# The influence of age on the maintenance of frontal plane dynamic stability

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THESIS

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This thesis is dedicated to my wife, Leslie, Audrey, our daughter, and my family. To Leslie and my family, thank you for being there step-by-step and encouraging me when I needed it.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| BOS | Base of support |
| COM | Center of mass |
| COS | Crossover step |
| CSR | Compensatory stepping response |
| HAT | Head arms and trunk |
| *LSS* | Loaded Sidestep |
| *MOS* | Margin of stability |
| $MOS_{min}$ | Minimum margin of stability |
| $MOS_{avg}$ | Average margin of stability between footstrike and ipsilateral toeoff |
| SS | Sidestep |
| SSS | Sidestep sequence |
| xCOM | extrapolated center of mass |
| $\omega_0$ | Eigenfreqency of a non inverted pendulum |

# SUMMARY

Compared to forward or backward-directed falls, laterally-directed falls significantly increase the risk of hip fracture by older adults. Identifying contributing factors that lead to laterally-directed falls is of clinical importance. Subsequently, the long-term goal of this work is to identify specific and modifiable risk factors for laterally-directed falls in older adults and to determine the effectiveness of clinical interventions targeting these risk factors. Currently however, it is unknown how laterally-directed falls are initiated. It is possible that with age the ability to regulate frontal plane center of mass (COM) motion with respect to the base of support (BOS) is compromised. This could increase the likelihood of becoming laterally unstable under conditions that challenge stability, therefore increasing the risk of a laterally-directed fall. In response to laboratory based postural disturbances the recovery responses of older adults suggest they may be particularly vulnerable to lateral instability. However, it is unknown if this finding translates to more dynamic tasks performed while walking. Thus, the purpose of the present dissertation was to investigate the effects of age on the maintenance of frontal plane dynamic stability across tasks that challenge frontal plane dynamic stability. Older and younger adults were observed while walking normally on a treadmill, while recovering from laterally-directed postural disturbances, and while performing laterally-directed steps during forward-directed walking.

Within the frontal plane, foot placement has been reported to be the primary determinant of maintaining frontal plane dynamic stability. The first investigation explored the extent to which foot placement was related to variations of the frontal plane trunk kinematics at midstance. We also investigated if this relationship was affected by age. Overall, 55% of the variance in step width was explained by variance in midstance trunk kinematics, and further, this relationship was stronger, almost 9% more variance explained, in older adults. This relationship provides a biomechanical basis by which a person could become unstable in the frontal plane. If this occurs, a compensatory reaction, such as a step, would be required.

For our second study, subjects responded to laterally-directed platform-based disturbances by performing laterally-directed compensatory steps. Predominantly, it has been reported, that subjects utilize sidesteps and crossover steps to recover from these disturbances. We found no age-related difference in the relative frequency of sidesteps and crossover steps between groups, however, older adults were less stable than younger adults upon completion of the initial stepping response. Age-related differences in the stepping responses were most pronounced for crossover steps. Although utilizing laterally-directed postural disturbances allows for precise control over the postural disturbance delivered to each subject, it may not represent the day-to-day challenges to frontal plane dynamic stability that subjects experience while walking in the community.

Performing laterally-directed steps while walking is a common task to avoid an obstacle in ones path or avoid an undesirable step location. These steps can be performed by utilizing both sidesteps and crossover steps. Overall, we found that older adults were as stable as or more stable than younger adults while performing sidesteps and crossover steps. Further, we observed that older adults utilized a greater hip abductor moment than younger adults while performing these laterally directed steps. This may be related to a more cautious approach of older adults performing these laterally-directed steps compared to younger adults.

The results of these investigations provide evidence that the reported instability of older adults in response to laterally-directed postural disturbances delivered to a standing posture may not relate to other tasks that challenge frontal plane dynamic stability. This suggests that the maintenance of frontal plane dynamic stability is context dependent, which is of clinical importance.  This information is particularly relevant when developing interventions that target risk factors related to frontal plane dynamic instability and ultimately laterally-directed falls.

# 1 **Introduction**

## 1.1 **Significance**

Falls by older adults are currently a leading public health problem due to the wide ranging effects they have on the individual, the community, and the health care system. Mortality, significant disability, decreased independence, and early admission to nursing homes are all reported sequelae associated with falls (Sterling et al., 2001). Among adults 65 and older, falls are the leading cause of unintentional injury and death and the most common cause of nonfatal injuries and hospital admissions for trauma. (data from 2008; CDC, 2011). Direct medical costs of falls to the healthcare system have been reported to be $19 billion (Stevens, 2006). In 2009, 582,000 older adults were admitted to the emergency room for injuries sustained from a fall (CDC, 2011). In fact, reducing emergency room visits due to falls by older adults by 10% has been identified as a target for Healthy People 2020 (US Department of Health and Human Services, Healthy People 2020, 2011).

It is commonly reported that one in three older adults will fall within a given year. However, this statistic is overly simplistic. Based on the number of risk factors present, older adults may have an annual fall incidence between 10% and more than 50% (Delbahare et al., 2010, Tinetti et al., 1988). Fall risk linearly scales with the presence of an increased number of risk factors (Tinetti et al., 1988). The risk of falling in a given year by subjects with four or more risk factors has been reported to be as high as 78% (Tinetti et al., 1988). The challenge for researchers and clinicians is to identify specific, modifiable risk factors of falls and to design effective targeted interventions that reduce falls. Of particular concern is the identification of risk factors that are associated with the incidence of injurious falls such as hip fractures. The majority of hip fractures, 90%, result from falls (Nevitt & Cummings, 1993), which suggests that efforts to reduce hip fractures may rely in part on decreasing the proximate cause of the fall.

The directionality of the fall may represent a risk factor amenable to targeted, clinically based intervention. Falls to the side significantly increase the likelihood of a hip fracture 600% in comparison to forward or backward directed falls (Greenspan et al 1994). Identifying contributing factors that lead to laterally-directed falls is of clinical importance. In response to laboratory based postural disturbances, the recovery responses of older adults suggest they may be particularly vulnerable to lateral instability (McIlroy et al., 1996, Maki et al., 2000, Rogers et al., 2001,Mille et al., 2005, Hilliard et al., 2008). Susceptibility to lateral instability may increase the risk for falls to the side. However, given that these investigations utilized postural disturbances delivered to standing subjects, it is currently unknown if these results relate to the ability of older adults to maintain lateral stability while walking. After all, the majority of falls, 67%, occur while walking (Berg et al., 1994).

## 1.2 **Background**

### 1.2.1 **Maintenance of dynamic stability while walking**

Dynamic stability, until more recently, has been defined by the maintenance of the position of the center of mass (COM) within an area bounded by the border of the foot or feet in contact with the support surface, called the base of support (BOS). This more traditional static definition of stability has been expanded upon to not only consider the position, but also the velocity vector of the COM with respect to the edge of the BOS (Hof, 2005). The position and normalized velocity of the COM define a new term called the extrapolated COM (xCOM). The xCOM is referenced to the BOS to quantify the margin of stability (MOS). The MOS is expressed in units of distance and has been suggested to be proportional to the minimum impulse that is required to cause the xCOM to extend beyond the border of the BOS (Hof, 2005), thus defining a dynamically unstable system. Theoretically, the more positive the MOS, the more dynamically stable the subject, and, alternatively, a negative MOS will require that the subject perform a compensatory response, such as a step, to restore dynamic stability. This measure has previously been utilized to quantify the dynamic stability of subjects recovering from postural disturbances and while walking normally (Arampatzis et al., 2008, Hurt et al., 2011, Hof et al., 2007).

On a step-by-step basis, frontal plane stability is tightly regulated around a constant minimum MOS (Hof et al., 2007). This suggests a strong coupling between frontal plane COM kinematics and step width. Thus, it is possible that the variations to step width, reported as step width variability, are not simply the product of a noisy sensorimotor system (Harris & Wolpert, 1998) but may, in part, be related to the control of frontal plane stability. Each step establishes a lateral border of the BOS within which the kinematics of the COM must be arrested and reversed in preparation for the next step. Thus, it is reasonable that adjustments to foot placement within the frontal plane are taken to aid in the control of COM kinematics, and thus, the maintenance of frontal plane dynamic stability. Adjustments to foot placement would likely be influenced by feedback related to the kinematics of the COM. Given the decreased fidelity of the aging sensorimotor system, it is possible that this relationship would be weaker in older adults compared to young. A failure to make necessary adjustments to step width may result in frontal plane instability that would require a compensatory response, such as a step, to regain frontal plane dynamic stability. The form that these compensatory stepping responses can take when initiated from a quasi-static position has been studied (Maki et al., 2000, Mille et al., 2005).

### 1.2.2. Lateral stability and postural disturbances

Previous investigations suggest that, compared to younger adults, older adults have an impaired ability to maintain frontal plane dynamic stability while stepping following a postural disturbance (McIlroy et al., 1996, Maki et al., 2000, Rogers et al., 2001, Mille et al., 2005, Hilliard et al., 2008). In response to fore-aft postural disturbances, which require a recovery step, older adults executed a more laterally directed 1st or 2nd recovery step as compared to younger adults (McIlroy et al., 1996, Rogers et al., 2001). Executing a stepping response creates a laterally unstable event insofar as the frontal plane position of the center of mass is medial to the edge of the BOS. This creates a destabilizing gravitational moment of the COM about the ankle joint of the stance limb. Thus, in addition to responding to the saggital plane instability induced by the external disturbance, instability is further created within the frontal plane, compounding the difficulty of the task.

In response to laterally-directed disturbances, older adults take more steps than young adults and may be at increased risk of limb collisions (Maki et al., 2000, Rogers et al., 2001). The need to execute extra steps to recover from an external disturbance has been related to an increased fall risk (Hilliard et al., 2008). Recovery responses to laterally-directed steps require that a series of hip adduction and abduction moments are created about the stance and swing limb to execute the step and re-establish lateral dynamic stability. The increased neuromuscular demands required and the reported age-related reduction in muscle function may explain the need for extra steps in response to postural disturbances and ultimately, a decreased ability to regulate frontal plane dynamic stability. Indeed, it has been reported that older adults produce significantly lower peak isokinetic and isometric moments about both the hip abductors and adductors and require more time to generate peak moments compared to younger adults (Johnson et al., 2004), which may reduce older adults' abilities to maintain or restore lateral stability when it is challenged.  Further, the form of the stepping response may also affect subjects' ability to re-establish dynamic stability.

Three recovery strategies in response to lateral postural disturbances have been identified (Maki et al., 2000, Rogers et al., 2005).  The three strategies include: 1) a sidestep sequence (SSS) in which a short medial step is taken with the limb that was passively unloaded by the disturbance followed by a larger lateral step with the contralateral limb, 2) a loaded leg sidestep (LLS) in which a step to extend the BOS is taken with the limb that was passively loaded by the disturbance , and 3) a crossover step (COS) in which a step to extend the BOS is taken with the limb that was passively unloaded by the disturbance and that crosses in front of or behind the stance leg.  In these studies, those older adults that utilized a COS to recover balance had an increased incidence of collisions between the stance and swing limb compared to younger adults (Maki et al., 2000, Rogers et al., 2005).  The performance of COS requires a more complicated foot trajectory and limits the extent to which the BOS can be extended laterally.  Thus, it would seem reasonable that, given the potential to utilize multiple forms of the recovery step (i.e. COS, SSS, LSS), older adults would avoid utilizing a COS to recover lateral stability.  While these studies provide information on the ability of older adults to produce a lateral recovery step to restore dynamic stability, it is currently unknown if the recovery response to postural disturbances delivered to standing subjects relate to the ability to perform laterally-directed steps during more functional tasks such as walking.

### 1.2.3 Performance of lateral steps during forward walking

Laterally-directed steps are common when walking in the community to circumvent an obstacle in the walking path or otherwise quickly avoid an undesirable step location.  The increase in lateral displacement and velocity of the COM needed to execute the step must be arrested and reversed so that the primary direction of travel (i.e. forward) can be maintained. The increased requirements to control the position and velocity of the COM with respect to the BOS, compared to normal walking, provides a discrete challenge to laterally-directed dynamic stability. Further, manipulating the available time that subjects have to prepare to execute a lateral step can provide an increased challenge to the execution of the step and maintenance of dynamic stability. It has been shown that younger adults require at least a full stride to complete a laterally-directed step after receiving a visual stimulus signaling that a lateral step is to be executed (Patla et al., 1999). Whether subjects are given specific instruction before the trial starts (preplanned) or are cued to step during the walking trial, the strategies utilized to execute the lateral step differ. For instance, subjects modify step widths under preplanned conditions to direct the COM in the appropriate direction and utilize a “hip strategy” when performing these laterally-directed steps under cued conditions (Patla et al., 1999). It is currently unknown if the amount of time subjects are provided to preplan the laterally-directed step affects the ability of subjects to re-establish lateral dynamic stability.

Finally, the size of these laterally-directed steps could also provide a further challenge to frontal plane dynamic stability. Utilizing a condition in which subjects execute lateral steps to specific locations on a laboratory walkway allow for the manipulation of the step width. Larger step widths result in greater COM displacement and velocity, which therefore, must be controlled with respect to the BOS resulting in an increased challenge to lateral dynamic stability. Given the decrease in peak force development and increase in time to peak force development of older adults compared to younger adults (Johnson et al., 2004), subjects stepping to the long target may not be able to arrest the increased lateral COM motion before the next step, therefore, becoming laterally unstable. It has yet to be established whether the reported age-related decreases in isokinetic and isometric muscular moments of older adults affect their ability to successfully execute laterally-directed steps.

## 1.3 **Purpose**

The purpose of the following four studies was to investigate the effects of age on frontal plane dynamic stability across tasks that challenge frontal plane dynamic stability. For each chapter of the dissertation, the specific purpose and hypotheses are listed below.

### **Chapter 2**

The purpose of this study was to characterize the relationship between variations in frontal plane trunk COM kinematics during the swing phase and variations in the subsequent step width.

We hypothesized that frontal plane trunk COM kinematics during swing phase would explain a significant proportion of variance in the subsequent step widths.

We further hypothesized that the relationship between trunk kinematics and step width would be stronger in younger adults.

### **Chapter 3**

The purpose of this study was to investigate the lateral stepping responses of older and younger adults while recovering from similar laterally-directed postural disturbances that required a step in every trial.

We hypothesized that the compensatory stepping response of older adults would result in an increase in the relative frequency of SSS to COS compared with younger adults.

We also hypothesized that older adults would be less dynamically stable than younger adults upon completion of the initial recovery step.

**Chapter 4**

The purpose of this study was to investigate the age-related differences to preplanned and cued COSs and sidesteps (SS) during forward locomotion.

We hypothesized that step widths of older adults in the cued lateral step conditions would be significantly smaller in magnitude than younger adults whereas no difference would be observed under preplanned conditions.

We also hypothesized that while performing these laterally-directed steps while walking, older adults would be less dynamically stable than younger adults.

**Chapter 5**

The purpose of this study was to investigate the age-related differences of subjects performing COS and SS to three different targeted step widths while walking.

We hypothesized that older adults would generate a significantly smaller hip abductor moment compared to younger adults at all step targets regardless of the type of step utilized.

We also hypothesized that older adults would be significantly less dynamically stable while performing crossover and sidesteps than younger adults, particularly at the longer step targets.

The results of the proposed investigations are *significant* because they will identify modifiable mechanisms that relate to the maintenance of frontal plane stability in older adults. It has been reported that older adults exhibit decreased laterally-directed dynamic stability while recovering from laterally-directed disturbances. It is currently unknown if the reported dynamic instabilities while recovering from laterally-directed disturbances transfer to tasks performed while walking. These studies are *innovative* because the results of these investigations will inform future assessments and interventions for fall prevention, specifically interventions that target a reduction in the incidence of laterally-directed falls.

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## 2 Variation in trunk kinematics influences variation in step width during treadmill walking by older and younger adults

### 2.1 **Introduction**

While walking, frontal plane dynamic stability is maintained through proper placement of the swing foot (Bauby & Kuo, 2000, Kuo, 1999) which is guided by active feedback processes (Bauby & Kuo, 2000, Kuo, 1999, Patla et al., 1999, Redfern et al., 1994). Foot placement, measured in the frontal plane as step width, establishes a lateral border within which the motion of the body center of mass (COM) must be arrested and reversed in preparation for the next step. If COM motion cannot be properly constrained within the lateral border of the BOS a compensatory action will be needed to re-establish lateral stability. Step-by-step control of step width ensures an adequate lateral distance is established between the BOS and COM, which in turn, contributes to the maintenance of dynamic stability.

Step width is significantly affected by age (Schrager et al., 2008). The age-related increase in step width is attributed to the selection of a more stable locomotion pattern (Murray et al., 1969). Step width variability has also been shown to be affected by age (Owings & Grabiner, 2004) and may reflect age-related increases in sensory noise that affects the precision of foot placement. However, step width variability has also been suggested to reflect active adjustments to foot placement in response to frontal plane trunk kinematics (Grabiner & Troy, 2005). The trunk, along with the head and arms, accounts for almost two-thirds of a person's body mass, highlighting the importance of controlling its motion during locomotion. Indeed, variability of trunk kinematics during gait is thought to be associated with age-related changes in the maintenance of dynamic stability (Yack & Berger, 1993, Menz et al., 2003, Moe-Nilssen et al., 2005).

Experimentally-derived evidence shows that restraining trunk motion decreases step width (Donelan et al., 2004), suggesting a relationship between trunk kinematics and control of step width. The existence of this relationship would rely on accurately sensing and responding to trunk kinematics. For example, trunk position and velocity relative to the stance leg could be sensed via somatosensory systems while the vestibular system could provide information related to acceleration of the head, arms and trunk (HAT) segment. The integration of this information could thus be utilized to provide feedback related to the dynamic states of the trunk. As humans age, the fidelity of sensory information from these systems degrade (Lord et al., 1996). It is therefore reasonable to assume that the ability of older adults to accurately sense and respond to trunk kinematics would be similarly degraded, resulting in less precise step-by-step control.

Thus, the purpose of the present study was to characterize the relationship between variations in frontal plane trunk COM kinematics during the swing phase and variations in the subsequent step width. We hypothesized that frontal plane trunk COM kinematics during swing phase would explain a significant proportion of variance in the subsequent step widths. We further hypothesized that the relationship between trunk kinematics and step width would be stronger in younger adults.

## 2.2 **Materials and Methods**

### 2.2.1 **Participants**

Twelve young adults (6 males 6 females, 170.0±9.5 cm, 67.4±8.9 kg) with an average age of 24.5±3.3 years (range 20-32) and eleven older adults (4 males 7 females,165.1± 5.43 cm, 78.0± 16.3 kg) with an average age of 60.6± 5.63 years (range 55-74) volunteered to participate in this institutionally reviewed and approved study. All older adults were screened for neurological, musculoskeletal, and cardiovascular disorders by a physician. All subjects provided written informed consent prior to participation.

2.2.2 **Data collection and analysis**

The motions of nine passive reflective markers were recorded by an eight-camera motion capture system (Motion Analysis, Santa Rosa, Ca) while the subjects walked at a self-selected velocity for 10 minutes on a motorized treadmill. Markers were placed over the $L_5S_1$ vertebra and bilaterally over the anterior superior iliac spines (ASIS), acromion processes, and the posterior aspect of the calcaneus and second metatarsophalangeal joint. The three-dimensional marker positions were tracked using commercial software (Motion Analysis, Santa Rosa, CA), and analyzed off-line using custom software in Matlab (MathWorks, Natick, MA).

The location of the trunk COM was estimated from three-dimensional spatial coordinates of markers placed over the acromion processes, the bilateral ASIS and $L_5S_1$ (Winter, 2005). Frontal plane trunk kinematics were extracted at midstance, which we defined as the instant when frontal plane velocity of the trunk COM was zero. Trunk COM position was defined as the horizontal distance between the vertical projection of the trunk COM on the ground and the centroid of the line connecting the heel and metatarsal markers of the stance foot. Velocity and acceleration of the trunk COM were calculated using a forward finite differences algorithm. Positive values for each were directed toward the swing limb.

