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Transition Step Mechanics: How Influential Are Age and Fall History?

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TRANSITION STEP MECHANICS: HOW INFLUENTIAL ARE AGE AND FALL HISTORY?

by

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ABSTRACT

TRANSITION STEP MECHANICS: HOW INFLUENTIAL ARE AGE AND FALL HISTORY?

by

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The purpose of this dissertation was to identify modifiable lower extremity kinematic and neuromuscular factors associated with step clearance and foot placement during transition step negotiation in older adult females with a history of falling. Specifically a full understanding of the contributions of bilateral joints of the hip, knee, and ankle during step clearance and landing was investigated (Chapter 2). Additionally to further understand how the task is accomplished, we examined the neuromuscular demands required to perform the previously mentioned kinematics (Chapter 3). Finally, to expand upon the knowledge of the multi-segment foot, the kinematics of the distal foot were examined during the landing phase of single step descent (Chapter 4).

Participants were 15 young adult females (18-40 years), 15 older adults without a history of falls in the last year (65+ years), and 15 older adults with a history of at least one fall in the previous year (65+ years). Three-dimensional motion capture and electromyography was collected as participants walked at their self-selected pace on a 5.5 m long raised walkway, descended (via forefoot landing) the 17 cm step leading with the right foot, and continued to walk 3 m.

It was anticipated older women with a history of falls would have the smallest lead and trail limb clearance and closest foot placement before and after the step followed by the older non-fallers and then the young adults. For lead limb clearance and placement, these differences were expected to be the result of greater extension of the lead (swing) limb hip, knee, and ankle and increased flexion (and

hip adduction) of the trail (support) limb in the older adult groups. This was not the case; the only difference found was by age with older adults with closer lead limb placement which was accomplished though greater knee flexion. The closer landing may function to reduce single limb stance time during the transition step negotiation to compensate for age-related decreases in lower extremity strength. However, the more flexed knee position may also increase the risk of a fall due to lead limb collapse, as there is an increased reliance on muscular strength rather than skeletal structure for stability.

Regarding the neuromuscular activity, a distal to proximal shift of peak joint moments and powers in older adults, consistent with that established during level walking, was predicted during transition step descent. This bilateral distal to proximal shift in lower extremity joint moments and powers was anticipated to be associated with increases in the co-activation patterns of the knee and ankle musculature during step negotiation. In actuality, no differences were found for either lead or trail limb moments or co-activation levels. However eccentric powers of the lead limb hip and knee were significant with older adults producing decreased power, while the peroneal activation as anticipated, was significantly greater in the older groups. This demonstrates single step descent does not follow the typical distal to proximal shift of moments and powers across age seen during level walking. However, it does establish significant normalized peroneal activation differences across age, which may be due to decreased peroneal strength.

For the distal foot, the older groups were hypothesized to demonstrate increased distal foot plantarflexion (rearfoot, medial midfoot, lateral midfoot, medial forefoot, lateral forefoot) and inversion (rearfoot, medial and lateral midfoot) at initial contact compared to the young group. Further, the older fall history group was anticipated to land with the distal foot more plantarflexed and inverted than the older non-fallers. During the landing phase, the older adult groups were hypothesized to demonstrate smaller ranges of motion in the knee and hip and greater ranges of motion across the distal foot joints in both the sagittal and frontal planes compared to the young group. The distal changes were anticipated

to be due to the differences in the initial contact positions and age-related decreased strength of the foot and ankle musculature. Despite previous findings that older adults land from a single step in a more plantarflexed position, this study found across the ankle as well as the distal foot, initial contact angles are similar across groups. Regarding the range of motion of the distal joints from initial contact through weight acceptance, only the midfoot demonstrated differences with the older groups dorsiflexing less than the young adult group at the lateral midfoot, while at the medial midfoot, the older non-fallers actually plantarflexed slightly while the young adults dorsiflexed. Overall, although only statistically significant at the midfoot range of motion, it is possible these differences are due to age-related changes within the joint structures of the distal foot.

The results of this dissertation contribute to the development of falls rehabilitation or prevention programs that are more specifically tailored to address the specific kinematic and neuromuscular dysfunctions contributing to step negotiation falls risk in older adult women.

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Chapter 1: Introduction

The yearly costs associated with treatment for non-fatal fall related injuries in the United States are estimated to be $31.3 billion (Burns, Stevens, & Lee, 2016). As age increases, so does the risk of fall related injuries. Older adults (65 and older) fall, most often during locomotion (H. J. Lee & Chou, 2007) and almost twice as often as middle aged adults (Skalska et al., 2013). Females specifically fall twice as often as men and incur almost three times the medical costs for treatment of fall related injuries (Burns et al., 2016). One of the most hazardous types of locomotion for older adults is step negotiation. In fact, steps or curbs account for the second most common activity during which falls take place in older adults (Koepsell et al., 2004). Further, the rate of injury due to falls during step negotiation is 12% greater than that during level walking, the most common activity during which falls occur (Duckham et al., 2013).

Direction of step negotiation

When assessing falls during stair negotiation, step ascent and descent are often considered together. However, when direction of travel has been examined, it has been reported that 75% of falls on stairs occur during descent (H. H. Cohen, Templer, & Archea, 1985; Masud & Morris, 2001) and falls when descending steps are more likely to result in serious injuries (Chiu, Chang, Dennerlein, & Xu, 2015). In addition, studies examining the mechanics of both ascent and descent have consistently found differences between the directions of travel. Specifically, differences have been reported in single and double support time, foot clearance, orientation, placement (Lythgo, Begg, & Best, 2007), and hip, knee, and ankle joint mechanics (Protopapadaki, Drechsler, Cramp, Coutts, & Scott, 2007). Further, studies aimed at identifying where most stair falls occur have found that 70% of falls occur within the first or last three steps and 30% percent of step related falls occur on the transition to or from level walking (Templer, 1992). The majority of previous step descent studies, however, have focused on continuous or mid-staircase mechanics and neuromuscular activity. This is important due to the fact that differences have been found both in the mechanics (Yu, Kienbacher, Growney, Johnson, & An, 1997) as well as

muscle activity (Andriacchi, Andersson, Fermier, Stern, & Galante, 1980) between continuous and transition steps. These data suggest the results of the continuous step studies cannot be generalized to transition step negotiation. Thus, there is currently a critical gap in the understanding of the mechanical and neuromuscular factors that may be associated with fall risk in older females during the transition step descent to level walking. The focus of this dissertation will be to address this critical gap.

Factors associated with fall risk in older adults

There are numerous risk factors for falling in older adults that include poor general health, impaired physical function (e.g. muscular weakness/dysfunction, gait/balance deficits) (Masud & Morris, 2001), and a history of falls (Kalula, Ferreira, Swingler, & Badri, 2016). The additional mechanical and neuromuscular challenges associated with negotiating stairs likely compounds these risk factors. The need for identification of these factors is emphasized by the results of a previous study that did not find improvements in step negotiation in a group of healthy older adults following completion of a generic exercise training program. The authors suggested future programs may benefit from inclusion of more step specific exercises (Mian, Thom, Narici, & Baltzopoulos, 2007). Thus, identifying modifiable lower extremity mechanical and neuromuscular factors associated with transition step negotiation may facilitate development of more effective intervention programs to reduce the risk of step related falls.

Causes of falls during step negotiation

Trips are one of the most common causes of falls in older adults (W. P. Berg, Alessio, Mills, & Tong, 1997), with step clearance (e.g. catching the foot on the stair) or misplacing the foot on the step (e.g. over or under stepping) being the most common reported reasons for trips on steps (Templer, 1992). However, results of previous studies examining step clearance and foot placement during transition step negotiation in older adults have been inconsistent. A single step (height = 15 cm) study by Lythgo et al. (2007) found healthy community dwelling female older adults had a significantly smaller foot clearance (cleared the step by a smaller margin) compared to young adults, while a study by Begg

and Sparrow (2000) also examining a 15-cm single step, found older females cleared the step by a larger margin than young females. Although it appears both studies utilized the same definition of clearance, some possible reasons for the inconsistent findings could be the difference in sample size (Begg and Sparrow (2000) n=6, Lythgo et al. (2007) n= 48) or variations in self-selected speed (Begg and Sparrow (2000): older = 0.94m/s, younger = 1.14m/s; Lythgo et al. (2007): older = 1.12m/s, younger = 1.38m/s).

With respect to foot placement, Lythgo et al. (2007), examined both the displacement from the step to the foot and the orientation of the foot at landing. In both cases, there were significant differences with older adults having a smaller displacement and a more plantarflexed foot position. A smaller displacement from the step would result in an increased likelihood for catching the foot on the step. A study by van Dieen and Pijnappels (2009) examined foot orientation after descent from a single step and found that regardless of step height or speed, healthy older adults landed in a plantarflexed position more often than young adults. An increased plantarflexed foot position places the ankle in a less stable position at initial contact and may increase the risk of a fall at contact or during the landing phase of step negotiation. Although based on the results of these studies there is some evidence suggesting age-related changes in foot clearance and placement during transition step negotiation, the differences between older females with and without a fall history have not been investigated. Further, very limited research has been conducted to identify potentially modifiable lower extremity mechanical and neuromuscular factors that may influence step clearance and placement during transition step negotiation in older adults.

Lower extremity kinematics during transition step negotiation

The studies that have investigated kinematic differences of foot clearance and placement between older and younger adults during step negotiation have focused on the lead limb ankle while examination of the more proximal lower extremity and distal foot joints of the lead or trail limb have not been widely investigated. To date, only one study has examined proximal lead limb lower extremity

kinematics across age during single step descent. Hortobagyi and DeVita (1999) examined older and younger females stepping off a platform of 10% and 20% of the participant's height. At initial contact no differences were found between groups in ankle angle and there was only a three degree reduction in knee angle. However, other possible contributing factors such as the motion of the lead limb hip and distal foot, or of the trail limb were not considered. Additionally, the Hortobagyi and DeVita (1999) study had participants stand statically, step down, and stop on the following step. However, as demonstrated by Alcock, O'Brien, and Vanicek (2015), kinematics can vary dependent upon activity before and after the step, therefore, the results may not be generalizable to typical transition step negotiation.

With respect to hip kinematics, a study investigating age-related changes in level walking by Anderson and Madigan (2014) found older adults walked with limited hip extension range of motion. Although compared to level walking, continuous step descent requires a smaller total range of motion at the hip (Riener, Rabuffetti, & Frigo, 2002), the same may not be true for single transition step descent. If this is the case, during single transition step descent older adults may be forced to compensate for limited hip extension range of motion by relying on more distal joints and muscles. Given the increased loss of distal versus proximal lower extremity strength with aging (Menz, 2015), the compensatory changes may influence both foot clearance and placement. Further, the few studies that have investigated hip kinematics during step descent have focused on the sagittal plane. However, Winter and Eng (1995) determined one of the primary controls of foot clearance during level walking was stance limb hip abduction, thus failure to also investigate the frontal plane hip kinematics during transition step negotation may represent another critical gap in literature.

The contralateral or trail limb has only occasionally been examined in step studies. Studies investigating the trail limb have primarily examined the displacement of the limb from the step edge (Barbieri, Lee, Gobbi, Pijnappels, & Van Dieen, 2012; Lythgo et al., 2007), the timing of weight transfer from the trail to lead limb (J. G. Buckley, MacLellan, Tucker, Scally, & Bennett, 2008; Karamanidis &

Arampatzis, 2011), or trail foot clearance (Lythgo et al., 2007). To date, only one study has examined the kinematics of proximal joints of the trail limb. Chiu et al. (2015) examined hip-knee and knee-ankle joint coordination of the trail limb, finding older adults had more consistent hip-knee coordination patterns compared to young adults. The more consistent, or less variable, coordination pattern may suggest a decreased ability to adjust to gait disturbances during step transitions (Chiu et al., 2015). The lack of studies investigating the trail limb mechanics during step transition negotiation in older adults with and without a history of falls is a critical gap given that the trail limb may significantly influence lead limb foot clearance and foot placement.

Finally, regarding lead limb distal foot kinematics, no study has investigated the influence of age or fall history on distal foot function during transition step negotiation. This may be especially important given the preferred landing strategy of older adults is with the forefoot (van Dieen & Pijnappels, 2009), which places the ankle in a less stable position and increases demand on both the distal foot static stabilizers and the musculature supporting the foot and ankle. While multi-segment foot models have been used to examine level walking and running (Arndt et al., 2007; Leardini, Benedetti, Catani, Simoncini, & Giannini, 1999; Lundgren et al., 2008), only two studies thus far have utilized a multi-segment foot model to investigate step negotiation. Rao, Baumhauer, Tome, and Nawoczenski (2009) found greater calcaneus eversion range of motion between older adults with and without midfoot arthritis during a step descent and Gerstle, O'Connor, Keenan, and Cobb (2017) found negotiation of higher step heights requires a more rigid distal foot position at initial contact along with greater distal foot range of motion during weight acceptance in young adults.

Lower extremity neuromuscular function during transition step negotiation

In addition to the kinematic factors discussed, neuromuscular factors associated with step clearance and foot placement during transition step negotiation may also identify areas that may be targeted by fall prevention or rehabilitation programs to decrease the risk of falls and subsequent injury

on steps in older adults. During level walking, older adults have been found to create similar total lower limb support moments compared to young adults, but with increased contribution from the hip and decreased contribution from the knee and ankle. This shift was also found across joint powers (DeVita & Hortobagyi, 2000a; Winter, 1991a). It has been suggested that older adults redistribute joint moments and powers more proximally either due to neuromuscular degeneration or as a protective mechanism to compensate for weakened muscle groups (DeVita & Hortobagyi, 2000a). Additionally, in a study between low and high performing older adults by Graf, Judge, Ounpuu, and Thelen (2005), the low performing adults had a more pronounced power shift from the ankle plantarflexors to the hip flexors compared to the high performing older adults.

Despite the high prevalence of falls and fall-related injuries in older adults during step negotiation, very little research has investigated lower extremity kinetics during transition step descent. This may be significant given that compared to level walking, sagittal plane moments at the ankle, knee, and hip are greater during step descent (Andriacchi et al., 1980) and maximum knee joint power may be almost four times greater (Riener et al., 2002). As step negotiation requires increased joint moments and powers, determining how moment and power redistributions in older adults influence transition step descent may reveal modifiable adaptations that can be addressed by fall prevention or rehabilitation programs.

In addition to examining joint kinetics, investigation of lower extremity muscle activity may further reveal the underlying neuromuscular changes, which influence the proximal shift in lower extremity joint moments and powers, and the resulting kinematic differences that occur with aging and in older adults with a fall history during transition step negotiation. During level walking it has been established that older adults have greater co-activation or neuromuscular stiffness about the ankle joint (tibialis anterior and gastrocnemius) but not the knee (rectus femoris and biceps femoris) compared to young adults (Hallal et al., 2013). Increased muscular co-activation is thought to compensate for reduced

joint stability and muscle strength by making joints more rigid. Thus, while the increased stiffness exhibited by older adults may function to partially compensate for decreased joint stability and muscle strength, it may also indicate an increased fall risk as co-activation may not fully compensate for losses in joint stability or muscle strength. Additionally, landing with stiffer (more extended) joints could also decrease the ability to adjust to gait disturbances during step negotiation. Furthermore, during level walking, older female fallers have been found to have a larger co-activation at the ankle (tibialis anterior and gastrocnemius) than older females without a fall history (Marques et al., 2013). Although increased muscle co-activation at the ankle has been reported in older adults and in those at high fall risk during level walking, no studies have examined lower extremity muscle co-activation during transition step negotiation. This may be important given the increased mechanical and neuromuscular challenges associated with negotiating stairs.

In addition to the co-activation between the lower extremity flexors and extensors, peroneal activity may also be a critical contributor to transition step fall risk in older adults. This may be especially true given the decline in muscle strength with age (Chodzko-Zajko et al., 2009; McKay et al., 2017) and older adults' preference in stepping down with the forefoot (van Dieen & Pijnappels, 2009). However, to date, no studies have investigated age or fall history related changes in peroneal muscle function during step descent.

Statement of Purpose

The primary purpose of this dissertation was to identify modifiable lower extremity kinematic and neuromuscular factors associated with step clearance and foot placement during transition step negotiation in older adult females with a history of falling. This was accomplished by identifying differences in step clearance, foot placement, and lower extremity kinematic and neuromuscular function during transition step negotiation between young adult females, older adult females with a fall history, and older adult females with no fall history. This new knowledge will contribute to the

development of falls rehabilitation or prevention programs that are more specifically tailored to address the specific kinematic and neuromuscular dysfunctions contributing to step negotiation falls risk in older adult women.

Specific Aims and Hypotheses

Aim #1: Determine the effect of age and fall history on step clearance, foot placement, and lower extremity kinematics during negotiation of a single transition step.

Step Clearance Working Hypotheses: It was hypothesized that older female adults with a history of falls would have the lowest foot clearance followed by the older females without a fall history, then the young female adults. Based on previous research that investigated the effect of aging on lower extremity kinematics during level walking, the reduced foot clearance during step negotiation in the older groups versus younger was anticipated to be due to decreased knee flexion and increased ankle plantarflexion of the swinging/stepping limb (Alcock, Vanicek, & O'Brien, 2013). Additionally, decreased foot clearance may also be due in part to increased knee flexion and/or increased hip adduction of the support limb (Mian et al., 2007; Saywell, Taylor, & Boocock, 2012). The foot clearance differences between the two older adult groups was hypothesized to be due to increased knee flexion and/or increased hip adduction of the support limb in the faller group. This hypothesis was based on the more pronounced lower extremity strength declines previously reported in older fallers versus non-fallers (McKay et al., 2017; Menz, 2015).

Foot Placement Working Hypotheses: It was anticipated that both older groups will place their lead limb closer to the step (position of the lead limb from the step edge at initial contact) than the younger group (Lythgo et al., 2007). Further, the older women with a history of falls were expected to land closer to the step than the older non-faller group. It was hypothesized that the older groups' lead limb would be more plantarflexed at the ankle and extended at the knee (Lythgo et al., 2007; van Dieen

& Pijnappels, 2009), while the trail limb would be more flexed at the knee (Hughes et al., 2001) at lead limb foot placement compared to the young group (Lythgo et al., 2007; van Dieen & Pijnappels, 2009). Regarding the older faller and non-faller groups, the faller group was expected to have increased lead limb plantarflexion and knee extension. The trail limb hip and knee of the older faller group were also anticipated to be more flexed (Anderson & Madigan, 2014; Lythgo et al., 2007; Saywell et al., 2012). The closer foot placement and the associated lower extremity kinematic differences between the groups may be a compensatory mechanism to create an earlier landing due to age-related lower extremity strength, range of motion, and/or balance loss (Marques et al., 2013). The difference between the fall history and non-faller groups may also be strength related given the results of a previous study that identified older adults with greater lower-limb weakness were at greater risk for falls (Robinovitch, Heller, Lui, & Cortez, 2002).

Aim #2: Identify the effect of age and fall history on lower extremity neuromuscular function during negotiation of a single transition step.

Lower Extremity Kinetics Working Hypotheses: A distal to proximal shift of peak joint moments and powers in older adults, consistent with that established during level walking (DeVita & Hortobagyi, 2000a; Graf et al., 2005; Winter, 1991b), was anticipated during transition step descent. During the descent phase (trail limb controlling lowering of the lead limb) as well the landing phase (weight acceptance of the lead limb), the peak internal hip extensor and abductor moments and powers were anticipated to be greatest in the older women with a fall history followed by the older women without a fall history, then the young women. At the knee and ankle, the older fall history group were projected to generate the least internal knee extension and internal ankle plantarflexion moments followed by the non-faller older women and then the young females during both the descent and landing phases. With

respect to peak knee and ankle joint power during the descent and landing phases, the older fallers were hypothesized to produce less negative (eccentric) power than the non-faller group while the young group were expected to produce the greatest power. The shift in lower extremity moments and powers during the descent and landing phases may be due to decreased distal limb strength.

Lower Extremity Muscle Activity Working Hypotheses: The bilateral distal to proximal shift in lower extremity joint moments and powers was anticipated to be associated with changes in the co-activation patterns of the knee and ankle musculature during step negotiation. The hypotheses were based on the findings from a level walking stroke study (Kitatani et al., 2016) and a study that investigated age-related changes during multi-step descent (J. G. Buckley, Cooper, Maganaris, & Reeves, 2013). The stroke study identified a decrease in ankle moments and powers with an associated increase in ankle muscular co-activation in stroke patients (Kitatani et al., 2016). Additionally comparing older and younger groups descending steps, J. G. Buckley et al. (2013) found increased co-activation of the ankle and knee in older adults. In this study, the older adults were expected to have greater neuromuscular co-activation than the young adults at both the knee and ankle to create stiffer joints in order to compensate for age-related muscle strength declines (Hallal et al., 2013). The difference between the older adult groups may also be strength related given the results of a previous level walking study that identified older fallers had greater muscle weaknesses and co-activation patterns compared to older non-fallers (Marques et al., 2013).

