengths, lower cadence, shorter step times, and greater variability than controls. In addition, significant main effects of surface and group by surface interactions were observed for stride length (surface: $F(1,26) = 16.29$, $p < 0.001$; interaction: $F(1,26) = 13.03$, $p = 0.001$), cadence (surface: $F(1,26) = 20.98$, $p < 0.001$; interaction: $F(1,26) = 11.90$, $p = 0.002$), step time (surface: $F(1,26) = 21.51$, $p < 0.001$; interaction: $F(1,26) = 14.50$, $p = 0.001$), and step time variability (surface: $F(1,26) =$

5.26, p = 0.03; interaction: $F(1,26) = 4.30$, p = 0.048). These results suggest that (1) controls had increased step lengths on the foam surface compared to the firm surface, while people with TFA maintained consistent step lengths across surface conditions; (2) both groups demonstrated decreased cadence on the foam surface compared to firm, but this reduction was more pronounced in people with TFA; (3) people with TFA have increased step time on the foam relative to the firm surface while controls maintain a consistent step time between surfaces; and (4) people with TFA walk with increased step time variability on the foam compared to firm surface while controls are similarly variable across surfaces. A main effect of task for step time ($F(1,26) = 5.55$, p = 0.026) and cadence ($F(1,26) = 5.71$, p = 0.024) was also observed, indicating that both groups demonstrated reduced step times and increased cadence in dual-task compared to single-task conditions on both surfaces. No other main effects or interactions were observed (all $p > 0.05$, Table 3.3).

Discussion

The goal of this study was to compare the effects of a concurrent cognitive task on walking performance between firm and foam surface conditions in participants with TFA and control participants. It was hypothesized that participants with TFA would slow walking, widen their steps, and increase step time asymmetry over the foam surface in dual-task compared to single-task conditions. In contrast, it was hypothesized that controls would either maintain or improve walking performance between single-task and dual-task conditions. Additionally, it was hypothesized that walking over the foam surface would negatively and disproportionately affect dual-task walking performance in people with LLL compared to controls. Although changes in walking speed and step width suggested different effects of a concurrent task on walking between groups and surfaces, no statistically significant group by task or group by task by surface interactions were observed for primary and secondary measures of walking performance.

These overall findings are consistent with two previous studies that examined effects of a dual-task when walking over firm surfaces (Lamoth, 2010; Chapter 2). Lamoth and colleagues (2010) studied the effect of a concurrent serial subtraction task on walking over a firm surface in controls and people with TFA who used a variety of prosthetic knee components, the majority of which did not have microprocessor control (Lamoth, 2010). Additionally, our research group has previously studied the effect of concurrent performance of the auditory Stroop task on walking over a firm surface in people with TFA using microprocessor knees and controls (Chapter 2). Both manuscripts reported overall differences in walking performance between people with TFA and controls, but importantly, no significant group differences in the effect of a concurrent cognitive task on walking (Lamoth, 2010; Chapter 2). However, the current study represents an important extension of this previous work by examining complex walking surfaces that may better represent the complexity of surfaces encountered in daily life.

The complex walking surface studied in the current research was a compliant foam walkway. Relative to the firm surface, walking was differentially impaired in participants with TFA compared to control participants over the compliant, foam surface. Participants in the current study walked with significantly slower walking speeds, wider steps, shorter strides, longer step times, and increased step time variability on the foam compared to firm surfaces across both single- and dual-task conditions. In contrast, control participants either maintained or improved walking performance when walking on the foam surface compared to the firm surface. These results suggest that the compliant, foam surface presented a greater challenge to participants with TFA compared to control participants. Therefore, use of the compliant, foam surface was able to differentiate the limits of walking performance between groups as evidenced by adoption of compensatory walking patterns in people with TFA. These walking compensations in people with TFA over the foam surface widened the already substantial gap in walking performance observed between people with and without LLL.

Interestingly, the TFA and control groups were similarly impacted by the addition of a concurrent cognitive task on both firm and foam surfaces, even though the foam surface disproportionately impacted walking in participants with TFA compared to controls. Because TFA and control groups responded similarly when a concurrent task was added, regardless of the surface, one might infer that walking over a foam surface did not require more cognitive resources for people with TFA compared to controls. It is possible that the use of microprocessor knees reduced the need to concentrate on walking over a compliant foam surface among those with TFA. Microprocessor knees have the ability to rapidly process information gathered from multiple sensors and respond by increasing or decreasing resistance to flexion and extension of the prosthetic knee (Berry, 2006). Evidence suggests that prosthetic knees with microprocessor control of stance and swing improve walking speed on both firm (Kahle, 2008; Segal, 2006) and uneven terrain (Kahle, 2008; Hafner, 2007; Hafner, 2009), decrease falls (Kahle, 2008; Hafner, 2007; Hafner, 2009), and reduce energy expenditure (Seymour, 2007) compared to non-microprocessor knee technology. However, previous research examining differences in the effect of a concurrent task on walking performance between microprocessor knees and non-microprocessor knees presented mixed results, with only one (Hafner & Smith, 2009) of five studies (Hafner, Willingham, Buell, Allyn, & Smith, 2007; Williams et al., 2006; Meier, Hansen, Gard, & McFadyen, 2012) providing objective evidence of improvement in dual-task walking with use of a microprocessor knee. In contrast, self-report data from three of these studies suggested that people with TFA experienced less difficulty with dual-task walking (Hafner, 2007; Hafner, 2009) and lower overall cognitive burden (Williams, 2006) when using a microprocessor compared to a non-microprocessor knee. Similar benefits associated with use of a microprocessor knee were communicated in discussions with participants in the current study, though all participants still reported that their need to concentrate on walking is problematic, even with use of microprocessor technology.

Because subjective evidence (Chapter 2) presented here and by others (Miller, 2001; Gauthier-Gagnon, 1999) supports the argument that people with LLL allocate additional concentration to walking compared to those without LLL, it is important to consider alternative explanations for the results of this study. One explanation for the inconsistency between objective results from the current study and self-reported data may be that people with LLL may employ a conservative strategy at all times when walking. For example, adopting a slow self-selected walking speed and wide base of support could reduce the need for cognitive control and may partially explain the lack of significant differences in walking performance between single- and dual-task conditions among the TFA group. Future dual-task studies might consider controlling for gait speed across participants and task conditions to examine interactions between cognition and walking to replicate situations when conservative gait patterns cannot be used. Alternatively, researchers could assess the relative cognitive demand of walking using a simple reaction time task as the cognitive task (e.g., respond to a stimulus as quickly as possible with a simple vocalized word, such as "pa") and instruct participants to concentrate on walking (Ojha, Kern, Lin, & Winstein, 2009). Reaction times on this cognitive task could then be compared to assess differences in processing time in single (i.e., performance of the cognitive task in a seated position) relative to dual-task (i.e., performance of the cognitive task while walking) conditions within people with TFA and matched controls to infer the relative cognitive demand of walking in each group.

Although many qualities of gait can be described with spatiotemporal measures, there are aspects of walking that are not captured by the measures used in this study. First, whole body center of mass (COM) movements may better reflect gait deviations and postural instability during walking than spatiotemporal measures. Future work will seek to describe differences in biomechanical stability and gait quality between groups, tasks, and surface conditions using whole body COM parameters, such as displacement, velocity, and COM-ankle inclination angles.