Step width was calculated as the difference between frontal plane locations of foot segment centroids during consecutive stance phases. Thus, for each step, the stance foot centroid defined the origin of a local coordinate system from which trunk COM position and step width were calculated. For regression analysis, the trunk COM position and acceleration at each midstance were paired with the following step width (i.e. values for midstance trunk COM kinematics during left stance were paired with value of the next right step width).

2.2.3 **Statistical analysis:**

Multiple linear regression analysis was used to relate variance in trunk COM position and acceleration at midstance and variance in subsequent step widths. Dummy variables were coded into the model to account for group membership (i.e., young and old) and stepping limb (i.e. left and right step width) which were subsequently used to create interaction terms with the continuous variables (i.e. trunk COM position and trunk COM acceleration (Kleinbuam et al. 2008) . Multiple partial F tests, which quantify the additional variance explained by a subset of variables within the model, were used to evaluate the effect of group membership and stepping limb on the relationship between trunk kinematics and step width. A significant interaction between group membership (younger vs. older) and stepping limb (left vs. right) with trunk kinematics resulted in four regression equations of the form:

$$\textit{Step Width}_{\text{(group, limb)}} = \beta_0 + \beta_1(\text{position}) + \beta_2(\text{acceleration}) \qquad (1)$$

The first hypothesis was tested by evaluating whether the single regression model with all variables included explained a significant proportion of the variance in step width. The second hypothesis was tested by performing a multiple partial F test to investigate whether interaction terms measuring the effect of group membership explained a significant amount of variance in step width. If group membership significantly interacted with trunk COM position and acceleration regressed onto step width, the strength of this interaction was explored with the Johnson-Neyman technique (Potthoff, 1983). Using this technique, regions are defined in which between-group differences in expected values for step width are significantly different using the regression equations and collected trunk kinematics. Lastly, in the regression model we tested whether the relationship between frontal plane trunk kinematics and the subsequent step width was bilaterally symmetric. Symmetry in gait is generally assumed, however, asymmetric gait patterns of healthy adults have been reported in the literature (Sadeghi et al 2000). Typically symmetry is assessed by comparing the average values of a given variable from the left and right side. However the relationship being characterized here involves complex interactions between trunk control and step width on a step-by-step basis which cannot be ascertained by considering mean values alone. Thus, bilateral symmetry was not assumed. We tested the symmetry of the relationship by performing a multiple partial F test on terms in the model that included stepping limb. For differences detected in group membership and stepping limb, an effect size was calculated using Cohen $f^2$ for which effect sizes of 0.02, 0.15, and 0.35 are termed small, medium, and large, respectively (Cohen, 1988). A hierarchical model was implemented in which trunk COM position and acceleration was individually added to the model followed by the interaction terms. This was performed to ensure that each variable explained a unique proportion of the variance in step width. Variability of kinematic variables was quantified as the standard deviation of each subject's mean. Independent t-tests were used to explore between-group differences in the means and variability of variables used in the regression analysis. An algorithm was written in Matlab to perform the Johnson-Neyman technique. All other statistical tests were performed using SPSS 12.0 (SPSS, Inc, Chicago, IL) and evaluated at the 0.05 level of significance.

## 2.3 **Results**

### 2.3.1 **Regression analysis of the aggregate dataset**

Step-by-step variations in frontal plane trunk kinematics at midstance appeared to influence the step-by-step variations in step width that occurred, on average, 186± 0.036ms later. Overall the regression accounted for 53.9% of the variance in step width ($F_{(10,17041)} = 1973.1$, $p<0.001$). Trunk COM position and acceleration accounted for 28.1% and 14.8% of the variance in step width respectively. Further, tests for collinearity, which is a measure of the magnitude of the relationship between independent variables, yielded a variance inflation factor of 8.1 and 5.9 for trunk COM position and acceleration respectively. A general rule of thumb for regression models suggests that values for the variance inflation factor should be below 10 (Kleinbuam et al., 2008).

2.3.2 **Between-group descriptive data**

Older and younger adults walked at similar self-selected treadmill velocities (0.86 m/s ±0.24 and 0.82 m/s ±0.21, $t(21) = 0.412$, $p=0.68$) for older and younger adults respectively. There was a tendency for older adults to walk with wider steps (14%) larger trunk COM positions (26%) and accelerations (16%) than younger adults, although these differences did not achieve significance (TABLE 1). Older adults exhibited 17% smaller step width variability ($t(21) = 2.155$, $p=0.033$), 48% ($t(21) = 14.392$, $p<0.001$) and 12% ($t(21) = 0.888$, $p=0.49$) less variability of trunk COM position and acceleration than the younger adults.

TABLE I. DESCRIPTIVE STATISTICS FOR THE CONTINUOUS VARIABLES USED IN THE REGRESSION ANALYSIS IS LISTED RELATIVE TO GROUP MEMBERSHIP. AN (*) DENOTES A SIGNIFICANT DIFFERENCE BETWEEN GROUPS (P<0.05)

| | Step width (mm) | Step Width Variability | Trunk COM Position (mm) | Trunk COM Position Variability | Trunk COM Acceleration ($mm/s^2$) | Trunk COM Acceleration Variability |
|---|---|---|---|---|---|---|
| Younger Adults | 124.7±29.6 | 28.3 ± 6.2* | 33.9 ± 11.6 | 25.2 ± 2.3* | 554.8 ± 113.5 | 157.8 ± 54.9 |
| Older Adults | 142.4±31.8 | 23.5 ± 3.9 | 42.8 ± 14.6 | 13.2 ± 1.6 | 642.2 ± 161.2 | 139.5 ± 42.3 |

### 2.3.3 **Regression analysis of between-group differences**

Age affected the relationship between frontal plane trunk kinematics at midstance and the subsequent step widths. The multiple partial F statistic revealed a significant interaction between group membership and the kinematic variables within the model ($F(5, 17040) = 1814.821$, $p<0.001$, Cohen $f^2$ 0.154). A significant interaction of group membership when regressing trunk kinematics onto step width can be visualized as intersecting planes of best fit (inset Figure 1). Exploring this interaction using the Johnson-Neyman analysis revealed that 90% of the trunk kinematic data entered into the regression equations would result in computed step widths between younger and older adults that would be significantly different (Figure 1).

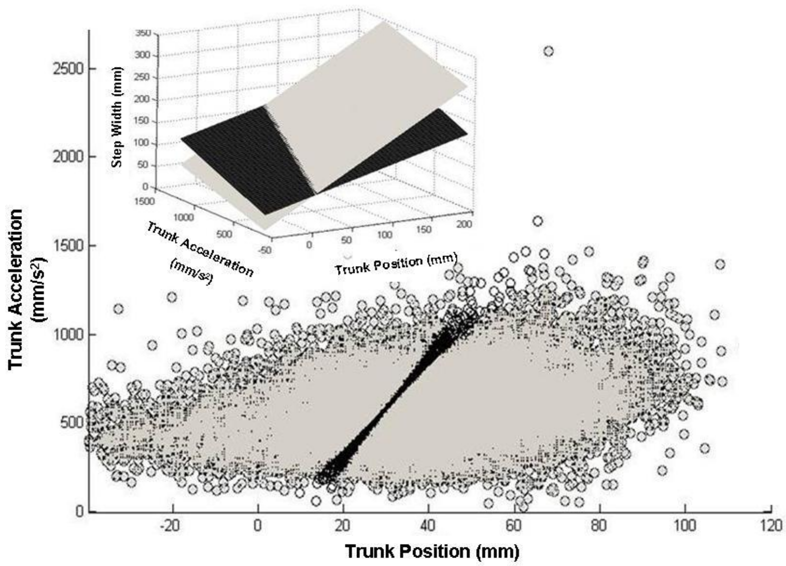


Figure 1. (Inset) Planes created by the regression equations for older adults (grey) and younger adults (black). A significant interaction between groups of both trunk COM position and trunk COM acceleration with step width is illustrated by the intersecting planes. (Main Figure) Results of the Johnson-Neyman analysis show that, except for the black region, all combinations of trunk position and trunk acceleration would produce an expected step width that would be significantly different between groups.

2.3.4 **Regression analysis of between-limb differences**

The relationship between variations in frontal plane trunk kinematics at midstance and variations in step width appeared to be bilaterally asymmetric. A significant interaction of stepping limb on trunk kinematics regressed onto step width was revealed by the multiple partial F statistic ($F$ (5, 17040) =1814.821, $p<0.001$, Cohen $f^2$ 0.184). A significant interaction between group membership (young vs. old) and stepping limb (right vs. left) with trunk kinematics at midstance and subsequent step widths was detected thus resulting in four regression equations (TABLE II).

TABLE II. REGRESSION EQUATIONS FROM THE LINEAR REGRESSION ANALYSIS. THE STANDARDIZED REGRESSION COEFFICIENTS ARE IN PARENTHESES BELOW THE UNSTANDARDIZED REGRESSION COEFFICIENTS. THE AMOUNT OF EXPLAINED VARIANCE OF STEP WIDTH (I.E. $R^2$) IS LISTED WITH EACH EQUATION.

| | |
|---|---|
| $SW_{old,right}$ **= 58.88 + 1.29*position + 0.04*acceleration**<br>**(0.80) (0.20)** | **Overall $R^2$=0.63** |
| $SW_{old,left}$ **= 56.68 + 0.84* position + 0.08*acceleration**<br>**(0.50) (0.53)** | **Overall $R^2$ =0.50** |
| $SW_{young,right}$**= 65.49+ 1.03* position + 0.08*acceleration**<br>**(0.64) (0.52)** | **Overall $R^2$ =0.55** |
| $SW_{young,left}$ **= 33.01 + 1.10 * position + 0.06*acceleration**<br>**(0.66) (0.41)** | **Overall $R^2$ =0.41** |

## 2.4. **Discussion**

The primary hypothesis of this study was that frontal plane trunk kinematics would explain a significant proportion of variance in the subsequent step widths. Trunk COM position and acceleration explained over half of the variance in step width (~54%) in the aggregate dataset. Thus we reject the null hypothesis and provide evidence to support the alternative hypothesis. We also hypothesized that the relationship between trunk kinematics at midstance and step width would be stronger for younger than older adults. On average more of the explained variance in step width was accounted for by trunk states at midstance for the older adults. Thus we reject the null hypothesis and further failed to provide evidence in support of the alternative hypothesis.

The relationship we show between trunk kinematics at midstance and step width is consistent with previously reported findings (Donelan et al., 2004, Winter, 1995). For example, compared to a control condition, walking with external pelvic stabilization decreased step width 47% while lateral displacement of the COM decreased 60% for young subjects (Donelan et al., 2004). However, another study reported a weak correlation between step width variability and interstride medio-lateral trunk acceleration variability (Moe-Nilssen & Helbostad, 2005). This finding is in contrast to the strong linear relationship reported here. This is likely because we related variations in trunk kinematics to variations in step width on a step-by-step basis whereas the aforementioned study correlated single measures of step width variability and trunk acceleration variability across all subjects. Thus, although variability provides a global measure of how step width and trunk kinematics vary about their respective means, the current analysis provides an understanding of how trunk COM kinematics may influence step kinematics step-by-step.

It is reasonable to assume that information associated with trunk COM position and acceleration may be utilized to adjust step width thus ensuring stable gait. For example, it has been suggested that instantaneous acceleration of the COM could be utilized by the central nervous system to predict future dynamic states (Hasson et al., 2008). Within the context of the present study, greater frontal plane trunk COM accelerations at midstance could be utilized to predict a higher frontal plane velocity of the trunk COM at the subsequent heelstrike. In such a case a wider step will be necessary to ensure stability. Mismatches between frontal plane trunk COM kinematics and subsequent step widths may increase the probability of a loss of stability. Step-by-step adjustments to step width could be influenced by either feedforward or feedback mechanisms during steady-state gait. Implicit in our interpretation of the regression is that step-by-step adjustments to step width are representative of a feedback process through which the swing foot trajectory is modified in response to predicted upcoming kinematic states of the body at heelstrike. We further suggest that trunk COM kinematics at midstance, after which frontal plane motion is directed towards the swing foot, may serve as a reasonable surrogate to predict such kinematic states.

On average older adults exhibited a stronger relationship between trunk COM kinematics at midstance and the subsequent step widths than younger adults, accounting for about nine percent more variance (Table 2). One interpretation of this result is that older adults had a more robust ability to sense and respond to trunk COM kinematics. However, insofar as the fidelity of sensory information from these systems is known to degrade with age (Lord et al., 1996) this interpretation seems implausible. Another interpretation is that the stronger relationship between trunk kinematics and step width of older adults reflects increased voluntary control to maintain dynamic stability while walking on the treadmill. This seems plausible given the decreased variability of step width and trunk COM kinematics compared to the younger adults as well as, the perception that a foot placement partially off of the treadmill belt could result in a dynamically unstable situation. Such a situation would require a compensatory response to restore stability, something older adults would likely attempt to avoid. Presently it is unknown if the age-related differences we report would be similar in overground conditions. Thus, without the benefit of further examination, the age-related difference between frontal plane trunk COM kinematics at midstance and the subsequent step width cannot presently be fully explained.

Finally, this study showed that the relationship between trunk kinematics at midstance and the subsequent step widths were bilaterally asymmetric. Although this finding is not the primary focus of the manuscript these results are important because they add to the body of literature that suggests that certain aspects of normal walking in healthy adults may not be bilaterally symmetric. Other evidence for left-right asymmetries have previously been described in the literature using kinetic and kinematic data for upper and lower extremities while walking (MacKinnon & Winter, 1993, Sparrow et al., 2008, Strike & Taylor, 2009, Kuhtz-Bushbeck et al., 2008, Giakas,1997). Small asymmetric variations in morphology and limb dominance (Sadeghi et al., 2000) could affect the complex interactions of upper and lower body control while walking. Some evidence in the literature suggests that asymmetries of certain parameters are related to a specific function during gait (Sadeghi et al., 2000). Although we observed left-right differences in this relationship we are presently unsure if this asymmetry serves a specific function or affects frontal plane stability differentially depending on stepping limb and thus warrants further study.

We recognize potential limitations in the present study. The self-selected walking speed of the younger adults was slower than what is commonly reported in literature. However, although we cannot explain why these subjects selected such a slow velocity, walking speed-related changes to frontal plane COM motion have been shown to co-vary with step width (Orendurff et al., 2004). The sensitivity of the relationship between trunk COM kinematics at midstance and step width to walking speed is of interest but will require further systematic study. Lastly the extent to which the relationship between step-by-step variations in step width and trunk COM kinematics would be altered overground versus treadmill is not presently known. The criticism of treadmill use relates mostly to reported differences between treadmill and overground walking. Although minimal differences have been reported in sagittal plane kinematics during treadmill versus overground walking (Lee & Hilder, 2008, Riley et al., 2007) we have recently shown within-subject differences in frontal plane step parameters for overground and treadmill walking (Rosenblatt & Grabiner, 2010). An important methodological advantage of using the treadmill, however, is the ability to collect hundreds of consecutive steps. This has been suggested as important to deriving an accurate measure of step kinematic variability (Owings &Grabiner, 2003).

### 2.4.1 **Conclusion**

In summary, we found a strong relationship between step-by-step variations in midstance trunk COM kinematics and step width during treadmill walking by young and older adults. This relationship provides more information than classical measures of variability and may reflect modifications to swing leg trajectory based on information related to, but not necessarily derived from measures of trunk COM kinematics. After all, two of the major systems that underlie dynamic stability, i.e., the visual and vestibular systems, reside in the head. The present study suggests that improper sensing of COM trunk kinematics, and in turn incorrect prediction of future kinematic states may result in a step width which is insufficient to ensure frontal plane stability.

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# 3 Age-dependent differences of the compensatory stepping response to laterally-directed platform-based disturbances

## 3.1 <u>Introduction</u>

The maintenance of frontal plane dynamic stability requires that a sufficiently wide step is taken to arrest and reverse the lateral motion of the center of mass (COM) in preparation for the next step. We have previously shown, that step-by-step, adjustments to foot placement were related to frontal plane trunk COM kinematics at the previous midstance, thus ensuring that dynamic stability is maintained (Chapter 2). Conversely, a step width that is insufficient to arrest and reverse the lateral motion of the COM before it extends beyond the lateral border of the BOS will result in a dynamically unstable situation. Under these conditions a compensatory reaction will be required to regain frontal plane dynamic stability. Lateral instability may increase the likelihood of a laterally-directed fall, which is particularly problematic because falls to the side increase the risk of hip fracture in older adults 600% compared to forward or backward directed falls (Greesnspan et al., 1994). Given that older adults appear particularly vulnerable to lateral instability (Maki et al., 2000, McIlroy & Maki, 1996, Mille et al., 2005, Rogers et al., 2001, Schrager et al., 2008), understanding deficiencies in the compensatory reactions to laterally-directed disturbances is necessary to develop effective interventions to improve lateral stability and potentially reduce fall-risk.

The relationship between frontal plane COM kinematics and the BOS can be manipulated by the use of external postural disturbances, allowing for the study of compensatory reactions. In response to an external postural disturbance, changing the location of the BOS using a compensatory stepping response (CSR) is a common strategy utilized to restore dynamic stability. Significant age-related differences of the CSR to postural disturbances suggest that older adults may have difficulty regaining dynamic stability within the frontal plane (Maki et al. 2000, McIlroy & Maki, 1996, Mille et al., 2005, Rogers et al., 2001). For instance, in response to fore-aft disturbances, the CSR of older adults resulted in a more laterally-directed first or second recovery step as compared to younger adults (Rogers et al., 2001, McIlroy and Maki, 1996). The wider first step suggests that the older adults may have been compensating for a perceived lateral instability (Rogers et al., 2001). The need for a laterally-directed second step suggests that performing the CSR created a lateral instability through insufficient control over frontal plane COM motion (McIlroy and Maki,1996). In response to laterally-directed postural disturbances, the reliance on a multiple step CSR in all trials and the age-related increase in the incidence of limb collisions by older adults are related to an increase in fall-risk (Hilliard et al., 2008, Maki et al., 2000). Consistently utilizing multiple steps provides evidence of an inability to plan and execute a sufficient CSR to regain control of the frontal plane COM kinematics. Under these conditions the instability caused by the disturbance is propagated across multiple steps. Furthermore, limb collisions result from insufficient end point control of foot trajectory with respect to the stance limb and, when they occur, increase the likelihood of a fall (Maki et al., 2000).

The CSR to laterally-directed postural disturbances delivered to subjects while standing can take three forms, a crossover step (COS), a sidestep sequence (SSS) and a loaded sidestep (LSS). The performance of a SSS involves an initial medial step with the limb that was passively unloaded by the disturbance, followed by a step with the contralateral limb, which acts to extend the BOS. For a COS, the limb passively unloaded by the disturbance crosses in front of or behind the stance limb to extend the BOS. Finally, the performance of a LSS involves extending the BOS with the limb that was passively loaded by the disturbance. In response to platform based disturbances, it has been reported that COS and SSS are primarily utilized (Maki et al., 2000, Figure 1). Older adults appear to prefer the SSS whereas results are mixed for the preferred CSR of younger adults (Maki et al., 1996, Maki et al., 2000, Hurt et al., 2011). For both a SSS and a COS, the limb that is passively unloaded by the disturbance initiates the response (Figure 1). However the potential for the swing limb to contact the stance limb is much greater for a COS because the swing limb must circumnavigate the stance limb (Mille et al., 2005, Maki et al., 2000). This may explain older adults' preference for the SSS. Limb collisions have adverse consequences on the recovery response, requiring the need for extra compensatory reactions to recover dynamic stability. Recently, researchers have attempted to reduce the incidence of limb collisions as part of a balance training program by training older adults to avoid performing a COS (Mansfield et al. 2007). However, the experimental evidence that suggests older adults are at risk for interlimb collisions during laterally-directed CSRs is limited.