Finally, although the peroneals are a distal muscle, they were anticipated to be more active in the older adult groups compared to the young adults. This hypothesis was based on older adults preference to land in a more plantarflexed position which is a less stable ankle position that may also require more frontal plane muscular stability (Lythgo et al., 2007). Additionally, between the older adult groups, the fallers were anticipated to have increased activity compared to the non-fallers due to placing the foot in a more vulnerable position at landing.

Aim #3: Identify the effects of age and fall history on distal foot kinematics at initial contact and during the landing phase of transition step negotiation.

Initial Contact Working Hypotheses: The older groups were hypothesized to demonstrate increased distal foot plantarflexion (rearfoot, medial midfoot, lateral midfoot, medial forefoot, lateral forefoot) and inversion (rearfoot, medial and lateral midfoot) at initial contact compared to the young group. Further, the older fall history group was anticipated to land with the distal foot more plantarflexed and inverted than the older non-fallers. The anticipated differences in distal foot posture between the older and younger adults was based on the older adults' preference to land with the forefoot (van Dieen & Pijnappels, 2009) and age-related decreases in lower extremity strength (McKay et al., 2017). The increased plantarflexed position may function to allow landing earlier and the more inverted posture may create a more rigid foot to further increase reliance on the bony versus muscular structures (DeVita & Hortobagyi, 2000b). The differences between the older faller and non-faller groups were also anticipated to be due to decreases in lower extremity strength previously reported in older adult fallers versus non-fallers (Robinovitch et al., 2002).

Landing Phase Hypotheses: During the landing phase, the older adult groups were hypothesized to demonstrate greater ranges of motion across the distal foot joints in both the sagittal and frontal planes compared to the young group. The greater range of motion in the older adult groups compared to the young group were anticipated to be due to the differences in the initial contact positions and age-related decreased strength of the foot and ankle musculature. Although the adaptations may function to increase reliance on the bony structures of the foot at initial contact, the increased plantarflexed and inverted position and age-related decreased strength of the foot and ankle musculature (DeVita & Hortobagyi, 2000b) may result in greater ranges of motion during the landing phase. Between the older groups, those with a fall history were expected to have greater range of motion due to the increased plantarflexion and inverted position at initial contact and decreased foot and ankle muscle strength.

Delimitations of the Study

1. The step height negotiated across all aims of this study was 17 cm. Although this is a common step height, it is possible that the kinematics and neuromuscular function assessed will not be reflective of those during the negotiation of higher or lower step heights.
2. The kinematics and neuromuscular function of transition step negotiation was preceded and followed by level walking. As a result, the findings may not be representative of other forms of transition step negotiation (e.g. step match).
3. Other factors that were not assessed (e.g. cognitive, other environmental) may influence the kinematics and neuromuscular function of transition step negotiation in older adults therefore, the results may not be generalizable to all older adults and/or step negotiation conditions.
4. Transition step negotiation of older women with a fall history was analyzed. As a result, the kinematics and neuromuscular function assessed may not be representative of older adults with a high fall risk, but that do not have a history of falls.

Assumptions

1. Participants provided maximal effort during strength testing.
2. All older adults had accurate recall of their fall history.
3. Marker placement over bony landmarks was accurate.
4. The lower extremity segments function as rigid bodies.
5. The sample of older and younger adult females reflect the population of interest.

Significance

The risk for falls on steps increases as older adulthood is achieved. Additionally, risk is increased in those with a prior history of falls and women fall more often than men. Identifying the differences in lower extremity and distal foot kinematics and neuromuscular function between healthy women with no fall history and those with a history of falls while negotiating stairs may facilitate development of more effective intervention programs to reduce the risk of step related falls in older adults.

Chapter 2: The influence of age and fall history on single transition step kinematics

Introduction

As age increases, so does the risk of fall related injuries. In fact, older adults (65 and older) fall almost twice as often as middle-aged adults (55-59 years) (Skalska et al., 2013). In addition to acute pain and dysfunction immediately following a fall, increased disability and reduced health related quality of life continue to plague older adults months after a fall (Hartholt et al., 2011; Thiem et al., 2014). Furthermore, the annual financial costs associated with treatment for non-fatal fall related injuries in the United States are estimated to be $31.3 billion, with women incurring far greater medical costs due to fall injuries than men (Burns et al., 2016).

Most falls occur during locomotion (Sheldon, 1960) and one of the most hazardous types of gait for older adults is step negotiation, with 23% of falls occurring on steps or curbs (Koepsell et al., 2004). Although a number of studies have investigated the effect of age on the mechanics of continuous step negotiation (Bosse et al., 2012; H. J. Lee & Chou, 2007; Mian et al., 2007; Samuel, Rowe, Hood, & Nicol, 2011; Zietz, Johannsen, & Hollands, 2011), the effect of age on single transition step negotiation during walking has received limited study (Begg & Sparrow, 2000; Lythgo et al., 2007; van Dieen & Pijnappels, 2009). The lack of studies investigating the effect of age on transition step negotiation is significant given that 30% of step related falls occur on the first or last step during the transition to level walking (Templer, 1992) and mechanics of continuous descent cannot be generalized to transition steps (Sheehan & Gottschall, 2011; Yu et al., 1997).

There are numerous risk factors for falling in older adults that include poor general health, impaired physical function, and a history of falls (Carpenter, Scheatzle, D'Antonio, Ricci, & Coben, 2009). Transition step negotiation may be particularly hazardous for older adults, and especially for high fall risk older adults, due to the changes in physical function (e.g. decreased muscular strength) that occur

with aging (McKay et al., 2017) and additional neuromuscular challenges associated with negotiating a level change while also continuing walking gait.

The most common subjectively reported causes of falls on steps are errors in step clearance (e.g. catching the foot on the stair) or misplacing the foot (e.g. over or under stepping) (Templer, 1992). However, results of previous studies examining the mechanics of transition step clearance and foot placement in older adults have been sparse and inconsistent. For lead limb transition step clearance, older women have been found to have a significantly lower heel clearance (Lythgo et al., 2007) and a significantly higher heel clearance (Begg & Sparrow, 2000) compared to young women. For trail limb clearance Lythgo et al. (2007) found older adults had a significantly smaller heel clearance and a less plantarflexed ankle than young adults. However, toe clearance was not significantly different between the groups in either the Begg and Sparrow (2000) or Lythgo et al. (2007) studies.

With respect to foot placement, Lythgo et al. (2007), reported that older women landed with the lead limb significantly closer to the step and in a more plantarflexed foot position compared to young women. Begg and Sparrow (2000) found lead foot placement to be similar between older and younger women, but did not investigate foot position. Finally, neither study reported trail foot placement differences between the age groups.

In addition to the general lack of research and the inconsistency between studies that have been conducted, critical gaps in the research aimed at identifying mechanical factors across age during stair negotiation remain. First, a history of a fall is one of the strongest predictors of a future fall (Carpenter et al., 2009), however, differences in transition step negotiation mechanics of older adults with and without a history of falls has not been investigated. Second, the kinematics of the lead and trail limb proximal joints at step clearance and during foot placement have not been investigated. This is significant given that the mechanical dysfunction causing improper foot clearance and placement is likely not isolated to the ankle joint or the leading limb.

The purpose of this study was to identify modifiable lower extremity kinematic factors associated with transition step clearance and foot placement in young women, older women with no fall history, and older women with a fall history. It was hypothesized that older women with a history of falls would have the smallest lead and trail limb clearance and closest foot placement before and after the step followed by the older non-fallers and then the young adults. For lead limb clearance and placement, these differences were anticipated to be the result of greater extension of the lead (swing) limb hip, knee, and ankle and increased flexion (and hip adduction) of the trail (support) limb in the older adult groups. For trail limb clearance, the differences were postulated to occur as a result of greater extension of the trail (swing) limb hip, knee, and ankle in the older adult groups. Although the kinematic changes in the older groups would result in lower step clearance and closer foot placement that could increase the risk of a fall/stumble, they may also be a strategy to create an early landing that would minimize the time in single limb stance to compensate for age-related loss of lower extremity strength, range of motion, and/or balance (Marques et al., 2013).

Methods

Participants

Fifteen female participants were recruited for each group (young adult, older no fall history, older fall history) from the surrounding community. Utilizing G*Power and the results of a previous study that reported significant differences in foot landing angle during step descent between young and older women (Lythgo et al., 2007), a minimum sample size of 13 participants per group was required to reach a power of 0.8 with alpha = 0.05. Participants in the young adult group (YA) were between the ages of 18 and 40 years, and older group participants were 65 years or older. The older no fall history (ONF) and fall history (OFH) groups were also matched by age (within 5 years) and Body Mass Index category. In addition, all participants must not: have had surgery to their lower back or lower extremities in the last year; have been taking any medication or had a medical condition that may impair

balance; or be pregnant. Further, all participants were able to walk and step down a single 17 cm step without stopping or using an assistive device and scored at least a five on the Six-Item Screener for Cognitive Impairment (Callahan, Unverzagt, Hui, Perkins, & Hendrie, 2002). In addition, the OFH group had a history of at least one fall during the last year; and the ONF group had not fallen within the last year and were classified as low fall risk via the Falls Risk Assessment Score. The definition of a fall used in the study was unintentionally coming to rest on a lower level, not as a result of a major intrinsic event (such as a stroke) or overwhelming hazard (M. E. Tinetti, Speechley, & Ginter, 1988).

Testing Protocol

Prior to testing, participants were informed of the study procedures and asked to sign an informed consent approved by the University's Institutional Review Board. To assess lower extremity function, pain, the ability to carry out activities of daily living, and physical activity; participants completed the Foot and Ankle Disability Index (FADI) (Hale & Hertel, 2005) modified to address the full lower extremity, and the Rapid Assessment of Physical Activity (RAPA) (Topolski et al., 2006). The Five Times Sit to Stand (FTSS) test was administered to assess participant mobility (Lord, Murray, Chapman, Munro, & Tiedemann, 2002), and fall risk was assessed via the Falls Risk Assessment Score (FRAS) (El Miedany, El Gaafary, Toth, Palmer, & Ahmed, 2011). These assessments were used as descriptive data of the mobility and activity behavior of participants, but were not used as inclusion criteria for either group. Lower extremity strength assessed via handheld dynamometer (Awwad et al., 2017; Kendall, McCreary, Provance, Rodgers, & Romani, 2005) and range of motion (ROM) (ankle dorsiflexion and hip extension) (Bennell et al., 1998; Wakefield, Halls, Difilippo, & Cottrell, 2015) were also collected for descriptive purposes (Table 1).

Table 1. Muscle strength tests

Joint	Muscles	Limb
Hip	Abductors	Bilateral
Knee	Flexors & Extensors	Bilateral
Ankle	Plantarflexors & Dorsiflexors	Bilateral
	Evertors	Right
Foot	Intrinsic Hallux Flexors	Right

Bilateral motion data of the lower extremity was collected using a 14 camera system (Raptor 4, Motion Analysis Inc., Santa Rosa, USA) sampling at 200 Hz with retro-reflective markers or marker clusters affixed to the great toes, first and fifth metatarsals, calcanei, shanks, thighs, and pelvis via double-sided adhesive tape (Figure 1). A static standing calibration trial was also collected to identify additional anatomical landmarks on the pelvis, thigh, and shank that were used to define local coordinate systems within each segment (Table 2).

Table 2. Anatomical Landmarks and Technical Marker locations

Segment	Marker Location
Pelvis	Right and left Anterior Superior Iliac Spine Right and left Posterior Superior Iliac Spine Right and left Iliac crests [b]
Thigh [a]	Greater trochanter [b] Lateral thigh plate (4 markers) Medial and lateral epicondyles [b]
Shank [a]	Tibial tuberosity [b] Lateral shank cluster (4 markers) Medial and lateral malleoli [b]
Heel [a]	Calcaneus cluster (4 markers)
Forefoot [a]	5^{th} metatarsal head 1^{st} metatarsal head hallux toenail
[a] Thigh, shank, heel and forefoot markers were placed bilaterally. [b] Indicates static calibration anatomical landmarks that were removed prior to the stepping trials.	

Following the calibration trials, participants began walking barefoot on a 5.5 m long raised walkway, descended the 17 cm step leading with the right foot, and continued walking 3 m (Figure 1).

Right (lead) limb initial contact was recorded by a force plate (AMTI, Inc., Watertown, USA) sampling at 2000 Hz located at the base of the step. To prevent falls during the trials, participants wore a harness connected to an overhead support system (SoloStep Inc., North Sioux City, USA). Gait speed during all trials was determined via electronic timing gates located on the level walkway prior to the step and landing strategy (heel or forefoot) was noted to allow for comparison across similar strategies. After practice trials to familiarize themselves with the task, participants performed seven successful trials at their preferred walking speed. Successful trials included continuous gait approaching the step edge, descent leading with the right limb, lead limb landing completely on the force plate, and continuing gait after step negotiation.

Figure 1. Protocol set-up

Data Processing

To define lead foot clearance, the minimum vertical distance between the step and the plantar surface of the hallux, first metatarsal head, and heel was identified during the period of time between the peak vertical height of the mid-foot following toe-off and the crossing of the step edge for each trial. Minimum lead foot clearance was then defined as the lowest vertical measurement of the three landmarks (heel, metatarsal, toe). To define trail foot clearance, the vertical position of the heel, first metatarsal head, and hallux were identified at the step edge for each trial. Minimum trail foot step edge clearance was then defined as the lowest vertical position of the three landmarks. Finally, lead foot and trail foot placement were defined as the horizontal distance from the step edge to the heel marker cluster and as the horizontal distance from the trail foot hallux marker to the step edge, respectively.

Kinematic data was tracked using Cortex software (v. 7.0 Motion Analysis Inc., Santa Rosa, USA) starting with toe-off of the lead foot prior to the step negotiation through weight acceptance of the lead foot after step negotiation. The kinematic and force plate data were exported to Visual 3D (C-Motion, Inc., Germantown, USA) for all data processing. Initial lead foot toe-off was determined via an over ground toe-off algorithm (Zeni, Richards, & Higginson, 2008) and the force plate was used to identify lead foot initial contact (20 N threshold). Both kinematic and force plate data were low pass filtered with a 4^{th} order zero-lag Butterworth filter and a cut-off frequency of 6 Hz. The joint coordinate system technique was used to calculate the hip, knee, and ankle joint kinematic variables of interest (Figure 2) (Grood & Suntay, 1983). Positive sagittal (hip, knee, ankle) and frontal (hip) plane rotations were defined as flexion/dorsiflexion and adduction, respectively. The variables were calculated from five of each subject’s successful trials and then averaged to calculate the participant’s mean values.

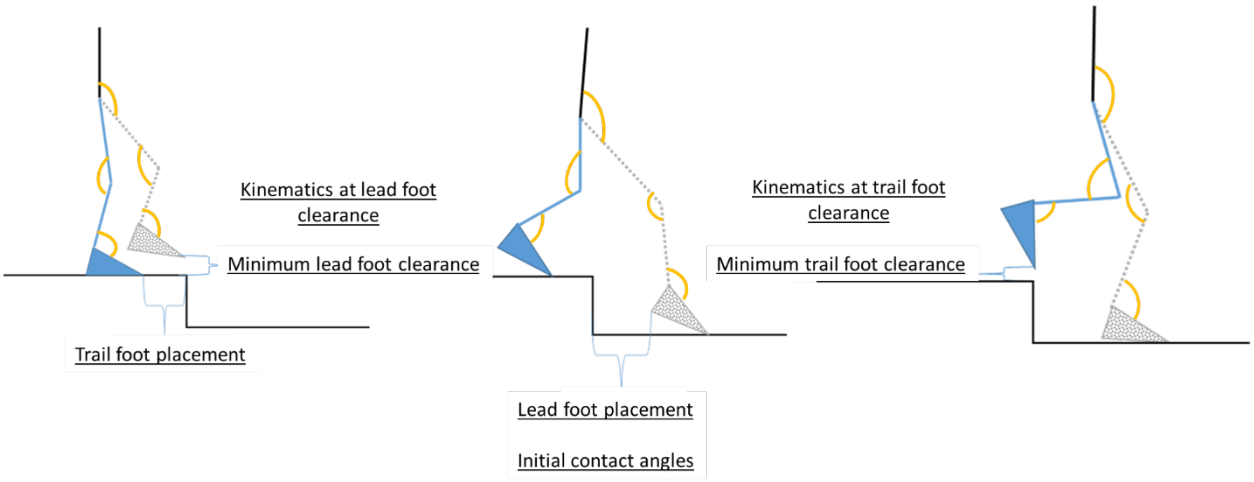

Figure 2. Variables of interest

Data Analysis

Initial ANOVAs of each group's self-selected speed, and descriptive data (age, body mass index, modified FADI, RAPA, FTSS score, strength, and ROM) were performed.

To investigate minimum foot clearance differences between the groups, separate one-way ANOVA tests with one between-subject (group) were run for the lead and trail limbs. Two one-way MANOVA tests with one between-subject factor (group) and eight dependent variables (bilateral sagittal plane knee and ankle position, bilateral sagittal and frontal plane hip position) were run to investigate lower extremity kinematic differences between the groups at minimum lead limb clearance and minimum trail limb step edge clearance.

To investigate foot placement, one-way ANOVAs were run for the lead and trail limbs. An additional one-way MANOVA test with one between-subject factor (group) and eight dependent variables (bilateral sagittal plane knee and ankle position, bilateral sagittal and frontal plane hip position) was run to investigate lower extremity kinematic differences at lead foot placement.

Equality of covariance was tested prior to MANOVA tests using Box's M test, and homogeneity of variances was checked prior to ANOVA tests using Levene's test. For violations of homogeneity of variances, Welch's test was used rather than Fisher's. For MANOVA and ANOVA tests, normality was

assessed with Shapiro-Wilk's test. For all MANOVAs, significant F tests were followed up with ANOVA tests and significant ANOVA tests were followed up with pairwise comparisons. All analyses were run with SPSS (v.23.0, IBM Corporation, Armonk, USA) and alpha was set to 0.05. Effect sizes via partial eta squared (η^2) were also calculated to facilitate interpretation of the clinical meaningfulness of the data. The partial η^2 were interpreted as small (0.01), medium (0.06), and large (0.14) effects, respectively (Cohen, 1988).

Results

Descriptive data results are presented in Table 3. There were no significant group differences in gait speed, height, activity level, or body mass index. There were significant group differences for the modified FADI, FRAS, FTSS, strength, and ROM variables assessed. The OFH group reported greater lower extremity dysfunction and higher risk of future falls compared to either ONF or YA groups. Additionally, both older adult groups had significantly longer FTSS results, and decreased strength in the more proximal muscles (hip abductors, rectus femoris, biceps femoris) compared to the YA group. Strength of the more distal muscles (hallux flexors, peroneals, tibialis anterior) were only significantly reduced in the OFH compared to the YA group. Finally, left hip extension ROM was reduced in both older groups while right ankle dorsiflexion ROM was only decreased in the OFH group compared to YA group.

All participants chose to land with the forefoot, thus all analyses were based on a forefoot landing strategy. Regarding lead limb clearance, there were no significant group differences in clearance height ($F_{(2,42)} = 0.481$, $P = 0.622$) or joint angles ($F_{(16,70)} = 1.24$, $P = 0.261$, Wilks' Lambda = 0.607) (Table 5). For the trail limb, neither clearance ($F_{(2,42)} = 0.995$, $P = 0.378$) nor joint angles at clearance ($F_{(16,70)}=1.24$, $P = 0.261$, Wilks' Lambda = 0.607) differed between the groups (Table 5).

There was a significant difference, and large effect size, in lead foot placement between the groups. At initial contact, the OFH and ONF groups placed the lead foot significantly closer to the step

than the younger group (Table 4). With respect to the lower extremity kinematics at lead foot placement, the older groups made initial contact with the lead limb knee significantly more flexed than the younger group (Table 4). There were no significant differences in trail foot placement ($F_{(2,42)} = 0.581$, $P = 0.564$) or in joint angles ($F_{(16,70)} = 1.23$, $P = 0.269$, Wilks' Lambda = 0.609) at initial contact (Table 4).