Finally, the discrepancy between self-reported need to concentrate on walking and objective measures of dual-task walking performance suggest that information about interactions between cognition and walking can be elicited directly from self-report experiences of people with LLL. Qualitative studies and development of psychometrically-sound self-report measures of cognitive burden under walking conditions have the potential to inform future research and technological advancements in the field of prosthetics.

Limitations

A number of limitations associated with the present study should be noted. First, the study may have had insufficient statistical power to detect group differences. A power analysis for this study was performed using walking speed results from a previous study that examined the impact of a concurrent task on walking in people with TFA compared to control participants (Lamoth, 2010). However, this previous study included participants using various prosthetic knees, the majority of which were not microprocessor-controlled. Differences in speed between single- and dual-task conditions were lower in the current study compared to reported differences between task conditions in previous research, thus it is possible that a higher sample size would have led to different statistical conclusions, particularly with respect to walking speed results.

In addition, the foam surface used in this study may not have sufficiently challenged participants with TFA because it was uniform in density throughout the length of the walkway. A main difference in the neural control of walking between people with and without LLL is the lack of sensory inputs that can quickly inform adjustments to that gait pattern that maintain stability over unpredictable surfaces. Overall, the foam surface in this study likely perturbed participants' biomechanical stability, but not unpredictably so. The lack of unpredictability in the foam surface could be observed based on improvements in walking between the first pass of the foam training trials and subsequent trials. It appeared that people with LLL were able to quickly learn how to walk on the foam surfaces, seemingly employing anticipatory postural control strategies rather than reactive postural control strategies. Because reactive control strategies rely on sensory input from the ground, people with LLL are likely at a distinct disadvantage when walking on unpredictable surface conditions. Future work is needed that assesses the effect of a concurrent cognitive task on walking in unpredictable surface conditions to better assess the range of challenging walking environments encountered in daily life.

Conclusions

Although many people with LLL report the need to concentrate on walking, results of this study suggest that walking performance is not differentially affected by a concurrent cognitive task when walking over simple or challenging walking surfaces in people with TFA compared to people without LLL. However, overall differences between groups reflect a gap in walking performance between people with TFA using microprocessor-controlled knees and people without LLL. Additionally, walking performance on a compliant foam surface was differentially and negatively impacted in people with TFA compared to people without LLL. Together, these results suggest that people with TFA using microprocessor knee technology may adopt a conservative strategy when walking over simple and challenging surfaces that may preemptively reduce the need for cognitive control.

Table 3.1. Participant Demographics/Characteristics

Part. #	Age (yr)	M/F	Ht (m)	Wt (kg)	MoCA	ABC	# cond.	Falls/ yr	Yrs since amp	Etiology
TFA-102	42	M	71	172	27	3.7	0	0	29	Tumor
TFA-103	55	M	75	210	26	3.1	0	3	17	Tumor
TFA-104	75	M	72	194	24	3.5	2	0	57	Trauma
TFA-105	39	M	67	155	27	3.5	0	2	12	Trauma
TFA-106	36	F	67	162	27	2.2	0	1	14	Trauma
TFA-107	77	F	67	148	28	2.4	1	2	5	Vascular
TFA-108	65	F	67	135	25	3.0	0	1	15	Trauma
TFA-109	49	M	70	195	29	3.8	0	0	10	Trauma
TFA-110	55	M	70	215	26	2.8	0	3	34	Trauma
TFA-111	39	F	63	103	27	2.6	0	3	25	Tumor
TFA-112	61	M	71	229	26	3.6	0	4	43	Trauma
TFA-113	45	M	70	162	25	3.1	0	12	4	Infection
TFA-114	47	F	66	138	28	3.0	0	4	28	Trauma
TFA-115	68	M	69	205	27	3.1	1	3	9	Infection
TFA mean (SD)	53.8 (13.6)	F: 35.7%	1.75 (0.08)	78.5 (16.4)	26.6 (1.3)	3.1 (0.5)	0.3 (0.6)	2.7 (3.0)	21.6 (15.3)	-
Control mean (SD)	53.8 (13.4)	F: 37.5%	1.76 (0.11)	77.2 (13.7)	28.3 (1.4)	3.7 (0.4)	0.3 (0.7)	0.1 (0.4)	-	-
p-value	1.0	1.0	0.61	0.71	0.006	0.003	1.0	0.009	-	-

Table 3.2. Single task (ST) and dual task (DT) means, standard deviations, and ANOVA *p*-values for walking and cognitive measures

	TFA				Control				*p*-value						
	FIRM		FOAM		FIRM		FOAM								
	ST	DT	ST	DT	ST	DT	ST	DT	Group	Task	Surface	Group x Task	Group x Surface	Task x Surface	Group x Task x Surface
WALKING TASK															
Walking Speed (m/s)	1.17 (0.17)	1.15 (0.17)	1.12 (0.19)	1.10 (0.17)	1.39 (0.18)	1.41 (0.20)	1.42 (0.17)	1.45 (0.18)	<0.001	0.66	0.36	0.09	<0.001	0.89	0.85
Step Width (m)	0.188 (0.041)	0.197 (0.045)	0.191 (0.047)	0.203 (0.050)	0.121 (0.025)	0.130 (0.021)	0.111 (0.027)	0.115 (0.020)	<0.001	<0.001	0.03	0.26	<0.001	0.66	0.09
Step Time Asymmetry (s)	0.08 (0.04)	0.08 (0.06)	0.07 (0.05)	0.08 (0.06)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	0.01 (0.01)	<0.001	0.21	0.52	0.11	0.28	0.96	0.23
Stride Length (m)	1.355 (0.172)	1.331 (0.177)	1.357 (0.196)	1.334 (0.192)	1.520 (0.138)	1.518 (0.145)	1.573 (0.153)	1.571 (0.139)	0.003	0.09	<0.001	0.15	0.001	0.93	0.89
Cadence (steps/s)	104.0 (7.0)	104.7 (7.8)	99.2 (5.5)	99.9 (5.6)	109.3 (9.2)	111.5 (8.8)	108.7 (7.8)	110.7 (7.8)	0.006	0.02	<0.001	0.26	0.002	0.88	0.82
Step Time (s)	0.58 (0.04)	0.58 (0.05)	0.61 (0.04)	0.61 (0.04)	0.55 (0.05)	0.54 (0.04)	0.56 (0.04)	0.55 (0.04)	0.004	0.03	<0.001	0.22	0.001	0.91	0.61
Step Time Variability (s)	0.02 (0.01)	0.02 (0.01)	0.02 (0.01)	0.02 (0.01)	0.01 (0.003)	0.01 (0.003)	0.01 (0.003)	0.01 (0.003)	<0.001	0.10	0.03	0.41	0.048	0.91	0.49
Step Time COV (%)	7.3 (3.3)	7.8 (4.5)	7.1 (3.5)	7.5 (3.6)	2.6 (0.6)	2.5 (0.6)	2.6 (0.7)	2.5 (0.5)	<0.001	0.32	0.68	0.10	0.58	0.78	0.96
	TFA				Control				*p*-value						
	ST	DT FIRM		DT FOAM	ST	DT FIRM		DT FOAM	Group	Task		Group x Task			
COGNITIVE TASK															
Response Latency (s)	0.81 (0.16)	0.85 (0.21)	-	0.86 (0.19)	0.69 (0.13)	0.74 (0.13)	-	0.71 (0.15)	0.04	0.006	-	0.39	-	-	-
Response Accuracy (%)	94.6 (8.8)	96.0 (5.8)	-	94.6 (8.4)	98.2 (3.8)	99.1 (3.3)	-	99.1 (3.3)	0.09	0.27	-	0.61	-	-	-