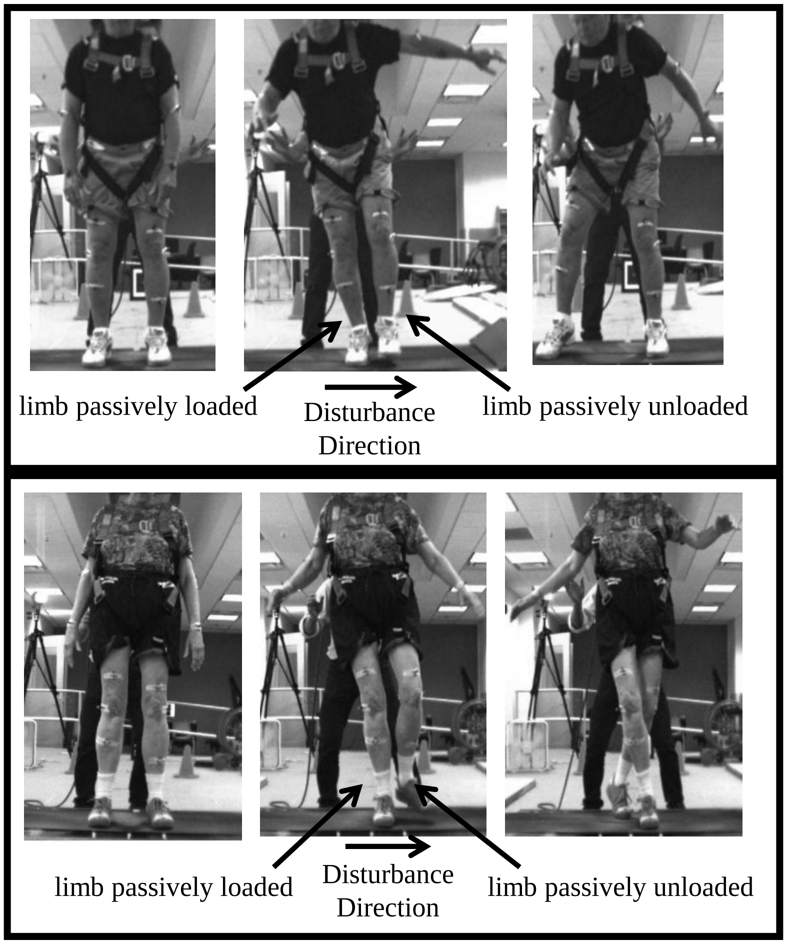


Figure 2. Example of the movement sequences involved in a sidestepping strategy (top) and a crossover step strategy (bottom). The panels for each recovery type, from left to right, are the initial stance position before disturbance onset, the initial response to the disturbance, and the final stepping position, respectively. Limbs passively loaded and unloaded by the disturbance are marked.

Currently, only one study has investigated age-related differences of the CSR following laterally-directed platform disturbances. In this study, the disturbances initiated a CSR by older and younger adults in only 43% and 20% of trials, respectively (Maki et al., 2000). Further, the data presented was primarily frequency data related to the CSR. Thus, little information exists on the mechanics of the stepping response to laterally-directed platform disturbances. Recovering from laterally-directed disturbances relies on the hip adductors and abductors to initiate and execute the stepping responses and arrest the lateral COM motion. Given the reported age-related reductions in the rate of peak isometric moment development and a marked decrease in the average isokinetic peak moment of both hip abduction and hip adduction (Johnson et al., 2004 ), it is reasonable to expect age related differences in measures of dynamic stability of the recovery response. It has previously been reported, using a measure of stability that considers both the position and velocity of the COM with respect to the base of support (BOS) called the margin of stability (MOS), that younger adults were more stable using a SSS in comparison to a COS (Hurt et al., 2011). This was in spite of similar foot displacements between the SSS and COS which ostensibly relates to anatomical limitations based on the initial limb configuration. In addition to the type of step utilized, successful recovery from postural disturbances may relate to the ability to limit trunk motion. Indeed, age-related differences in trunk motion have been reported in response to frontal plane postural disturbances (Mille et al., 2005, Allum et al., 2002).

The purpose of this study was to investigate the lateral stepping responses of older and younger adults while recovering from similar laterally-directed postural disturbances that required a step in every trial. We were particularly interested in characterizing the age-related effects on step choice and the mechanics of each step. We hypothesized that the compensatory stepping response of older adults would result in an increase in the relative frequency of SSS to COS compared with younger adults. We also hypothesized that older adults would be less dynamically stable than younger adults upon completion of the initial recovery step.

## 3.2 Materials and Methods

### 3.2.1 Participants

Ten healthy young adults (6 women and 4 men, 172.5±9.3cm, 67.9±12.4 kg) with an average age of 24± 2.0 years (range 20-31) and eighteen older adults (9 women and 9 men, height: 174.9± 8.6 cm, mass 82.6± 15.8 kg), with an average age of 72.8± 5.2 years, (range 65-81) volunteered to participate in this institutionally reviewed and approved study. Subjects were not permitted to participate if they provided affirmation to questions related to any neurological, musculoskeletal, or other injuries or disorders that would limit their functional mobility, as this would not allow for safe participation. Also, older adults were not allowed to participate if they used a cane or an assistive walking device or if the bone mineral density of their proximal femur was less than 0.65 g/cm$^2$ (Cummings et al., 1993) measured using dual energy X-ray absorptiometry (Hologic QDR 1000, Waltham, Mass., USA). All subjects provided written informed consent prior to participation.

All older subjects completed the Godin leisure time questionnaire (Godin & Shephard,, 1985) along with the physical functioning subsection of the Medical Outcome Survey (MOS) 36-item short form health survey (Ware & Sherbourne, 1992).

3.2.2 **Data collection**

Data from younger adults has previously been published (Hurt et al., 2011). For the present analysis, the data for young adults was truncated to the first 20 disturbances for comparison with older adults who were exposed to 20 laterally-directed disturbances. For both subjects, the direction of the disturbances was randomized to reduce the ability of the subjects to adjust their initial posture in anticipation of a specific disturbance direction. The disturbance waveform was triangular in shape with a peak velocity and total displacement of 1.0 ms$^{-1}$ and 0.24 m respectively (Figure 2), and was similar to that of a previous study that elicited a stepping response in all trials (Maki et al., 1996).

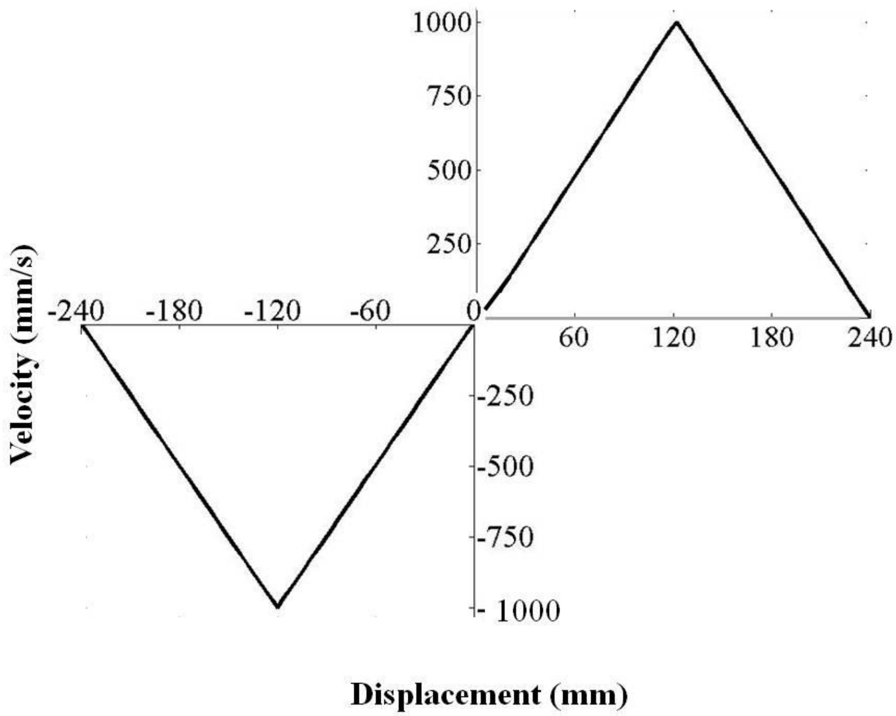


Figure 3. Displacement-velocity profiles for the bi-directional disturbances delivered to the subjects in this investigation.

The platform used to deliver the disturbances was a dual-belt microprocessor-controlled, stepper motor-driven treadmill (Simbex, Lebanon NH) with a belt length and width (across both belts) of 1.5m and 0.6 m respectively. The belts were programmed to move synchronously. For this study, subjects stood on both belts with their feet perpendicular to the direction the treadmill belts traveled, enabling a multiple recovery step response to the laterally-directed disturbances.

For each trial, the stance-width was standardized as the horizontal distance between the ASIS markers and was approximately 15% of body height for both groups. Subjects were instructed to "do whatever it takes to recover your balance".

Passive reflective markers were placed bilaterally on the acromiom, the medial epicondyle of the humerus, between the heads of ulna and the posterior radial tuberosity, over the inferior angle of the left scapula, and on the anterior surface along the long axis of the thigh and shank so as not to be collinear with the markers on the lateral malleolus, and approximately over the knee joint center over the flexion-extension axis. Markers were also placed over the ASIS and the $L_5S_1$ as well as on the subjects' shoes, over the heel and over the 2$^{nd}$ metatarsal phalangeal joint. The three-dimensional marker positions were recorded using an eight camera motion capture system (Motion Analysis, Santa Rosa, CA) recorded at 120 Hz. The three-dimensional marker positions were tracked using commercial software (Cortex, Motion Analysis, Santa Rosa, CA). Frontal plane kinematics of the compensatory stepping response was computed off-line using custom software in Matlab (MathWorks, Natick, MA).

### 3.2.3 **Data analysis**

For each disturbance, the form of the CSR was documented and subsequently confirmed during data analysis based on the following: a COS was identified if the limb that was passively unloaded by the disturbance achieved foot-off (quantified when both the vertical velocity of the heel marker and the second metatarsophalangeal joint marker exceeded 0.07m/s) and crossed, within the frontal plane, anteriorly or posteriorly to the centroid of the stance foot; a LSS was identified if the limb that was passively unloaded by the disturbance did not achieve foot-off and the loaded limb was used to extend the BOS laterally; finally, a SSS was identified if the limb that was passively unloaded by the disturbance achieved foot-off and the foot moved medially toward but not past the passively loaded limb. The foot centroids were calculated as the midpoint of the line connecting markers on the subjects' shoes over the heel and distal end of the 2nd metatarsal phalangeal joint. We quantified step efficiency of the recovery response as the number of steps subjects utilized to recover from the disturbances. An extra-step recovery response was defined as any trial during which extra steps were executed to extend the BOS laterally beyond the initial recovery response. Although two steps comprise the SSS recovery response, the initial medially directed step executed with the passively unloaded limb does not extend the lateral border of the BOS. Thus, we did not consider this multiple-step recovery response to be an extra recovery step, which is consistent with previous literature (Maki et al., 2000).

The position of COM for each subject was calculated using anthropometric estimations (Winter, 2005) applied to a ten segment model generated from the three-dimensional marker positions. The velocity of the COM (vCOM) was calculated using a first-central difference algorithm. The position and vCOM was used to create a term, the extrapolated COM (xCOM- Eq. 1) that is calculated by summing the frontal plane position of the COM with the normalized frontal plane vCOM. The velocity of the COM is normalized by the eigenfrequency of a non-inverted pendulum with length 1.34 times the trochanteric height ($\omega_0$) (Massen & Kodde, 1979). The eignenfrequency of a non-inverted pendulum refers to the natural frequency or period of a pendulum of a given length, and results in the xCOM having units of distance (i.e. mm).

$$xCOM = COM + v_{COM} / \omega_0 \qquad (1)$$

Theoretically, in the frontal plane, a subject is stable if their xCOM remains medial to the lateral border of their BOS. The more medial the xCOM is relative the lateral edge of the BOS, the more stable the subject. Conversely, subjects are considered unstable if their xCOM moves lateral to the edge of the BOS. Ultimately, stability is quantified by expressing the margin of stability (MOS), which is calculated as the distance between the xCOM and the lateral border of the BOS (Hof et al., 2005- Eq. 2). The MOS is proportional to the impulse needed to cause the MOS to become negative.

$$MOS = BOS_{lat} - xCOM. \qquad (2)$$

The MOS has previously been utilized to quantify the stability of subjects performing dynamic tasks such as walking and recovering from postural disturbances (Hof, 2008, Arampatzis et al., 2008 Hasson et al., 2008, Hurt et al., 2011). The MOS was calculated during the entire CSR. The minimum MOS (MOSmin) was extracted from a window that was defined by footstrike to 50ms after footstrike. If the xCOM at footstrike was beyond the lateral border of the BOS (i.e. a negative MOSmin), then the value at footstrike was recorded as the minimum value. However, if the xCOM was medial to the lateral border of the BOS at footstrike but then extended beyond that border within the sampling window, a -0.01 was entered as the MOSmin. It was reasoned that if the xCOM extended beyond the lateral border of the BOS within the sampling window, the value for the MOSmin would continue to become increasingly more negative. Thus, the value for MOSmin would theoretically be dependent on the size of the sampling window (i.e. the larger the window the more negative the number).

Recovery step kinematics was quantified with respect to the foot that was used to laterally extend the BOS. Step displacement of the foot in the frontal plane was calculated as the difference in position of the centroid of the recovery foot at foot-off and footstrike. We also quantified the minimum distance between the stance and swing limb for both recovery responses.

For those subjects performing a SSS, the minimum distance between the frontal plane positions of the foot centroids was calculated. For the COS response, the saggital plane distance between the centroids of the stance and swing foot segments at the instant when they crossed was also characterized. Step onset latency was quantified as the difference in time between disturbance onset and the initiation of the recovery step. Recovery step time was quantified as the difference in time between the disturbance onset and footstrike of the recovery step. For the SSS, step time was calculated as the difference in time between foot-off of the first medially directed step and the footstrike of the second laterally-directed step.

To quantify angular excursions for lateral trunk flexion, minimum and maximum values were extracted from a window defined by disturbance onset to 100 ms after footstrike. The absolute value of trunk excursion measures was utilized to allow comparison of these variables with respect to the bi-directional disturbances. Finally, we descriptively compared the vCOM of single and extra step responses of older adults by computing the means and 95% confidence intervals from a window defined by treadmill onset to 100ms after footstrike of the recovery limb

### 3.2.4 **Statistical analysis**

To test the hypothesis that older adults would exhibit an increase in the relative frequency of SSS to COS compared to younger adults, we first calculated the relative percentage of SSS to COS. The difference between groups was tested using a Mann-Whitney U test. To test the hypothesis that the MOSmin of younger adults would be larger in magnitude than older adults, we first subdivided MOSmin with respect to the recovery response utilized. This was compared by utilizing a two factor ANOVA (age X step). The difference in step efficiency between groups was also tested using a Mann-Whitney U test. To explore differences in frontal plane kinematic variables between group and step type, we utilized a two factor (age X step) ANOVA. Statistical significance was set at the 0.05 level. Effect size was reported as $\eta^2$, which is interpreted as the amount of variance in the dependent variable that can be accounted for by the independent variable (Levine & Hullet, 2002). This is similar to $R^2$ in an analysis using a regression approach.

$$\eta^2 = SS_{between}/SS_{total} \quad (3)$$

All statistics were performed with SPSS 17.0 (Chicago, IL).

### 3.3 **Results**

#### 3.3.1 **Frequency data of the compensatory stepping response**

Older and younger adults primarily utilized a SSS in response to laterally-directed disturbances. Of the three possible recovery strategies, both older and younger adults primarily utilized a SSS or a COS. Thus, subsequent analysis only considered recovery responses utilizing these responses. Both older and younger adults utilized a SSS in 73% and 68% of all trials involving a COS or SSS, respectively (TABLE III). No significant difference was found in the relative frequencies of SSS to COS between groups (U = 67.5 $n_1$=18, $n_2$=10, p=0.271).

No difference in the utilization of an extra stepping response was found between younger and older adults. The recovery response of older adults included extra recovery steps in 25% of all stepping trials in comparison to 15% of recovery responses in younger adults. This difference was not significant (U = 69.0 $n_1$=18, $n_2$=10, p=294, Figure 3).

Considering the extra stepping responses between step types, a COS resulted in a greater proportion of extra stepping responses for older adults compared to younger adults whereas no difference existed between SSS response. Subjects utilizing the COS response performed an extra stepping response with greater frequency than subjects performing a SSS ($U = 34.00$ $n_1=15$, $n_2=25$, $p<0.001$). Older adults utilizing a SSS executed extra steps in 4% (10/254) of recovery responses compared to 3% (4/125) of trials for younger adults ($U = 68.00$ $n_1=16$, $n_2=9$, $p=0.846$). Older adults utilized extra steps in 87% of the COS trials (82/94), which was significantly different than younger adults who took extra steps in 38% (22/58) of COS step trials ($U = 8.00$ $n_1=10$, $n_2=5$, $p=0.028$). For older adults, the extra step responses involving COS and SSS responses resulted from a recovery step that was insufficient to re-establish stability (i.e. a negative MOS) in half of those trials, 46/92. The majority of those trials, (40 of 92) were related to the performance of a COS. Only one limb collision occurred across subjects in this study. That subject was attempting to perform a COS. The collision did lead to the older subject being fully supported by the safety harness qualifying as an unambiguous fall.

T**ABLE III.** PATTERN OF CSR TO LATERALLY-DIRECTED DISTURBANCES AMONG OLDER AND YOUNGER ADULTS. ALSO LISTED ARE STEP EFFICIENCIES FOR BOTH GROUPS.

| | | **Recovery Strategy** | | | | |
|---|---|---|---|---|---|---|
| | **Subject** | **SSS** | **LSS** | **COS** | **Single step** | **Extra step** |
| Older Adults | 1 | 8 | 0 | 8 | 6 | 10 |
| | 2 | 20 | 0 | 0 | 20 | 0 |
| | 3 | 19 | 1 | 0 | 20 | 0 |
| | 4 | 14 | 0 | 6 | 14 | 6 |
| | 5 | 10 | 0 | 9 | 9 | 10 |
| | 6 | 0 | 0 | 20 | 4 | 16 |
| | 7 | 10 | 0 | 10 | 10 | 10 |
| | 8 | 19 | 1 | 0 | 20 | 0 |
| | 9 | 20 | 0 | 0 | 20 | 0 |
| | 10 | 15 | 0 | 5 | 13 | 7 |
| | 11 | 12 | 0 | 8 | 12 | 8 |
| | 12 | 20 | 0 | 0 | 20 | 0 |
| | 13 | 20 | 0 | 0 | 20 | 0 |
| | 14 | 8 | 5 | 7 | 16 | 4 |
| | 15 | 20 | 0 | 0 | 19 | 1 |
| | 16 | 20 | 0 | 0 | 20 | 0 |
| | 17 | 0 | 0 | 20 | 4 | 16 |
| | 18 | 19 | 0 | 1 | 16 | 4 |
| | **Total** | **254** | **7** | **94** | **263** | **92** |
| Young Adults | 1 | 11 | 0 | 9 | 11 | 9 |
| | 2 | 10 | 10 | 0 | 20 | 0 |
| | 3 | 14 | 4 | 2 | 20 | 0 |
| | 4 | 20 | 0 | 0 | 20 | 0 |
| | 5 | 0 | 0 | 20 | 19 | 1 |
| | 6 | 19 | 1 | 0 | 20 | 0 |
| | 7 | 14 | 0 | 6 | 19 | 1 |
| | 8 | 10 | 0 | 10 | 15 | 5 |
| | 9 | 20 | 0 | 0 | 20 | 0 |
| | 10 | 7 | 0 | 13 | 9 | 11 |
| | **Total** | **125** | **15** | **60** | **174** | **28** |

SSS=sidestep sequence LSS=loaded sidestep COS=crossover step

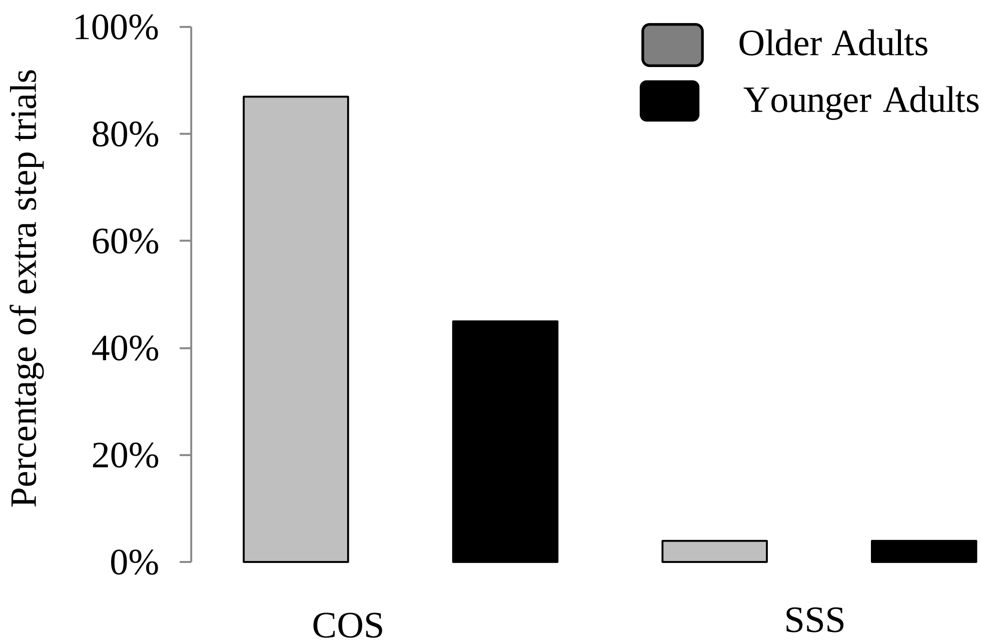


Figure 4.Percentage of trials for older and younger adults that required an extra step response among the sidestep sequence and crossover step response.