Table 3. Descriptive variables

	OFH	ONF	YA	Effect size partial η^2
Age (years)	71.5 (5.0) [a]	71.6 (4.4) [b]	22.6 (3.2) [ab]	0.968
Height (m)	1.627 (0.06)	1.628 (0.06)	1.65 (0.08)	0.04
BMI (kg/m^2)	26.7 (4.7)	27.7 (6)	26.2 (6.3)	0.012
Speed (m/s)	0.99 (0.22)	0.99 (0.21)	1.1 (0.17)	0.113
Modified FADI [d]	93.69 (9.13) [ac]	99.94 (3.1) [c]	103.87 (0.52) [a]	0.371
FRAS [e]	3.6 (1.7) [ac]	1.1 (1) [c]	0.3 (0.5) [a]	0.6
Five time Sit-to-Stand (s)	10.3 (1.7) [a]	10.2 (2.8) [b]	7.4 (1.8) [ab]	0.277
RAPA [f]	7.1 (2.9)	7.8 (2.6)	8.1 (2.5)	0.017
Normalized Muscle Strength (N/kg)				
Right Hip abductors	2.37 (0.8) [a]	2.51 (0.9) [b]	4.00 (1) [ab]	0.41
Left Hip abductors	2.56 (0.9) [a]	2.54 (0.8) [b]	4.09 (1.1) [ab]	0.416
Right Rectus femoris	3.54 (1.1) [a]	3.17 (0.8) [b]	5.17 (1) [ab]	0.524
Left Rectus femoris	3.31 (1.3) [a]	3.09 (0.8) [b]	5.44 (1.3) [ab]	0.527
Right Biceps femoris	1.91 (0.5) [a]	1.92 (0.4) [b]	2.75 (0.6) [ab]	0.435
Left Biceps femoris	1.68 (0.5) [a]	1.73 (0.4) [b]	2.61 (0.8) [ab]	0.495
Right Tibialis anterior	1.51 (0.51)	1.72 (0.6)	1.96 (0.72)	0.162
Left Tibialis anterior	1.54 (0.51) [a]	1.78 (0.48)	2.08 (0.66) [a]	0.275
Right Gastrocnemius	3.81 (1.3)	4.00 (1.2)	5.19 (2.7)	0.088
Left Gastrocnemius	4.64 (1.8)	4.77 (1.62)	5.40 (2.61)	0.028
Right Peroneals	0.868 (0.27) [a]	1.10 (0.31)	1.29 (0.42) [a]	0.276
Right Halluces Flexors	0.828 (0.23) [a]	0.948 (0.24)	1.09 (0.27) [a]	0.172
Range of Motion (^{o})				
Right ankle dorsiflexion	37.17 (6.2) [a]	39.44 (7.9)	44.56 (4.1) [a]	0.203
Left ankle dorsiflexion	38.69 (6.3)	38.88 (6.7)	43.97 (1.5)	0.136
Left hip extension	23.36 (7.6) [a]	25.92 (7.6) [b]	34.84 (13.4) [ab]	0.208

[a] = Significant differences between YA & OFH
[b] = Significant differences between YA & ONF
[c] = Significant differences between OFH & ONF
[d] FADI – lower score = greater disability, total possible 104
[e] FRAS – fall risk cutoff ≥3.5
[f] RAPA – higher score = more active, total possible 10

Table 4. Initial contact placement & joint angles

	OFH	ONF	YA	Effect size partial η^2
Lead foot placement (cm)	17.14 (6.9) [a]	18.65 (5.5) [b]	26.34 (6) [ab]	0.313
Trail foot placement (cm)	8.18 (6) cm	7.85 (4.9)	6.24 (4.8)	0.02
Joint angle at initial contact (^{o})				
Sagittal lead ankle	-12.9 (4.6)	-12.59 (3.9)	-12.4 (4.5)	0.002
Sagittal lead knee	15.45 (4.9) [a]	15.13 (5.9) [b]	10.21 (3.3) [ab]	0.21
Sagittal lead hip	26.68 (9.9)	30.11 (12.3)	23.11 (9.8)	0.071
Sagittal trail ankle	26.1 (4.1)	26.75 (3.6)	27.33 (4.7)	0.016
Sagittal trail knee	60.62 (7.7)	60.47 (10.9)	61.09 (6.3)	0.001
Sagittal trail hip	12.43 (12.5)	15.28 (15)	7.16 (10.5)	0.069
Frontal lead hip	-6.12 (3)	-5.62 (4.1)	-5.31 (4.6)	0.008
Frontal trail hip	6.2 (3)	3.55 (4.8)	3.83 (4.4)	0.081
[a] = Significant difference between YA & OFH [b] = Significant difference between YA & ONF Positive angles flexion/dorsiflexion & adduction				

Table 5. Minimum Step clearance & joint angles

	OFH	ONF	YA	Effect size partial η^2
Lead foot minimum clearance (cm)	2.1 (0.9)	2.2 (0.6)	1.9 (0.9)	0.02
Joint angles at Lead foot minimum clearance (^{o})				
Sagittal lead ankle	6.36 (4.9)	8.13 (3.9)	9.65 (4.2)	0.092
Sagittal lead knee	51.5 (12.4)	49.88 (9.5)	54.75 (9.2)	0.038
Sagittal lead hip	37.74 (10.9)	44.58 (13.4)	35.25 (10.7)	0.108
Sagittal trail ankle	17.45 (3.3)	19.26 (2.3)	17.56 (3.7)	0.07
Sagittal trail knee	35.53 (5.3)	36.73 (9.1)	35.11 (5.3)	0.011
Sagittal trail hip	18.72 (9.9)	21.58 (15.3)	13.77 (11.1)	0.068
Frontal lead hip	-1.67 (2.8)	-2.22 (5.3)	-3.5 (4.6)	0.032
Frontal trail hip	3.26 (2.7)	2.15 (4.7)	4.16 (4.4)	0.042
Trail foot minimum clearance (cm)	2.6 (1.3)	3.1 (1.2)	2.5 (1)	0.045
Joint angles at Trail foot minimum clearance (^{o})				
Sagittal lead ankle	10.2 (3.4)	12.44 (2)	10.13 (3.9)	0.1
Sagittal lead knee	28.35 (5.1)	32.45 (6.7)	30.49 (5.7)	0.081
Sagittal lead hip	20.77 (10.8)	26.17 (12.3)	21.08 (9.0)	0.053
Sagittal trail ankle	14.52 (4.4)	13.41 (5.1)	12.5 (4.6)	0.032
Sagittal trail knee	89.46 (6.4)	89.39 (6.6)	88.35 (6)	0.01
Sagittal trail hip	17.69 (13.6)	20.73 (14.5)	12.26 (11.1)	0.071
Frontal lead hip	-1.00 (3.7)	0.14 (5.4)	2.24 (4.2)	0.087
Frontal trail hip	-1.26 (3.5)	-4.51 (5.3)	-5.28 (4.0)	0.146
Positive angles flexion/dorsiflexion & adduction				

Discussion

The purpose of this study was to identify modifiable lower extremity kinematic factors associated with step clearance and foot placement in young women, older women with no fall history, and older women with a history of falls. It was hypothesized that the older fall history group would have the smallest lead and trail limb clearance and closest foot placement followed by the older non-fallers, then young adults. For lead limb clearance and placement, these differences were anticipated to be the result of greater extension of the lead (swing) limb hip, knee, and ankle and increased flexion (and hip adduction) of the trail (support) limb in the older adult groups. For trail limb clearance, the differences were postulated to occur as a result of greater extension of the trail (swing) limb hip, knee, and ankle in the older adult groups. The kinematic changes in the older groups were hypothesized to create an early landing to minimize the time in single limb stance to compensate for age-related loss of lower extremity strength, ROM, and/or balance (Marques et al., 2013).

The FADI, FRAS, FTSS and lower extremity strength group differences were consistent with previous studies investigating fall risk in older adults (El Miedany et al., 2011; M. C. Perry, Carville, Smith, Rutherford, & Newham, 2007; Tiedemann, Shimada, Sherrington, Murray, & Lord, 2008; Mary E. Tinetti & Williams, 1998). Despite the group differences in the clinical measures of function and strength that have been associated with increased fall risk, the only significant kinematic differences were in lead foot placement and knee flexion at lead contact between the older and younger groups. Although the argument has been made that reduced foot placement may increase fall risk due to late heel contact with the step; based on the non-significant minimum lead limb clearances in the current study and the relatively large placement distances in this and the Lythgo et al. (2007) (Elderly displacement: 29.1 (13.3) cm, Young displacement: 44.2 (15.1) cm) studies, this seems unlikely (Table 4). Rather, the decreased distance from the step may support the theory of older adults reducing step length during descent to minimize time in single limb stance in order to compensate for age-related decreases in lower extremity

ROM and/or strength. The decrease in lead foot placement may create an earlier lead limb contact and reduced reliance on the musculature of the trailing support limb. Interestingly, the only lower extremity joint angle difference between the groups associated with lead limb placement was the lead knee flexion angle. Both older adult groups landed with a more flexed knee than the young adults, which may explain the decreased foot placement (Table 4). Furthermore, van Dieen, Spanjaard, Konemann, Bron, and Pijnappels (2008) found that the lead limb performs negative work sequentially from distal to proximal during the weight acceptance period of a forefoot landing strategy. The study suggested the sequential pattern could allow the proximal musculature to compensate for insufficient work performed by the distal musculature. Therefore, the increased knee flexion at contact in the older adult groups may be part of a strategy that would enable the knee extensors to compensate for weakness of the more distal muscles during weight acceptance. However, a more flexed knee position may also increase the chances of a fall due to lead limb collapse, as there is an increased reliance on muscular strength rather than skeletal structure for stability (Hortobagyi & DeVita, 1999). This may be especially true given the decreased quadriceps strength in the older adults. It should also be noted that, although only lead knee flexion at landing differed significantly between the groups, there were moderate effect sizes for the lead and trail sagittal plane and trail frontal plane hip positions (Table 4). Thus, the increased hip flexion in the older groups and hip adduction in the older fallers may be clinically relevant and warrant further investigation.

With respect to previous investigations of lower extremity joint angles at initial foot contact, only the ankle and knee have been studied. The lack of significant difference in ankle plantarflexion between the older adult groups and the young adults is inconsistent with Lythgo et al. (2007). In the current study, the older and young adult groups made lead foot contact with the ankle in a plantarflexed position (Table 4). However, in the Lythgo et al. (2007) study, the young adult group made initial contact in a dorsiflexed position. The difference between the landing strategy preference of the young adult

groups in the two studies may be due to the footwear worn by participants in the study (Gerstle et al., 2017). At the knee joint, the increased flexion position of the older adult groups compared the younger adults was inconsistent with the study by Hortobagyi and DeVita (1999) that found older adults landed with a more extended knee than young adults. Differences between the current study and the Hortobagyi and DeVita (1999) findings may be due to differences in methodology, as the previous study had participants stand statically prior to step descent and step heights were based on a percentage of participant height.

Based on the results of the current study, neither age nor fall history influence lead or trail foot minimum clearance or lower extremity position at clearance. Comparison of the clearance results with previous studies is difficult due to methodological differences. Begg and Sparrow (2000) reported increased lead heel clearance in older adults and no difference in trail toe clearance between younger and older adults. However, given that the study only examined heel clearance of the lead limb and toe clearance of the trail limb, it is unclear if actual minimum foot clearance was assessed for either limb. Lythgo et al. (2007) measured both heel and toe clearance of the lead and trail limbs and found that older adults had significantly lower lead and trail limb heel clearance compared to young adults. However, lead and trail limb toe clearance did not differ between the groups. Given that the toe clearances were less than the heel clearances, it is likely that minimum foot clearance did not differ between the groups.

Despite the lack of significant findings, large effect sizes for several joints (Lead clearance: sagittal plane bilateral ankle and hip; Trail clearance: frontal plane bilateral hip, sagittal plane trail hip, lead ankle and knee) suggest further study may be warranted (Table 5). Additionally, examining other aspects such as variability of clearance and/or joint position may elucidate differences due to age or fall history.

As mentioned previously, the overall decreased lower extremity strength in the older adult groups was anticipated and consistent with previous studies investigating fall risk in older adults (McKay et al., 2017; M. C. Perry et al., 2007; Skelton, Kennedy, & Rutherford, 2002; Tsuyuguchi et al., 2018). The gastrocnemius was the only muscle strength measure that did not differ between the groups. Although the result was unanticipated, previous studies have reported both significant decreases (Spink, Fotoohabadi, & Menz, 2010) and no significant differences (Cheng, Yang, Cheng, Chen, & Wang, 2014) between older and younger adults. The inconsistency in the studies may be related to the testing position used to assess gastrocnemius strength. The position (seated on a treatment table with a bolster under the knees) may have allowed some participants to utilize their hip and/or knee extensors during the test. Those with weak plantar flexors may have been more likely to try to compensate with the more proximal musculature. For the most distal muscles (tibialis anterior, peroneals, hallux flexors), strength was significantly decreased between the older fallers and young adults, but not between the older non-fallers and young adults. Thus, in addition to confirming many of the age-related changes in lower extremity strength previously reported, the current data also suggests that older adults with a history of falls may have greater strength declines in the dynamic stabilizers of the ankle and foot (Table 3). This could be especially important in step negotiation for older adults given their increased preference of landing with a forefoot strategy (van Dieen & Pijnappels, 2009), which increases demand on the ankle and foot dynamic stabilizers.

With respect to lower extremity ROM, the decreased dorsiflexion ROM of the older fallers compared to the young adults in the current study is consistent with a study by Nitz and Choy (2004) that found decreased dorsiflexion ROM was associated with a fall history in older women. Although only the right dorsiflexor ROM was significantly different between young and older faller group, the left ROM group difference was similar and the effect size was large (Table 3). Despite the differences in static weight bearing dorsiflexion ROM, no kinematic differences were found during stepping gait. This is most

likely due to the required motion during step descent being well below the groups' dorsiflexion ROM. Finally, the hip ROM results in the current study is in agreement with the study by Anderson and Madigan (2014) that found static hip extension ROM in the older adult groups were significantly less than that of the young adults. Anderson and Madigan (2014) also found older adults demonstrated significantly less hip extension during level walking than young adults. In the current study, however, hip extension did not differ between the groups at step negotiation clearance or landing. Once again, this may have been because the required ROM during step descent was well below their limits of hip extension (Table 3).

Before drawing conclusions, it is important to recognize some of the limitations of this study. First, although there was no statistical difference in the preferred speeds across groups, the difference in the mean speed of the older adult groups and the young adults was close to ten percent, which suggests the possibility of speed related effects cannot be completely ruled out. Second, because participants were assessed during a barefoot condition, the results may not be generalizable to a shod condition. The barefoot condition was chosen due to the fact that older adults tend to fall most frequently when not wearing shoes (Kelsey, Procter-Gray, et al., 2010). Finally, despite differences in the clinical measures of function and fall risk between the older groups, it is possible, the inclusion criteria of at least one fall in the last year may not have been sufficient to differentiate between the older groups.

In conclusion, kinematic differences between young and older women during a single step descent appear to be limited to initial contact of the lead limb. Specifically, the older adults landed more closely to the step with the knee more flexed. The closer landing may function to reduce single limb stance time during the transition step negotiation to compensate for age-related decreases in lower extremity strength. However, the more flexed knee position may also increase the risk of a fall due to lead limb collapse, as there is an increased reliance on muscular strength rather than skeletal structure

for stability. The results of this study emphasize the importance of lower extremity strength, especially of the quadriceps for fall prevention or rehabilitation programs.

Chapter 3: The effect of age and fall history on lower extremity neuromuscular function during negotiation of a single transition step

Introduction

The estimated annual medical costs associated with older adult falls in the US is $49.6 billion (Florence et al., 2018). In addition to the financial burden of experiencing a fall, older adults face increased disability and long-term reduced quality of life after injury from a fall (Hartholt et al., 2011; Thiem et al., 2014). Furthermore, older adults that experience a fall are significantly more likely to be female (Florence et al., 2018). The two most common locations during which older adult falls occur are on level ground (40%) and during step (stair/escalator/curb/sidewalk) negotiation (20%) (Choi, Choi, DiNitto, Marti, & Kunik, 2019). Given the significant personal and financial costs associated with gait-related falls in older adults, a great deal of research has been dedicated to identification of modifiable factors that may be addressed to decrease the incidence/recurrence of falls in the aging population.

The influence of aging and fall history on neuromuscular function during level walking has been extensively examined. It has been suggested that older adults redistribute joint moments and powers proximally from the ankle to the hip either due to neuromuscular degeneration or as a protective mechanism to compensate for weakened muscle groups (DeVita & Hortobagyi, 2000a; Tibor Hortobágyi, Rider, Gruber, & DeVita, 2016). Further, studies examining lower extremity joint moments during level walking gait (Marques et al., 2013) or isometric muscle actions (Luciano Fernandes Crozara et al., 2013) in older females with and without a fall history, have found that fallers produced decreased knee extension moments. Collectively, these data suggest that the shift in moments and powers not only occurs across age, but also within older females with a history of falls.

Although falls are more prevalent on level ground, the incidence of injury is 12% greater in falls related to step negotiation (Duckham et al., 2013). Despite the higher injury rate of falls on steps versus level ground, far fewer studies have examined the influence of age and fall history on step negotiation.

This may be a critical gap in the literature given the mechanical differences between the tasks and the declines in strength and balance associated with aging. Compared to level walking, successful step negotiation requires larger knee and ankle joint moments and greater eccentric power in early stance (Andriacchi et al., 1980; Riener et al., 2002). A study investigating the influence of age on continuous step descent, reported that older adults generate decreased moments at the ankle and utilize a larger percentage of their maximal capacity generating knee moments compared to young adults (Reeves, Spanjaard, Mohagheghi, Baltzopoulos, & Maganaris, 2008). Another study examining the transition from a level surface to the first of two steps found older adults with significantly reduced moments at both the ankle and knee for both lead and trail limbs (Karamanidis & Arampatzis, 2011). It should be noted however, that both the older adult groups in both the Reeves et al. (2008) and Karamanidis and Arampatzis (2011) studies included males and females. This may be important given the study by Singhal et al. (2014) that demonstrated gender differences in older adults in both moments and powers during transition step descent. With differences demonstrated across gender and females more likely to sustain an injurious fall, it is important to specifically examine changes in step descent in females across age and fall history. Further, it has been demonstrated that stepping mechanics vary based on continuous or transition steps (Whatling & Holt, 2010), and 70% of stair incidents occur on transition steps (Templer, 1992). To date, only three studies have investigated kinetics during transition step descent (Andriacchi et al., 1980; Karamanidis & Arampatzis, 2011; Singhal et al., 2014).

Quantifying net joint moments and powers provides an overall assessment of neuromuscular function, however, they cannot identify activity of the opposing muscles across the joint (co-activation). This is important, as studies have suggested increased co-activation in older adults assists in increasing joint stiffness and stability to compensate for decreases in neuromuscular function (T. Hortobágyi & DeVita, 2000). Previous studies investigating the influence of age on lower extremity muscle co-activation have indicated older adults have greater co-activation at the knee (Mian, Thom, Ardigò,

Narici, & Minetti, 2006) and ankle (Schmitz, Silder, Heiderscheit, Mahoney, & Thelen, 2009) during level walking and during step descent (J. G. Buckley et al., 2013; Chandran et al., 2019; T. Hortobágyi & DeVita, 2000; Larsen, Puggaard, Hamalainen, & Aagaard, 2008). Further, studies examining the influence of fall history in older females have found increased co-activation at the ankle during level walking in those with a history of falls (Marques et al., 2013; Schmitz et al., 2009). Although the increased co-activation may function to create a more rigid base during step negotiation; increased joint stiffness is associated with increased energy cost (Mian et al., 2006) and may decrease the ability to adapt to unexpected perturbations. While these studies have advanced the understanding of aging and fall history on lower extremity muscle activation during gait, the step studies have primarily focused on healthy older adults. Thus far, no studies have examined the influence of fall history and muscular co-activation in older adult females during transition step descent. This may be important given fall history is one of the strongest predictors of a future fall (Carpenter et al., 2009).

Therefore, the purpose of this study was to determine the influence of age and fall history on neuromuscular function in older adult females during single transition step negotiation. A distal to proximal shift of peak joint moments and powers in older adults, consistent with that established during level walking (DeVita & Hortobagyi, 2000a; Graf et al., 2005; Winter, 1991b), was hypothesized during transition step descent. This bilateral distal to proximal shift in lower extremity joint moments and powers was anticipated to be accompanied by increases in the co-activation patterns of the knee and ankle musculature. Furthermore, it was expected that older adults with a history of falls would have greater co-activation than healthy age-matched counterparts (Marques et al., 2013).