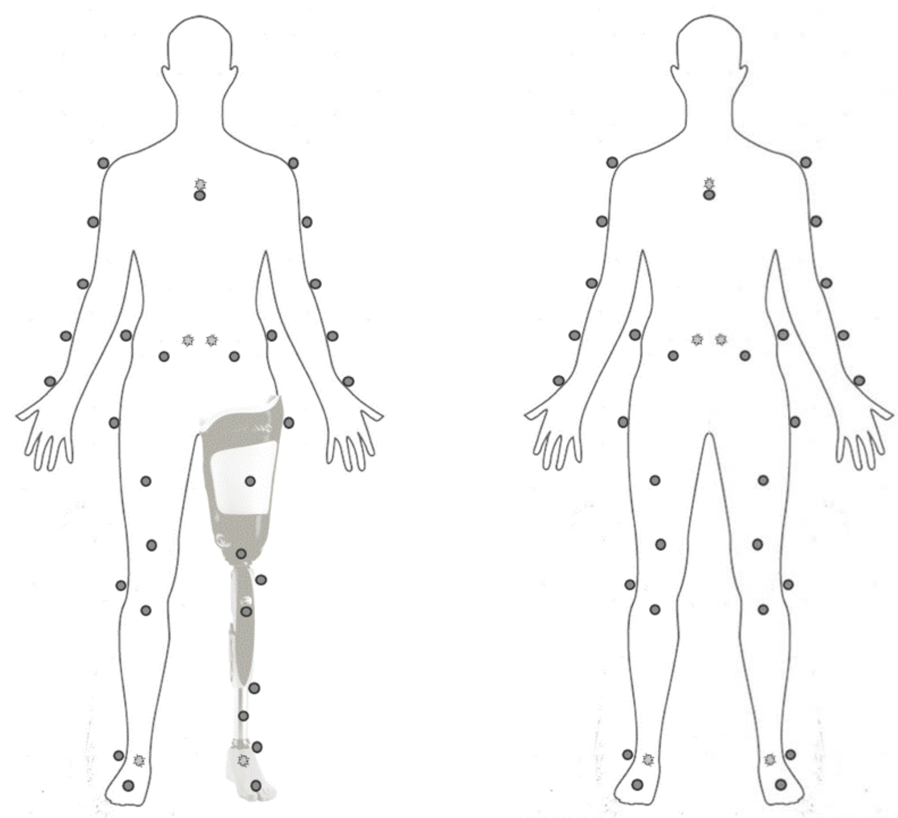

Figure 3.1. Marker set for participants with and without lower limb loss.

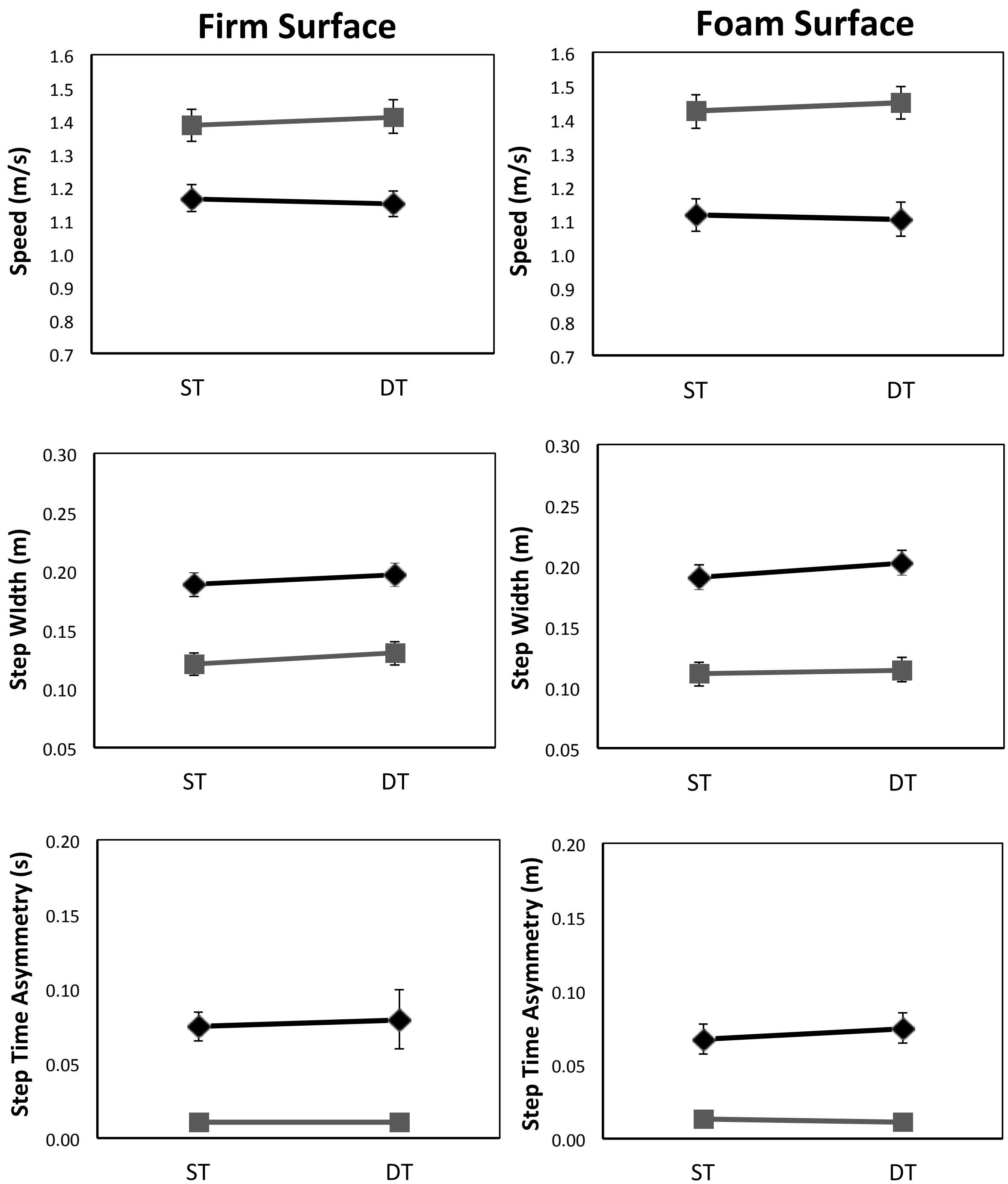

Figure 3.2. Single-task (ST) and dual-task (DT) walking performance over the foam and firm surfaces in both people with TFA (◆) and controls (■). Error bars indicate standard error.