3.3.2 **Dynamic stability between step types**

Older adults were less dynamically stable than younger adults performing a CSR to laterally-directed disturbances while the SSS conferred greater stability than the COS response. Differences in the MOSmin of the recovery response were detected between older and younger adults and between the recovery steps utilized. Within the statistical model, the step X age interaction was not significant ($F(1, 35) = 3.690$, $p=0.068$, $\eta^2 = 0.092$, Figure 4). A significant main effect of step was detected ($F(1, 35) = 37.118$, $p<0.001$, $\eta^2 = 0.520$) as well as age ($F(1, 35) = 4.814$ $p=0.031$, $\eta^2 = 0.126$). Older adults established a MOSmin that was, on average, 40% smaller in magnitude compared to younger adults. With respect to the type of step, subjects performing a SSS established a MOSmin that was three times larger in magnitude than COS.

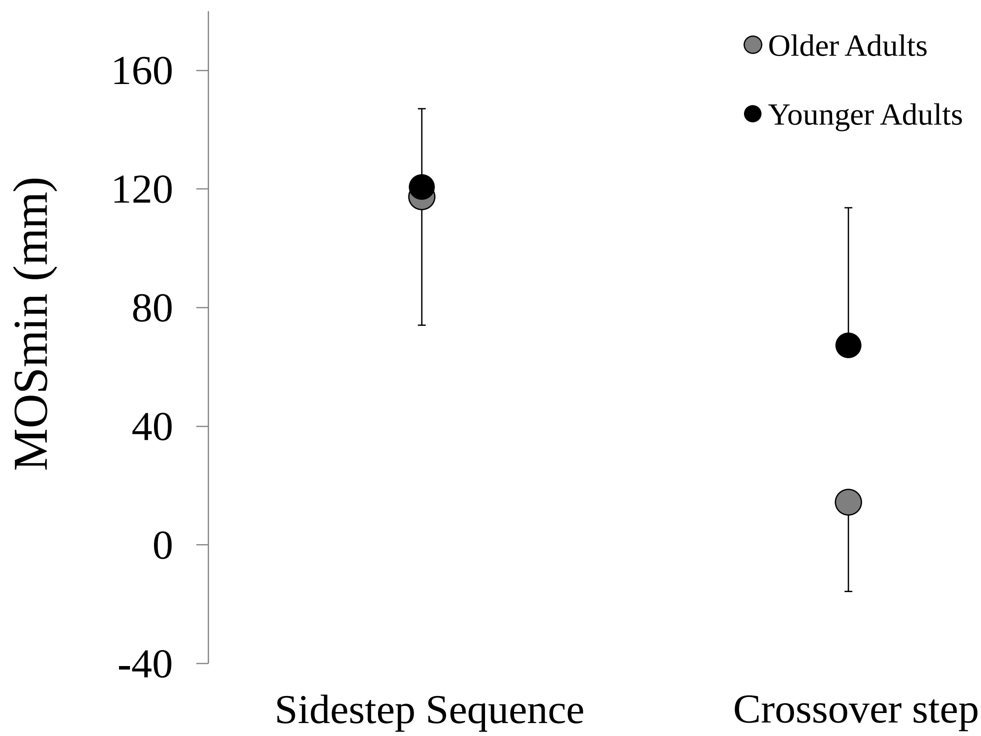


Figure 5. MOSmin by step type is shown between groups. The sidestep sequence (SSS) resulted in a larger MOSmin than the crossover steps (COS), ($p<0.001$). A significant effect of age was also detected, ($p=0.031$), although the age X step interaction was not significant ($p=0.068$).

3.3.3 **Mechanics of the compensatory stepping response**

The age-related mechanics of COS and SSS were similar except that older adults exhibited greater step onset latency and a shorter distance between their COM and BOS at footstrike compared to younger adults. Further, the COS response resulted in a longer step onset latency with a shorter distance between subjects COM and BOS compared to a SSS. A lack of significance was detected in the step type X age interaction for step onset latency (F (1, 35) =1.577, p=0.218, $\eta^2$=0.043, TABLE IV), however, a significant main effect of step (F (1, 35), 5.822, p=0.021, $\eta^2$=0.143) and age (F ( 1, 35) =8.405, p=0.006 0, $\eta^2$=0.194, TABLE IV) was detected. Significance was not detected for the interaction term (F (1, 35) =0.150, p=0.701, nor for the main effects of age and step type for step time (F (1, 35) =2.742, p>0.107 for the main effect of age, F (1,35) =1.374, p=0.249 for the main effect of step type). No significant differences were detected for step displacement within the model (F (1, 35) =0.010, p= 0.920 for the step type X age interaction, F (1,35) =0.000, p=0.997 for the main effect of age, F (1, 35) =0.109 p=0.743 for the main effect of step type). Minimum frontal plane distance between the stance and swing leg of subjects performing a SSS was not significantly different between older and younger adults (Older=122.2±35.0mm, Younger 126.8±46.3mm, F (1, 22) =0.077 p=0.783, $\eta^2$=0.004). The fore-aft distance of the swing and stance leg for subjects performing COS was also not significantly different (Older=236.1±38.3mm, Younger 253.7±18.5mm, F (1, 14) =1.213, p=0.286, $\eta^2$=0.081). The interaction of step type X age was not significant for COM position (F (1, 35) =0.250, p=0.620), however, significant main effects were detected for step type (F (1, 35) =45.638, p<0.001, $\eta^2$=0.568) and age (F (1, 35) =4.587,p=0.04, $\eta^2$=0.113, TABLE IV). With respect to trunk excursion, no significant differences were detected within the model (F (1,35) = 0.083, p>0.776 for the step type X age interaction, F (1, 35) = 0.753, p=0.391 for the main effect of age, F (1, 35) =1.332, p= 0.256 for the main effect of step type, TABLE IV). Lastly, no difference existed for the mean vCOM of older adults recovering with a single stepping response compared to those older adults that utilized a COS response that required extra steps (Figure 5). This is inferred from the overlap of the 95% confidence intervals of the time normalized velocity curves.

TABLE IV. MEANS AND STANDARD DEVIATIONS FOR KINEMATIC VARIABLES RELATED TO THE RECOVERY RESPONSE OF LATERALLY-DIRECTED TREADMILL DISTURBANCES.

| | | Step onset latency (sec) *# | Step Time (sec) | Foot Displacement (mm) | COM position (mm) *# | Trunk Excursion (deg) |
|---|---|---|---|---|---|---|
| SSS | Old | 0.20 ±0.02 | 0.47±0.14 | 293.8± 68.1 | 201.8± 48.7 | 14.6±5.0 |
| | Young | 0.19 ±0.02 | 0.42±0.12 | 289.9± 53.9 | 228.9± 49.0 | 12.9±4.7 |
| COS | Old | 0.23 ±0.03 | 0.53±0.05 | 298.9± 80.5 | 81.8± 51.6 | 12.5±3.7 |
| | Young | 0.19±0.01 | 0.45±0.10 | 297.5± 50.0 | 125.5± 45.3 | 11.5±3.2 |

***** significant main effect of Age, **#** significant main effect Step

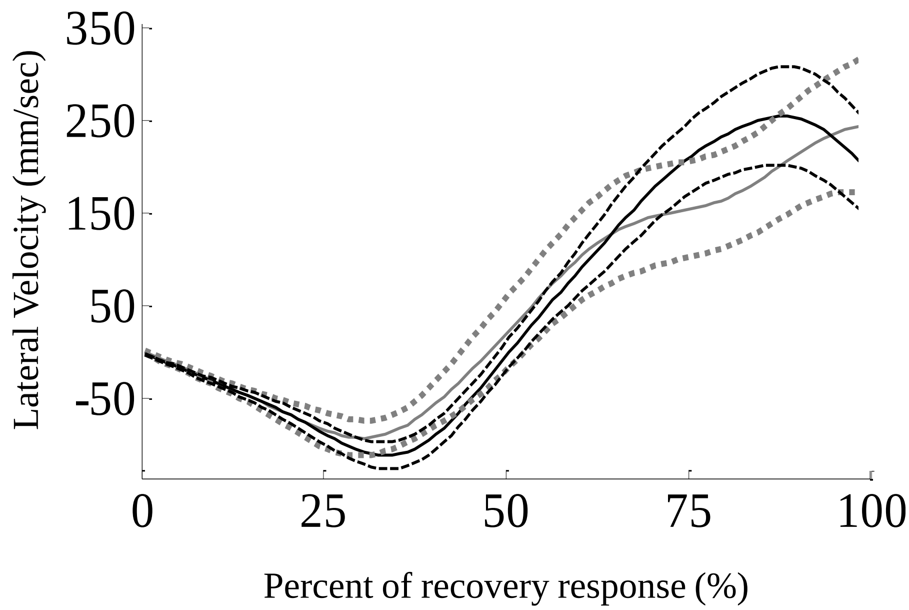


Figure 6. Average medial-lateral center of mass (COM) velocity curve and 95% confidence intervals for subjects who utilized a sidestep sequence that did not require an extra step (black) and those older adults who utilized an extra step COS response. The average curves were all normalized as a percent of the recovery response from treadmill onset to 100ms after footstrike of the recovery limb.

### 3.3.4 **Physical functioning and activity questionnaires.**

The older adults utilized in this study were, on average, a healthy and active cohort. The range of older subject scores on the Godin leisure-time questionnaire was 14-185 with an average of 52.7 ± 39.0. Older adults reported a high level of physical functioning with respect to MOS-36 with scores ranging from 75 to 100 with an overall average of 86.4 ± 8.5. A previous study employing the physical functioning scale of the MOS-36 among a group of independently ambulatory community dwelling older adults reported a mean of 74.7 ± 19.4 (Bohannon et al., 2010). No correlation was detected between the Godin leisure-time questionnaire and the physical functioning scale of the MOS36 ($r(17) = 0.05$, $p = 0.834$).

### 3.4 **Discussion**

The purpose of this study was to investigate the lateral stepping responses of older and younger adults while recovering from similar laterally-directed treadmill disturbances that required a step in every trial. We hypothesized that the compensatory stepping response of older adults would result in an increase in the relative frequency of SSS to COS compared with younger adults. Both older and younger adults utilized a SSS in 73% and 68% of trials, which was not significantly different. Thus we accept the null hypothesis and failed to support our alternative hypothesis. We also hypothesized that older adults would be less dynamically stable than younger upon completion of the initial recovery step. Older adults established a MOSmin that was, on average, 40% smaller in magnitude compared to younger adults. Thus, we reject the null hypothesis and provide evidence that supports our alternative hypothesis.

#### 3.4.1 **Frequency data of the compensatory stepping response**

The results of this study suggest that for older and younger adults, the SSS was the preferred CSR. A previous investigation reported no difference in the choice of CSR across groups, although, there was a trend for older adults to utilize a SSS (29/42 CSR), and younger adults to utilize a COS (11/17 CSR) (Maki et al., 2000). In that investigation, only 25% of the disturbances required a laterally-directed step among both groups whereas 100% of the trials in the current study required subjects to step. It is possible that disturbance magnitude may affect the choice of stepping response; however, this does not appear to be the case. When younger adults were presented with disturbances of similar duration but a range of peak disturbance velocities varying between 0.6 m/s up to 1.75 m/s, subjects utilized the same CSR on all trials that they used on their first disturbance (Hurt unpublished data, 2011).

It is somewhat surprising, given the increased disturbance magnitude, that only one incidence of limb collision was recorded. Previous investigations have suggested that older adults are at increased risk of limb collisions while performing laterally-directed recovery steps (Maki et al., 2000, Mille et al., 2005). Importantly, however, it should be noted, that in both investigations, only 6% of recovery responses have involved limb collisions which, when compared statistically, was not significantly different between young and old (Maki et al., 2000). The results of the present study questions the impetus to expressly train older adults to avoid crossover steps. Currently, one training study has, as part of a multi-directional disturbance paradigm, attempted to encourage older adults to utilize a SSS to recover from laterally-directed disturbances due to the increased risk of limb collisions (Mansfield et al., 2007). Indeed limb collisions, when they do occur, can result in negative consequences as was observed in the present investigation. However, it may be more useful to train older adults to improve any deficiencies in the performance of the COS response. After all, under some circumstances, it may be necessary for subjects to execute a COS. For instance, a COS may be a necessary result of a misstep on an irregular surface that causes a medial forefoot perturbation (Theis et al,. 2007).

It was also somewhat surprising that no difference was detected in the occurrence of extra stepping responses between younger and older adults. This is in contrast to a previous investigation utilizing a platform-based laterally-directed postural disturbance, which reported that older adults required extra steps in 39% of all trials (Maki et al., 2000). In the current investigation, extra steps were utilized in 25% of all trials. Potential differences in classifying extra steps may relate to the reported discrepancies. In the current investigation, extra steps were identified only if the extra step acted to extend the BOS laterally whereas no such explicit distinction as to what constituted an extra stepping response was made in the aforementioned study (Maki et al., 2000). The previously mentioned study also did not report the occurrence of extra steps with respect to the specific CSR (i.e. SSS or COS). In the current investigation, older adults utilizing a SSS required fewer extra stepping responses compared to the COS response. The extra stepping responses of older adults performing a COS resulted from the initial step being insufficient to establish positive MOSmin in close to half of the trials, 40/82.

3.4.2 **Dynamic stability between step types**

Older adults established a significantly smaller MOSmin than younger adults while subjects utilizing a SSS established a significantly larger MOSmin. On average, no difference was detected in foot displacement, although subjects performing a SSS established a significantly greater distance between the position of the COM and the edge of the BOS at footstrike. The performance of a SSS provides the advantage of re-configuring the BOS with the initial step such that the second step in the sequence can more effectively extend the BOS than a COS. Indeed, subjects performing a SSS rarely required an extra step to complete the recovery response.

In the present investigation, we observed that older adults utilizing a COS performed extra steps to a greater extent and established a significantly smaller MOSmin compared to SSS. Thus, we elected to compare the frontal plane vCOM (Figure 5) of the extra step COS and the single step SSS. The overlap of the 95% confidence intervals of older adults vCOM curves between a single step SSS compared to the extra step COS responses suggests that the control of vCOM during the performance of the CSR was not different. The differences in step efficiency between the CSR may have resulted than from a step that was insufficiently wide to arrest the lateral momentum of the body imparted by the disturbance. Increasing the distance between the COM and BOS defines the maximum impulse that can be generated to decelerate the COM. For extra step COS responses, it has been reported that the initial step lands closer to the boundary limit of stability than COS responses involving a single recovery step (Patton et al., 2006). It is possible that performance of the COS is more difficult for older adults due to decreased range of motion with respect to hip abductors-adductors. Although we did not quantify the range of motion of older adults included in this study, another study, which reported range of motion values for 1,892 subjects, found no meaningful age-related differences for hip abductors and hip adductors (Roach & Miles, 1991). Because the instruction set delivered to subjects did not require that they try to recover within a single stepping response, it is also possible that these subjects simply chose to execute the CSR with two steps instead of one. It should be noted, however, that even with a similar instruction set as the present study (i.e. "react naturally to prevent yourself from falling"), those subjects who utilized multiple steps to recover from all ten laterally-directed postural disturbances they were exposed to, were 6.2 times more likely to fall within the subsequent year (Hilliard et al., 2008).

### 3.4.3 **Limitations**

We recognize several limitations of the current study. The sample of older adults in this study was healthy, active older adults. Incidences of hip fractures are higher in less active individuals (Nevitt & Cummings, 1993). Given that the majority of falls in older adults occur while walking, the conditions under which the CSR was studied in this investigation may have low ecological validity. However, the intent of this study was to investigate the CSR to laterally-directed disturbances and platform-based disturbances allow for a high level of control over the disturbance parameters. Future research should try to incorporate challenges to frontal plane dynamic stability under ambulatory conditions.

### 3.4.4 **Conclusions**

In summary, older and younger adults both responded to laterally-directed platform disturbances by utilizing a SSS. Older and younger adults also utilized extra steps with similar frequency. However, when considering a COS response, older adults were more likely to utilize an extra step response than younger adults. For older adults, the initial step of the COS response in over half of the extra step trials was insufficient to restore a positive MOS. This study is the first to quantify the mechanics of the stepping response to laterally-directed platform disturbances. Further, we observed that the need for extra steps by older adults related to an insufficient first step response presents a target for training to improve the CSR to laterally-directed disturbances. Given that multiple step responses may be predictive of falls in older adults, future studies should try to identify the specific mechanisms that relate to the need for multiple step responses and how those mechanisms relate to falls.

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## 4 Age-related effects on performing preplanned and cued crossover and sidesteps while walking

### 4.1 Introduction

Laterally-directed steps are common when walking in the community to circumvent an obstacle or otherwise quickly avoid an undesirable step location. These steps require an increase in the lateral displacement and velocity of the center of mass (COM) to alter its trajectory. After completion of the step, the increased displacement and velocity of the COM must then be arrested and reversed to regain the primary direction of travel (i.e. forward). The increased requirements to control the position and velocity of the COM with respect to the base of support (BOS) compared to normal walking, creates a discrete challenge to lateral dynamic stability. Here, dynamic stability refers to the condition in which the position and velocity of the COM are considered with respect to the edge of the BOS.

The increased challenge to lateral dynamic stability may be particularly problematic for older adults given their reported difficulty regaining frontal plane dynamic stability in response to external postural disturbances (Mille et al., 2005, Maki et al., 2000, Patton et al., 2006). A loss of frontal plane dynamic stability may increase the risk of a fall with a lateral component. Falls with a lateral component increase the likelihood of a hip fracture as compared to forward or backward directed falls (Greenspan et al., 1994). It is currently unknown, however, if reported frontal plane dynamic instability of older adults in response to postural disturbances translate to more ambulatory conditions. Given that most falls occur while walking and 90% of hip fractures result from a fall (Cummings et al., 1995), identifying mechanisms that relate to laterally-directed dynamic instability while walking is clinically important.

Two different strategies are utilized by subjects to perform laterally-directed steps during forward locomotion, and these strategies are dependent upon the available response time to execute the step. Under conditions in which subjects are provided instruction prior to the start of the trial, referred to as the preplanned condition, subjects alter their step width two or more steps prior to the lateral step to alter the trajectory of the COM towards the intended change of direction (Fueller et al., 2007, Patla et al., 1999). Under conditions in which a visual cue is provided after the start of the trial, referred to as the cued condition, subjects primarily alter COM trajectory with a “hip strategy”. For this strategy, the body is controlled within the frontal plane as a double pendulum with the upper body and lower body rotating in opposite directions of each other (e.g. clockwise and counterclockwise respectively) resulting in the COM being displaced (e.g. to the left in the presented example) in the desired direction of travel (Patla et al., 1999). It is currently unknown how differences in the cued and preplanned conditions affect the ability of subjects to maintain lateral stability.