Participants

A total of 45 female participants were recruited for one of three groups (young adult, older no fall history, older fall history) from the surrounding community. Utilizing G*Power and the results of

previous studies that reported significant differences in ankle power between older and older low performing adults (Graf et al., 2005) and ankle co-activation between older faller and non-fallers (Marques et al., 2013) that both reported large effect sizes (1.18 and 1.16, respectively), a minimum sample size of four participants per group was required to reach a power of 0.8 with alpha = 0.05. Participants in the young adult group (YA) were between the ages of 18 and 40 years and those in the older groups were 65 years or older. The older no fall history (ONF) and fall history (OFH) groups were matched by age (± 5 years) and category of Body Mass Index. Within the last year, participants in the OFH group must have had at least one fall during an activity of daily living or light to moderate leisure time activity. Those in the ONF group must not have fallen within the last year and were classified as low fall risk via the Falls Risk Assessment Score (El Miedany et al., 2011). All participants must not: have had surgery to their lower back or lower extremities in the last year; have a medical condition or be taking any medication that may impair balance; or be pregnant. Further, all participants were able to walk and step down a single 17 cm step without stopping or with assistance and scored at least a five on the Six-Item Screener for Cognitive Impairment (Callahan et al., 2002). The definition of a fall used in the study was unintentionally coming to rest on a lower level, not as a result of a major intrinsic event (such as a stroke) or overwhelming hazard (M. E. Tinetti et al., 1988). Prior to participation, subjects were informed of study procedures and provided written consent approved by the Institutional Review Board.

Testing Protocol

Bilateral motion data of the lower extremity was collected using a 14 camera system (Raptor 4, Motion Analysis Inc., Santa Rosa, CA) sampling at 200 Hz with retro-reflective markers or marker clusters affixed to the great toes, first and fifth metatarsals, calcanei, legs, thighs, and pelvis via double-sided adhesive tape. Prior to stepping trials a standing calibration trial was completed with additional markers on anatomical landmarks to define joint centers and local coordinate systems within each segment of interest. Lower extremity muscle activity was assessed via bipolar surface electrodes (Trigno, Delsys,

Natick, MA) sampling at 2000 Hz. Surface electrodes were placed bilaterally on the tibialis anterior, medial gastrocnemius, rectus femoris, and medial hamstrings and on the lead (right) leg peroneals. The electrodes were placed following SENIAM guidelines (Hermens HJ, 1999) and the modifications proposed by Sacco, Gomes, Otuzi, Pripas, and Onodera (2009) after shaving and cleansing the skin with alcohol. Prior to data collection, appropriate muscle testing was performed for each muscle to confirm correct EMG placement (Kendall et al., 2005). Ground reaction forces were assessed via force plates (AMTI, Inc., Watertown, MA) sampling at 2000 Hz embedded in the floor under the final portion of the platform before stepping down (FP1) and at the base of the step (FP2). The force plate data were used for kinetic analyses and to determine lead (right) limb initial contact (FP2) and trail (left) limb toe-off (FP1) (20 N threshold) (Figure 3).

After EMG placement and the standing calibration trial, participants completed seven transition step descent trials. The trials consisted of walking barefoot at self-selected speed on a 5.5 m long raised walkway, descending the 17 cm step leading with the right foot, and continuing to walk 3 m. Prior to recorded trials, practice trials were given to familiarize participants with the task. After completion of the stepping trials, three maximum voluntary isometric contractions were assessed for each of the recorded muscles with a handheld dynamometer (Awwad et al., 2017; Kendall et al., 2005) and the peak EMG activity was used to normalize muscle activity during the step trials.

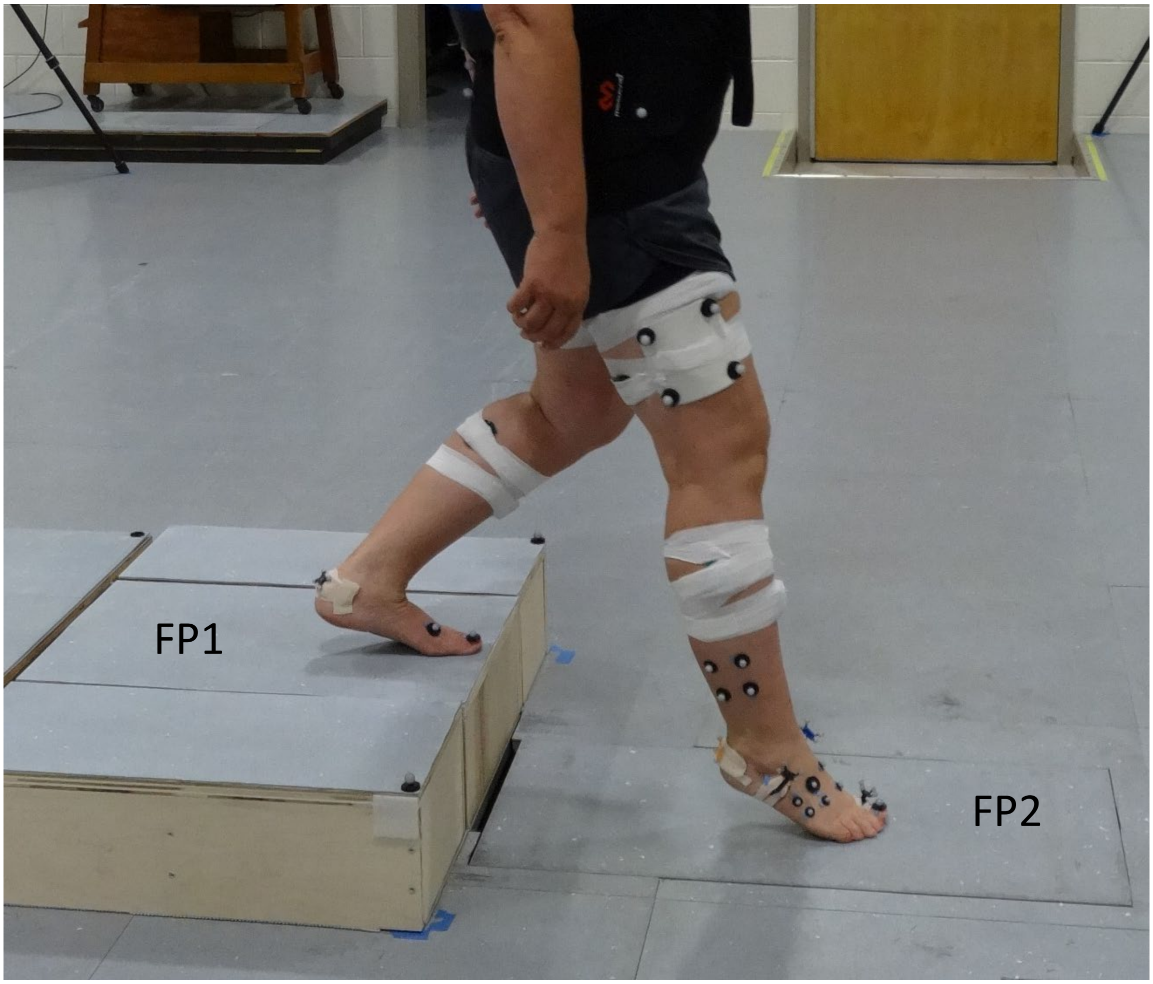

Figure 3. Protocol set-up

Data Processing

Lower extremity joint kinetics were calculated via Visual 3D (C-Motion, Inc., Germantown, MD) after identifying three-dimensional marker position data and exporting the synchronized ground reaction force and EMG data using Cortex software (Motion Analysis Inc., Santa Rosa, CA). Both kinematic and force plate data were low pass filtered with a 4^{th} order zero-lag Butterworth filter and a cut-off frequency of 6 Hz. Joint centers of the knee and ankle were defined as the midpoint between the medial and lateral epicondyles and malleoli, respectively. The hip joint center was calculated as 25% of the distance between the greater trochanters (Weinhandl & O'Connor, 2010). Body segment parameters were defined using the regression equations by Dempster (1955). Joint moments were expressed as

internal net joint moments in the proximal segment coordinate system (positive moments: extension/plantarflexion, abduction) and normalized to the participant's body mass. Joint powers, calculated as the product of net joint torques and joint angular velocities, were also normalized to body mass (positive = concentric power). For analysis, variables of interest were calculated from five successful trials from each subject with a forefoot landing strategy and then averaged to generate mean values for each subject. Peak sagittal plane joint moments and powers were determined for the ankle, knee, and hip of the trail limb during the descent phase (lead foot toe off until lead limb initial contact below the step) and of the lead limb during the landing phase (lead limb initial contact through trail limb toe-off). Peak moments and powers were also calculated for the trail and lead hip joint in the frontal plane during the descent and landing phases, respectively (Table 6).

EMG data for each trial were filtered with a Butterworth bandpass filter (20 Hz – 390 Hz), fully rectified, smoothed (30 ms moving window average) and normalized to each muscle's activity during maximum voluntary isometric contraction. Co-activation of the knee (rectus femoris and biceps femoris) and ankle (tibialis anterior and medial gastrocnemius) was determined via the percentage of co-activation during the appropriate phase (Falconer & Winter, 1985; Hallal et al., 2013).

*% Co-activation = 2*Integrated common area of antagonist and agonist / total integrated area * 100*

Co-activations were calculated for the trail limb for the descent or lowering phase and for the lead limb during the landing phase. In addition to the co-activation of the ankle and knee flexors and extensors, lead limb peroneal activity was calculated as the integrated area during the landing phase.

Table 6. Kinetic Variables

Phase	Limb	Plane	Variable
Descent	Trail	Sagittal	Peak hip extension moment
			Peak knee extension moment
			Peak ankle plantarflexion moment
			Peak hip eccentric power
			Peak knee eccentric power
			Peak ankle eccentric power
		Frontal	Peak hip abduction moment
			Peak hip eccentric power
Landing	Lead	Sagittal	Peak hip extension moment
			Peak knee extension moment
			Peak ankle plantarflexion moment
			Peak hip eccentric power
			Peak knee eccentric power
			Peak ankle eccentric power
		Frontal	Peak hip abduction moment
			Peak hip eccentric power

Data Analysis

Descriptive group data was tested for differences with ANOVAs. The lower extremity net joint moments and powers of each limb were assessed via four separate one-way between-groups Multiple Analysis of Variance (MANOVA) tests. Two examined trail limb moment and power differences between the groups during descent phase and two examined lead limb moment and power differences during the landing phase. The dependent variables for the MANOVAs were sagittal plane knee and ankle and sagittal and frontal plane hip moments and powers, respectively.

Muscle co-activation at the ankle and knee were examined via one-way between-groups MANOVAs for the trail limb during the descent phase and the lead limb during the landing phase. Finally, peroneal activation was examined across the three groups with a one-way between-groups ANOVA. Equality of covariance was tested prior to MANOVA tests using Box's M test and homogeneity of variances was checked prior to ANOVA tests using Levene's test. For MANOVA and ANOVA tests normality was assessed with Shapiro-Wilk's test. Significant MANOVA F tests were followed up with

ANOVAs, significant ANOVA results were followed up with pairwise comparisons. All analyses were run with SPSS (v.23.0, IBM Corporation, Armonk, NY) and alpha was set to 0.05. Effect sizes (partial eta squared) were also calculated to assist in interpreting clinical significance of the data. Small, medium, and large effects were interpreted as 0.01, 0.06, and 0.14, respectively (Cohen, 1988).

Results

There were 15 participants in each group and no significant differences between groups in height (OFH: 1.6 $\pm$ 0.06 m, ONF: 1.6 $\pm$ 006 m, YA: 1.7 $\pm$ 0.08 m), Body Mass Index (OFH: 26.7 $\pm$ 4.7 kg/m^2, ONF: 27.7 $\pm$ 6 kg/m^2, YA: 26.2 $\pm$ 6.3 kg/m^2), or self-selected speed (OFH: 0.99 $\pm$ 0.22 m/s, ONF: 0.99 $\pm$ 0.21 m/s, YA: 1.1 $\pm$ 0.17 m/s). There were no significant differences in age between the ONF and OFH groups, but both were significantly older than the YA group (OFH: 71.5 $\pm$ 5 years, ONF: 71.6 $\pm$ 4.4 years, YA: 22.6 $\pm$ 3.2 years).

There were no significant between group differences in the trail limb peak moments during the descent phase; however, effect sizes for all of the trail limb sagittal plane moments were moderate or large with the older adults demonstrating greater hip extension moments and smaller knee and ankle moments compared to the YA group (Table 7). For the leading limb, there were no significant between group differences for the sagittal or frontal plane peak moments. Effect sizes during the landing phase were moderate or large for the hip abduction and knee extension moments with the older adults demonstrating decreased moments compared to the YA group (Table 7).

Table 7. Peak Moments (Mean (SD) Nm/kg)

Descent (trail limb lowering)				Effect size Partial η^2
	OFH	ONF	YA	
Hip Abduction	0.868 (0.11)	0.782 (0.16)	0.809 (0.13)	0.069
Hip Extension	0.138 (0.10)	0.135 (0.21)	0.008 (0.12)	0.149
Knee Extension	1.07 (0.24)	0.976 (0.33)	1.20 (0.30)	0.096
Ankle Plantarflexion	1.01 (0.18)	0.998 (0.08)	1.11 (0.17)	0.101
Landing (lead limb weight acceptance)				
Hip Abduction	0.814 (0.17)	0.787 (0.25)	0.942 (0.20)	0.098
Hip Extension	0.749 (0.23)	0.674 (0.30)	0.743 (0.35)	0.013
Knee Extension	0.498 (0.24)	0.690 (0.30)	0.870 (0.31)	0.230
Ankle Plantarflexion	1.181 (0.23)	1.126 (0.19)	1.143 (0.13)	0.016
Positive Internal moments = plantarflexion, extension, abduction				

Trail limb power differences during descent were not significant between the groups. However, sagittal plane ankle and frontal plane hip effect sizes were moderate or large with the older adults demonstrating decreased eccentric ankle plantarflexor and increased eccentric hip abductor power (Table 8). There were significant between group lead limb power differences with large effect sizes during the landing phase. Eccentric knee power was significantly less in the OFH group compared to the YA group and eccentric sagittal plane hip power was significantly less in the ONF versus the YA group. Although the differences were not statistically significant, frontal plane hip power effect sizes were moderate with the older adult groups demonstrating decreased eccentric power compared the YA group (Table 8).

Table 8. Peak Eccentric Powers (Mean (SD) W/kg)

Descent (Trail limb lowering)					Effect size Partial η^2
		OFH	ONF	YA	
Frontal	Hip	-0.365 (0.13)	-0.295 (0.15)	-0.244 (0.11)	0.135
Sagittal	Hip	-0.282 (0.42)	-0.161 (0.26)	-0.335 (0.23)	0.052
	Knee	-2.38 (0.54)	-2.38 (0.82)	-2.66 (0.53)	0.044
	Ankle	-0.896 (0.24)	-0.887 (0.25)	-0.983 (0.28)	0.067
Landing (lead limb Weight Acceptance)					
Frontal	Hip	-0.488 (0.24)	-0.682 (0.45)	-0.849 (0.49)	0.122
Sagittal	Hip	-0.230 (0.21)	-0.137 (0.21)^	-0.399 (0.32)^	0.163
	Knee	-1.16 (1.1)*	-1.88 (1.5)	-2.53 (1.3)*	0.162
	Ankle	-3.74 (1.2)	-3.93 (1.2)	-3.68 (1.2)	0.014

Negative = eccentric power
* Significant difference ($p < 0.05$) between YA & OFH
^ Significant difference ($p < 0.05$) between YA & ONF

Due to technical problems, the left biceps femoris data from one of the OFH participants was not collected, and on one ONF participant the left gastrocnemius electrode fell off before collecting the maximal voluntary isometric contraction. Therefore, EMG co-activation analysis is based on 15 YA and 14 OFH and ONF participants. There were no significant differences in knee or ankle co-activation between the groups in the trail limb during descent or in the lead limb during landing. There was a large effect size for the trail limb knee co-activation during descent with the older adults demonstrating increased activation compared to the YA group (Table 9). There were significant between group differences, and a large effect size, for peroneal activation during the landing phase. Peroneal activation was significantly greater, in the older adult groups compared to the YA group (Table 10).

Table 9. Lower extremity muscle Co-Activation (Mean (SD) % MVC)

Descent (Trail limb lowering)				Effect size Partial η^2
	OFH	ONF	YA	
Trail limb ankle	47.97 (18)	53.32 (9.6)	47.45 (16)	0.033
Trail limb knee	56.5 (10)	51.71 (13.6)	43.11 (15.8)	0.163
Landing (Lead limb Weight Acceptance)				
Lead limb ankle	30.75 (17.8)	23.52 (12.3)	23.38 (15.4)	0.051
Lead limb knee	52.8 (20)	52.98 (23)	56.26 (11.4)	0.008

Table 10. Landing Phase Peroneal iEMG

	OFH	ONF	YA	Effect size partial η^2
Peroneal iEMG (%ms (SD))	0.0785 (0.045)*	0.0679 (0.028)^	0.0317 (0.020)*^	0.286
* Significant difference between YA & OFH; ^ Significant difference between YA & ONF; $p < 0.05$				

Discussion

The purpose of this study was to determine the influence of age and fall history on neuromuscular function in older adult females during single transition step negotiation. A distal to proximal shift of peak joint moments and powers in older adults, consistent with that established during level walking (DeVita & Hortobagyi, 2000a; Graf et al., 2005; Winter, 1991b), was anticipated during the descent and landing phases. During the lead limb landing phase there were significant sagittal plane hip and knee eccentric power differences between the ONF and YA and between the OFH and YA groups, respectively, but no group differences at the ankle. The decreased power at the knee in the OFH would be consistent with a proximal shift in powers; however, as there were not associated differences at the hip or ankle, the hypothesized lower extremity shift was not supported. The difference at the knee may have been due to decreased knee extensor strength in OFH group (Chapter 2 Table 3). In the sagittal plane, peak hip eccentric power was significantly less in the ONF group compared to the YA group, which was counter to what was anticipated. The unexpected change may have been due to the ONF group adapting their stepping gait to include increased trunk lean, which could function to reduce the power at the hip. There are no previous studies examining the influence of age and fall history on lower extremity power during transition step negotiation to which the results of the current study may be compared. The only studies investigating similar comparisons across age have been level walking studies, which have reported the proximal shift in powers. The inconsistency of the results with the

previous walking studies may be due to the mechanical differences between walking and step negotiation gaits.

With respect to the lead limb peak moments, the lack of significant differences at the hip, knee, and ankle between the older groups and the YA group is inconsistent only at the ankle compared to the study by Novak and Brouwer (2011). In looking only at the first peak moments provided by Novak and Brouwer (2011) as an estimate of landing phase, the only significant difference occurs at the ankle, with older adults showing greater plantarflexor moments. The inconsistency may be due to the continuous rather than transition step descent, or both genders versus only female participants. Despite the established distal to proximal shift in older adults of moments and powers during level walking, it appears during the landing phase of transition step descent these shifts are not demonstrated. It could be these differences become more apparent when examining stance phase as a whole as the study by DeVita and Hortobagyi (2000a) did and/or the shift is seen only when participants are stationary before and after the step task.

The hypothesized bilateral distal to proximal shift in lower extremity joint moments and powers in the older adult groups was anticipated to be associated with increased co-activation patterns of the knee and ankle musculature during step negotiation. As was the case with the net joint moment and power hypothesis, the postulated co-activation pattern differences were not supported. The results of the current study are inconsistent with previous level walking (Marques et al., 2013; Mian et al., 2006; Schmitz et al., 2009) and step descent studies (J. G. Buckley et al., 2013; Chandran et al., 2019; T. Hortobágyi & DeVita, 2000; Larsen et al., 2008). The inconsistency in results may be due to methodological differences. The previous step descent studies examined continuous step descent (Chandran et al., 2019; Larsen et al., 2008), a step-match gait (J. G. Buckley et al., 2013), or isolated single step descent with participants stationary before and after the step. As this study had participants step down during ambulation, the additional challenge of maintaining forward speed while landing may

have required the YA group to increase co-activation bringing their values into the range of the older adults.

During the landing phase both older groups had significantly greater peroneal activation compared to the YA group. The increased activity may function to assist in providing additional frontal plane stability to the ankle joint in lieu of increased co-activation of the sagittal plane ankle musculature (Table 5). Increased stability may be required due to decreased strength of the ankle musculature and/or age-related decreases in balance. As no other study has examined the influence of age or fall history on peroneal activation during step descent, there is no previous literature to which the results of the current study can be compared.