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Chapter 4. Biomechanical modeling of people with lower limb loss who use prosthetic limbs: A proof of concept study

Abstract

Center of mass (COM) movements can be used to examine joint kinetics, gait quality, and postural stability. For people without limb loss, established methods for deriving COM position exist using the weighted sum of body segments. However, no standard adaptations to these methods have been adopted for people with transfemoral amputation (TFA), who typically have marked asymmetry in mass and mass distribution between the intact and prosthetic limbs. The aim of this research was to assess the equivalency of two different modeling approaches to estimate COM position: an anatomical approach, based on the mass distribution properties of the intact side; and a prosthetic-specific approach, based on the masses of prosthetic components. COM parameters, such as displacement, peak velocity, and COM-ankle inclination angle, during gait were calculated and compared between models to explore the effects of modeling approach on kinematic outcomes related to gait quality and postural stability in people with TFA.

Introduction

People with lower limb loss (LLL) rely on prostheses to regain ambulatory mobility. Although prostheses serve as a replacement for some limb structures and functions, prosthetic limb users often need to adopt compensatory strategies to safely ambulate (Smith, Michael, & Bowker, 2004). These compensations often manifest as gait pattern impairments that may lead to large, asymmetrical center of mass (COM) movements, particularly in the vertical and mediolateral directions. COM movements are often used in prosthetic research as an indicator of increased energy expenditure and postural instability in people with LLL (Bell, Wolf, Schnall, Tis, & Potter, 2014; Hak, van Dieën, van der Wurff, & Houdijk, 2014; Hak et al., 2013; Beltran, Dingwell, & Wilken, 2014; Major, Stine, & Gard, 2013; Hof, van Bockel, Schoppen, & Postema, 2007). Abnormal gait mechanics may also contribute to excessive joint forces, which may lead to arthritic changes in intact joints (Morgenroth, Gellhorn, & Suri, 2012).

There are many approaches to the estimation of COM position (Gard, Miff, & Kuo, 2004; Thirunarayan, Kerrigan, Rabuffetti, Croce, & Saini, 1996; Lenzi, Cappello, & Chiari, 2003; Mapelli et al., 2014). One approach is the segmental analysis method, which is recommended for assessing movement in people with gait pathologies (Gard, 2004). To study COM movements using this method, the COM position must first be estimated from position data derived from motion capture. This method is also desirable for its ability to estimate COM position in complex walking tasks, such as turning and walking over challenging surfaces. Segmental COM analysis determines position in the fore-aft (x), medial-lateral (y), and superior-inferior (z) directions using weighted averages of body segments (e.g., trunk, thigh, forearm) based on anthropometric measurements, marker position, and total body mass (Eq. 1-3).

$$COM_x = \frac{m_1x_1+m_2x_2+\cdots+m_nx_n}{M_{total}} \tag{1}$$

$$COM_y = \frac{m_1y_1+m_2y_2+\cdots+m_ny_n}{M_{total}} \tag{2}$$

$$COM_z = \frac{m_1z_1+m_2z_2+\cdots+m_nz_n}{M_{total}} \tag{3}$$

where COM_x, COM_y, and COM_z represent whole body COM position in the x, y, and z directions; M_{total} denotes the whole body mass; $m_{1,2,\ldots n}$ denotes the mass of each segment; and $x_{1,2,\ldots n}$, $y_{1,2,\ldots n}$, $z_{1,2,\ldots n}$ represents the x, y, z position of each segment's COM.

Body segments in segmental analysis are represented by geometric solids (e.g., truncated cones and cylinders) and segmental masses and mass distributions are derived from data gathered in cadaver studies (Hamill and Knutzen, 2003). However, people with LLL have unique mass distributions because the prosthetic limb is often lighter than the missing limb structures (Gailey et al., 1997). For example, the intact foot on a 100-kilogram person would be approximately 1.45% of the whole body mass, or about 1.45 kilograms. A typical carbon fiber prosthetic foot that is similar in height to an intact foot has mass between 0.45-0.59 kilograms (Össur Americas). Similar discrepancies in mass exist for the calf and knee sections of transfemoral prostheses compared to intact limbs. Asymmetries in mass distribution between intact and prosthetic limbs should result in an estimated COM position that is shifted upward and towards the intact side.

Although asymmetrical mass distribution is common in people who use lower limb prostheses, there is no consensus or standard on how to model the prosthetic limb for the purposes of estimating COM position (Kent & Franklyn-Miller, 2011; Sagawa et al., 2011). A recent review found that investigators who study walking in people using prostheses generally match mass distribution of segments bilaterally or do not report their modeling strategies (Kent, 2011). Further, the effects of modeling strategies on COM position estimates in people with proximal levels of LLL (e.g., transfemoral amputation, TFA), where mass asymmetries are pronounced, is not well understood. Thus, the ability to derive COM parameters to study gait quality or postural stability in people with LLL is currently limited.

The purpose of this study was to compare kinematic COM parameters derived from two different approaches to prosthetic limb modeling within a whole-body link-segment model: a conventional anatomical approach, based on the mass distribution properties of the intact side; and a prosthetic-specific approach, based on the masses of prosthetic components. These models were used to calculate and compare COM parameters of participants with LLL while they walked over a firm surface. We hypothesize that modeling the prosthetic limb using specific qualities of the prosthesis will yield different results than modeling the prosthetic limb using traditional approaches.

Methods

Participants

In this observational, cross-sectional study, participants with transfemoral amputation attended a single test session at a human motion analysis laboratory. Eligibility criteria were (1) 18 years of age or older; (2) the ability to walk without physical assistance from another person or an assistive device; (3) unilateral transfemoral limb loss; (4) most recent amputation surgery more than one year ago; (5) use of a prosthesis with a microprocessor-controlled knee; and (6) no medical conditions that affected ability to complete the protocol. This study was conducted with approval from the institution's Human Subjects Division. All participants provided informed consent prior to beginning the study.

Procedure

A clinical evaluation was performed with each participant, including collection of self-report demographic and health information (e.g., age, gender, date and etiology of amputation). Participants were weighed while wearing their prosthesis. Then, the prosthesis was removed and weighed separately using a The First Years™ by Tomy American Red Cross Baby Scale with digital accuracy to +/- 10 grams. In addition, each participant's prosthesis was examined to determine manufacturer and model information for specific components (e.g., foot, knee, pylon).

Retroreflective markers were placed on the participants' trunk (sternum and thorax), pelvis (anterior and posterior superior iliac spines, iliac crests), and bilateral arms (acromions, lateral epicondyles, wrists, upper and lower arms). On the intact side, markers were positioned at the trochanter, thigh, patella, lateral knee joint, tibial tubercle, lateral malleolus, posterior heel, and between the second and third metatarsal phalangeal joint. Markers were also placed over the prosthetic socket (trochanter, distal end, and anterolateral socket), knee (prosthetic knee joint, anterior knee, and knee/pylon junction), pylon (pylon/foot junction), and foot (lateral, posterior, and dorsal aspects). (Figure 4.1). As needed, markers were added to characterize other components, such as pylons connecting the socket to the knee or rotation adaptors located proximal to the knee. Three-dimensional marker position data was collected at 120 Hz using an 8-camera Qualisys Motion Capture System (Gothenburg, Sweden).