The type of laterally-directed step may also affect the ability of subjects to maintain lateral stability. For instance, in response to laterally-directed disturbances to quasi-static standing posture, younger and older adults primarily respond with a crossover step (COS) or a sidestep (SS) sequence (Chapter 2). Subjects often required extra compensatory steps while performing a COS (Chapter 2, Patton et al., 2006). Further, it was also reported that older adults were less stable than younger adults (Chapter 2)

Performance of laterally-directed steps during forward locomotion can be executed by utilizing both a SS and COS. Much of the existing literature on turns and laterally-directed steps focus on how subjects reorient their body in preparation for the change in direction (Patla et al., 1999, Fuller et al., 2007, Paquette et al., 2008, Fuller et al., 2010), however, to the best of our knowledge, there is an absence of studies that have investigated how the type of step (i.e. COS or SS) interacts with the amount of time the subjects have to prepare to take that step (i.e. cued or preplanned conditions).

It is well established that a general decrease in reaction time occurs with aging (Houx & Jolles, 1993), therefore, it is reasonable to assume that, in time critical situations, older adults would have greater difficulty performing cued lateral steps. For instance, older adults required, on average, an extra 112 milliseconds compared to younger adults to successfully complete a turning task while walking (Cao et al., 1997). The increased time to complete the task was attributed to a decreased capacity of older adults to perceive, plan, and execute a complex and time critical task while attempting to maintain dynamic stability. Further, reported age-related reductions in the rate of moment generation of the hip abductors and hip adductors (Johnson et al., 2004) suggest that older adults may be less able to execute laterally-directed steps as effectively under time critical cued conditions in comparison to preplanned conditions.

The purpose of the present study was to investigate the age-related differences to preplanned and cued COSs and SSs during forward locomotion. Given the reported reduced functional capacity of the hip musculature and the decreases of reaction time of older adults, we hypothesized that step widths of older adults in the cued lateral step conditions would be significantly smaller in magnitude than younger adults. We further hypothesized that an absence in age-related differences in preplanned conditions would be observed. Lastly, we hypothesized that while performing these laterally-directed steps while walking, older adults would be less dynamically stable than younger adults.

## 4.2. **Materials and Methods**

### 4.2.1 **Participants**

Nineteen younger adults (9 males, 10 females, age: 22.9±3.1 years, height: 174.3±10.2 cm, mass: 71.7±13.0 kg) and eighteen older adults (9 males, 9 females age: 72.8± 5.2 years, height: 174.9± 8.6 cm, mass 78.0± 16.3 kg) volunteered to participate in this institutionally reviewed and approved study. Subjects were not permitted to participate if they provided affirmation to questions related to any neurological, musculoskeletal, or other injuries or disorders that would limit their functional mobility, as this would not allow for safe participation. Also, older adults were not allowed to participate if they used a cane or an assistive walking device or if the bone mineral density of their proximal femur was less than 0.65 $g/cm^2$ (Cummings et al. 1993), which was measured using dual energy X-ray absorptiometry (Hologic QDR 1000, Waltham, Mass., USA). All subjects provided written informed consent prior to participation.

All older subjects completed the Godin Leisure time questionnaire (Godin & Sheppard, 1985) along with the physical functioning subsection of the Medical Outcome Survey (MOS) 36-item short form health survey (Ware & Sherbourne, 1992). Finally, subjects completed the Revised Waterloo Footedness Questionnaire to assess lower limb dominance (Elias et al., 1998). Subjects performed all lateral steps with their dominant limb as the lead limb. All subjects wore their own walking shoes for the data collection.

### 4.2.2 **Data collection**

Subjects walked along a carpeted eight meter walkway. Lanes, which were 0.31 m wide (Figure 1) were demarcated on the walkway surface with white tape (Figure 1). Initially, five normal, unconstrained walking trials were collected followed by five normal walking trials that subjects were constrained to a lane. For all walking trials, subjects were instructed to walk at a speed that felt comfortable to them. For the lane walking trials, subjects were instructed to walk within the lane for the length of the walkway.

For the laterally-directed step trials, subjects performed the step into the lane adjacent to the one they started in (see Figure 1). A total of ten cued trials were performed with five catch trials that were included to minimize the ability of the subjects to preplan the performance of a laterally-directed step on a given trial. For the cued trials, an 8X10 picture frame with an array of three LEDs embedded into it was positioned at the end of the walkway at ground level. The LEDs were encased in a reflector modified from a bicycle light.

Subjects were instructed to transition into the adjacent marked lane as quickly as possible while performing the appropriate step (i.e. a SS or a COS) if the light was illuminated for a given walking trial. The light was illuminated when subjects stepped on a custom-made pressure mat that was concealed under a carpet square approximately midway along the walkway. The cue, which was integrated within a custom circuit connected to a switch, allowed the experimenter to disconnect the light from the pressure mat for the catch trials. For the preplanned lateral step trials, subjects performed five SS and COS trials. At the outset of all trials, a demonstration was provided for all subjects. If requested by the subject, multiple demonstrations of the task to be carried out for the subsequent block of trials were performed. The trials were completed in the same order for all subjects. Cued SSs and COSs were performed first, followed by preplanned SSs and COSs. Subjects did not wear a safety harness, however, a spotter walked approximately two meters to the side and slightly behind the subjects on the side to which the laterally directed steps were to be taken. The position of the spotter was selected to ensure that assistance could be provided should the subject appear to be at risk for a fall as the result of taking a laterally-directed step while not influencing the selected walking speed of the subject.

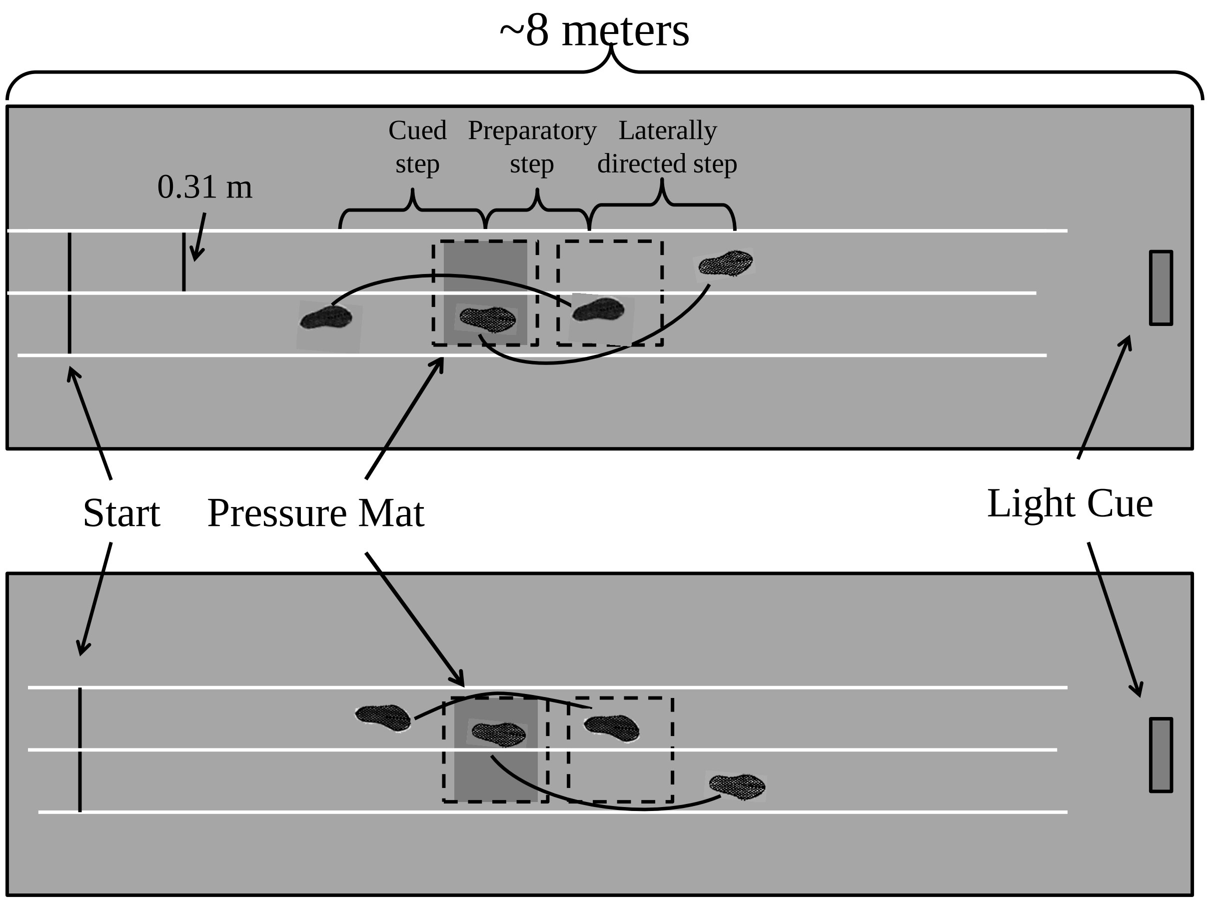


Figure 7. Schematic diagram of the experimental setup used for the experimental protocol. The step sequence for a cued crossover step (top) and a cued sidestep (bottom) is presented for a right limb dominant subject. Thus, crossover steps were directed to the subject's left and sidesteps were directed to the subject's right. All subjects performed the laterally-directed steps within a stride after the light cue was illuminated. For cued trials, the cue was received two steps prior to the laterally-directed step (cued step). The step prior to the laterally-directed step was termed the preparatory step.

Passive reflective markers were placed bilaterally on the acromiom, the medial epicondyle of the humerus, between the heads of ulna and the posterior radial tuberosity, over the inferior angle of the left scapula, and on the anterior surface along the long axis of the thigh and shank so as not to be collinear with the markers on the lateral malleolus, and approximately over the knee joint center over the flexion-extension axis. Markers were also placed over the ASIS and the $L_5S_1$ as well as on the subject's shoes, over the heel and 2nd metatarsal phalangeal joint. The three-dimensional marker positions were recorded using an eight camera motion capture system (Motion Analysis, Santa Rosa, CA) recorded at 120 Hz. The three-dimensional marker positions were tracked using commercial software (Cortex, Motion Analysis, Santa Rosa, CA). Frontal plane kinematics of the compensatory stepping response was computed off-line using custom software in Matlab (MathWorks, Natick, MA).

The position of COM for each subject was calculated using anthropometric estimations (Winter 2005) applied to a ten segment model generated from the three-dimensional marker positions. The velocity of the COM (vCOM) was calculated using a first-central difference algorithm. Average forward directed step vCOM and peak lateral vCOM were quantified, step-by-step, in a window that was defined from a given heelstrike to the contralateral heelstrike.

For this investigation, we quantified dynamic stability, which for this study refers to the frontal plane position and vCOM with respect to the edge of the BOS. The position and vCOM creates a term, the extrapolated COM (xCOM- Eq. 1), that is calculated by summing the frontal plane position of the COM with the normalized frontal plane vCOM. The velocity of the COM is normalized by the eigenfrequency of a non-inverted pendulum with length 1.34 times the trochanteric height ($\omega_0$) (Massen & Kodde, 1979). The eignenfrequency of a non-inverted pendulum refers to the natural frequency or period of a pendulum of a given length, and results in the xCOM having units of distance (i.e. mm).

$$xCOM = COM + v_{COM} / \omega_0 \tag{1}$$

Theoretically, in the frontal plane, a subject is stable if their xCOM remains medial to their BOS, and the more medial the xCOM is relative the BOS, the more stable the subject. Conversely, subjects are considered unstable if their xCOM moves lateral to their BOS. Ultimately, stability is quantified by expressing the margin of stability (MOS), which is calculated as the distance between the xCOM and the lateral border of the BOS (Hof et al., 2005-Eq. 2). The MOS is proportional to the impulse needed to cause the MOS to become negative.

$$MOS=BOS_{lat}-xCOM. \tag{2}$$

The lateral border of the BOS was calculated with respect to positions of the heel and toe markers, the angle of toe-in or toe-out for a given step, and anthropometric estimations of foot width (Rosenblatt & Grabiner, 2010). The average MOS ($MOS_{avg}$) was quantified step-by-step between heelstrike and contralateral toeoff.

Step width was calculated as the difference between frontal plane locations of foot segment centroids during consecutive stance phases. The foot centroids were calculated as the midpoint of the line connecting the markers on the subjects' shoes, which were over the heel and at the distal end of the $2^{nd}$ metatarsal phalangeal joint. Step length was calculated as the difference between the saggital plane positions of the foot segment centroids at midswing. Midswing was identified as the instant when the foot segment centroid of the swing limb crossed anterior to the foot segment centroid of the stance foot. Step time was quantified as the elapsed time between one midswing to the next.

### 4.2.3 **Statistical analysis**

We tested the hypothesis that laterally-directed step widths of older adults would be significantly smaller than those of younger adults during cued but not preplanned conditions using a mixed, three-factor (step X condition X age) ANOVA. Within the model, condition and age were treated as repeated measures. To test the hypothesis that older adults would be less stable than younger adults and that the utilization of a SS would result in greater stability than a COS regardless of age, we utilized a mixed, three-factor (step X condition X age) ANOVA. Within the model, condition and age were treated as repeated measures. We also tested differences between the forward directed vCOM, peak lateral vCOM, and step time of the laterally-directed steps using a mixed three-factor ANOVA with repeated measures on the target and step terms.

For the cued condition, all subjects required a full stride to complete the laterally-directed step. Thus, alterations to gait kinematics, if they existed, were assumed to occur during the step prior to the laterally-directed step termed the preparatory step. This was tested by analyzing the differences between kinematics two steps prior to the laterally-directed step (cued step) and the preparatory step. To test this, we performed a mixed, three-factor (condition X preparatory step X age) ANOVA on variables that represented forward progression (i.e. step length and step time and step velocity). The condition X preparatory step term in the statistical model was of particular interest as it would suggest that, for a given variable, such as step length, a significant difference may exist between the preparatory step and cued step for the cued condition but not for the preplanned conditions.

For instances where significant interactions were detected, *post hoc* tests were performed on the simple comparisons with Bonferoni corrections applied for the number of comparisons made. Significance was set at $p<0.05$ unless corrections were applied. Effect size was reported as $\eta^2$, which is interpreted as the amount of variance in the dependent variable that can be accounted for by the independent variable (Levine & Hullet, 2002). This is similar to $R^2$ in an analysis using a regression approach.

$$\eta^2=SS_{between}/SS_{total} \quad (3)$$

All statistics were performed with SPSS 17.0 (Chicago, IL).

## 4.3 **Results**

### 4.3.1 **Step width of laterally-directed steps**

The laterally-directed steps of younger adults were larger than older adults regardless of condition or the step utilized. Younger adults utilized steps that were, on average, around 10% greater than older adults across all conditions and steps (Figure 2). Within the model, the step X condition X age interaction term was not significant ($F(1, 35) =1.104$, $p=0.300$). The condition X age interaction was not significant either ($F(1, 35) =0.016$ $p=0.900$). Younger adults took significantly larger laterally-directed steps than older adults ($F(1, 35) =10.837$, $p=0.002$, $\eta^2 =0.236$).

Step widths were larger in the cued than preplanned conditions while SSs resulted in larger step widths than COSs. Within the model, the step X condition interaction was significant ($F(1, 35) =14.388$, $p<0.001$, Figure 3). *Post hoc* tests for this ordinal interaction were performed on the simple effects in the model. Four statistical tests were performed so the adjusted p-value for significance was $p<0.01$. The step widths of cued steps were larger than preplanned steps (cued crossover vs. preplanned crossover $F(1, 36) = 17.815$, $p<0.001$, $\eta^2 = 0.331$, cued SSs vs. preplanned SSs $F(1, 35) = 51.593$, $p<0.001$, $\eta^2 = 0.596$) and SSs were significantly larger than COSs (cued SSs vs. cued crossovers steps, $F(1, 36) = 211.699$, $p<0.001$, $\eta^2 = 0.885$, preplanned sidesteps vs. preplanned crossover steps, $F(1, 36) = 146.034$, $p<0.001$, $\eta^2 = 0.807$).

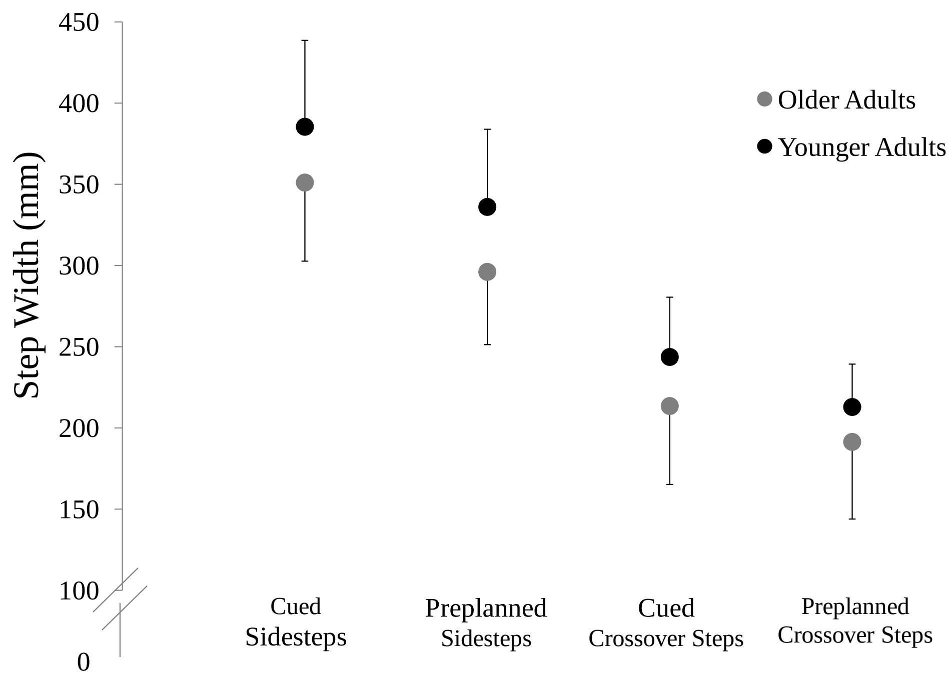


Figure 8. Average step widths and standard deviations are shown of younger and older adults between cued and preplanned laterally-directed steps. On average the laterally directed steps of young adults were 10% larger than older adults (main effect of age p<0.001).

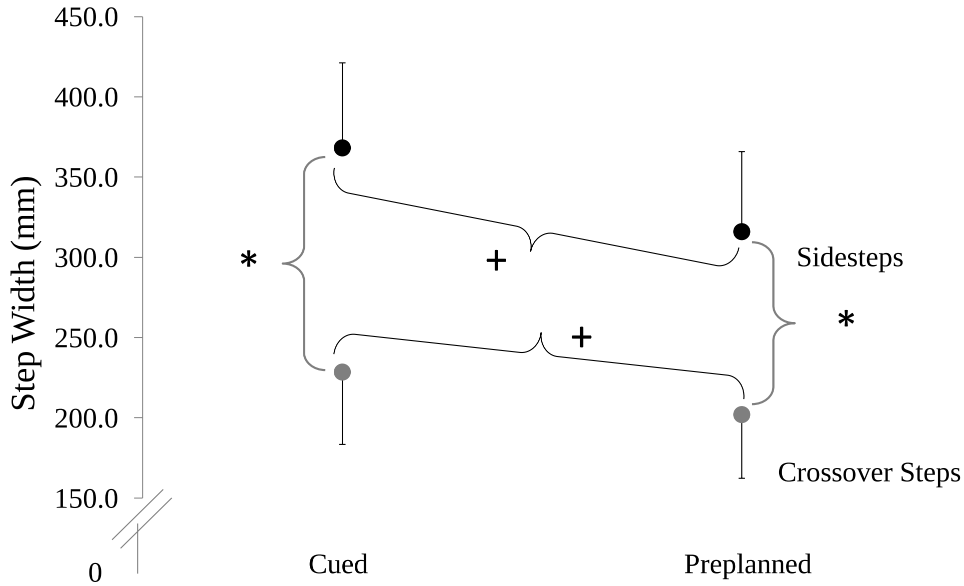


Figure 9. Average step width and standard deviations are shown for the significant condition X step interaction. Post hoc tests revealed significant differences among the conditions and steps utilized. All comparisons were significant at the p < (0.05/4) 0.0125 level. A (*) denotes significant differences between the conditions and a (+) denotes significant differences between the step type utilized.