Before drawing conclusions, it is imperative to consider the limitations of the current study. First, although the study aimed to identify neuromuscular differences between older adult females with and without a history of falls during transition step negotiation, no comparisons were significant between the two groups. It is possible the definition used to determine fall history, was not stringent enough to elicit differences between groups. Second, participants walked at their self-selected speed in this study. Although, there was no significant differences in speed across groups there may be clinical differences as the difference in mean speed between the older and young adults was close to ten percent. Third, participants completed the step trials barefoot, which corresponds to the condition during which most older adult falls occur (Kelsey, Berry, et al., 2010), but may not be generalizable to footwear conditions. Finally, only women were examined so results are not generalizable to men.

In conclusion, this study demonstrates single step descent does not follow the typical distal to proximal shift of moments and powers across age seen during level walking. Nor is there an increase in co-activation at the ankle or knee in older adults. However, it does establish significant normalized peroneal activation differences across age, which may be due to decreased peroneal strength. Including

assessment of peroneal function in future step studies and addressing peroneal strength deficits in fall prevention/rehabilitation programs may be beneficial in reducing falls during transition step negotiation.

Chapter 4: Distal foot kinematics across age and fall history during transition step negotiation

Introduction

More than $49.5 billion dollars were spent in 2015 on healthcare due to falls (Florence et al., 2018) and reduced quality of life has been reported up to nine months after a fall (Hartholt et al., 2011). Together, these data suggest falls are a significant public health concern. Accidents or falls on steps commonly occur during transition step negotiation as the result of foot misplacement (Templer, 1992). Further, as individuals' age, the likelihood of experiencing a fall increases significantly (Skalska et al., 2013), with those falling more likely to be female (Florence et al., 2018). Age-related changes in lower extremity (hip, knee, ankle) and distal foot function may be important factors influencing foot placement and landing phase kinematics during transition step negotiation.

Although multi-segment foot models have been used to examine distal foot function during walking and running gait in young adults (Arnold, Caravaggi, Fraysse, Thewlis, & Leardini, 2017; Bruening, Pohl, Takahashi, & Barrios, 2018; Cobb, Joshi, & Pomeroy, 2016; Leardini et al., 2007; Morio, Lake, Gueguen, Rao, & Baly, 2009; Takabayashi et al., 2017), very few studies have utilized the models to investigate older adult walking gait (Arnold, Mackintosh, Jones, & Thewlis, 2014; D. Y. Lee et al., 2017; Legault-Moore, Chester, & de Vries, 2012; van Hoeve, Leenstra, Willems, Poeze, & Meijer, 2017) and none have investigated the influence of age on transition step negotiation. This may be especially important given the preferred landing strategy of older adults is with the forefoot (van Dieen & Pijnappels, 2009), which places the ankle in a less stable position at foot placement and increases demand on both the distal foot and the musculature supporting the foot and ankle during the landing phase of step negotiation.

To date only two studies have utilized a multi-segment foot model to investigate step descent kinematics (Gerstle et al., 2017; Rao et al., 2009). Rao et al. (2009) examined foot segment motion of

older adults with and without midfoot arthritis both during walking and stepping down a single step. They found differences in mechanics between the groups, which differed by task. During step descent, the arthritis group had greater calcaneus eversion range of motion; while during level walking the only difference was less plantarflexion motion at the first metatarsal in the arthritis group (Rao et al., 2009). Gerstle et al. (2017) investigated differences in foot segment motion across different height steps in young adults. The findings indicated, as step height increased, sagittal plane range of motion of the distal foot increased. While these studies have improved the understanding of distal foot function during transition step negotiation, there is a critical gap in knowledge regarding the influence of age and distal foot function during step negotiation. Additionally, risk for a future fall increases for older adults that have already experienced a fall in the previous year (Carpenter et al., 2009).

Therefore, the purpose of this study was to identify lower extremity and distal foot kinematic differences during transition step descent between young women and older women with and without a history of falls. At initial contact, due to older adults' preference to land with the forefoot (van Dieen & Pijnappels, 2009) and age-related decreases in lower extremity strength (McKay et al., 2017), the older groups were hypothesized to demonstrate increased distal foot plantarflexion (rearfoot, medial midfoot, lateral midfoot, medial forefoot, lateral forefoot) and inversion (rearfoot, medial and lateral midfoot) compared to the young group. The increased plantarflexed position may function to allow landing earlier and the more inverted posture may create a more rigid foot to further increase reliance on the bony versus muscular structures (DeVita & Hortobagyi, 2000b). Further, the older fall history group was anticipated to land with the distal foot more plantarflexed and inverted than the older non-fallers. The differences between the older faller and non-faller groups were also anticipated to be due to decreases in lower extremity strength previously reported in older adult fallers versus non-fallers (Robinovitch et al., 2002). With respect to the hip and knee joints at initial contact, we previously reported the findings;

both older groups landed with the knee significantly more flexed than the young adult group and no differences were found between groups at the hip (Chapter 2).

During the landing phase, the older adult groups were hypothesized to demonstrate smaller ranges of motion in the knee and hip and greater ranges of motion across the distal foot joints in both the sagittal and frontal planes compared to the young group. Between the older groups, those with a fall history were expected to have less range of motion at the knee and hip, but greater distal foot range of motion. The hip and knee changes were postulated based on the walking study by Anderson and Madigan (2014) and the single step study by Saywell et al. (2012). The distal foot changes were anticipated to be due to the differences in the initial contact positions and age-related decreased strength of the foot and ankle musculature. Although the adaptations may function to increase reliance on the bony structures of the foot at initial contact, the increased plantarflexed and inverted position and age-related decreased strength of the foot and ankle musculature (DeVita & Hortobagyi, 2000b) may result in greater ranges of motion during the landing phase.

Participants

Healthy young females (YA) (n = 15, 18-40 years), older females with no fall history (ONF) (n = 15, 65+), and older females with a fall history (OFH) (n = 15, 65+) participated in the study. Participants in the older groups, were matched by age and Body Mass Index category. The sample size was calculated based on the significant results between age groups of foot landing angle during step descent by Lythgo et al. (2007), to reach a power of 0.8 with alpha = 0.05, a minimum of 13 participants per group were required. All participants were able to walk and step down a 17 cm step without stopping or the use of an assistive device, and had no cognitive impairment as determined via the Six-Item Screener (Callahan et al., 2002). The fall history group was defined as those older adults with a history of at least one fall in the previous year during an activity of daily living or light to moderate leisure time activity.

Within the last year, the older non-faller group must not have fallen and were classified as low fall risk via the Falls Risk Assessment Score (El Miedany et al., 2011). A fall was defined as unintentionally coming to rest on a lower level, not as a result of a major intrinsic event (such as a stroke) or overwhelming hazard (M. E. Tinetti et al., 1988). Exclusion criteria for all participants included: pregnancy; a history of lower back or lower extremity surgery within the last year; currently taking any medication or having a medical condition that may impair balance.

Testing Protocol

Three dimensional kinematic data was collected via retro-reflective markers (6.4 – 10 mm) and marker clusters placed on the pelvis, right thigh, shank, calcaneus, navicular, cuboid, medial and lateral metatarsals and hallux of the right foot (Figure 4) by 14 cameras (Raptor 4, Motion Analysis Inc., Santa Rosa, CA) sampling at 200 Hz. Prior to performing the stepping trials, a static standing calibration trial was collected to obtain additional anatomical landmark positions (Table 11). The additional markers were used to perform an anatomical calibration procedure to establish time-invariant positions of the anatomical landmarks relative to the technical markers (Cappozzo, 1984) in order to define local Cartesian coordinate systems embedded within each segment of interest during the gait trials (Cobb et al., 2016). Functional articulation positions calculated during the calibration were used as offset angles in calculating the distal foot functional articulation positions during the stepping trials. Following completion of the standing calibration trial and practice trials to familiarize them with the task, participants performed stepping trials that consisted of walking 5 m on a 17 cm raised level walkway, stepping down to level ground and continuing to walk another 3 m. Force plates (AMTI, Inc., Watertown, MA) sampling at 2000 Hz were embedded at the base of the step to determine the beginning of the landing phase (lead limb initial contact), as well as the end of the walkway to determine the end of the landing phase (trail limb toe-off) (20 N threshold). Seven trials were collected with participants walking

at their preferred speed. Gait speed during all trials was determined via electronic timing gates located on the level walkway before the step.

Table 11. Multi-segment foot anatomical landmarks identified via calibration markers

Pelvis	Right posterior superior iliac spine
	Left posterior superior iliac spine
	Right anterior superior iliac spine
	Left anterior superior iliac spine
	Left greater trochanter
Thigh	Right greater trochanter
	Medial femoral epicondyle
	Lateral femoral epicondyle
Shank	Tibial tuberosity
	Lateral malleolus
	Medial malleolus
Calcaneus	Sustentaculum tali
	Dorsal posterior calcaneus
	Peroneal tubercle
Navicular	Proximal dorsal edge
	Proximal plantar edge
	Distal plantar edge
Cuboid	Proximal dorsal edge
	Proximal plantar edge
	Distal plantar edge
Medial rays	Base of 1^{st} metatarsal
	Head of 1^{st} metatarsal
	Head of 2^{nd} metatarsal
Lateral rays	Base of 5^{th} metatarsal
	Head of 5^{th} metatarsal
	Head of 4^{th} metatarsal
Hallux	Base of 1^{st} proximal phalanx
	Head 1^{st} distal phalanx
	Medial surface 1^{st} distal phalanx

Figure 4. The multi-segment foot model. **Top Figure:** Calcaneus technical markers (CA) and anatomical landmarks. The sustentaculum tali (ST), peroneal tubercle (PT, see bottom figure) and posterior calcaneus (PC) anatomical landmarks will be used to define the calcaneus local coordinate system. Navicular technical markers (N) and anatomical landmarks. The proximal dorsal aspect (PDN), proximal plantar edge (PPN), and distal plantar edge (DPN) of the navicular will be used to define the navicular local coordinate system. Medial metatarsals technical markers (MMT) and anatomical landmarks. The base of the 1st metatarsal (lMTB), head of the 1st metatarsal (IMTH), and head of the 2nd metatarsal (2MTH) anatomical landmarks will be used to define the medial metatarsals local coordinate system. Hallux technical (H) and anatomical landmarks. The base of the first proximal phalanx, head of the 1st distal phalanx, and medial surface of the 1st distal phalanx will be used to define the hallux local coordinate system. **Bottom Figure:** Leg technical markers (L) and anatomical landmarks. The medial malleolus (MM, see top figure), lateral malleolus (LM), and tibial tubercle (not pictured) anatomical landmarks will be used to define the leg local coordinate system. Cuboid technical markers (CU) and anatomical landmarks. The proximal dorsal (PDCU), proximal plantar (PPCU), and distal plantar (DPCU) edges of the cuboid will be used to define the cuboid local coordinate system. Lateral metatarsals technical markers (LMT) and anatomical landmarks. The base of the 5th metatarsal (5MTB), head of the 5th metatarsal (5MTH), and head of the 4th metatarsal (4MTH) anatomical landmarks were used to define the lateral metatarsals local coordinate system. Aside from the first metatarsal head, the anatomical landmarks are identified by green squares.

Data Processing

After post-processing in Cortex (v 7.2, Motion Analysis Inc., Santa Rosa, CA) all data was exported to MATLAB (MathWorks, Natick, MA) to be filtered (fourth order zero-lag Butterworth filter; cutoff frequency of 6 Hz). Rigid body transformations were performed via the calibrated anatomical systems technique (Cappozzo, 1984) and joint angles of the hip, knee and five functional articulations of the distal foot (Table 12) were identified using the joint coordinate system technique (Grood & Suntay, 1983) from initial contact through the end of landing phase. The kinematic variables of interest from five successful trials from each subject were averaged for subsequent statistical analysis (Table 13). Positive rotations were defined as dorsiflexion/flexion and inversion of the distal segment relative to the proximal segment.

Table 12. Functional articulations of multi-segment foot model

Functional Articulation	Segments	
	Proximal	Distal
Rearfoot complex	Shank	Calcaneus
Medial midfoot complex	Calcaneus	Navicular
Lateral midfoot complex	Calcaneus	Cuboid
Medial forefoot complex	Navicular	Medial rays
Lateral forefoot complex	Cuboid	Lateral rays

Table 13. Kinematic variables

Variable	Plane	Joint
Initial contact position	Sagittal	Rearfoot
		Medial midfoot
		Lateral midfoot
		Medial forefoot
		Lateral forefoot
	Frontal	Rearfoot
		Medial midfoot
		Lateral midfoot
Landing phase range of motion	Sagittal	Hip
		Knee
		Rearfoot
		Medial midfoot
		Lateral midfoot
		Medial forefoot
		Lateral forefoot
	Frontal	Rearfoot
		Medial midfoot
		Lateral midfoot

Data Analysis

One-way between groups ANOVA tests were run to test for significant differences between descriptive values (age, height, Body Mass Index, speed). Sagittal plane position at initial contact was determined for the rearfoot, medial and lateral midfoot, and medial and lateral forefoot. Frontal plane position at initial contact was calculated for the rearfoot and the medial and lateral midfoot. For initial contact angles, two one-way between groups MANOVA tests were done to determine differences between groups in the sagittal plane (rearfoot, medial midfoot, medial forefoot, lateral midfoot, lateral forefoot) and frontal plane (rearfoot, medial midfoot, lateral midfoot).

Range of motion during the landing phase was also calculated. In the sagittal plane landing phase hip, knee, and distal foot range of motion were calculated. In the frontal plane, range of motion was computed for the hip, rearfoot, and medial and lateral midfoot. Two additional one-way between

groups MANOVA tests were run to test for group landing phase range of motion differences in the sagittal (hip, knee, rearfoot, medial midfoot, medial forefoot, lateral midfoot, lateral forefoot) and frontal (hip, rearfoot, medial midfoot, lateral midfoot) planes. Equality of covariance was tested prior to MANOVA tests using Box's M test and homogeneity of variances was checked prior to ANOVA tests using Levene's test. For MANOVA and ANOVA tests, normality was assessed with Shapiro-Wilk's test. Significant MANOVA F tests were followed-up with ANOVAs and significant ANOVAs were analyzed via pairwise comparisons. All analyses were run with SPSS (v.23.0, IBM Corporation, Armonk, NY) and alpha was set to 0.05. Effect sizes (partial eta squared) were also calculated to assist in interpreting clinical significance of the data. Small, medium, and large effects were interpreted as 0.01, 0.06, and 0.14, respectively (Cohen, 1988).

Results

There were no significant differences among groups in height, Body Mass Index, or self-selected speed. Regarding age, the two older groups were significantly older than the YA group; however, there were no differences between the ONF and OFH groups (Table 14).

Initial contact distal foot angles were not significant between groups (Table 15). However, moderate or large effect sizes were seen in the sagittal plane rearfoot as well as both midfoot segments. At the rearfoot, both older groups landed in a more plantarflexed position, while at the midfoot the older adults were in a less plantarflexed position (Table 15).

During the landing phase, there were no significant differences between the OFH and ONF groups, however, there were significant differences with large effect sizes between the older and younger groups, the ONF and young group, and the OFH and young group. The significant between-group range of motion differences were at the hip, knee, and both midfoot segments. At the hip, both older groups went through significantly greater extension range of motion and significantly less adduction range of motion compared to the YA group. At the lateral midfoot, the older groups went

through significantly less dorsiflexion (Table 16). Between the ONF and YA, the non-faller group demonstrated a small plantarflexion range of motion at the medial midfoot while the YA group went through dorsiflexion. Finally, the OFH had significantly reduced knee flexion range of motion compared to the YA group (Table 16).

Table 14. Descriptive variables

	OFH	ONF	YA	Effect size partial η^2
Age (years)	71.5 (5.0) *	71.6 (4.4) ^	22.6 (3.2) *^	0.97
Height (m)	1.627 (0.06)	1.628 (0.06)	1.65 (0.08)	0.04
BMI (kg/m2)	26.7 (4.7)	27.7 (6)	26.2 (6.3)	0.01
Speed (m/s)	0.99 (0.22)	0.99 (0.21)	1.1 (0.17)	0.11
FRAS	3.6 (1.7) *#	1.1 (1) #	0.3 (0.5) *	0.60
FRAS – fall risk cutoff ≥3.5 *= Significant difference (p <0.05) between YA & OFH ^ = Significant difference (p <0.05) between YA & ONF #= Significant difference (p <0.05) between OFH & ONF				

Table 15. Distal foot initial contact angles (Mean (SD) degrees)

Sagittal plane Initial contact angles	OFH	ONF	YA	Effect size partial η^2
Rearfoot	-23.53 (5.1)	-25.64 (5.5)	-22.45 (4.5)	0.07
Medial Midfoot	-0.47 (3.1)	0.64 (2.7)	-2.42 (2.3)	0.19
Lateral Midfoot	-8.53 (3)	-7.68 (3.6)	-10.79 (3.8)	0.13
Medial Forefoot	-20.80 (5.6)	-20.76 (4.2)	-19.32 (5.1)	0.02
Lateral Forefoot	-6.6 (2.4)	-6.02 (1.8)	-6.18 (2.4)	0.01
Frontal plane initial contact angles				
Rearfoot	4.12 (4.5)	1.24 (4.8)	3.56 (4.8)	0.07
Medial Midfoot	-2.21 (3.3)	-2.8 (3.2)	-4.16 (4.8)	0.05
Lateral Midfoot	-2.83 (4.0)	-1.87 (3.6)	-1.43 (6.0)	0.02
Positive = dorsiflexed/inverted position				

Table 16. Range of motion (Mean (SD) degrees) during landing phase

Sagittal plane ROM	**OFH**	**ONF**	**YA**	**Effect size partial η^2**
Hip	-4.63 (1.7)*	-3.65 (2.8)^	-1.16 (3.2)*^	0.25
Knee	13.38 (4.9)*	16.38 (4.9)	20.12 (3.9)*	0.23
Rearfoot	21.63 (4.0)	24.13 (5.6)	22.20 (3.7)	0.06
Medial Midfoot	0.65 (3.1)	-0.22 (2.7)^	2.96 (1.7) ^	0.23
Lateral Midfoot	8.80 (3.3)*	7.70 (2.7)^	11.99 (3.1)*^	0.28
Medial Forefoot	20.39 (4.3)	21.95 (6.5)	20.96 (4.1)	0.02
Lateral Forefoot	7.79 (2.2)	7.78 (2.7)	7.71 (2.3)	0.00
Frontal plane ROM				
Hip	3.85 (1.9)*	4.18 (2.0)^	6.23 (1.5)*^	0.27
Rearfoot	-6.82 (3.8)	-5.80 (3.5)	-6.81 (3.6)	0.02
Medial Midfoot	1.06 (2.6)	0.78 (2.8)	1.35 (3.1)	0.01
Lateral Midfoot	1.31 (5.1)	0.79 (5)	-2.65 (6.7)	0.09
Positive = dorsiflexion/flexion, inversion/adduction * Significant difference (p < 0.05) between YA & OFH ^ Significant difference (p < 0.05) between YA & ONF				

Discussion

The purpose of this study was to identify lower extremity and distal foot kinematic differences during transition step descent between young women and older women with and without a history of falls. At initial contact, the older adult groups were hypothesized to initially land with the hip and knee in a more extended position and the distal foot functional articulations in greater plantarflexed and inverted positions in order to increase reliance on bony rather than muscular structures. During the landing phase, knee and hip range of motion were anticipated to be reduced in the older groups to create a stiffer landing. In the distal foot functional articulations, range of motion was anticipated to be larger due to the more plantarflexed and inverted initial contact position and age-related decreases in muscle strength. Other than the increased knee flexion position in the older adult groups that we reported previously (Chapter 2), there were no significant between group differences at initial contact. There were, however, significant differences in landing phase range of motion between the older and younger groups, the ONF and young group, and the OFH and young groups at the hip, knee and in the distal foot at the midfoot.

As discussed in chapter 2, the increased knee flexion position in the older adult groups at initial contact may have been done to facilitate an earlier landing, decreasing the time in single limb stance to accommodate for age-related changes in strength or balance. The lack of a significant difference between groups in rearfoot complex initial contact position was inconsistent with previous findings that older adults land from a single step in a more plantarflexed foot position (Lythgo et al., 2007). The inconsistency between the studies may have been the result of differences in the footwear conditions and landing strategies. The Lythgo et al. (2007) study had participants wear shoes and based on the mean group data, older adults landed in a plantarflexed position while young adults were dorsiflexed. In the current study, participants were barefoot and all analyzed trials utilized a forefoot landing strategy. There are no previous studies to which the distal foot functional articulation results in the current study may compared.