Participants were asked to walk back and forth at their self-selected speed across a 10-meter walkway for two 24-second walking trials. Qualisys Track Manager was used to identify markers, interpolate gaps in marker position data (generally <0.25 second long), and truncate trials to include only data collected in the center of the capture volume, where data quality was optimized. Visual 3D motion analysis software (C-Motion, Inc., Rockville, MD) was used to filter data using a fourth order bidirectional low pass Butterworth filter with a cutoff at 6 Hz, build link-segment models (described below), and label heel strike and toe off events.

Models

Two link-segment models were created for each participant. The first model depicted the prosthetic limb with the same segments and mass distributions as the intact side (anatomical model, Figure 4.2a). The second model depicted segments and mass distributions attributed to components on the prosthetic limb (prosthetic-specific model, Figure 4.2b).

Anatomical Modeling of the Prosthesis. The anatomical model was a 12-segment model with the head integrated into the trunk segment and the hands integrated into the forearm segments. The geometric dimensions (i.e., length and circumference) of the prosthetic thigh, shank, and foot were scaled using measurements taken from the prosthesis, but mass distributions, based on Dempster & Gaughran's cadaver research (1967), were the same for the intact and prosthetic lower limb.

Prosthetic-Specific Modeling of the Prosthesis. The prosthetic-specific model was a modified version of the anatomical model described above. In brief, modifications made to create prosthetic-specific models included: (1) modeling of prosthetic segments to reflect the mass of the prosthesis; (2) measurement and subsequent calculation of prosthetic-side masses to accurately represent the segment proportions relative to the whole body mass; and (3) redistribution of intact- and prosthetic-side proportions based on the calculated mass proportions of the prosthetic limb and Dempster's tables. Modeling methods and calculations are discussed in detail below.

The segments modeled for the prosthetic side were: (1) combined residuum/prosthetic socket, (2) prosthetic knee, (3) prosthetic pylon, and (4) prosthetic foot. Prosthetic component masses (i.e., foot, pylon, and knee) were characterized using manufacturer-published characteristics. The mass of the prosthetic socket (m_{socket}) was calculated as the mass of the prosthesis ($m_{prosthesis}$) minus the combined masses of the remaining prosthetic components (i.e., prosthetic knee (m_{p_knee}), pylon $\left(m_{pylon}\right)$, and foot (m_{p_foot})) (Eq. 4):

$$m_{socket} = m_{prosthesis} - (m_{p_{knee}} + m_{pylon} + m_{p\_foot}) \tag{4}$$

Mass proportions for remaining intact and prosthetic side segments were then calculated. First, the mass of the prosthetic limb was subtracted from the total mass of the person wearing the prosthesis (M_{total}) to find the mass of the person without their prosthesis (M_{nopro}) (Eq. 5):

$$M_{nopro} = M_{total} - m_{prosthesis} \tag{5}$$

Next, volumes were calculated for the residuum and intact thigh (Figure 4.3, Eq. 6 and 7):

$$Volume\ Residuum = \frac{\pi}{3} l_{residuum}\left({r_{thigh}}^2 + r_{thigh} r_{residuum} + {r_{residuum}}^2\right) \tag{6}$$

$$Volume\ Intact = \frac{\pi}{3} l_{intact}\left({r_{thigh}}^2 + r_{thigh} r_{knee} + {r_{knee}}^2\right) \tag{7}$$

In the equations above and below, $l_{residuum}$ is the length of the residual limb, l_{intact} is the length of the intact thigh, r_{thigh} is the radius of the proximal intact thigh, r_{knee} is the radius of the intact knee, and $r_{residuum}$ is the calculated radius of the intact thigh at the level of the contralateral amputation, equation below (Eq. 8):

$$r_{residuum} = \frac{l_{missing}r_{thigh} - l_{missing}r_{knee} + l_{intact}r_{knee}}{l_{intact}} \qquad (8)$$

where $l_{missing}$ is the length of the missing portion of the thigh calculated from motion capture data and comparison with the intact limb.

The ratio of the residual limb volume to the volume of the intact thigh is calculated using Eq. 6 and 7 above (Eq. 9):

$$Residuum\ Ratio = \frac{Volume\ Residuum}{Volume\ Intact\ Thigh} \qquad (9)$$

The proportion of the residuum to the total body was then calculated to be the residuum ratio multiplied by 0.1 (the relative mass of the intact thigh from Dempster's tables).

$$Proportion\ Residuum = 0.1 \times Residuum\ Ratio \qquad (10)$$

Similarly, the proportion missing was calculated using Dempter's tables to sum the proportions of the missing foot, shank, and missing thigh section (Eq. 11):

$$Proportion\ Missing = 0.0145 + 0.0465 + (0.1 - Proportion\ Residuum)] \quad (11)$$

Dempster's tables were then used to find the approximate proportion of the intact body.

$$Proportion\ Intact = 1.0 - Proportion\ Missing \quad (12)$$

The mass of the person without their prosthesis was then divided by $Proportion\ Intact$ to find an approximation of what the total body mass of the individual would have been without amputation (Eq. 13):

$$M_{noamp} = \frac{M_{total}}{Proportion\ Intact} \quad (13)$$

Next, the masses of remaining segments (i.e., head/trunk; pelvis; bilateral upper and lower arms; intact thigh, shank, and foot) were calculated by multiplying the segment proportion from Dempster's tables by M_{noamp} (Eq. 14):

$$m_{segment} = M_{noamp} \times segment\ proportion \quad (14)$$

Similarly, the mass of the residuum was calculated by multiplying the approximated total mass (M_{noamp}) by the residuum's proportion to the whole body. The mass of the residuum was then added to the calculated mass of the socket to estimate the mass of the residuum/ socket segment. These intact and prosthetic side segments masses were then divided by the measured total body mass with the prosthetic limb (M_{total}) to find the redistributed segment proportions for the prosthetic-specific model (Eq. 15)

$$redistributed\ segment\ proportion = \frac{m_{segment}}{M_{total}} \qquad (15)$$

The redistributed segment proportions for prosthetic and intact segments were then used to build the prosthetic-specific model in Visual 3d.

Walking Parameters

For each participant, both the anatomical and prosthetic-specific link-segment models were used to separately calculate COM parameters using all strides with sufficient marker position data to build the link-segment models described above. COM parameters included medio-lateral (ML) and vertical COM displacement, ML and vertical COM peak velocity, peak ML COM-ankle inclination angle during single limb support on the prosthetic and intact sides, and the standard deviation (SD) of the ML COM-ankle inclination angle at HS. These parameters (e.g., COM displacement, peak velocity, and inclination angle) were selected to provide insights into gait quality (Shumway-Cook & Woollacott, 2012). Movement of the COM is likely altered in people with TFA because of gait deviations such as vaulting and lateral trunk lean (Smith, Michael, & Bowker, 2004). Similarly, the magnitude of the peak ML COM-ankle inclination angle (i.e., the angle between a line connecting the COM with the ankle marker and the center of gravity) has been shown to distinguish elderly fallers from non-fallers (Chen & Chou, 2010, Figure 4.4). The SD of the ML COM-ankle inclination angle at HS is also considered an indicator of walking variability and is proposed to indicate the need for active control of lateral balance (Sawers & Hahn, 2012).