### 4.3.2 **Dynamic stability of laterally-directed steps**

Older adults performing a SS and a COS were as dynamically stable or more so compared to younger adults. Within the model, the step X condition X age interaction term was not significant (F(1, 35) =107.566, p=0.359). The step X condition interaction was not significant, nor was the condition X age (F (1, 35) =1.134, p=0.266, F (1, 35) =1.277, p=0.294 respectively). A significant interaction of the $MOS_{avg}$ was detected between the type of step utilized, COS vs. SS, and group membership, old vs. young (F (1, 35) = 9.613, p=0.004, Figure

4). *Post hoc* tests of the ordinal interaction with an adjusted p-value for significance set to 0. 01 were performed on the simple effects in the model. Overall, SSs of subjects established greater dynamic stability than COSs (older adults performing SS vs. older adults performing COS, F (1, 17) = 87.802, $p<0.001$ $\eta^2 =0.838$, younger adults performing SSs vs. younger adults performing COSs, F (1, 18) =175.311, $p<0.001$ $\eta^2 =0.907$) and COSs by older adults established greater stability than those steps for younger adults (older COS vs. younger COSs, F (1, 35) = 12.143, $p<0.001$, $\eta^2 =0.258$). However, no difference was detected in $MOS_{avg}$ between the SSs of older adults compared to the SSs of younger adults (F (1, 35) =.0408, $p<0.527$, $\eta^2 =0.012$).

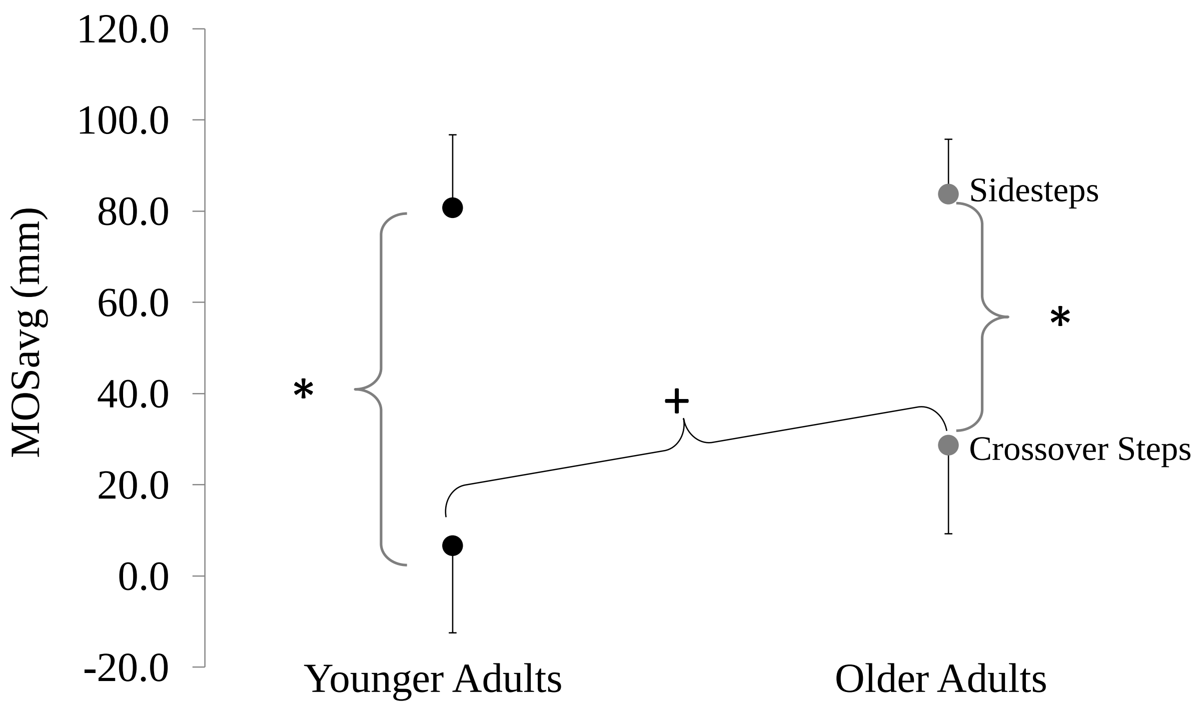


Figure 10. Average $MOS_{avg}$ and standard deviations are shown for the significant condition X step interaction. Follow-up tests revealed significant differences among the groups and steps utilized. All comparisons were significant at the p< (0.05/4) 0.0125 level. A (*) denotes significant differences between the conditions and a (+) denotes significant differences between the step type utilized.

4.3.3 **Step kinematics of laterally-directed steps**

The forward-directed step vCOM was significantly slower for older adults performing the laterally-directed steps (TABLE V). For forward-directed step velocity, the step X condition X age interaction was not significant (F (1, 35) =1.227, p=0.276), nor the step X age (F (1, 35)

=0.210, $p=0.650$), nor the condition X age ($p=0.712$). A significant main effect of age ($F (1, 35) = 25.198$, $p<0.001$) was also detected. On average, older adults performed the laterally-directed steps with an average step velocity 20 % slower than younger adults.

The peak lateral vCOM was larger for SSs compared to COSs among both groups while overall, the peak lateral vCOM of older adults was slower than younger adults (TABLE V). For peak lateral vCOM, the step X condition X age interaction was not significant ($F (1, 35) =3.023$, $p=0.091$), nor the step X age ($F (1, 35) = 0.027$, $p=0.871$), nor the condition X age ($F (1, 35)= 0.106$, $p=0.747$). A significant step X condition interaction was detected ($F (1, 35) =5.400 p=0.026$). *Post* hoc tests on the simple effects in the model showed that all comparisons were significant at the $p<0.001$ level. Performing a SS resulted in a larger peak lateral velocity than a COS, and cued steps resulted in a larger peak lateral velocity than COSs. There was a significant main effect of age ($F (1, 35) =30.998$, $p<0.001$). Older adults executed the lateral steps with a 16% decrease in peak lateral velocity compared to younger adults.

The step time of COSs of older adults was significantly longer than younger adults performing COSs while no age-related differences existed with SSs (TABLE V). With respect to step time, the step X condition X age was not significant ($F (1, 35) =1.391$, $p=0.246$). The step X age interaction was significant ($F (1, 35) =11.919$, $p<0.001$) as well as the step X condition ($F (1, 35) = 8.693$, $p=0.006$), although, the condition X age interaction term was not significant in the model ($F (1, 35) =0.514$, $p=0.478$). *Post hoc* tests, with an adjusted p-value of 0.01 for significance, on the step X age interaction found that the step time of older adults performing a COS was significantly longer than younger adults performing a COS ($F (1, 35) =18.544$, $p<0.001$, $\eta^2 =0.346$) whereas no age-related differences were detected between subjects performing a SS ($F (1, 35) =2.286$, $p=0.140$, $\eta^2 =0.061$). For both older and younger adults, within group comparisons revealed that the step time of SSs was significantly shorter than COSs ($F(1, 17) = 55.007$, $p<0.001$, $\eta^2=0.764$, and $F(1, 18) = 40.033$, $p<0.001$, $\eta^2=0.690$).

TABLE V. MEANS ± STANDARD DEVIATIONS ARE DISPLAYED FOR STEP KINEMATICS OF CUED AND PREPLANNED SIDESTEPS AND CROSSOVER STEPS FOR OLDER AND YOUNGER ADULTS.

| | | **Step Velocity (mm/s)** | | **Peak Lateral Velocity (mm/s)** | | **Step Time (sec)** | |
|---|---|---|---|---|---|---|---|
| Condition | Step | Older | Younger | Older | Younger | Older | Younger |
| Cued | Sidestep | 1083.7±260.8 | 1414.9±223.3 | 441.4±46.7 | 501.3±55.0 | 0.51± 0.06 | 0.49±0.06 |
| | Crossover | 1196.0±200.9 | 1490.7±180.7 | 371.3±83.3 | 410.5±71.0 | 0.64±0.07 | 0.55±0.07 |
| Preplanned | Sidestep | 1166.0±159.7 | 1463.7±208.4 | 328.6±29.4 | 444.7±48.0 | 0.55±0.05 | 0.52±0.05 |
| | Crossover | 1199.6±186.9 | 1504.7±172.5 | 302.2±46.7 | 360.2±53.5 | 0.63±0.06 | 0.56±0.06 |

### 4.3.4 **Kinematic differences in preparatory steps of cued and preplanned trials**

The step length of subjects was shorter for the preparatory step compared to the cued step in the cued condition, but there was no difference in the preplanned condition. For step length, a significant condition X preparatory step X age interaction was detected in the model for step length ($F(1, 35) = 6.097$ $p = 0.019$, Figure 5). Given that we were particularly interested in the condition X preparatory step interaction, we divided the dataset by age group and re-ran the models. For both groups, the condition X preparatory step interactions were significantly different ($F(1, 17) = 29.194$, $p < 0.001$, $\eta^2 = 0.129$ for older adults and, $F(1, 18) = 58.404$, $p < 0.001$, $\eta^2 = 0.252$ for younger adults). For both older and younger adults, the step length of the preparatory step for the cued condition was 22% shorter than the cued step. A statistical difference was not detected between the step lengths of the preplanned condition.

The step time of the preparatory step was shorter than the cued step in the cued condition, but there was no difference in the preplanned condition. The condition X preparatory step X age interaction was not significant for step time ($F(1, 35) = 1.055$, $p = 0.311$), however, the condition X preparatory step interaction was significant ($F(1, 35) = 88.740$, $p < 0.001$). On average, step time for the preparatory step decreased 20% compared to the cued step (0.42 sec vs. 0.53 sec) whereas no difference was detected between steps of the preplanned condition (0.51 sec vs. 0.53).

The forward directed step vCOM was slower for the preparatory step compared to the cued step in the cued condition, but there was no difference in the preplanned condition. Finally, with respect to walking velocity, the condition X preparatory step X age interaction was not significant ($F(1, 35) = 0.493$, $p = 0.487$), however, the condition X preparatory step interaction was significant ($F(1, 35) = 46.739$, $p < 0.001$). The step velocity of subjects, on average, was 9% slower (1262.6 mm/s vs. 1386.9 mm/s) for the preparatory step compared to the cued step. No statistical difference was detected between steps in the preplanned condition (1329.3 mm/s vs. 1347.6 mm/s).

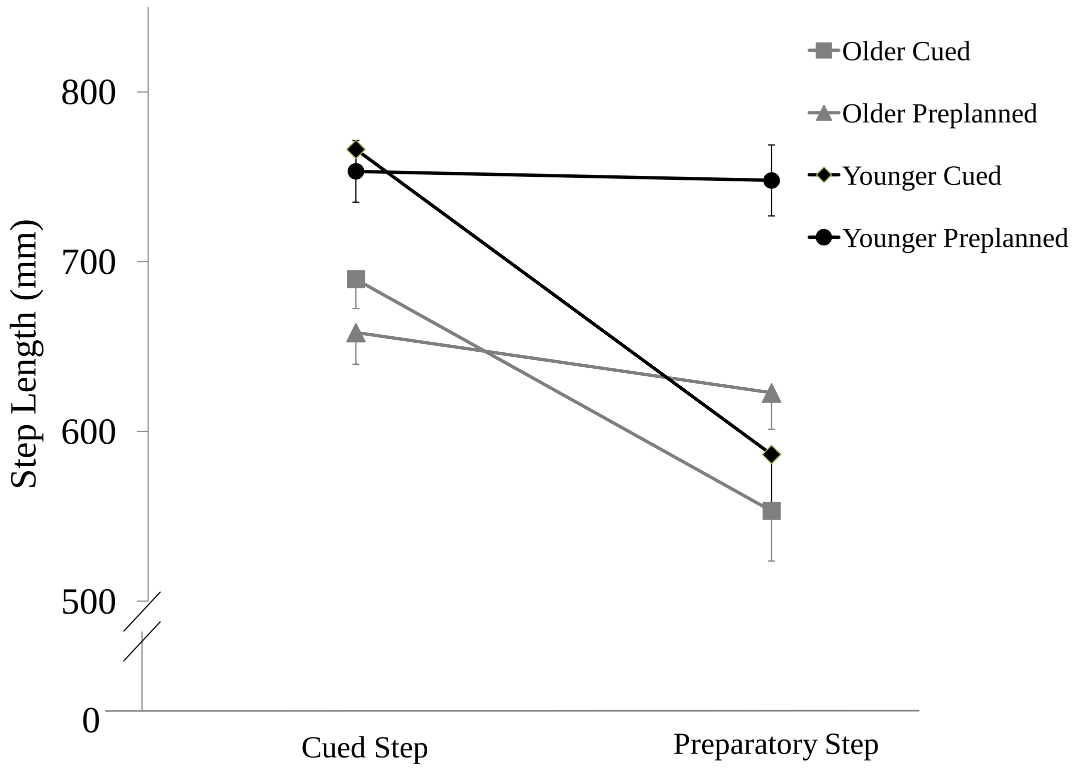


Figure 11. Differences between the average step length of two and one step prior to the performance of the laterally-directed step are shown. The older (grey) and younger (black) subjects responded with little alteration to step length under the preplanned condition. While performing the cued condition, the step prior to the laterally-directed step was significantly shorter than the previous step suggesting a more reactive response for these subjects.

4.3.5 **Physical functioning and activity questionnaires.**

The older adults utilized in this study were, on average, a healthy and active cohort. The range of older subjects' scores on the Godin leisure-time questionnaire was 14-185 with an average of 52.7 ± 39.0. Older adults reported a high level of physical functioning with respect to MOS-36 with scores ranging from 75 to 100 with an overall average of 86.4 ± 8.5. A previous study employing the physical functioning scale of the MOS 36 among a group of independently ambulatory community dwelling older adults reported a mean of 74.7 ± 19.4 (Bohannon et al., 2010). No correlation was detected between the Godin leisure-time questionnaire and the physical functioning scale of the MOS36 ($r(17) = 0.05$, $p = 0.834$).

## 4.4 **Discussion**

The purpose of the present investigation was to compare the age-related differences of preplanned and cued COSs and SSs during forward locomotion. We hypothesized that the step width of the cued lateral steps of older adults would be significantly smaller than younger adults during cued but not during preplanned conditions. Within our statistical model, the condition X age interaction was not significant, thus, we accept the null hypothesis and failed to provide evidence to support our alternative hypothesis. Younger adults executed steps that were, on average, 10% greater than older adults regardless of step or condition. With respect to dynamic stability, we hypothesized that older adults would be less stable than younger adults and performance of a SS would result in greater stability than a COS regardless of age. A significant step X age interaction was detected in the statistical model. Subjects performing a SS resulted in a $MOS_{avg}$ that was 78% larger than a COS regardless of condition. Sidesteps of younger adults were 3% larger than SS of older adults, which was not statistically different, however, somewhat surprisingly, older adults executed a COS that resulted in $MOS_{avg}$ to be four times greater than younger adults (28mm vs. 7mm). Therefore, we rejected the null hypothesis and only provided partial supported our alternative hypotheses.

### 4.4.1 **Step width of laterally-directed steps**

The step width of older adults was significantly smaller than younger adults across all tasks. Initially, it was reasoned that older adults would be less able to quickly generate the abduction and adduction moments about the stance and swing limbs needed under the cued condition to execute a step that was as large as younger adults. Whereas, when subjects were allowed to preplan the execution of the laterally-directed step, older adults would utilize as wide of a step width as younger adults. In partial support of this contention, a study reported that, for a SS task, the step widths of younger adults were significantly larger for cued but not preplanned conditions (Cho et al., 2008). However, in the present study, the condition X age interaction was not significant suggesting that the smaller steps taken by older adults were not dependent on condition. It is possible that a reduced range of motion could have limited these subjects' ability to take larger steps, however, a previous study has suggested that no marked differences exist in hip range of motion between younger and older adults (Roach & Miles, 1991). Further, the older adults in this study were active with a high degree of physical functioning. The smaller step widths of older adults may have related to a more cautious laterally-directed step. Wider steps would increase the displacement and velocity of the COM (Donelan et al., 2001), which could potentially require increased control to arrest and reverse the increased motion. Finally though, it should be noted that the instruction set to subjects did not encourage a large laterally-directed step; the instructions simply stated that the subjects transition into the adjacent lane as quickly as possible.

4.4.2 **Dynamic stability of laterally-directed steps**

Despite smaller step widths, older adults were as dynamically stable, if not more so, than younger adults while performing laterally-directed steps. Subjects established a larger $MOS_{avg}$ while executing a SS compared to a COS, which is in keeping with larger step widths for a SS compared to a COS. Performance of a SS allows the subjects to fully extend their BOS within anatomical constraints (i.e. leg length). Surprisingly, older adults performing a COS were four times more stable than younger adults (28 mm vs. 7 mm, respectively). It is possible that older adults were more cautious when executing these steps. After heelstrike, the lead limb is crossed in front of the trailing limb resulting in a posture that may create a vulnerability to lateral instability should the subject encounter an external disturbance. Given the present results the greater $MOS_{avg}$ means that a larger laterally-directed external disturbance would be required to cause the older adults to become unstable compared to younger adults while performing a COS. Thus, the increase in MOS of older adults may be representative of an increased safety factor while performing a COS.

Why were older adults so much more dynamically stable given the smaller step widths of older compared to younger adults performing COSs? As mentioned above, this may relate to older adults performing this task more conservatively regardless of condition. When considering the COS response, older adults' step velocity was 20% slower than younger adults. Further, the step time of older adults was 13% longer in duration compared to younger adults. Lastly, the peak lateral velocity of older adults was 18% smaller in magnitude than younger adults. In total, a slower vCOM and increased step time could have allowed older adults to maintain a greater degree of control over COM motion resulting in a more stable stepping response. It has been reported that during normal walking, reductions in step length, step velocity and increases in step time may represent a more cautious or conservative gait pattern that acts to provide increased stability to older adults (Winter, 1990, Maki, 1993). The results of the current investigation suggest that this may extend to the performance of laterally-directed steps as well.

The COS while walking involves more complicated control of the whole body motion than a laterally-directed SS. To execute the COS, the xCOM is displaced beyond the lateral border of the BOS in the direction of the lateral step creating a dynamically unstable state even if only transiently (See Figure 6). This instability is ultimately resolved by the placement of the swing limb on the ground. However, the swing limb must first cross in front of the stance limb while avoiding a limb collision. Finally, the trailing limb must then circumnavigate the leading limb to further avoid a limb collision in order to enable subjects to regain the primary direction of travel. Also, given the configuration of the limbs, the extent that the BOS can be extended is limited. It is possible that for conditions that require a large step width or require a much faster step execution, a COS may put older adults at greater fall risk compared to a SS. It is of interest to investigate if the COS response could be modified with training so that subjects could maintain the stability of the step while performing a quicker and wider step.

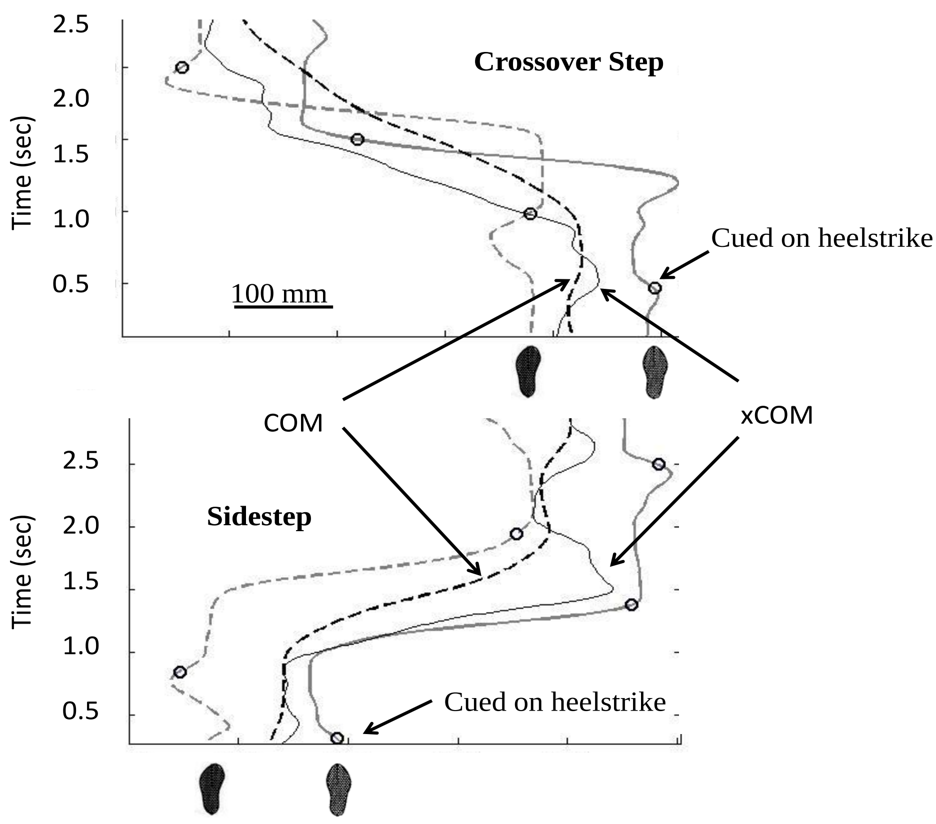


Figure 12. Time series of a cued crossover step (top) and sidestep (bottom) is displayed. Notice, in the execution of the crossover step, how the center of mass (COM) and extrapolated COM

(xCOM) extend beyond the lateral border of left foot (grey dashed line) at the second heelstrike (circles). For sidesteps, the COM and xCOM always remain medial to the time series of the right foot (solid grey line).