During the landing phase, significant range of motion differences between the groups were found at the hip, knee, and medial and lateral midfoot. The sagittal plane hip motion found both older adult groups to go through more extension than the YA group. The hip extension motion during the landing phase, as opposed to flexion, may have been due to the distal to proximal sequential absorption of landing forces associated with transition step negotiation using a forefoot landing strategy (van Dieen et al., 2008). The sequential absorption may have enabled the hip to maintain forward progression into midstance. The differences between age groups may be due to the closer landing position (Chapter 2, Table 4) of the older adults changing the orientation of the center of mass relative to their landing foot. In the frontal plane, both older groups demonstrated decreased hip adduction motion. The reduced frontal plane hip motion may be due to an increase in stance limb lateral trunk lean, which is a common adaptation for older adults with decreased hip abductor strength (Hsue & Su, 2014). Although initially it was anticipated the reduced knee range of motion would accompany a more extended initial contact, in the current study both older groups initially landed with a more flexed knee (Chapter 2, Table 4). The

reduced flexion through the landing phase may be due to increased quadriceps activity of the older adults compensating for reduced strength to prevent the knee from collapsing or from the closer step landing, which may position the center of mass more anteriorly than the young adults requiring less knee flexion during landing. Previous step studies examining the influence of age on landing phase kinematics during transition step negotiation have only investigated sagittal plane knee or frontal plane hip range of motion (Hortobagyi & DeVita, 1999; Saywell et al., 2012). Regarding the reduced knee flexion, there is agreement that older adults utilize significantly less knee flexion during step descent (Hortobagyi & DeVita, 1999; Saywell et al., 2012). The frontal plane hip motion results in the current study differed from the Saywell et al. (2012) study that did not report significant peak hip adduction angle differences between older and young adults. The difference in studies may be due to the current study examining the range of motion rather than discrete peaks or due to limiting the investigation to females rather than including both genders.

Regarding range of motion of the distal foot during the landing phase, only the midfoot functional articulations demonstrated differences between the groups. The older groups reduced range of motion in the midfoot segments, although only significantly different between the non-fallers and young adults on the medial side, both older groups reduced motion significantly on the lateral side. The decrease in range of motion may be due to age-related declines in midfoot joint structure. As this is the first study to examine differences across age of the distal foot during a transition step down, comparison across similar studies is not possible.

Prior to drawing conclusions, limitations of the current study must be acknowledged. The study examined only females due to their higher likelihood of falls with age, however the study is therefore not generalizable to males. Additionally due to the marker placement for the multi-segment foot model, participants were barefoot and results may not be generalizable to a shod condition. Finally, participants walked at their self-selected pace, which was not statistically different, however the difference in the

mean speed of the older groups and the young adults was close to ten percent, which suggests the possibility of speed related effects cannot be completely ruled out and there may be clinical differences.

In conclusion, this was the first study to examine the lower extremity and distal foot kinematics of young women and older women with and without a history of falls during the landing phase of a transition step descent. All of the participants in the current study utilized a forefoot landing strategy during the barefoot transition step negotiation. This has not been the case in some previous studies. To facilitate comparison between studies and to differentiate the effect of age and/or fall history versus landing strategy, future transition step studies would benefit from ensuring all participants have a consistent landing strategy. Although initial contact angles between the groups only differed at the knee, there were significant differences at the hip, knee, and midfoot segments during the landing phase. The older adults exhibited increased hip extension, decreased hip adduction, and reduced medial and lateral midfoot dorsiflexion range of motion during the landing phase. Fall prevention/rehabilitation programs may benefit from focusing on the landing phase of transition step negotiation and including assessments of distal foot mobility and strength.

Chapter 5: Summary and Conclusions

Objectives

The overall aim of this dissertation was to determine kinematic and neuromuscular influences of age and fall history during descent of a single transition step. Specifically, differences in step clearance and displacement, as well as lower extremity kinematics during minimum step clearance (Aim 1), initial contact (Aims 1 & 3), and through weight acceptance (Aims 1 & 3) were examined. Additionally, neuromuscular function during step descent was analyzed via peak moments and powers, co-activation of the ankle and knee, and muscle activity of the lateral ankle (Aim 2).

Summary of Methods

Forty-five participants were recruited and divided into groups of 15 made up of young women, older women with no history of falls, and older women with a history of at least one fall. Participants walked at their self-selected pace along a 5.5 m walkway, stepped down 17 cm and continued walking. Three-dimensional kinematics of both lower extremities were captured as well as ground reaction forces before and after the step and bilateral muscle activity during the gait trials. Maximum strength measures were also recorded for normalization. Group differences were tested for minimum clearance and joint angles at clearance, bilateral displacement from step, initial contact angles, range of motion from initial contact through weight acceptance, bilateral peak moments and powers, bilateral co-activation of the ankles and knees, and peroneal activity of the landing limb.

General Conclusions

Lower extremity kinematic differences between young and older women during a single step descent appear to be limited to initial contact and during weight acceptance of the lead limb. Specifically, the older adults landed more closely to the step with the knee more flexed. The closer landing may function to reduce single limb stance time during the transition step negotiation to compensate for age-related decreases in lower extremity strength. However, the more flexed knee

position may also increase the risk of a fall due to lead limb collapse, as there is an increased reliance on muscular strength rather than skeletal structure for stability.

This study does not support the general distal to proximal shift of moments and powers from ankle to hip in older adults during step negotiation. Although the lead knee had reduced eccentric power during the landing phase in the older faller group as anticipated, the sagittal plane lead hip eccentric power was significantly less in older non-fallers compared young adults, contrary to expected. Both differences at the hip and knee may be due to the closer landing foot placement of the older adults. Additionally, the significant differences in powers may have occurred despite the lack of differences in moments due to the adjustments in range of motion at the hip and knee or potential adjustments of the trunk. Co-activation of the ankle or knee also did not differ between groups. However, lead limb peroneal activation was significantly increased in the older adult groups. Although peroneal differences have not been a focus of previous studies examining age or step negotiation the current results indicate further study should be made.

Throughout weight acceptance, there were significant differences between groups in range of motion of the hip, knee, and distal foot, specifically at the midfoot. Both sagittal and frontal plane hip motion was significantly different between age groups. In the frontal plane the older adults adducted less, while in the sagittal plane the older adults extended more. At the knee the older groups flexed less than the younger group, the older fallers significantly different. These proximal differences during the landing phase may be due to the older adults closer foot placement to the step as well as adaptations of the trunk, both laterally and anteriorly. Within the distal foot, both midfoot segments had decreased range of motion in the older adults, however the medial midfoot was only significantly different between the non-fallers and young adults, while the lateral midfoot was significantly different between the older groups and the young. These midfoot range of motion decreases may be due to age-related declines in distal foot joint structure.

This work provides a comprehensive look of the kinematics and neuromuscular function of lead and trail limbs descending a single transition step between older women with and without a fall history and younger adults. As both age and fall history are risk factors for future falls, identifying differences during transition step descent provides clinicians a baseline for assisting older adults in preventing or rehabilitating fall injuries. Based on the results from this study, it appears the landing phase (weight acceptance) may be the primary area to focus on for transition step negotiation. Specifically, it may be important for rehabilitation or prevention programs aimed at decreasing falls during transition step negotiation to focus on lead limb landing position and weight acceptance range of motion. Additionally, strength of the distal lower extremity musculature, including the peroneals and intrinsic foot flexors, and the mobility of the distal foot may be beneficial.

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Appendix A: Literature Review

Falls

In the United States, the costs associated with treatment for non-fatal fall related injuries are estimated to be $31.3 billion, with both cost and fall frequency increasing with age, particularly in women (Burns et al., 2016). A challenge in developing intervention programs that successfully reduce the prevalence of fall related injuries is that there are numerous risk factors for falls including, but not limited to, age, weakness, balance deficits, medications, and limited mobility (Masud & Morris, 2001). Furthermore, the presence of multiple risk factors further increases the likelihood of falling (M. E. Tinetti et al., 1988).

Fall risk

A National Health Interview Survey found the most common cause of older adults restricting their activities is due to limitations after a fall (Laurence Z. Rubenstein, 2006). In an effort to reduce the prevalence of falls, and associated restriction in activities associated with falls, in older adults a great deal of literature has focused on identification of fall-related risk factors. To date many factors such as: reduced flexibility/range of motion, lower extremity weakness, balance deficits, limited mobility, previous falls in the last year, and non-healing foot sores have been associated with increased falls risk (Carpenter et al., 2009; Masud & Morris, 2001; Menz, Morris, & Lord, 2006; Schwenk et al., 2013). Additionally, the risk of falling is increased when multiple risk factors are present (M. E. Tinetti et al., 1988). Although some risk factors are inevitable (e.g. aging), it has been shown that various training protocols can help mitigate the advancement of at least some (e.g. strength, flexibility, balance) of these risk factors. Generally, Chodzko-Zajko et al. (2009) found a combination of balance and strength training reduces the risk of falls in older adults. Specifically exercises targeting foot and ankle flexibility and

strength have been shown to improve the balance and flexibility risk factors in older adults (Schwenk et al., 2013) as well as reduce the rate of falls (Spink et al., 2011).

***Age*.** As we age our bodies physically decline, the American College of Sports Medicine released a position statement regarding exercise and physical activity for older adults, in which they stated general areas of decline in older adults (Chodzko-Zajko et al., 2009). Structural and functional declines are attributed to changing body composition as well as reductions in skeletal muscle performance with older adults requiring a higher percentage of maximum capacity and effort to do the same task as younger adults. Additionally, older adults have a higher prevalence of chronic disease, which can influence their ability to carry out activities of daily living and function as a barrier to physical activity (Chodzko-Zajko et al., 2009). Unfortunately, these age related changes are also primary factors associated with increasing falls risk.

Although a study by Malta et al (2012) suggested that just over ten percent of total falls in the general population occur in older adults, their definition of a fall included falls during sporting events as well as those caused by interactions with other individuals. Therefore the distribution of falls in the study may have been considerably different if the definition of falls would have been defined as, ‘unintentionally coming to rest on the ground or at some other lower level, not as a result of a major intrinsic event or overwhelming hazard’ as proposed by M. E. Tinetti et al. (1988). In an Australian study on over 700 older community dwelling women that used the definition proposed by Tinetti et al (1988), it was found that the prevalence of falls increased as age increased. In the study, approximately 30%, 40% and 50% of women aged 65-74, 75-84, and > 85 years of age, respectively, reported falling at least once during the previous year (Lord, Ward, Williams, & Anstey, 1993). Additionally, as this was a retrospective study, it is possible the total number of falls was under-reported due to participant recall as well as the study being unavailable to individuals still requiring acute care for a previous fall. More

recently, studies of older adults in both Poland (Skalska et al., 2013) and China (Shi et al., 2014) have also reported an increase in the percentage of individuals falling as age advances.

***Gender*.** The risk of falls increases in both men and women as age progresses. However, in a study examining the cost of falls among older adults in the United States it was found that women experienced twice the number of non-fatal falls as men which resulted in 71% of the total medical costs due to older adults falling (Burns et al., 2016). This discrepancy in injury prevalence and severity indicates a need to specifically investigate fall related factors in older women.

Fall risk assessment

Although previous studies have examined differences between low and high fall risk groups, conclusions are difficult to draw due to the wide range of methods used to assess fall risk. Generally, fall risk is assessed either through clinical/functional tests or via questionnaires.

Clinical/functional tests. There are numerous clinical/functional methods available to assess fall risk. Some of the most commonly used methods are the Berg Balance Scale (K. O. Berg, Wood-Dauphinee, Williams, & Maki, 1992) or a modified version of the scale. The scales typically include a multiple item functional assessment of balance that has been demonstrated to indicate fall risk in older adults (Hohtari-Kivimaki, Salminen, Vahlberg, & Kivela, 2013). However, although the Berg Balance Scale does not require much in the way of equipment, it does take 20 to 30 minutes to administer. As a result, other single item tests such as the Five Times Sit to Stand (FTSS) test (Buatois et al., 2010) or the Timed Up and Go (TUG) test (Bohannon, 2006), which both take less than five minutes to administer have been developed. The TUG test requires standing from a chair, walking a set distance away from the chair, turning, and returning to the chair. Although the Centers for Disease Control and Prevention recommends the TUG with a suggested twelve second cut-off time to differentiate fall risk (CDC, 2017), a review of the TUG by Barry, Galvin, Keogh, Horgan, and Fahey (2014) suggests that within community

dwelling members the test by itself cannot differentiate those at high risk of falling. The FTSS test, which requires participants to start in a seated position, stand without use of the arms, return to the seated position and repeat for a total of five times has also been found to reliably predict fall risk in older adults (cut-off time of ≥ 12 seconds) (Tiedemann et al., 2008). Although these and similar clinical/functional tests enable accurate identification of fall risk, these measures require physical time spent with the participant which may be a limitation in some types of studies (e.g. large scale epidemiology/prevalence studies). As a result of this potential limitation, a number of questionnaire based methods have been developed to identify those at high falls risk.

Questionnaires. Although several questionnaires to identify fall risk have been developed, most include questions that are based on confidence in accomplishing specific tasks and may assess fear of falling compared to fall risk (Delbaere et al., 2010; El Miedany et al., 2011; Hamel & Cavanagh, 2004; Hirase, Inokuchi, Matsusaka, Nakahara, & Okita, 2014; L. Z. Rubenstein, Vivrette, Harker, Stevens, & Kramer, 2011). There are many areas included in the fall risk questionnaires including medications, previous health history, fear of falling, and functional task performance. However as the focus of this study is mechanics, screening for functional and mechanical factors is most applicable. At present only one study has developed a questionnaire based only on functional and mechanical factors. El Miedany et al. (2011), developed the Falls Risk Assessment Score (FRAS) (Table 1) based on the Guideline for the prevention of falls in older persons ("Guideline for the prevention of falls in older persons," 2001). The FRAS includes five questions based on a patient's self-assessment over the past 12 months and includes a cutoff threshold of 3.5 for a high fall risk. Although questionnaires are dependent on participant recall in assessing fall risk, they do allow for screening without a physical visit and with no risk of injury. Both clinical screening and questionnaires identify fall risk, however only general fall risk is possible and the assessments are not necessarily predictive of step falls.

Table 1. Falls Risk Assessment Score

	Points
1 year increase from 60 years old	0.02
I have had more than one fall	>1fall = 2 points
My walking speed has got slower/my gait has changed	1.5
I have lost my balance	1
I have problems with my sight	1
My grip strength got weaker	1
Point total:	

Score of 3.5 or higher indicates higher risk for falls

Step falls

In those studies that have categorized stair related falls, the prevalence has been reported at 13-14.6% of all falls (Kelsey, Berry, et al., 2010; Malta et al., 2012). Although falls on a level surface are more common than step-related falls, Malta et al. (2012) found that step-related falls resulted in more severe injury and therefore higher cost of care. Additionally, studies that have differentiated falls on steps into direction of travel (ascending or descending), have reported that 75% of falls on stairs occur during descent (H. H. Cohen et al., 1985; Masud & Morris, 2001) and 30% of step related falls occur on the transition to or from level walking (Templer, 1992). Studies investigating factors associated with stair-related falls have identified performance factors such as misplacing the foot, reaching, or inattention to contribute to 50% of all total step falls with half of those occurring during the transition from stair to level ground or vice versa (H. H. Cohen et al., 1985). After user performance factors, the design and environmental conditions of the stairs made up 47% of the other elements contributing to stair related falls in the workplace (H. H. Cohen et al., 1985). With respect to design factors, Archea et al. (1979) examined characteristics of low and high risk stairways finding greater risk on stairways with just a few steps or with the riser height less than 15.9 cm (6.25 inches). It is possible stairways with fewer steps require transition mechanics across all steps and therefore produce a greater likelihood of stumbling. Regarding step height, there is considerable range in height codes of steps (10.2-17.8 cm)

(International_Code_Council, 2015) or curbs (10.0-22.5 cm) (Beneficial_Designs et al., 1999). While step heights of less than 15.9 cm have shown increased risk of falls (Archea et al., 1979), another study using curbs of 15.4 cm, suggested lowering curb heights may be helpful in improving older adults' ability to cross streets (Dommes et al., 2015). Additionally, it has been demonstrated that stepping mechanics are influenced by the height of the step (Gerstle et al., 2017). The previous research is valuable in determining where falls on stairs occur and demonstrating the height of the step influences stepping mechanics, however differences in stepping mechanics or neuromuscular activity across age and fall history have not been clearly established. Understanding of the mechanics and neuromuscular activity during step negotiation will enable practitioners to identify potential areas patients can work on in order to maintain functional independence.

Step Gait

Kinematics

Despite the fact that most falls occur during transition step negotiation, most step studies have focused on the middle steps during continuous descent (Andriacchi et al., 1980; Bosse et al., 2012; McFadyen & Winter, 1988; Protopapadaki et al., 2007; Zachazewski, Riley, & Krebs, 1993). This is significant given the fact that transition step mechanics are different than continuous step mechanics (Yu et al., 1997). Therefore, results cannot be generalized across studies. Yu et al. (1997) found increased variability in hip, knee and ankle joint angles and corresponding moments during transition steps (last steps in descent; first steps in ascent) compared to other steps. One study examining gaze (Miyasike-daSilva & McIlroy, 2016), found continuous descent requires less visual attention than that of transition steps, indicating transition steps may require more executive function. Further, many of the studies that have used a single step have required participants to step down from a static position, as a representative of stairway negotiation to reduce participant fatigue (Rao et al., 2009) or to examine

transition to a lower level such as a curb (J. G. Buckley, Jones, & Johnson, 2010; Freedman & Kent, 1987). As found in an ascent study (Vallabhajosula, Yentes, & Stergiou, 2012), kinematics will likely be different during descent based on how the step is negotiated during the course of walking or statically standing before or after the step.

Multiple steps. To investigate mechanics during multiple step negotiation, previous studies have partitioned the step cycle into phases and subphases (Table 2). As in level walking, weight acceptance is from initial contact through weight transfer to the lead limb. Forward continuance is the first half of single limb support when the center of mass only moves anteriorly. Finally controlled lowering, is when the center of mass is lowered as the opposite limb reaches for the next step. The swing phase is made up of leg pull through and foot placement (Zachazewski et al., 1993).

Table 2. Phases of Stair Descent

Double Support	Single Limb Support		Double Support	Leg Pull Through	Foot Placement
Weight Acceptance	Forward Continuance	Controlled Lowering			
Stance Phase				Swing Phase	

0%   14   34   53   68   84   100%

(Zachazewski et al., 1993)

Step cycle kinematics. Patterns of joint motion have been examined primarily in young adults during continuous step descent, with general agreement across the studies (Andriacchi et al., 1980; McFadyen & Winter, 1988; Protopapadaki et al., 2007; Riener et al., 2002). Joint motions during step descent stride are as follows. The hip reaches maximum flexion during leg pull through then steadily extends until contact. Following initial contact there is slight hip flexion during weight acceptance extending through forward continuance, then during controlled lowering, the hip is most extended before increasing flexion just before the swing phase. The knee begins swing at maximal flexion decreasing to nearly full extension at contact. During weight acceptance there is a slight increase in

flexion, during forward continuance the knee maintains the slight flexion, then at the start of controlled lowering knee flexion increases steadily into the swing phase. The ankle is neutral to slightly dorsiflexed at the start of swing phase and steadily plantarflexes into maximal plantarflexion during late foot placement. The foot then begins to dorsiflex quickly through weight acceptance at which time it slows dorsiflexion from forward continuance through mid controlled lowering when the ankle planarflexes for toe-off (Andriacchi et al., 1980; McFadyen & Winter, 1988; Protopapadaki et al., 2007; Riener et al., 2002).

Foot clearance kinematics. Many studies have examined clearance, however, the definitions and marker placements have varied considerably across studies. A study of older women descending steps (17.8 cm high) found minimum lead foot clearance, defined by smallest total distance from shoe sole to step edge, calculated via digitized two dimensional film to be 2.1 cm (Simoneau, Cavanagh, Ulbrecht, Leibowitz, & Tyrrell, 1991). A study of young adults calculated both lead and trail foot clearance as the minimum resultant distance from the heel marker to the step edge. The average minimum step clearance of the 15.2 cm steps in the study with the lead foot was 4.59 cm, and 10.7 cm with the trail foot (Muhaidat, Kerr, Rafferty, Skelton, & Evans, 2011). Yet another study (sedentary and physically active older adults (65 years and up) descending 17 cm steps) defined minimum clearance as the vertical distance between the step and heel marker when the heel marker was aligned with the step edge. This study found the trail limb to have consistently greater heel clearance (~17 cm) than the lead foot (~ 7.5 cm) (Kunzler, da Rocha, Bobbert, Duysens, & Carpes, 2017). Finally, Hamel, Okita, Higginson, and Cavanagh (2005) examined foot clearance of older and younger adults utilizing the foot clearance measurement suggested by Startzell and Cavanagh (1999) which involves digitizing multiple points on the sole of the shoe. The minimum point is used as the measure of clearance. Using this method, the study found minimum lead foot clearance of older adults to be just under 1.5 cm and younger adults to be 1.7 cm. The Hamel et al. (2005) results suggest that the large range of minimum clearances across

these studies is most likely due to the different methods used to calculate clearance rather than the age differences of the participants. Further, a recent study by Telonio et al. (2014) examining clearance determined using the digitized sole compared to the heel and toe markers during descent of five 18.8 cm high steps, found that the sole method consistently measured the smallest clearance. Additionally, the Telonio et al. (2014) study found the rearfoot to have the smallest clearance 69% of the time with the midfoot and forefoot with the smallest clearance 17% and 14% of the time, respectively. Thus, in measuring minimum foot clearance, it is imperative to capture the closest point to the step surface, whether it occurs at the forefoot or heel.