Analysis

Statistical analyses were not applied because of the small sample (n=2). Means and standard deviations of the selected parameters (e.g., displacement, peak velocity, inclination angle) were used to assess differences between the anatomical and prosthesis-specific gait models. Differences between models were also expressed as a percentage to depict the magnitude of the error (Eq. 16)

$$\frac{parameter_{prosthetic-specific} - parameter_{anatomical}}{parameter_{anatomical}} \tag{16}$$

Results

Two people with TFA participated in this study. Participants differed in sex, height, body mass, etiology of amputation, and time since amputation (Table 4.1). Segment proportions (i.e., segment masses as a proportion of the total body mass) differed between models for both participants. Differences were most pronounced for the prosthetic knee and foot segments, where proportions were smaller in the prosthetic-specific model (Table 4.2).

COM displacement and velocity parameter means were calculated for participant TFA-114 (15 strides) and TFA-115 (10 strides). Overall, prosthetic-specific models resulted in about

1 mm increases in displacement outcomes and 3-17 mm/s increases in peak velocities, representing as much as a 4.1% difference in displacement and a 5.8% difference in peak velocity. Mean COM-ankle inclination angle values were also calculated for participants' intact (TFA-114: 15 steps, TFA-115: 10 steps) and prosthetic (TFA-114: 16 steps, TFA-115: 12 steps) sides. Prosthetic-specific models resulted in angles that were 0-0.5 degrees smaller than those derived with the anatomical model. These differences represent as much as a 6.3% difference in COM-ankle peak inclination angle. Larger differences in angles between models were observed on the intact compared to the prosthetic side for peak inclination angle. Standard deviations of inclination angles at HS were between 0.02-0.04 degrees smaller in prosthetic-specific models, representing between 1.8-4.4% differences in inclination angle variability (Table 4.3).

Discussion

The purpose of this study was to compare COM parameters from participants with TFA calculated using two link-segment models: (1) an anatomical model with symmetrical intact and prosthetic limb mass distributions, and (2) a prosthetic-specific model with asymmetrical intact and prosthetic limb mass distributions. The smaller mass of the prosthetic limb, relative to the intact limb shifted the modeled COM position upward and toward the intact side in both participants. Segment mass asymmetries, and the resultant shift of the COM upward and toward the intact limb, were greater in TFA-115 than in TFA-114. The disproportionate shift between participants is likely because TFA-115 weighed more than TFA-114, resulting in greater mass asymmetries in the lower limbs.

The observed shift in COM position between models resulted in small differences in stride-to-stride COM displacement, velocity, and inclination angle parameters between models. The magnitude and direction of discrepancies in COM parameters between models were similar for most of the parameters examined. Differences in ML and vertical COM displacement were small in both participants. A recent study by Bell and colleagues (2014) reported non-significant differences in COM displacement between people with TFA who have long and short residual limbs to be 7 mm in the ML direction and 5 mm in the vertical direction. The discrepancies between models in the current study (between 1-2 mm) are smaller than the non-significant differences reported in Bell's study, suggesting that modeling strategy may not appreciably affect displacement parameters.

Discrepancies in ML peak velocities between models were also small (between 3-4 mm/s), representing approximately a 2% difference between models. Kelly and colleagues (2008) reported significant differences in ML COM velocity between age-related subgroups of older adults without LLL to be approximately 30 mm/s, suggesting that discrepancies in peak ML velocity between models in the current study may also be too small to substantially affect outcomes.

Differences in vertical peak velocities between models (between 8-17 mm/s) were larger than ML peak velocities (between 3-4 mm/s), suggesting that vertical peak velocity is more affected by modeling strategy than ML peak velocity. In a study by Chastan and colleagues (2010), a significant discrepancy in COM vertical velocity of approximately 30 mm/s at initial contact was observed when walking on foam compared to firm surfaces. This change is similar in magnitude to the difference observed when using anatomical compared to prosthetic-specific models in the current study. Another study by Chong and colleagues (2009) observed discrepancies in COM vertical velocity at initial contact between adults without LLL younger than 34 and those older than 64 to be as little as 10 mm/s. Together, the results of these previous studies suggest that modeling strategy may markedly impact calculated vertical COM peak velocities in participants with TFA. In addition, discrepancies between models for both COM peak velocity measures were greater in TFA-115 compared to TFA-114, suggesting that greater asymmetries in lower extremity mass distribution are associated with a larger effect of model type on COM velocity parameters.

Differences in prosthetic and intact COM-ankle inclination angles between models were between 0-0.5 degrees. This discrepancy between models was slightly smaller than the 0.9-degree significant difference between fallers and non-fallers observed by Chen and Chou (2010). Inclination angles were smaller in the prosthetic-specific model compared to the anatomical model, likely due to the vertical shift of the estimated COM position. Additionally, differences between intact peak COM-ankle inclination angle and the SD of the inclination angle at heel strike between models were larger in TFA-115 compared to TFA-114, whereas the prosthetic peak COM-ankle inclination angle was smaller in TFA-115 compared to TFA-114. These discrepancies in the effect of model type on inclination angle parameters also support the assertion that body weight may impact the magnitude of resultant differences in parameters between models.

A consideration for the approach used to create the prosthetic-specific model in this manuscript was the method for mass estimation of the residual limb. The approach detailed above modeled the residual limb to be a shorter version of the intact thigh. However, typical residual limbs are considerably smaller than this estimate due to soft tissue atrophy over time. An imaging study assessing residual limb changes in people with TFA found 40-60% atrophy in sectioned muscles, 0-30% atrophy in non-sectioned muscles, and fat tissue degradation in the residuum compared to the intact thigh (Jaegers, Arendzen, & de Jongh, 1995). Thus, it is likely that the mass of the residuum/socket segment in the current study was overestimated, resulting in greater intact and prosthetic limb symmetry and smaller discrepancies between models. Modeling residual limb atrophy would likely result in greater differences in COM-related parameters between models than those reported here.

Even with an overestimation of the residuum/socket mass, these findings suggest that the modeling approach may have a small but meaningful effect on estimation of COM-related parameters. Improved accuracy of prosthetic limb modeling can be obtained by direct examination and measurement of the prosthesis and the residual limb. However, practical constraints, such as identification of prosthetic components and participant comfort with donning and doffing a prosthesis, may limit an investigator's ability to collect data needed for the creation of a prosthetic-specific model.

Identification of prosthetic components may be challenging if researchers are not able to visually identify component manufacturer and type. It may seem feasible to weigh each component individually since most prostheses can be disassembled with common tools, however, liability concerns such as improper alignment and under- or over-torqueing screws makes prosthetic disassembly unsafe and inadvisable. Researchers may want to request permission to contact a participant's prosthetist to gather specific component information, which would require the participant to authorize provider-researcher communication by signing a Health Insurance Portability and Accountability Act (HIPAA) Privacy form.