### 4.4.3 **Kinematic differences in preparatory steps of cued and preplanned trials**

The differences observed in the preparatory step between cued and preplanned conditions provide evidence that subjects responded to the cued trials with a more reactive response. These results are in agreement with a previous investigation (Paquette & Vallis, 2010) that reported significant changes in the preparatory step length and step velocity of cued steps compared with the previous step. In the current investigation, it is recognized that subjects performing the more reactive cued condition were not penalized if they were unable to change lanes quickly enough. The time constraint being exercised in the task was, to a degree, imposed by each subject. This limitation could be addressed by forcing subjects to react to some obstruction in their path, virtual or real. This could be accomplished by utilizing virtual reality to create a virtual environment with obstacles present, or by creating conditions where subjects would have to navigate around a physical object that appear in their path.

### 4.4.4 **Limitations**

We recognize potential limitations of the current study. The conditions of this study were performed in the same order for all subjects potentially leading to an ordering effect. However, differences between conditions (i.e. cued and preplanned) and step type (i.e. COS and SS) may limit any transfer of skills from one condition to the next. For instance, the cued trials are a more reactive task than the preplanned trials. For preplanned conditions, subjects begin altering body configurations in preparation for the change in direction two or more steps before the laterally-directed step (Patla et al., 1999, Fuller et al., 2007) whereas under conditions where subjects receive a cue, much of the kinematic alterations must occur on the step prior to the laterally-directed step (Patla et al., 1999). Preplanned conditions utilize alterations to step width to alter COM kinematics whereas cued conditions require that subjects perform a hip strategy where the trunk and lower limbs counter-rotate to move the COM laterally. Further, differences between SSs and COSs could preclude transfer. Because these steps were taken with the dominant limb, the direction the subject executed the step was different (e.g. for a right-limb dominant subject, a COS would be directed to the left while a SS would be directed to subjects right) providing inherent differences in the task. Additionally, given four different conditions, there would be 24 unique ordering combinations that this study could be conducted. This would have required a much larger dataset to protect against any ordering effect. Finally, the older adults utilized in this study were healthy and active. However, investigations that have suggested that older adults may be more laterally unstable have utilized a similarly healthy cohort of older adults as their subject population (Mille et al., 2005, Maki et al., 2000).

### 4.4.5 **Conclusions**

Age-related differences exist in the performance of COSs and SSs under cued and preplanned conditions. With respect to step width, laterally-directed steps of younger adults were significantly larger than older adults, and SSs were larger than COSs. These step widths resulted in age-related differences in the $MOS_{avg}$ between COSs but not SSs. Surprisingly, older adults performing a COS resulted in four times greater $MOS_{avg}$ than younger adults. It was reasoned that older adults may have performed the COSs more cautiously given the decreased COM velocity and increased step time. These results seem to suggest that, contrary to results of external postural disturbances, the older adults utilized for this study do not appear to be more laterally unstable than younger adults while performing a task that transiently challenges lateral dynamic stability. Future research should attempt to verify these results by creating a more challenging cued task in which subjects must circumnavigate an obstacle in their path.

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## 5 Age-related effects of performing sidesteps and crossover steps to targets during forward locomotion

### 5.1 Introduction

Based on the number of risk factors present, older adults may have an annual fall incidence between 10 and more than 50% (Delbaere et al., 2010). Of major concern is the identification of risk factors that are associated with the incidence of injurious falls such as hip fractures. Laterally directed falls, in comparison to forward or backward directed falls, increase the likelihood of a hip fracture 600% (Greenspan et al., 1994). Therefore, identifying modifiable mechanisms that increase risk for laterally-directed falls is of clinical importance.

The recovery response of older adults to postural disturbances suggests that they may be particularly vulnerable to lateral instability (Maki et al., 1996, Maki et al., 2000, Mille et al., 2005, Hilliard et al., 2008). The results of these previous investigations suggest that the initial step of the recovery response was insufficient to re-establish stability, thus forcing the utilization of extra steps. The reliance on extra steps in response to laterally directed postural disturbances has been related to an increase in fall risk of older adults (Hilliard et al., 2008). However, the aforementioned investigations utilized external postural disturbances that were delivered to subjects during a quasi-static standing posture. It is currently unknown if the reported postural instability of older adults translate to more functional tasks performed while walking. After all, 90% of hip fractures occur as the result of a fall and close to 70% of hip fractures occur while walking (Cali & Keil, 1995).

Laterally-directed steps are commonly utilized while walking to circumvent an obstacle or to quickly avoid an undesirable step location. These laterally-directed steps require an increased displacement and velocity of the center of mass (COM) to quickly alter its trajectory.

The change in lateral displacement and velocity of the COM needed to execute the step must then be arrested and reversed if the previous direction of travel (i.e. forward) is to be maintained. The increased requirements to control the position and velocity of the COM with respect to the base of support (BOS) compared to normal walking provides a discrete challenge to lateral stability. It was previously reported that older adults executing laterally directed steps during forward locomotion were actually more stable than younger adults (Chapter 3). In that investigation, dynamic stability was quantified by using the margin of stability (MOS), which considers the position and normalized velocity of the COM with respect to the lateral border of the BOS (Hof, 2005). The larger MOS of older adults compared to younger adults was likely related to the 18% smaller peak lateral velocity of older adults' COM (Chapter 3).

Whereas the aforementioned investigation manipulated temporal aspects of performing laterally directed steps, it is also possible to manipulate the spatial aspects of the step. Performing laterally-directed steps to targets provide control over the size of the step, which further allows control over the created challenge to lateral stability. An increase in the lateral distance of the step target results in an increase of the peak lateral COM velocity (Donelan et al., 2001) that must be arrested so that in original direction of travel (i.e. forward) can be regained. Within the frontal plane, the hip musculature is primarily responsible for controlling COM motion with respect moment generation after heelstrike (Mackinnon & Winter, 1993, Pandy et al., 2010) thus aiding in regulating dynamic stability.

Compared to younger adults, marked reductions in the force generating capacity of the hip abductors of older adults have been reported (Johnson et al., 2004). In older adults, reductions in peak isometric force and time to peak moments have been reported to be greater than 24% of the peak values of younger adults (Johnson et al., 2004). Further, decreases in peak moment generation under isokinetic conditions at 60 degrees per second were reported to be 40% lower for both abductors and adductors (Johnson et al., 2004). It was also reported that these older adults were unable to consistently generate a moment against the arm of a dynamometer moving at 90 degrees per second (Johnson et al., 2004). Although older adults can develop adequate moment production to ensure dynamic stability for standing and normal walking, tasks for which rapid, large moment generation is required may be particularly problematic.

The purpose of the present study was to investigate the age-related differences of subjects performing crossover (COS) and sidesteps (SS) to three different targeted step widths while walking. Given the reported weakness of hip abductors in older adults, we hypothesized that older adults would generate a significantly smaller hip abductor moment compared to younger adults at all step targets regardless of the type of step utilized. We also hypothesized that, given the importance of the hip abductors in regulating dynamic stability, older adults would be less dynamically stable while performing COS and SS than younger adults, particularly at the longer step targets.

## 5.2. **Materials and Methods**

### 5.2.1 **Participants**

Nineteen young adults (9 males, 10 females, age: 22.9±3.1 years, height: 174.3±10.2 cm, mass: 71.7±13.0 kg) and eighteen older adults (9 males, 9 females age: 72.8± 5.2 years, height: 174.9± 8.6 cm, mass 78.0± 16.3 kg) volunteered to participate in this institutionally reviewed and approved study. Subjects were not permitted to participate if they provided affirmation to questions related to any neurological, musculoskeletal, or other injuries or disorders that would limit their functional mobility, as this would not allow for safe participation. Also, older adults were not allowed to participate if they used a cane or other assistive walking device or if the bone mineral density of their left proximal femur was less than 0.65 g/cm$^2$ (Cummings et al., 1993), which was measured using dual energy X-ray absorptiometry (Hologic QDR 1000, Waltham, Mass., USA). All subjects provided written informed consent prior to participation.

All older subjects completed the Godin Leisure time questionnaire (Godin & Sheppard, 1985) along with the physical functioning subsection of the Medical Outcome Survey (MOS) 36-item short form health survey (Ware & Sherbourne, 1992). Finally, subjects completed the Revised Waterloo Footedness Questionnaire to assess lower limb dominance (Elias et al, 1998). Subjects performed all lateral steps with their dominant limb as the lead limb. All subjects wore their own walking shoes during the data collection.

### 5.2.2 **Data collection**

All walking trials were performed along an eight meter carpeted walkway. Lanes were demarcated on the walkway surface over the carpet with white tape. Each lane was 0.31m wide (Figure 2). Initially, five normal, unconstrained walking trials were collected. These were followed by five lane-walking trials during which subjects were constrained to a lane. For all walking trials, subjects were instructed to walk at a comfortable speed. For the lane-walking trials, subjects were instructed to walk within the lane for the length of the walkway.

All laterally directed step trials were executed with subjects' dominant limb as the lead limb to targets placed at three locations on a force plate flush with the walkway surface. The three targets created step widths of three different distances (see Figure 2). Subjects performed five SS trials at each distance followed by five COS trials at all distances. At the outset of each set of SS and COS trials, a demonstration was provided to all subjects. If requested by the subject, multiple demonstrations of the task to be carried out were performed. The order of the laterally directed step trials were the same for all subjects. Subjects performed SS trials first followed by the COS trials. Subjects did not wear a safety harness, however, a spotter walked approximately two meters to the side and slightly behind the subjects on the side to which the laterally directed steps were to be taken. The position of the spotter was selected to ensure that assistance could be provided should the subject appear to be at risk for a fall as the result of taking a laterally-directed step while not influencing the selected walking speed of the subject.

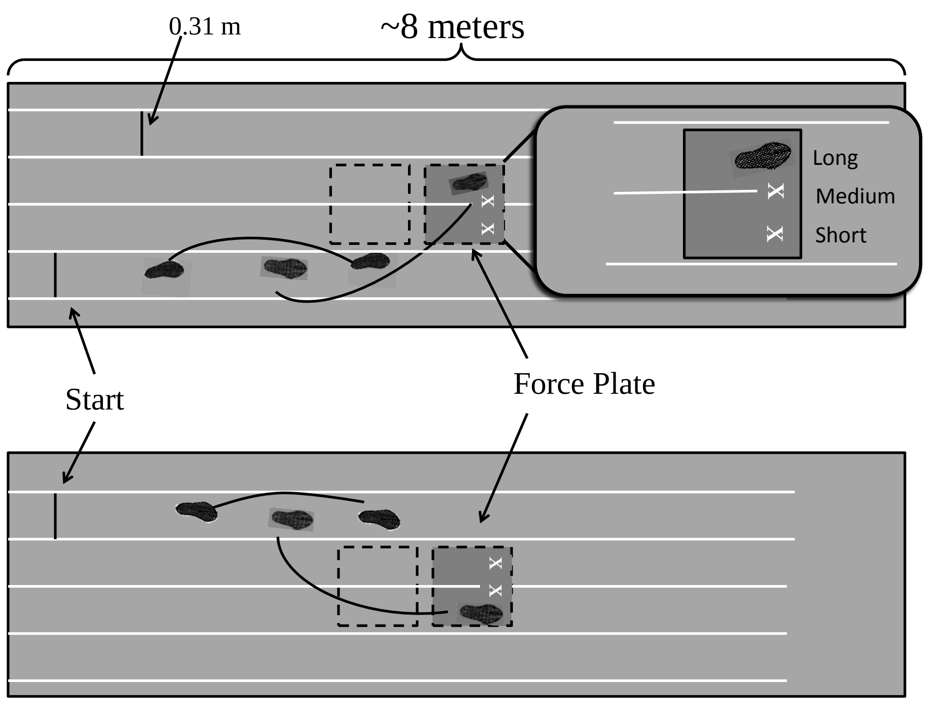


Figure 13. Schematic diagram of the experimental setup used for this protocol. The step sequence for a cued crossover step (top) and a cued sidestep (bottom) is presented for a right limb dominant subject. Thus, crossover steps were directed to the subject’s left and sidesteps were directed to the subject’s right. Also illustrated are the targets to which subjects stepped during the data collection (top inset).

The motions of twenty two passive reflective markers were recorded by an eight-camera motion capture system recording at 120 Hz (Motion Analysis, Santa Rosa, Ca). Passive reflective markers were placed bilaterally over the acromiom, the medial epicondyle of the humerus, between the heads of ulna and the posterior radial tuberosity, over the inferior angle of the left scapula, and over the anterior surface along the long axis of the thigh and shank so as not to be collinear with the markers placed over the lateral malleolus, and approximately over the knee joint center over the flexion-extension axis. Markers were also placed over the ASIS and $L_5S_1$ as well as on the subjects shoe over the heel and $2^{nd}$ metatarsal phalangeal joint (i.e. the toe marker). The three-dimensional marker positions were tracked using commercial software (Cortex, Motion Analysis, Santa Rosa, CA), and analyzed off-line using custom software in Matlab (MathWorks, Natick, MA). Ground reaction forces were collected from the force plate upon which the stepping targets were placed (AMTI, Newton, MA) and sampled at 1200 Hz. Inverse dynamics were computed from the synced motion capture and force plate data using a commercial software package (Orthotrak, Motion Analysis Corporation, Santa Rosa, CA). Given that lateral motion of the center of mass is largely controlled by the hip abduction moment, we focused on this variable for the analysis (Pandy et al., 2010). During normal walking, an internal abduction moment is generated that is bimodal with the first peak occurring within the first 25% of the step cycle. Peak values during this time frame were extracted for analysis. The peak hip joint abduction moments were correlated to body height, body mass, body height*body mass, and leg length. The dimension that demonstrated the strongest correlation was used to normalize the moments.

The position of COM for each subject was calculated using anthropometric estimations (Winter 2005) applied to a ten segment model generated from the three-dimensional marker positions. The velocity of the COM (vCOM) was calculated using a first-central difference algorithm. Average forward step vCOM and peak lateral vCOM were calculated for each step within a window that was defined from a given heelstrike to the contralateral heelstrike.

For this investigation, we quantified dynamic stability, which for this study, refers to the frontal plane position and vCOM with respect to the edge of the BOS. The position and velocity of the COM is used to define the extrapolated COM (xCOM- Eq. 1) that is calculated by summing the frontal plane position of the COM with the normalized frontal plane velocity of the center of mass. The velocity of the COM is normalized by the eigenfrequency of a non-inverted pendulum with length 1.34 times the trochanteric height ($\omega_0$) (Massen & Kodde, 1979). The eignenfrequency of a non-inverted pendulum refers to the natural frequency or period of a pendulum of a given length, and results in the xCOM having units of distance (i.e. mm).

$$xCOM = COM + v_{COM}/ \omega_0 \tag{1}$$

Theoretically, in the frontal plane, a subject is stable if their xCOM remains medial to their BOS, and the more medial the xCOM is relative the BOS, the more stable the subject. Conversely, subjects are considered dynamically unstable if their xCOM moves lateral to their BOS. Ultimately, dynamic stability is quantified by the margin of stability (MOS), which is calculated as the distance between the xCOM and the lateral border of the BOS (Hof et al., 2005- Eq. 2). The MOS is proportional to the impulse needed to cause the MOS to become negative.

$$MOS=BOS_{lat}-xCOM. \tag{2}$$

The lateral border of the BOS was calculated with respect to positions of the heel and toe markers, the angle of toe-in or toe-out for a given step, and anthropometric estimations of foot width (Rosenblatt & Grabiner, 2010). Average MOS ($MOS_{avg}$) was quantified step-by-step between heelstrike and contralateral toe-off.

### 5.2.3 **Statistical analysis**

We tested the hypothesis that the peak abduction hip moment of older adults would be significantly smaller compared to younger adults at all step targets regardless of the step with a three-factor (step X target X age) ANOVA with repeated measures on the step and target terms. To test the hypothesis that older adults would be less stable than younger adults, particularly at the longer step targets, we utilized a mixed three-factor (step X target X age) ANOVA with repeated measures on the target and step terms. We also tested differences between the forward directed vCOM and peak lateral vCOM using a mixed three-factor ANOVA with repeated measures on the target and step terms. Finally, for reference values, we present kinematic data related to normal overground and lane walking. The differences between these conditions were tested with a two factor age X condition ANOVA with repeated measures on the condition term. For instances in which significant interactions of interest were detected, follow up tests were performed on the simple comparisons with Bonferroni corrections applied for the number of comparisons made. Significance was set at $p<0.05$ unless corrections were applied.

To determine the normalization procedure, the peak moment data was correlated with subjects' leg length, body mass, body height, and finally, body height*body mass using a Pearson's r statistic. In the event of a significant relationship between peak moments and multiple anthropometric variables, we performed Fisher z transformations on the correlation coefficients and then statistically compared the values to determine which anthropometric variable was most strongly correlated. Effect size was reported as $\eta^2$, which is interpreted as the amount of variance in the dependent variable that can be accounted for by the independent variable (Levine & Hullet, 2002). This is similar to $R^2$ in an analysis using a regression approach.

$$\eta^2 = SS_{between}/SS_{total} \tag{3}$$

All statistics were performed with SPSS 17.0 (Chicago, IL).

## 5.3 **Results**

### 5.3.1 **Scaling of kinetic variables**

The peak hip abduction moments were more strongly correlated to body mass than other anthropometric variables tested. Leg length was not correlated to any of the peak hip abduction hip moments of the different targeted step type or step distance ($r (35) <= 0.187$, $p>0.267$). Body height was significantly correlated to only two of the six peak moment values. Body mass and body mass * body height were both significantly correlated to all six peak hip abduction moments. Correlation for body mass and peak abduction moment ranged from $r (35) = 0.52$ to 0.65 ($p=< 0.001$), with an average correlation coefficient of 0.59 while correlation for body mass * body height ranged from $r (35) = 0.49$ to 0.63 ($p<=0.002$) with an average correlation coefficient of 0.56. After transforming the correlation coefficients with a Fisher z transformation and statistically comparing the values, body mass was more strongly correlated with the peak abduction moments than body mass * body height ($t (5) = 9.3$, $p<0.001$).

### 5.3.2 **Peak hip abduction moments**

Peak hip abduction moments of older adults were larger than younger adults while performing laterally directed steps to targets. Regardless of the step utilized, the peak hip abduction moments of older adults were on average 30% greater than younger adults ($F (1,35)=8.085$, $p<0.001$, $\eta^2 =0.188$, 0.846 Nm/kg for older adults and 0.592 Nm/kg for younger adults), which was consistent across step type or target distance. On average, a crossover step resulted in a 30% greater peak abduction moment than sidesteps (Figure 3).