Transition steps. *Step cycle kinematics.* Although the kinematic patterns of multiple step descent have been determined, full lower extremity kinematics when transitioning between levels or from a curb have not yet been clearly established. Further, the methodology of the studies have varied, making comparisons across studies difficult. A single step has been examined as negotiating a curb during continuous ambulation (Begg & Sparrow, 2000; J. G. Buckley, Timmis, M.A., Scally, A.J., Elliott, D.B., 2011; Lythgo et al., 2007; van Dieen & Pijnappels, 2009), as a step down from a static standing position (Rao et al., 2009), or as a means to examine landing mechanics (DeVita & Hortobagyi, 2000b). Given the fact that mechanical adjustments may be made a few steps before the transition stair (Peng, Fey, Kuiken, & Hargrove, 2016) and differences can also be seen in the placement of the lead foot during landing (Lythgo et al., 2007), it is important to re-create typical transition step or curb usage which typically involves continuous ambulation prior to and following the step negotiation. Further, the initial contact landing strategy (heel vs forefoot) utilized by an individual may be influenced by the height of the step (Freedman & Kent, 1987; Gerstle et al., 2017), age of the participant (van Dieen & Pijnappels, 2009), and the approach gait speed (van Dieen & Pijnappels, 2009). It is possible previous studies may have found differences between groups that were influenced by differences in landing strategy rather

than group differences. Thus, to create more generalizable conclusions, studies must address these known variables.

Step clearance kinematics. Another important consideration is the definition of step clearance on transition steps. The most common definition has been heel clearance at the edge of the step (Begg & Sparrow, 2000; J. G. Buckley, Timmis, M.A., Scally, A.J., Elliott, D.B., 2011; Lythgo et al., 2007). However, a study by Loverro, Mueske, and Hamel (2013) that digitized multiple locations on the shoe sole to identify minimum clearance during negotiation of a single 17 cm step found minimum clearance occurred with equal frequency over the step surface versus the step edge. Additionally, it was found that the frequency of minimum clearance occurred equally between the toe and heel regions. As a result, the authors concluded that using minimum toe clearance rather than minimum foot clearance overestimated the actual clearance by 33% (Loverro et al., 2013).

Foot positioning. Foot positioning is a variable typically not examined in continuous step descent as the parameters of the staircase constrain an individual to landing on their forefoot. In a single step however, foot position can vary considerably both for the lead and trail limbs. Most commonly, the variables of interest have been the angle of the foot at contact and the displacement of the foot from the step. Three studies have confirmed the height of the step can influence the ankle position at contact. At step heights of 5 cm most individuals utilize a heel strategy or dorsiflexed ankle position at contact. Preferred strategies are seen to be mixed (heel, forefoot) on step heights ranging from 10 to 20 cm. At heights greater than 20 cm, the preferred strategy is typically a forefoot or plantarflexed ankle position (Freedman & Kent, 1987; Gerstle et al., 2017; van Dieen & Pijnappels, 2009). Despite different landing strategies, especially at intermediate step heights, studies have not often reported which strategies were used. However, based on large standard deviations reported, it appears that strategies have been mixed within the groups (Lythgo et al., 2007). Inclusion of multiple landing strategies within a group at a step height could potentially mask differences between groups/conditions. Foot

displacement from the step is also a variable constrained in continuous step descent but a potentially modifiable variable in single step negotiation (J. G. Buckley, Timmis, M.A., Scally, A.J., Elliott, D.B., 2011; Lythgo et al., 2007), however, typical values have not yet been determined. Therefore, to establish potential kinematic differences across groups, it is of utmost importance to include landing strategy considerations before generalizations can be made.

Changes with age/fall risk. To date, very few studies have investigated the effect of age/fall risk on transition step kinematics. Generally, negotiating steps becomes an activity with an increased likelihood of falling, with those aged 65 and over almost twice as likely to fall as someone between the ages of 55-59 with women falling more often than men (Skalska et al., 2013). Age related step parameter changes include longer descent, stride and single support time as well as more variance in step width with increasing age (Mian et al., 2007; Zietz et al., 2011). Additionally, older adults are also more likely to use a forefoot landing strategy when stepping down regardless of the step height (Lythgo et al., 2007; van Dieen et al., 2008). Despite this preference to land in a plantarflexed position, Nigg, Fisher, Allinger, Ronsky, and Engsberg (1992) found with increasing age a decrease in plantarflexion, abduction and adduction range of motion of both genders, while females also significantly decreased inversion, eversion and dorsiflexion range of motion of the ankle. It is possible the less stable forefoot landing position in conjunction with the decreased range of motion as well as decreased distal strength (Menz, 2015) contribute to the increased number of older women that fall. In addition to the changes at the ankle joint, other aging related kinematic changes that occur in the lower extremity during multiple stair descent include decreased sagittal plane knee range of motion and an increase in hip and pelvis range of motion in the frontal and transverse planes (Mian et al., 2007).

Clearing the step is also a potential factor in causing older adults to fall. Two studies have found healthy older adults have a step clearance greater than young adults (Begg & Sparrow, 2000; Zietz et al., 2011). Interestingly, the Zietz et al. (2011) study also included older adults with a high fall risk, but did

not find any difference in step clearance between the high risk older adults and young adults. Another study with considerably more participants found older healthy adults had a smaller foot clearance than young adults (Lythgo et al., 2007). Although it is possible the difference in subject numbers explains the discrepancy between the studies, the difference in footwear conditions between the studies may also have been a factor. Neither the Begg and Sparrow (2000) nor Zietz et al. (2011) mention any footwear while Lythgo, Wilson, and Galea (2011) had participants wearing shoes. Level walking in footwear has been demonstrated to change the kinematics of the ankle and knee compared to barefoot gait (Zhang, Paquette, & Zhang, 2013), it is possible then that stepping gait may be influenced as well. Additionally, a survey of footwear preferences in older adults reported that the majority of individuals do not wear shoes in and around the home (Munro & Steele, 1999). This finding is significant given the fact that the majority of falls take place in the home (Duckham et al., 2013). In addition to step clearance, where the foot is placed in relation to the step may be a modifying factor older adults use to mitigate other age related changes. Lythgo et al. (2007) found older women decreased the distance the foot is placed from the step, which may be a coping mechanism to improve stability or a necessity brought on to limit needed dorsiflexion or compensate for lack of strength of the trail limb on the step. Jette and Jette (1997) found a nonlinear relationship between knee extension strength and the time to ascend and descend two steps, indicating there may be a threshold of needed knee extensor strength to maintain typical stair negotiation. By identifying the age-related kinematic changes during step negotiation in healthy older adults, the progression of detrimental changes can be classified enabling identification of target training areas before detriments reach the point of increased falls risk.

Kinetics

Step descent compared to level or ascent. Although descending steps results in the highest incident rate of injury during falls, studies have primarily compared step descent to level walking or step ascent rather than differences between groups during descent. While these studies have been valuable

in determining differences between types of gait, they do little to further the understanding of step mechanics that may be associated with falls during descent. Across both ascent and descent, at the ankle, two external dorsiflexion moments occur during stance phase with a larger first peak in descent and a larger second peak in ascent (Protopapadaki et al., 2007; Riener et al., 2002). Although both Andriacchi et al. (1980) (21 cm step) and Riener et al. (2002) (13.8, 17, 22.5 cm steps) found sagittal plane ankle moments were not larger than level walking. At the knee, Andriacchi et al. (1980) found external flexion moments during descent to be three times greater than ascent or level walking. Riener et al. (2002) also found external knee flexion moments to be up to three times greater than during level walking. However, Riener et al. (2002) and Protopapadaki et al. (2007) found knee extension moments during descent were only slightly greater than ascent. At the hip, external flexion moments occur during the stance phase for both ascent and descent, with generally slightly greater moments during ascent, during controlled lowering of descent there is also a brief period of hip extension moment (Andriacchi et al., 1980; McFadyen & Winter, 1988; Protopapadaki et al., 2007). In the frontal plane, the largest external moments were found for the hip, knee and ankle during step descent compared to ascent and level walking (Andriacchi et al., 1980). As descent requires the largest moments in the frontal plane in all three joints as well as at the knee in the sagittal plane, step descent gait may reveal detrimental declines earlier than during a level walking gait assessment and therefore indicate areas to focus on in fall prevention and rehabilitation protocols.

Regarding joint powers during multiple step descent, powers across all three joints are primarily negative, absorbing the energy of landing (Riener et al., 2002). Although Riener et al. (2002) found a relationship between joint powers and staircase inclination, with a steeper slope producing greater power, it is possible the greater powers may be produced as the horizontal distance from the step decreases, a necessary change as the staircase inclination increased in their study. At initial contact in multiple step descent, the ankle power is eccentric through weight acceptance with some concentric

power just before toe off (McFadyen & Winter, 1988; Riener et al., 2002). In contrast, during ascent, power is primarily generated just before toe off (McFadyen & Winter, 1988) very similar to that of level walking (Riener et al., 2002). At the knee, power is consistently concentric in step ascent (McFadyen & Winter, 1988; Riener et al., 2002) while eccentrically absorbing during step descent (peaks at weight acceptance and controlled lowering) and level walking (peaks at weight acceptance and pre-swing) (Riener et al., 2002). Hip power, in relation to the knee and ankle is much smaller in magnitude. In ascent, hip power is concentrically generated in the first half of stance similar to level walking (McFadyen & Winter, 1988; Riener et al., 2002), hip power in descent absorbs energy in the first half of stance while generating power in the second half of stance (Riener et al., 2002). As with the joint moments, the joint powers during step descent are considerably different than ascent or level walking. It is possible falls occur during step descent due to unnoticed declines in capabilities as they are required only during descent rather than the more common level walking.

Multiple step descent compared to transition steps. In negotiating stairs, Yu et al. (1997) found the ankle, knee and hip kinetics were more reproducible than the kinematics, however kinetics were found to be significantly more variable when examined on transition steps. Despite the knowledge of differences in transition step kinetics, few studies have examined these differences. At both the hip and knee, flexion moments descending multiple steps had larger increases compared to transition step moments (Andriacchi et al., 1980). However, in a study examining differences between transitioning onto steps and transitioning to level walking in older women, Alcock et al. (2015) found the transition to level walking resulted in significantly increased internal plantarflexor moments. In the frontal plane, hip and knee external adduction moments were greatest during transition step descent, while external ankle inversion moment was largest during multiple step descent (Andriacchi et al., 1980). Alcock et al. (2015) also examined joint powers between the two transition steps and found the transition to level walking produced a significantly larger burst of concentric power generation at the knee during mid-

stance compared to transitioning on to steps. Differences between multiple and single transition steps have been demonstrated in healthy adults, as there are differences across age in level walking and multiple step descent, most likely there will be differences in transition step negotiation as well. Examining changes through aging or fall history on transition step descent will allow a better understanding of the progression of decline in stepping performance.

Changes with age/fall risk. A study examining step descent between young and elderly adults found the elderly had significantly smaller maximal ankle and knee moments, however during step descent the relative knee moments were not significantly different while the elderly had significantly smaller relative ankle moments (Reeves et al., 2008). Reeves et al. (2008) suggested this difference was a strategy the elderly used to protect the ankle which was approaching maximal limits by redistributing moments more proximally. Several studies of level walking have confirmed there is a distal to proximal shift in mechanical work (Tibor Hortobágyi et al., 2016), joint moments, and powers as aging occurs (DeVita & Hortobagyi, 2000a; Winter & Eng, 1995). Additionally, in a study between healthy elderly and low-performing elderly the increase in hip power and decrease in ankle power was further emphasized in the lower performance group (Graf et al., 2005). Older adults have been demonstrated to have a more plantarflexed ankle when stepping down (Lythgo et al., 2007; van Dieen & Pijnappels, 2009), in a study comparing differences between landing strategies in young adults van Dieen et al. (2008) found landing with the forefoot requires greater peak power and peak moments at the ankle than landing with the heel. As shifts from distal to more proximal moments and powers have been demonstrated in level walking as aging occurs, and the preferred landing strategy of older adults is one that requires greater moments and powers, determining how older adults adapt and what strategies allow for successful or unsuccessful step negotiation will enable more beneficial prevention and rehabilitation programs to be developed.

Electromyography

Gait**.** Muscle activity patterns for the lower extremities during level walking are relatively well established (Freedman & Kent, 1987; Mann & Inman, 1964; J. Perry, Burnfield, J.M., 2010) and step negotiation of continuous and some transition steps has been examined (Andriacchi et al., 1980; Freedman & Kent, 1987; Freedman, Wannstedt, & Herman, 1976; Joseph & Watson, 1967; Mann & Inman, 1964; McFadyen & Winter, 1988), however step negotiation has far more variables making comparisons across the studies difficult. The variables include, the number of steps encountered, whether negotiation is during a transition step or mid-flight, the height of the step, the depth of the step, the landing strategy, and if step negotiation occurs from a static position or during continuous ambulation. All of these variables may influence muscle activity. Generally, ascending steps muscle activity is concentric pushing the body upwards, while descent is eccentric controlling the lowering of the center of mass (McFadyen & Winter, 1988). In multiple step descent there is general agreement that the triceps surae muscles or the soleus and gastrocnemius in some combination are active during late swing and into early stance (Andriacchi et al., 1980; Joseph & Watson, 1967; Mann & Inman, 1964; McFadyen & Winter, 1988). The tibialis anterior, however, has not been consistent across studies. Mann and Inman (1964) (six steps, 13.5 cm high) concluded the tibialis anterior is not active at all during descent, Andriacchi et al. (1980) (three steps, 21 cm high) found activity only during the swing phase, and both McFadyen and Winter (1988) (five steps, 22 cm high) as well as Joseph and Watson (1967) (number of steps not reported, 16.5 cm high) found tibialis anterior activity during both swing and during mid-stance during descent. The differences across these studies may be due to small sample sizes as all had ten or fewer subjects, differences in step height, speed of descent (preferred speed or not reported), and/or which step was examined during staircase descent (mid-staircase, transition, or not reported).

Not extensively studied during stepping is the peroneus longus, which assists in providing frontal plane stability for the ankle and support for the longitudinal arch during forefoot landings. In level walking the peroneus longus of those with functional ankle instability has demonstrated increased activity after foot contact compared to healthy controls (Delahunt, Monaghan, & Caulfield, 2006a). However, in a study comparing individual's injured to uninjured ankles the peroneals were found to be more active on the uninjured side (Santilli et al., 2005). Peroneal activity during step negotiation thus far has been limited to landing studies with the results being somewhat inconsistent. Delahunt, Monaghan, and Caulfield (2006b) found in landing from a 35 cm platform there was decreased peroneal activity only during pre-contact in those with functional ankle instability compared to healthy controls. In a study examining landings from 1, 1.5, and 2 meters of healthy gymnasts it was found that both pre-contact and landing phases increased muscle activity as the heights increased (Arampatzis, Morey-Klapsing, & Bruggemann, 2003). In these studies the heights are far greater than a step that would be encountered during daily activity, however the studies only examined young adults. As declines in strength occur with age and older adults' preference to land with the forefoot, there is a clear need for understanding peroneal muscle activity and how it may change with age.

Changes with age/fall risk. Strength decreases have been associated with aging, with females losing a larger percentage in the lower limbs compared to the upper limbs (Hughes et al., 2001). Another study examining muscle strength and aging in females also found strength declines were more distinct in the lower extremity than the upper extremity (Amaral et al., 2014). It has been suggested that changes within the nervous system due to aging decrease the ability to activate muscles manifesting the decline as decreased strength (Manini, Hong, & Clark, 2013). During step descent, older adults have longer co-contractions indicating stiffer limbs than young adults (J. G. Buckley et al., 2013). Within older adults, females that have fallen have slower muscle recruitment of the knee flexors and ankle dorsiflexors than in their non-faller similar aged counterparts when producing maximal joint torques (L. F. Crozara et al.,

2013). The co-contraction ratio of the shank muscles during walking are also greater in older female fallers than non-fallers (Marques et al., 2013). With changes in strength as age progresses, adaptations must be made to continue to meet the demands of the task. Determining what these adaptations are will enable better rehabilitation or prevention protocols to be developed to prolong healthy, lower risk motions.

The distal foot

Multi-segment foot model

The majority of previous studies have modeled the foot as a single rigid segment. However, in the 1990's recognition that the foot, made up of 26 bones, may move as independent segments began to be explored. Studies by S. H. Scott and Winter (1993), Kidder, Abuzzahab, Harris, and Johnson (1996), and Leardini et al. (1999) found independent motion consistently occurs between the rearfoot, metatarsals and hallux during level walking. While bone pin studies by Nester et al. (2007), Lundgren et al. (2008), and Wolf et al. (2008) confirmed surface markers were able to identify functional motions of the underlying bones within the foot.

Level walking. As the use of multi-segment foot models is relatively new, the motions captured thus far have been primarily during walking gait on level ground (Jenkyn, Anas, & Nichol, 2009; Kidder et al., 1996; Leardini et al., 1999). Further, comparison between studies of distal foot motion is difficult due to varying foot segment definitions and definitions of neutral stance. However, during level walking, typical motion of the rearfoot is dorsiflexed at contact, plantarflexion as the foot becomes flat then dorsiflexion until toe off to begin swing. Between the rearfoot and midfoot the joint is relatively neutral to plantarflexed during weight acceptance, slightly dorsiflexes during mid-stance and plantarflexes along with the rearfoot for toe-off (Rankine, Long, Canseco, & Harris, 2008).

Steps. As stairs are a more challenging task than level walking it is possible early adaptations due to age or fall risk may be seen during step negotiation that are not apparent during level ground walking. In a landing task from a 40 cm box comparing kinematics of the foot as a single segment or five segments, differences were found within the multi-segment model that were not evident using the single segment model (De Ridder et al., 2015). In another landing study comparing different stiffness landing mats on a drop jump of 80 and 115 cm, variations were seen within the distal foot joints, while the tibiotalar joint was not influenced by the different stiffness of the mats (Arampatzis, Bruggemann, & Klapsing, 2002). Only two studies to date have examined step descent with a multi-segment foot model. One study utilized a multi-segment foot model during descent of a single step (19.7 cm) and level walking to investigate differences between patients with midfoot arthritis and age matched controls (Rao et al., 2009). For the level walking trials no differences were found between the two groups in calcaneus eversion excursion, however, during step descent those with midfoot arthritis demonstrated significantly more excursion than matched controls. The opposite was found with the first metatarsal phalangeal joint range of motion; during the step task no differences were found but in level walking the midfoot arthritis group had less plantarflexion range of motion than controls. The second multi-segment foot model step study by Gerstle et al. (2017) examined differences in young adults across different step heights (5 cm, 15 cm, 25 cm). An increase in step height increased the likelihood of a forefoot landing strategy and required greater distal foot range of motion. The differences found within the distal foot demonstrate the importance of examining the various modes of locomotion with a multi-segment foot model.

Changes with age/fall risk. Only a few studies have focused on changes to the distal foot during aging. Older adults were more likely to have more pronated feet, decreased range of motion in both the ankle as well as the first metatarsal phalangeal joint, and a higher prevalence of deformities (G. Scott, Menz, & Newcombe, 2007). Additionally, isometric toe flexor strength was found to be decreased by

almost 30% in healthy older adults compared to younger counterparts (Endo, Ashton-Miller, & Alexander, 2002). Only two studies specifically examine age differences utilizing a multi-segment foot model. Arnold et al. (2014) utilized a five segment model (shank, calcaneus, midfoot, forefoot, hallux) to examine older and younger adults during level walking, finding the older adults had less mobile mid- and forefoot joints and were less plantarflexed at the rearfoot during toe-off. In agreement with Arnold et al. (2014), a four segment foot model (shank, rearfoot, forefoot, hallux) study by D. Y. Lee et al. (2017) found the sagittal plane forefoot range of motion of older adults to be less than younger adults during level walking. Regarding changes within the distal foot and fall risk, currently no studies have investigated differences between older adults with and without a fall history. However, it has been noted that older adults with foot pain are more likely to experience a fall (Menz et al., 2006). The lack of studies examining the distal foot and fall history, and the age-related distal foot differences during level walking highlight the importance of utilizing multi-segment foot models to investigate other high risk forms of gait such as step descent. Doing so will help track the progression of chronic pathologies and assist in developing training protocols to prolong mobility.