Further, collection of prosthesis weights and measurement of the residual limb would require the removal of the prosthesis, which may require the participant to bring items to assist with redonning (e.g., donning sleeve, lotions, sprays). Also, not all participants will feel comfortable with prosthesis removal and residual limb inspection in a laboratory environment. Finally, doffing and redonning a prosthesis would be best done at the end of a research session, as suboptimal donning could impact prosthetic fit or comfort and, as a result, walking performance. Researchers will need to inform participants in advance if prosthesis removal will be requested and ask them to bring donning devices to their appointment. It is recommended that researchers involve people with clinical expertise to assist with these considerations surrounding component identification and participant comfort.

Limitations

Limitations with this study include the small sample size, strategies for residual limb mass estimation, and assumptions associated with use of the segmental analysis modeling method. The small sample is appropriate to establish proof of concept, but assessment of discrepancies between models in a larger number of participants who range in residual limb length and whole body mass are needed to inform modeling recommendations. Estimations of residual limb mass were based on the length of the segment and did not take into account soft tissue atrophy. This approach to residual limb modeling likely underestimated the asymmetry between limbs and the resultant discrepancies between models. Future studies should seek to better assess residual limb atrophy through calculated ranges of residual limb mass or detailed measurements of participants' residual limbs. It is important to reiterate that these detailed measurements may require clinical expertise and sensitivity to participants' comfort with such intimate measurement procedures. Finally, although the link-segment modeling method has benefits when assessing COM movements in complex walking tasks and people with gait pathology, there are several well-documented limitations to this approach. Overall proportion estimates are based off of cadaver studies representing a small subset of body structures that may be relatively similar in height, mass, and mass distribution (Clauser, McConville, & Young, 1969; Dempster & Gaughran, 1967; Chandler, Clauser, McConville, Reynolds, & Young, 1975). Thus, generalization of these anthropometric parameters is likely problematic because mass distribution differs widely between individuals. Previous studies examining the accuracy of such COM estimations provide evidence that mass distributions may need to be modified to account for differences in age (Stoudt, 1981; Pavol, Owings, & Grabiner, 2002), sex (Jensen & Fletcher, 1994) and body type (Jensen, 1978). It may be necessary to assess ways to account for these differences in future work, however, the purpose of this study is to compare models within a participant, so age, gender, and body-type modifications would be consistent across comparison conditions and would not impact results.

Conclusions

Compared to a model based on the relative mass proportions of an anatomically-intact limb, a model incorporating mass distributions based on prosthetic componentry had a small, but potentially meaningful effect on COM position and related parameters such as COM displacement, velocity, and COM-ankle inclination angle. The small differences observed between models may affect interpretation of COM parameter results, especially for heavier individuals who have pronounced asymmetry between limbs. Future directions for this work include assessment of additional participants to allow for statistical testing, accounting for residual limb atrophy in the prosthetic-specific model to further capture existing asymmetries, and examination of COM parameters in challenging walking conditions where COM movements are larger.

Table 4.1. Participant characteristics

	TFA-114	TFA-115
Sex	Female	Male
Age (yrs)	47	68
Prosthetic side	Left	Left
Etiology of amputation	Trauma	Infection
Time since amputation (yrs)	28	9
Height (m)	1.68	1.75
Body mass (kg)	66.77	91.89
Prosthesis mass (kg)	4.05	4.61
Prosthetic components	Ischial containment socket, Ottobock C-Leg, C-leg pylon, Ottobock Axtion foot	Ischial containment socket, rotation adaptor, Ottobock C-Leg, C-Leg pylon, Ottobock C-Walk foot

Table 4.2. Calculated proportions of body segments relative to the total body mass for anatomical and prosthetic-specific models

	TFA-114		TFA-115	
Segment	Anatomical	Prosthetic-Specific	Anatomical	Prosthetic-Specific
Thorax (+ head)	0.436	0.449	0.436	0.449
Pelvis	0.142	0.146	0.142	0.146
Upper Arms (ea.)	0.028	0.029	0.028	0.029
Lower Arms (ea., + hands)	0.022	0.023	0.022	0.023
Intact Thigh	0.100	0.103	0.100	0.103
Intact Shank	0.0465	0.048	0.0465	0.048
Intact Foot	0.0145	0.015	0.0145	0.015
Residuum/Socket	0.100	0.110	0.100	0.117
Prosthetic Knee	0.0465	0.017	0.0465	0.012
Prosthetic Pylon	-	0.003	-	0.002
Prosthetic Foot	0.0145	0.006	0.0145	0.004
Total	1.0	1.0	1.0	1.0

Table 4.3. Participant means for COM parameters

	TFA-114			TFA-115		
	Anatomical	Prosthetic-Specific	% Difference	Anatomical	Prosthetic-Specific	% Difference
Number of strides	15		-	10		-
Number steps (intact, pro)	31 (15, 16)		-	22 (10, 12)		-
ML displacement (m)	0.053	0.054	1.9%	0.050	0.051	2.0%
ML peak velocity (m/s)	0.185	0.189	2.2%	0.182	0.185	1.6%
Vertical displacement (m)	0.046	0.047	2.2%	0.049	0.047	-4.1%
Vertical peak velocity (m/s)	0.294	0.311	5.8%	0.245	0.253	3.3%
Intact peak angle SLS (°)	7.9	7.7	-2.5%	7.9	7.4	-6.3%
Prosthetic peak angle SLS (°)	7.6	7.4	-2.6%	8.3	8.3	0.0%
SD of angle at HS (°)	1.14	1.12	-1.8%	0.91	0.87	-4.4%

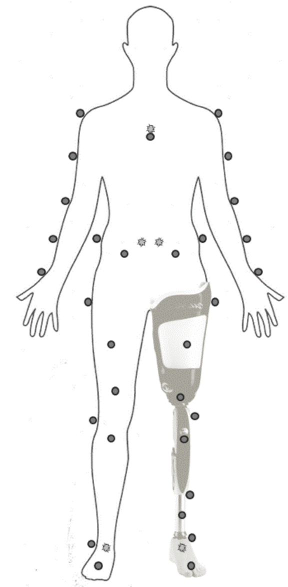

Figure 4.1. Marker set for participants

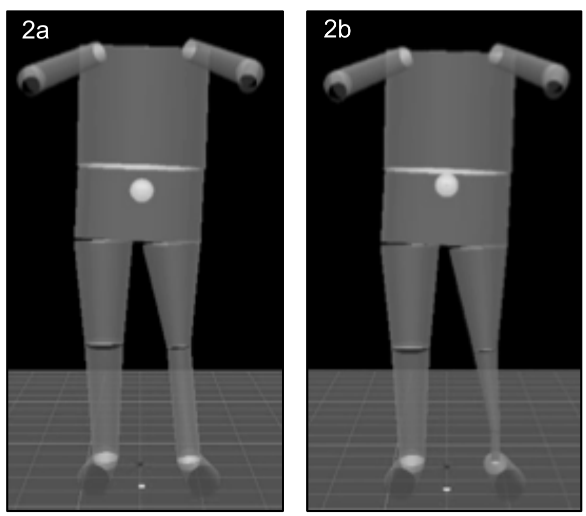

Figure 4.2. Example of anatomical (4.2a) and prosthetic-specific (4.2b) models. The anatomical model mirrors the mass distributions of the intact side. The prosthetic-specific model approximates prosthetic components and segment mass distribution.