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Appendix B: Research Flyer

Research Participants Needed for Step Negotiation Study

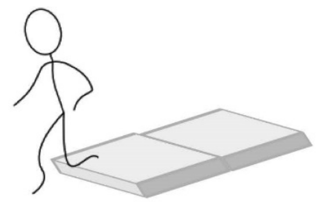
University of Wisconsin – Milwaukee
Gait and Biodynamics Laboratory, USRB 285

Title: Transition step mechanics: how influential are age and fall history?

Purpose: The purpose of this study is to investigate joint motion and lower extremity muscle activity differences during a step descent in young women, older women that have not fallen, and older women that have fallen.

Who can participate?

- Women
- Ages 18-40 OR 65+
- No current or recent (within 30 days) lower extremity injuries
- No major surgery to lower extremities in the past year
- No medications or medical conditions that impair balance
- Not pregnant
- Able to walk & step off a 17 cm (6.7 in) curb without assistance



What will I do? (~3 hours):

- Initial Screening: Phone assessment (~15 min)
  -General Health and Fall risk questionnaire
- Preliminary procedures (~20 min)
  -Questionnaires about difficulty with various daily tasks and physical activity
  -Height, weight, and ankle & hip range of motion measured
  -
- Step gait analysis (~1 hour 30 min)
  - Walk, step down a single 17 cm (6.7 in) step and continue walking.
- Muscle strength testing (55 min)

Will I receive anything for participating?

- Yes!
- Each participant will receive a $25 gift card

Questions?

Principal Investigator:
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Scan this QR code to sign up!
Or contact us via phone or email

This research project has been approved by the University of Wisconsin-Milwaukee Institutional Review Board for the Protection of Human Subjects (IRB Protocol Number 18.226, expires 4/11/2018)

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Appendix C: Inclusion/exclusion Phone Screening form

How old are you?

In the last 30 days have you had any lower extremity injuries?

Have you ever had surgery to your back or either of your lower extremities?

How long ago was your surgery?

Do you have any persistent pain associated with your surgery?

Do you have any limitations of activities of daily living due to your surgery?

How many prescription medications are you currently taking?

Do any of your medications impair your balance?

Do you have a medical condition that may impair your balance?

Have you been diagnosed with cardiovascular &/or neurological conditions? (stroke, poorly controlled hypertension, recent myocardial infarction; diabetes, multiple sclerosis, Parkinson's, etc.)

Do you have any orthopedic conditions/arthritis limiting activities of daily living?

Do you wear multi-focal glasses?

Can you walk and step down from a curb (~6.7 inches) without assistance?

How tall are you?

What is your weight?

Have you ever fallen?

When was your last fall?

How many times have you fallen in the last 12 months?

What were the circumstances of your fall(s)?

Are you pregnant?

Falls risk assessment questionnaire (El Miedany, 2011)
Over the past year:

	Yes/No	Points
Have you had more than one fall		>1fall = 2 points
Has your walking speed slowed/has your gait changed		1.5
Have you lost your balance		1
Do you have problems with your sight		1
Has your grip strength gotten weaker		1
1 year increase from 60yr		0.02
	Total score:	

Scores of 3.5 or greater indicating greater risk of falling

Six-Item Screener for Cognitive Impairment (Callahan, 2002)

I would like to ask you some questions that ask you to use your memory. I am going to name three objects. Please wait until I say all three words, then repeat them. Remember what they are because I am going to ask you to name them again in a few minutes. Please repeat these words for me: **APPLE – TABLE – PENNY;**

If alternate words needed: **(Grass – Paper – Shoe)**

Did patient correctly repeat all three words? Yes ________ No _______

(Interviewer may repeat names up to 3 times if necessary but repetition not scored)

1. What year is this?	0	1
2. What month is this?	0	1
3. What is the day of the week?	0	1

What were the three objects I asked you to remember?

Apple	0	1
Table	0	1
Penny	0	1

TOTAL ______________

Cut-off score of 4 or more errors = cognitive impairment

Appendix D: General Health & Function Questionnaire

The Foot & Ankle Disability Index (FADI) (Martin, 1999)
Modified

Participant ID: Date:

Please answer each question with one response that most closely describes your condition within the past week.
Please write what part of your lower extremity (Hip, Knee, Ankle, and/or Foot) is the main cause of the difficulty

Question	No difficulty	Slight difficulty	Moderate difficulty	Extreme difficulty	Unable
Standing					
Walking on even ground					
Walking on even ground without shoes					
Walking up hills					
Walking down hills					
Going up stairs					
Going down stairs					
Walking on uneven ground					
Stepping up and down curbs					
Squatting					
Sleeping					
Coming up to your toes					
Walking initially					
Walking 5 minutes or less					
Walking approximately 10 minutes					
Walking 15 minutes or greater					
Home responsibilities					
Activities of daily living					
Personal care					
Light to moderate work (standing, walking)					
Heavy work (push/pulling, climbing, carrying)					
Recreational activities					
	None	Slight	Moderate	Extreme	Unbearable
General level of pain					
Pain at rest					
Pain during your normal activity					
Pain first thing in the morning					

Rapid Assessment of Physical Activity

Physical Activities are activities where you move and increase your heart rate above its resting rate, whether you do them for pleasure, work, or transportation.

The following questions ask about the amount and intensity of physical activity you usually do. The intensity of the activity is related to the amount of energy you use to do these activities.

Examples of physical activity intensity levels:

Light activities • your heart beats slightly faster than normal • you can talk and sing	 Walking Leisurely  Stretching  Vacuuming or Light Yard Work
Moderate activities • your heart beats faster than normal • you can talk but not sing	 Fast Walking  Aerobics Class  Strength Training  Swimming Gently
Vigorous activities • your heart rate increases a lot • you can't talk or your talking is broken up by large breaths	 Stair Machine  Jogging or Running  Tennis, Racquetball, Pickleball or Badminton

How physically active are you? *(Check one answer on each line)*

			Does this accurately describe you?	
RAPA 1	1	I rarely or never do any physical activities.	Yes ☐	No ☐
	2	I do some **light** or **moderate** physical activities, but not every week.	Yes ☐	No ☐
	3	I do some **light** physical activity every week.	Yes ☐	No ☐
	4	I do **moderate** physical activities every week, but less than 30 minutes a day or 5 days a week.	Yes ☐	No ☐
	5	I do **vigorous** physical activities every week, but less than 20 minutes a day or 3 days a week.	Yes ☐	No ☐
	6	I do 30 minutes or more a day of **moderate** physical activities, 5 or more days a week.	Yes ☐	No ☐
	7	I do 20 minutes or more a day of **vigorous** physical activities, 3 or more days a week.	Yes ☐	No ☐
RAPA 2 (3 = Both 1 & 2)	1	I do activities to increase muscle **strength**, such as lifting weights or calisthenics, once a week or more.	Yes ☐	No ☐
	2	I do activities to improve **flexibility**, such as stretching or yoga, once a week or more.	Yes ☐	No ☐

Appendix E: Scoring for the FADI

Score:					
Question	No difficulty at all	Slight difficulty	Moderate difficulty	Extreme difficulty	Unable to do
Standing	3.9	2.9	1.9	1	0
Walking on even ground	3.9	2.9	1.9	1	0
Walking on even ground without shoes	3.9	2.9	1.9	1	0
Walking up hills	3.9	2.9	1.9	1	0
Walking down hills	3.9	2.9	1.9	1	0
Going up stairs	3.9	2.9	1.9	1	0
Going down stairs	3.9	2.9	1.9	1	0
Walking on uneven ground	3.9	2.9	1.9	1	0
Stepping up and down curbs	3.9	2.9	1.9	1	0
Squatting	3.9	2.9	1.9	1	0
Sleeping	3.9	2.9	1.9	1	0
Coming up to your toes	3.9	2.9	1.9	1	0
Walking initially	3.9	2.9	1.9	1	0
Walking 5 minutes or less	3.9	2.9	1.9	1	0
Walking approximately 10 minutes	3.9	2.9	1.9	1	0
Walking 15 minutes or greater	3.9	2.9	1.9	1	0
Home responsibilities	3.9	2.9	1.9	1	0
Activities of daily living	3.9	2.9	1.9	1	0
Personal care	3.9	2.9	1.9	1	0
Light to moderate work (standing, walking)	3.9	2.9	1.9	1	0
Heavy work (push/pulling, climbing, carrying)	3.9	2.9	1.9	1	0
Recreational activities	3.9	2.9	1.9	1	0
	No pain	mild	moderate	severe	unbearable
General level of pain	3.9	2.9	1.9	1	0
Pain at rest	3.9	2.9	1.9	1	0
Pain during your normal activity	3.9	2.9	1.9	1	0
Pain first thing in the morning	3.9	2.9	1.9	1	0
Total Score					

Appendix F: Aim 1 Statistics tables

Aim 1 Descriptive variable F-test ANOVA results

Variable	F	df	p
Age	662.873	2	**<0.001**
Height	0.838	2	0.440
BMI	0.262	2	0.771
Speed	2.742	2	0.076
Five time Sit-to-Stand	8.426	2	**0.001**
RAPA	0.373	2	0.691
Right Hip abductors	15.218	2	**<0.001**
Left Hip abductors	14.462	2	**<0.001**
Right Rectus femoris	18.503	2	**<0.001**
Left Rectus femoris	19.382	2	**<0.001**
Right Biceps femoris	12.532	2	**<0.001**
Left Biceps femoris	16.632	2	**<0.001**
Right Tibialis anterior	1.998	2	0.148
Left Tibialis anterior	3.653	2	**0.034**
Left Gastrocnemius	0.597	2	0.555
Right Peroneals	6.134	2	**0.004**
Right Halluces Flexors	4.507	2	**0.017**
Right ankle dorsiflexion ROM	5.587	2	**0.007**
Left ankle dorsiflexion ROM	3.476	2	**0.04**

Aim 1 Descriptive variable Welch's ANOVA results

Variable	Statistic	df 1	df 2	p
Modified FADI	21.751	2	21	**<0.001**
FRAS	28.535	2	26	**<0.001**
Right Gastrocnemius	1.553	2	27	0.230
Left hip extension ROM	4.139	2	28	**0.027**

Aim 1 MANOVA results

Effect	Wilks' Lambda	F	Hypothesis df	Error df	Sig.
Lead limb minimal clearance joint angles	.607	1.240	16	70	.261
Trail limb minimal clearance joint angles	.609	1.229	16	70	.269
Initial contact angles & Trail displacement	.419	2.057	18	68	**.017**

Aim 1 ANOVA results

Variable	F	df	p
Lead minimum clearance	0.481	2	0.622
Trail minimum clearance	0.995	2	0.378
Lead foot displacement	9.569	2	**<0.001**

Aim 1 Initial contact follow-up ANOVA results

Variable	F	df	p
Trail foot displacement	0.581	2	0.564
Trail hip Frontal plane	1.852	2	0.170
Trail hip Sagittal plane	1.557	2	0.223
Trail knee Sagittal plane	0.022	2	0.978
Trail ankle Sagittal plane	0.331	2	0.720
Lead hip Frontal plane	0.160	2	0.852
Lead hip Sagittal plane	1.599	2	0.214
Lead knee Sagittal plane	5.587	2	**0.007**
Lead ankle Sagittal plane	0.051	2	0.950

Appendix G: Aim 2 Statistics tables

Aim 2 MANOVA results

Effect	Wilks' Lambda	F	Hypothesis df	Error df	Sig.
Descent Peak Moments	0.721	1.736	8	80	0.101
Descent Peak Eccentric Power	0.712	1.853	8	80	0.079
Landing Peak Moments	0.710	1.824	8	78	0.085
Landing Peak Eccentric Power	0.677	2.099	8	78	**0.046**
Trail Limb Co-Activation	0.802	2.273	4	78	0.069
Lead Limb Co-Activation	0.940	0.644	4	82	0.633

Aim 2 Landing Eccentric Power follow-up ANOVA results

Variable	**F**	**df**	**p**
Frontal plane Hip	2.932	2	0.064
Sagittal plane Hip	4.082	2	**0.024**
Sagittal plane Knee	4.069	2	**0.024**
Sagittal plane Ankle	0.289	2	0.751

Aim 2 Landing Phase Integrated Peroneal EMG ANOVA results

Variable	**Welch**	**df 1**	**df 2**	**p**
Landing Phase Integrated Peroneal EMG	12.134	2	26	**<0.001**

Appendix H: Aim 3 Statistics tables

Aim 3 MANOVA results

Effect	Wilks' Lambda	F	Hypothesis df	Error df	Sig.
Distal foot sagittal plane initial contact angles	0.723	1.340	10	76	0.225
Distal foot frontal plane initial contact angles	0.801	1.567	6	80	0.168
Distal foot sagittal plane Range of Motion	0.587	2.319	10	76	**0.019**
Distal foot frontal plane Range of Motion	0.804	1.533	6	80	0.178
Proximal joint landing phase range of motion	0.581	2.373	10	76	**0.017**

Aim 3 Follow-up ANOVA results

Variable	**F**	**df**	**p**
Frontal plane hip ROM	7.605	2	**0.002**
Sagittal plane hip ROM	6.799	2	**0.003**
Sagittal plane knee ROM	6.369	2	**0.004**
Sagittal plane rearfoot ROM	1.250	2	0.297
Sagittal plane medial midfoot ROM	6.118	2	**0.005**
Sagittal plane lateral midfoot ROM	8.038	2	**0.001**
Sagittal plane medial forefoot ROM	0.358	2	0.701
Sagittal plane lateral forefoot ROM	0.004	2	0.996

Curriculum Vitae

EDUCATION

September 2014- Present	**University of Wisconsin-Milwaukee, WI** **PhD in Kinesiology, concentration in Neuromechanics** Dissertation: "Transition step mechanics, how influential are age and fall risk?"
December 2014	**University of Wisconsin-Milwaukee, WI** **Master's in Kinesiology, concentration in Neuromechanics** Thesis: "Foot and ankle kinematic and lower extremity muscle activity during descent from varying step heights"
May 2006	**Spring Arbor University, Spring Arbor, MI** **Secondary Teacher certification in Biology and** **Exercise Sport Science minor**
May 2001	**Denison University, Granville, OH** **Bachelor of Science in Biology**

EXPERIENCE

Fall 2017 – Present
Aug. 2012-Fall 2015
University of Wisconsin-Milwaukee, WI, Teaching Assistant
Taught and graded lab sections:
- Principles of Motor Learning (KIN 361)
- Biomechanics (KIN 320)
- Anatomical Kinesiology (KIN 325)
- Graduate Occupational Therapy Musculoskeletal Pathology and Occupational Function (OT 704)
- Graded online course Health Aspects of Exercise and Nutrition (KIN 200)
- Led discussions and graded Introduction to Kinesiology (KIN 200)

2013-Present
Little Switzerland, Slinger, WI, Ski Instructor
Instructor of beginner and intermediate lessons for all ages.

Fall 2018-Present
2016
University of Wisconsin-Milwaukee; Milwaukee, WI, Ad Hoc Professor
Online instructor for Introduction to Kinesiology (KIN 200)
Instructor for undergraduate Biomechanics (KIN 320) and managed lab graduate teaching assistants.

Spring 2016 – Summer 2017
University of Wisconsin-Milwaukee; Milwaukee, WI, Graduate Research Assistant
Responsible for participant recruitment and data collection of 160 participants to form a normative gait database with Moire Phase Tracking (Metria Innovation Inc.) system.
Provided feedback to Metria Innovation Inc. to provide a more clinician-friendly software.

August 2006- July 2012
Lumen Christi High School, Jackson, MI, High School Science Teacher
Developed and implemented curriculum for General Science and Physics, taught Biology.
Head Coach Junior Varsity Soccer.

Summer 2008
Philmont Scout Ranch, Cimarron, NM, Ranger
Trained high school scout crews in backcountry skills.
Planned and led a 20-day excursion as a Rayado Ranger.

Fall 2005
Spring Arbor University; Spring Arbor, MI, Ad Hoc Professor
Lectured and facilitated lab for Personal Fitness Class (ESS100).

Summer 2004 - 2006
Jackson County Youth Center; Jackson, MI, Summer-School Science Teacher
Prepared and organized lesson plans and instructed general science to students ages 11-17 years.

Sept 2002-June 2004
Jackson County Intermediate School District; Jackson, MI, Substitute Teacher
Taught grades K-12 within four districts and a charter school

Fall 2003
Dahlem Environmental Education Center; Jackson, MI, Fall Naturalist/ Intern
Researched and prepared resources; Instructed grades Pre-K through 5; Maintained equipment.

Aug 2001- Summer 2003
YMCA Storer Camps; Jackson, MI, Program Instructor and Trail Guide
Taught Natural Science, Cultural History, Environmental Awareness, Team building for students in grades3-8.
Organized logistics, equipment and directed Junior High and High School students on backpacking trips, ranging 8-17 days, to various locations around the United States.

RESEARCH

Manuscripts:

Gerstle, E., Keenan K., O'Connor K., Cobb S. (2018). Muscle activity of the lower leg during descent from varying step heights. *Journal of Electromyography and Kinesiology, 42, 57-65.*

Gerstle, E., O'Connor K., Keenan K., Cobb S. (2017). Foot and ankle kinematics during descent from varying step heights. *Journal of Applied Biomechanics, 33(6), 435-459.*

Conference Abstracts/ Presentations:

Gerstle, E., O'Connor, K., Slavens, B.A., Keenan, K., Cobb, S.C. Transition step mechanics: How influential are age and fall history? ISB/ASB 2019 Podium Presentation

Gerstle, E., Rodriguez, K., Cobb, S.C. A comparison of preferred and requested step landing strategies. ASB Midwestern Regional Conference, Spring 2017

Gerstle, E., O'Connor, K., Keenan, K., Cobb, S.C. Lower extremity muscle activity during descent from varying step heights. GCMAS National Conference Spring 2016; CHS Spring 2016 Research Symposium Podium Presentation

Gerstle, E., O'Connor, K., Keenan, K., Cobb, S.C. Foot and ankle kinematics during descent from varying step heights. ASB National Conference Summer 2015; CHS Fall 2014 Research Symposium Podium Presentation

Grant Proposals:
ASB Graduate Student Grant-In-Aid
"Transition step mechanics, how influential are age and fall history?"
Submitted: January 2018
Amount requested: $2000. Amount funded: $1000

ISB Matching Dissertation Grant
"Transition step mechanics, how influential are age and fall risk?"
Submitted: December 2017
Amount requested: $2000. Amount funded: $2000

UWM College of Health Science Student Research Grant Award
"Kinematic differences in step negotiation across young adults, older non-fallers and older fallers."
Submitted: March 2017
Amount requested: $2000. Amount funded: $2000

GCMAS Student Travel Scholarship
"Lower extremity muscle activity during descent from varying step heights."
Submitted: December 2015
Amount requested: $400. Amount funded: $400

UWM College of Health Science Student Research Grant Award
"Biomechanical analysis of foot and ankle kinematics and lower extremity muscle activity during descent from varying step heights"
Submitted: March 2014
Amount requested: $500. Amount funded: $500

Denison University Senior Honors Project, Anderson Summer Scholar Grant
Identified, collected, and preserved herbaceous specimen from the Denison University Biological Reserve.
Submitted: Summer 2000
Amount requested: $2000 Amount funded: $2000

Memberships in Professional Organizations

American Society of Biomechanics, 2013-present
Gait & Clinical Movement Analysis Society, 2016- present
International Society of Biomechanics, 2017 - present
Professional Ski Instructors of America, 2013 –present

Volunteer

Whitefish Bay Community Garden Volunteer, Summer 2019

Judge for University of Wisconsin – Milwaukee Undergraduate Research Symposium, Spring 2019

Administrative and technical work for RestoreTheHonor.org, Milwaukee, WI, 2014-2016
Brochure layout and website design

Belayer at Urban Ecology Center Climbing Wall, Open climbs Ages 6 - Adult, 2013

Small Group leader for Spring Arbor Free Methodist Church, Spring Arbor, MI, 2003-2010
Facilitated weekly middle and high school student small groups, chaperoned weekend retreats and weeklong missions trips.