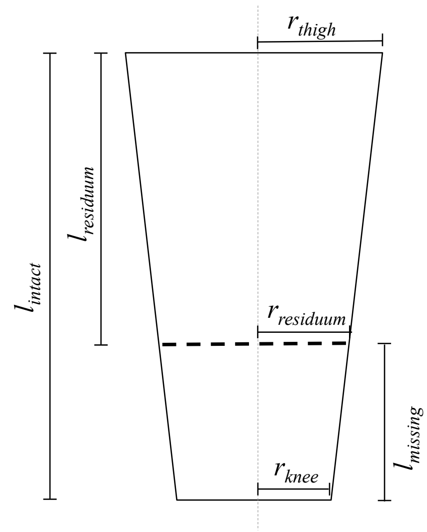

Figure 4.3. Truncated cones representing the modeled segment of the intact thigh and residual limb.

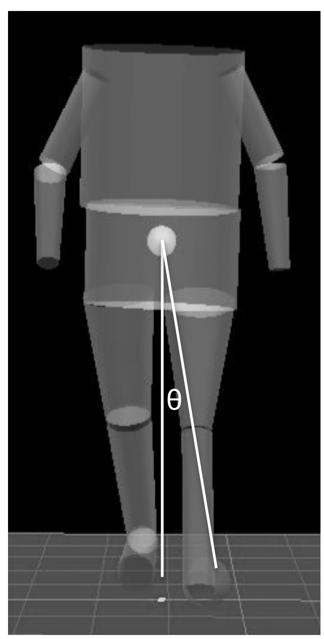

Figure 4.4. Center-of-mass-ankle inclination angle (θ).

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Chapter 5. Summary and conclusions

Together, the chapters presented in this dissertation present a comprehensive examination of the interactions between cognition and walking in people with lower limb loss (LLL). Insights into the use of cognitive control for walking are gained through comparisons of movement strategies employed by people with and without LLL in both simple and challenging walking conditions. These findings enable further discussions of how the control of walking may differ between those with and without LLL.

In Chapter 1, previous dual-task research in people with LLL was reviewed. The relatively small number of dual-task studies identified in a review of the literature suggests that little is known about interactions between cognition and postural tasks in this population. Dual-task research that assesses both standing postural control and walking between people with and without LLL is needed to better understand potential differences in cognitive control between those with and without LLL. In addition, the need to concentrate on walking may be associated with select individual characteristics, such as etiology or limb loss level, and/or situations, such as uneven terrain or crowded environments. Future research should assess individual and situational characteristics to guide future rehabilitation efforts and technological advancements that aim to address the reported need to concentrate on walking in people with LLL (Miller, Speechley, & Deathe, 2001a; Gauthier-Gagnon, Grisé, & Potvin, 1999).

In Chapter 2, a dual-task paradigm was used to assess interactions between cognition and walking over a firm surface in people with transfemoral amputation (TFA) using microprocessor knees and matched controls. Quantitative motion analysis was used to examine how spatiotemporal walking parameters were affected by the performance of a concurrent cognitive task in both groups. Although people with TFA walked more slowly, with wider steps, and with reduced walking quality compared to controls, differences in single- compared to dual-task walking performance were not observed between people with and without TFA. These results suggest that, compared to controls, people with TFA who use microprocessor knees may not differentially rely on cognitive control when walking over a firm surface.

In Chapter 3, the interactions between cognition and walking by assessing the effects of a concurrent cognitive task on walking over a compliant, foam surface between people with and without TFA were further examined. The compliant, foam surface was used to more accurately reflect challenging walking scenarios that might be encountered outside of a laboratory environment. Quantitative motion analysis was again used to assess spatiotemporal characteristics of walking. Similar to the results for Chapter 2, main group differences were observed in walking performance, but significant differences in single- compared to dual-task walking over the foam surface were not found. The combined results from Chapters 2 and 3 may imply that people with TFA employed conservative walking strategies to reduce the need for cognitive control of walking. In addition, people with TFA were differentially impacted by the compliant foam surface, as evidenced by slower walking speeds, wider step widths, and impaired gait quality. The foam surface walking results suggest that people with TFA were challenged by the compliant surface condition more than people without LLL. However, it is possible that the uniformity of the compliant surface was predictable in nature and people with LLL were likely relying on anticipatory postural control strategies to safely walk. Future work should assess walking surfaces that are unpredictable and require people to rely on sensory feedback mechanisms that are impaired in people with LLL (Smith, Michael, & Bowker, 2004).

Spatiotemporal measures, such as walking speed, step width, and step time, can be used to characterize walking performance in people with LLL. However, these parameters may not fully capture whole body motions and postural stability while walking. Additional information about the impact of a concurrent cognitive task on whole body motions and biomechanical measures of stability can be examined with parameters describing center of mass (COM) movements. To determine the location of the COM in people with LLL, we needed guidance on the most appropriate biomechanical modeling technique for the prosthetic limb. However, modeling guidance was not well documented in the literature for the assessment of kinematic COM motion in people with LLL (Kent & Franklyn-Miller, 2011). Thus, Chapter 4 assessed differences in biomechanical modeling techniques to determine the most appropriate modeling technique to apply in future explorations on the effect of a concurrent task on whole body motions and biomechanical measures of stability in people with LLL. Small differences in kinematic COM parameters suggest that choice of model may affect the estimated position of the COM and calculations derived from estimated COM position. In addition, models created in this study likely underestimate differences between models due overestimation of residual limb mass. Future work will assess a range of residuum masses to examine the maximum effect that choice of model may have on COM-related kinematic parameters.

Overall, the work described in this dissertation will add to previous knowledge about the cognitive control of walking in people with LLL. Primarily, results of this dissertation suggest that people with TFA adopt conservative walking patterns that may preclude the need to rely on cognition during walking. Further, results of these studies demonstrate that there remains a wide gap in functional abilities between people with and without LLL, even when using state-of-the-art microprocessor knee technology. Therapeutic techniques and emerging prosthetic technologies that have the potential to narrow this gap should continue to be a research priority in the rehabilitation of people with LLL.

Overall limitations

Similar to previous research in people with LLL, small sample sizes were a limitation to the studies discussed in this dissertation work and may have resulted in statistical results that were underpowered. While narrowing the patient population to people with TFA who solely used microprocessor technology for ambulation was a general strength of these studies, identifying participants that fit such narrow inclusion criteria was challenging, even over a two-year recruitment period. Future research using quantitative gait analysis technologies that do not require data collection in fixed location, such as the GAITRite System (CIR Systems, Inc., Clifton, NJ) or Opal wireless sensors (APDM, Inc., Portland, OR), may help to build upon the initial results reported in Chapters 2 and 3 of this dissertation.

Considerations for Future Studies

Proximate next steps for this body of work will be to expand the analysis of the effect of model type on COM-related outcomes described in Chapter 4 and then apply the results to the assessment of whole body movements and measures of biomechanical postural stability in the dual-task studies described in Chapters 2 and 3. In addition, collection of pilot data to assess the effects of a concurrent task on walking over a custom, unpredictable surface in people with transfemoral amputation using microprocessor knees, people with transtibial amputation who have concurrent diagnosis of diabetes, and matched-controls is currently underway. Results of this pilot study, in addition to the work described in this dissertation, will be used to apply for grant funding to support continuation of this research program.

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