Among both older and younger adults, performing a COS to the long and medium targets resulted in a larger peak abduction moment compared to a SS while a long COS and SS generated a higher peak abduction moment compared to a short COS and SS, respectively. Within the model, the three way step X target X age interaction was not significant ($F$ (2,70) = 0.863, $p$=0.427) nor was the target X age interaction ($F$ (2, 70) = 0.086, $p$=0.086) or step type X age interaction ($F$ (1, 70) =1.686, $p$=.203). A significant interaction was detected for step X target ($F$ (2, 70) =171.151, $p<0.001$, Figure 4). *Post-hoc* tests were performed on the peak hip abduction moment of the three targeted conditions amongst each step type (i.e. a long, medium, and short crossover step) and on differences between step type at each target (i.e. a long crossover and sidestep). Five statistical tests were performed so the adjusted p-value for significance was $p<0.01$. A significant difference was detected amongst the different targeted conditions of SS and COS ($F$ (2, 108) = 17.417, $p<0.001$ $\eta^2$ =0.139 for sidesteps, $F$ (2, 108) =8.746, $p<0.001$, $\eta^2$ =0.244 for crossover steps). Within each statistical model, peak abduction hip moment for long COSs was significantly larger than that for short COSs (long crossover step =1.03±0.36 Nm/kg, short crossover step =0.66 ± 0.41 Nm/kg, $p<0.001$). The peak hip abduction moment of medium SSs was significantly larger than that of large SSs (medium sidestep=0.61± 0.24 Nm/kg large sidesteps= 0.40 ± 0.28 Nm/kg, $p$=0.001). For comparisons between the type of step utilized at each targeted distance, the peak abduction moments of long crossover steps was two and a half times larger than sidesteps (crossover step =1.03±0.36 Nm/kg compared to sidesteps= 0.40 ± 0.28 Nm/kg, $F$ (1, 72)=70.858, $p<0.001$, $\eta^2$=0.496). Significant differences also existed between medium crossover and sidesteps (crossover step =0.83 ± 0.37 Nm/kg compared to sidestep=0.61±

0.24 Nm/kg, $F(1, 72) = 9.474$ $p=0.003$, $\eta^2 = 0.116$). No differences were detected for short steps (crossover step =0.66 ± 0.41 Nm/kg compared to sidestep=0.76± 0.24 Nm/kg, $F(1, 72) = 1.356$, $p=0.240$, $\eta^2 = 0.018$).

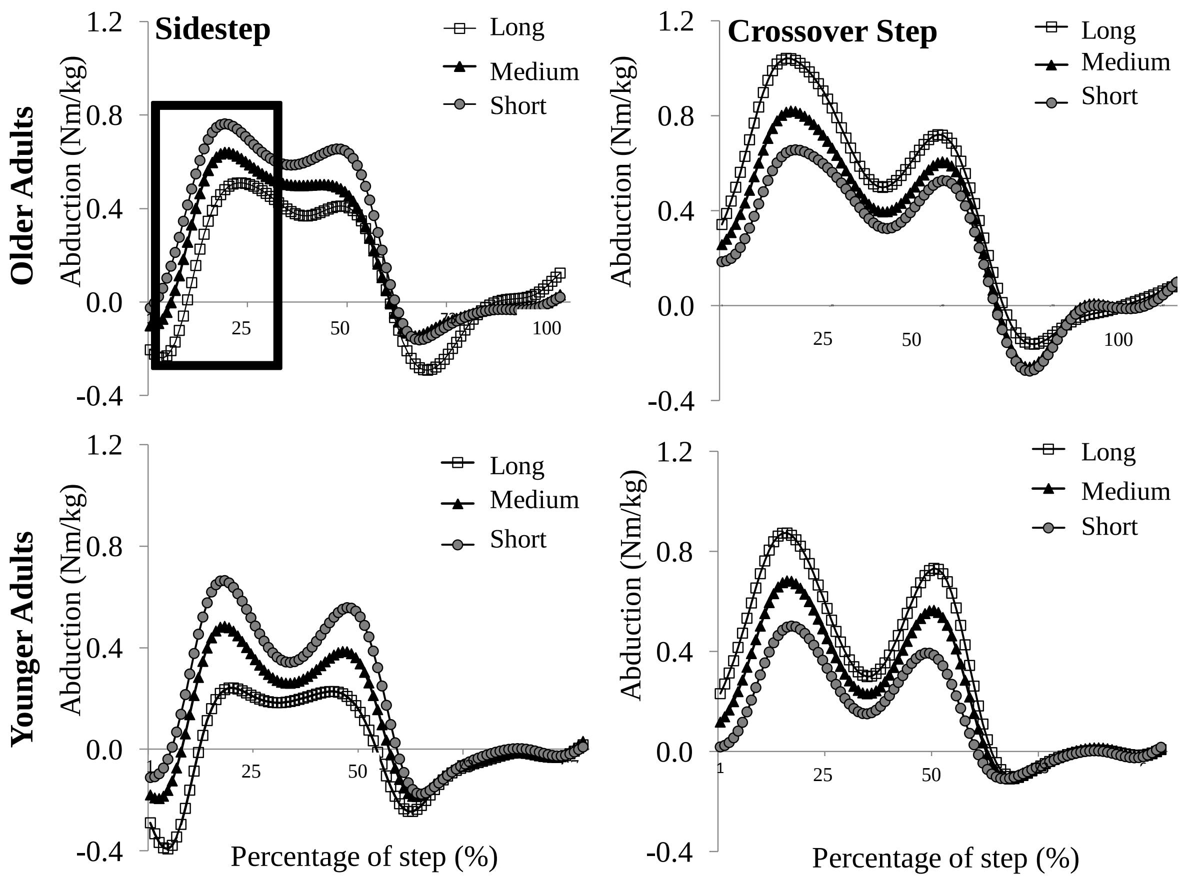


Figure 14. Abduction-adduction moment curves normalized by body mass are presented as a percentage of the step cycle for older (top panels) and younger adults (bottom panels) performing sidesteps (left panels) and crossover steps (right panels). The adduction-abduction moments for long (squares) medium (triangles) and short (circles) steps are represented. For this investigation, of particular interest were the peak values during the loading phase of the gait cycle. The loading phase constituted the initial peak of the bimodal curve. The area of interest is highlighted within the box for older adults performing sidesteps (upper left panel). On average, older adults peak abduction moment was 30% higher than younger adults ($p<0.001$)

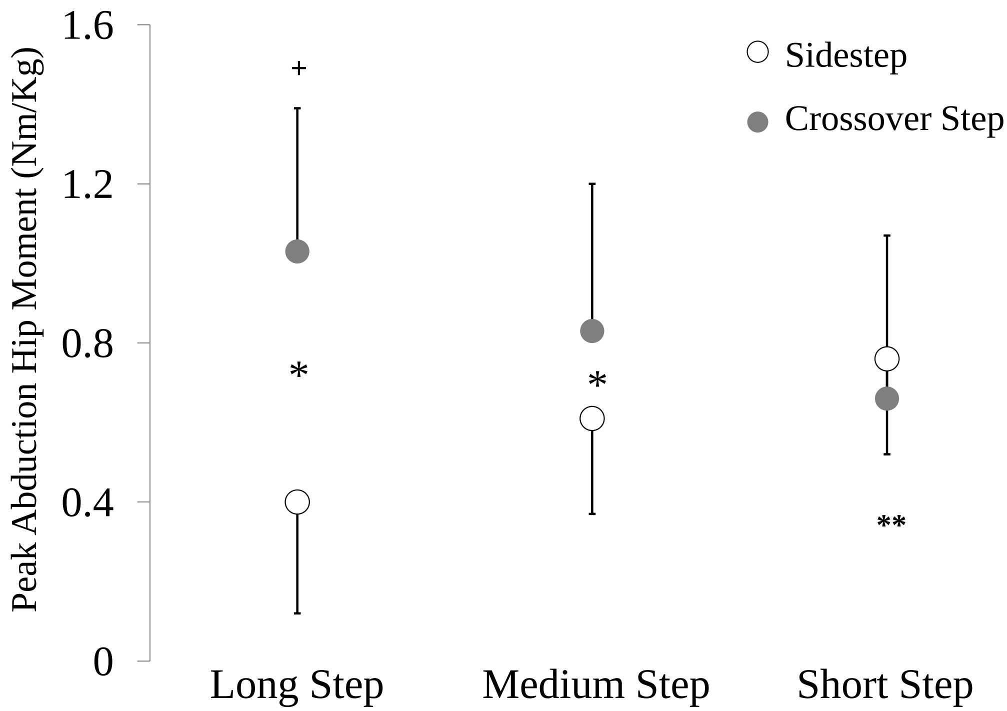


Figure 15. Represented is the significant step type by target interaction. The average value of peak hip abduction moment for long medium and short step targets are shown for sidesteps (white circles) and crossover steps (grey circles). *Post hoc* tests on the simple effects detected significant differences amongst long and short sidesteps (+) and long and short crossover steps (**). A significant difference was also detected between the long and medium (*) sidesteps and crossover steps.

5.3.3 **Effect of step type and target distance on dynamic stability**

Older adults were more stable than younger adults at the long and medium target distances and subjects utilizing a SS were more stable than those utilizing a COS to all target distances (TABLE VI). Within the statistical model, the step X target X age interaction term was not significant ($F_{(2, 70)}$ =45.254, $p$=0.683) nor was the step X target term ($F_{(1, 70)}$ =2.016, $p$=0.165). A significant interaction of the $MOS_{avg}$ was detected between age and the stepping target ($F_{(2, 70)}$ =4.540, $p$=0.014, Figure 5). A significant step type X target interaction was also detected within the statistical model ($F_{(2, 70)}$ =0.632, $p$<0.001, Figure 6). Succeeding paragraphs will present results from the post hoc analysis of the significant interaction terms.

Older adults were more stable than younger adults specifically at the long and medium step targets while long steps conferred a more stable step than medium and short steps for both groups. *Post hoc* tests on the significant age X target interaction were performed with an adjusted p-value of 0.01 for significance. Older adults compared to younger adults established a larger $MOS_{avg}$ for the long step (30% larger, $F_{(1, 35)}$ =14.133, $p$<0.001, $\eta^2$ =0.288) and medium step (23% larger, F= (1, 35) =9.971, $p$=0.003, $\eta^2$ =0.222). The $MOS_{avg}$ of older adults compared to younger adults while performing stepping to the short target was 17% larger, however, the difference did not achieve significance ($F_{(1, 35)}$ =5.202,$p$=0.029, $\eta^2$ =0.129). Within each age group, a significant effect of target was detected for older adults ($F_{(2, 34)}$ = 24.798, $p$<0.001, $\eta^2$ =0.666) and younger adults ($F_{(2, 36)}$ = 9.055, $p$=0.001, $\eta^2$ =0.335). For both groups, the $MOS_{avg}$ established for steps to the long target were significantly larger than the medium and short steps ($p$<0.01) while steps to the medium target were larger than the short target only within older adults.

TABLE VI. MEANS AND STANDARD DEVIATIONS OF THE AVERAGE MARGIN OF STABILITY OF OLDER AND YOUNGER ADULTS PERFORMING SIDESTEPS AND CROSSOVER STEPS TO TARGETS. REFERENCE VALUES OF SUBJECTS ARE ALSO PRESENTED FOR NORMAL WALKING.

| Group | | Normal Walking | Long sidestep | Medium sidestep | Short sidestep | Long crossover step | Medium crossover step | Short crossover step |
|---|---|---|---|---|---|---|---|---|
| Older | $MOS_{avg}$ (mm) ± SD | 80.3 ± 9.5 | 107.8 ± 24.5 | 97.3 ± 18.3 | 62.8 ± 18.1 | 51.4 ± 24.5 | 40.3 ± 21.8 | 41.7 ± 27.3 |
| Younger | $MOS_{avg}$ (mm) ± SD | 81.2 ± 8.7 | 90.9 ± 18.2 | 86.8 ± 13.8 | 62.6 ± 17.0 | 21.8 ± 27.3 | 19.6 ± 25.6 | 25.1 ± 18.2 |

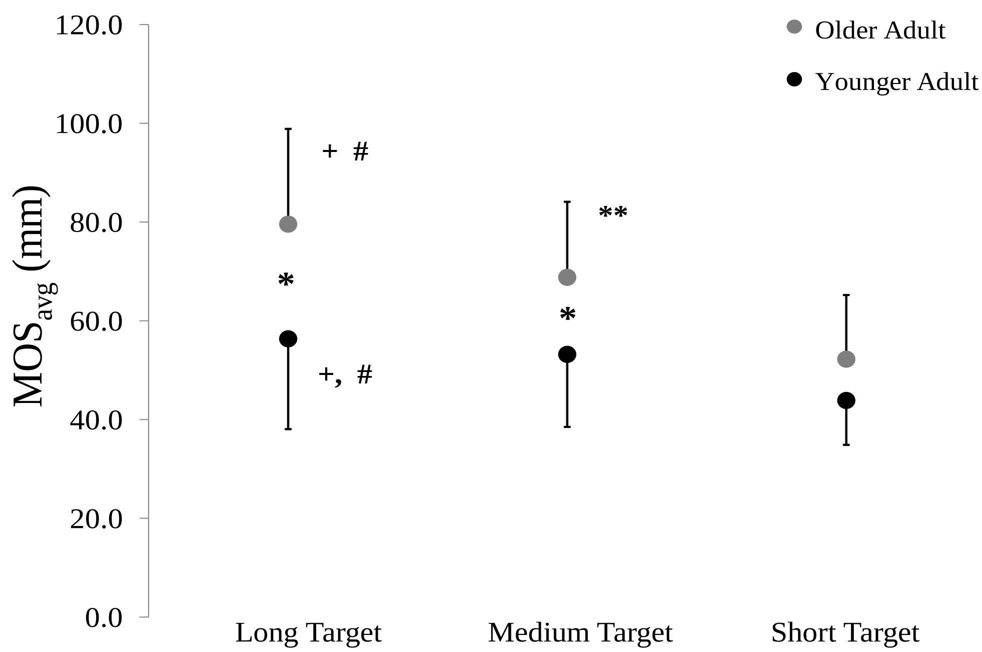


Figure 16. The significant step target by age interaction is displayed. Older adults (grey) established significantly larger $MOS_{avg}$ than younger adults (black) for all step targets (*) except the short target. Within each group, long targets were significantly larger than medium (+) and

short (#) targets ($p<0.01$). For older adults, the medium target was significantly greater than the short target (**).

Performing a SS conferred more stability than performing a COS to all step targets. Those performing a SS were more stable at each succeeding step distance (i.e. short to medium, medium to long) whereas no difference existed for COSs performed to the different target distances. *Post hoc* tests on the significant step X target interaction were performed with an adjusted p-value of 0.01 for significance. In comparison to sidesteps, the $MOS_{avg}$ of COSs were, on average, 60%, 67%, and 47% smaller in magnitude for long, medium, and short steps. Sidesteps established a larger $MOS_{avg}$ for the large step (99.1 mm ± 22.9 vs. 36.2 ± 29.7 mm, $F(1,36) = 351.826$, $p<0.001$, $\eta^2 =0.907$), medium step (91.9 ± 16.8 mm vs. 29.7± 25.7 mm larger, $F(1,36)= 484.576$, $p<0.001$, $\eta^2 =0.931$), and the short step (62.7± 17.2 mm vs. 33.2 ± 24.3 mm larger, ($F(1,36)= 26.435$, $p<0.001$, $\eta^2 =0.423$). The $MOS_{avg}$ of subjects performing sidesteps was significantly reduced as subjects stepped to the shorter targets ($F(2, 72) = 86.432$, $p<0.001$, $\eta^2 =0.706$). All the possible post hoc comparisons of SSs to the different targets were significantly different ($p<0.001$). No statistical difference was detected for subjects performing crossover steps ($F(2, 72) = 1.982$, $p<0.145$, $\eta^2 =0.052$).

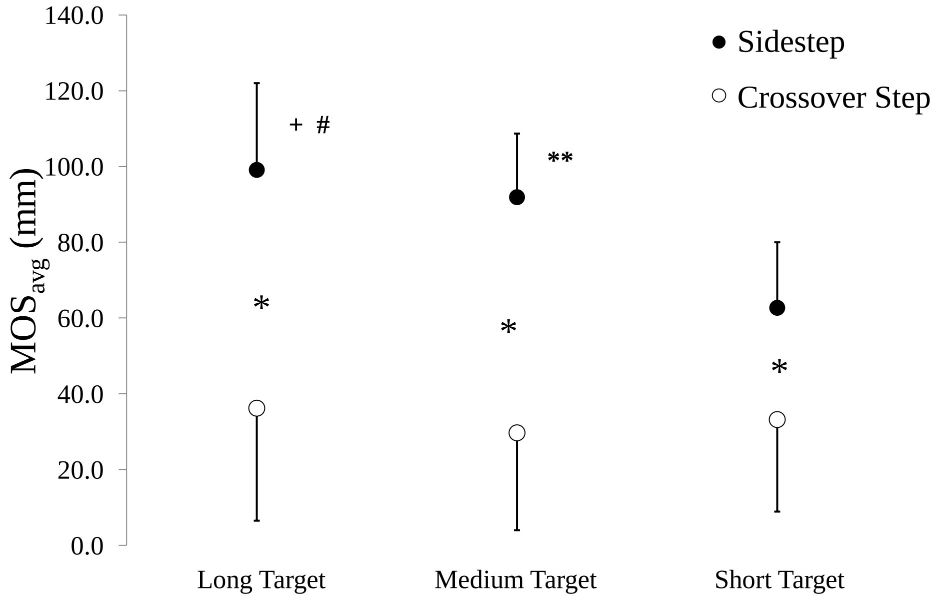


Figure 17. The significant step target by step type interaction is displayed. Older adults (grey) established significantly larger $MOS_{avg}$ than younger adults (black) for all step targets (*) except the short target. Within each group, long targets were significantly larger than medium (+) and short (#) targets (p<0.01). For older adults, the medium target was significantly greater than the short target (**).

5.3.4 **<u>Effect of step type and target distance on center of mass velocity</u>**

On average, the forward directed COM step velocity of older adults was significantly slower than that of younger adults. The forward step velocity of older adults performing laterally directed steps to the long, medium, and short targets was 25%, 20% and 20% slower than that of younger adults. With respect to forward step velocity, the step X target X condition interaction was not significant (F (2, 70) = 0.563, p=0.572). The step X target interaction (F (2, 70) = 0.395, p=0.584) and step X age interaction (F (1, 70) =0.009, p=0.925) were also not significant. A significant target X age interaction was detected (F (2, 70) = 4.216, p=0.019). *Post hoc* tests on this ordinal interaction were performed with an adjusted p-value of 0.01for significance. The age-related comparisons amongst the different step targets were all significant (long: $F(1, 35) = 44.441$, medium: $F(1, 35) = 29.424$, short: $F(1, 35) = 32.350$, $p<0.001$ for all models). Within each group, a significant effect of target was detected ($p<0.001$). For older adults, the average step velocity for the long target was significantly slower compared to the lateral steps to the medium and short targets ($F(2, 34) = 16.551$, $p<0.001$), however, no difference existed amongst the medium vs. short targets ($p=0.303$). Within younger adults, all comparison between the different target distances were significantly different ($F(2, 36) = 30.867$, $p<0.002$ for all comparisons).

The peak lateral step velocity of older adults was slower at all targeted steps. With respect to peak lateral step velocity, the step X target X condition interaction was not significant ($F(2, 70) = 0.777$, $p=0.464$). The step X target interaction ($F(2, 70) = 1.974$, $p=0.147$) and step X age interaction ($F(1, 70) = 0.832$, $p=.368$) were also not significant. A significant target X age interaction was detected ($F(2, 70) = 6.599$, $p=0.002$). *Post hoc* tests on this ordinal interaction were performed with an adjusted p-value of 0.01 for significance. All within group comparisons on target were significant ($p<0.001$), and all age-related comparisons on target distance were significant (long: $F(1, 35) = 32.633$, medium: $F(1, 35) = 18.514$, short: $F(1, 35) = 18.872$, $p<0.001$ for all models).

5.3.5 **Physical functioning and activity questionnaires.**

The older adults utilized in this study were, on average, a healthy and active cohort. For the physical functioning questionnaires, the range of older subject scores on the Godin leisure-time questionnaire was 14-185 with an average of $52.7 \pm 39.0$. Older adults reported a high level of physical functioning with scores ranging from 75 to 100 with an overall average of $86.4 \pm 8.5$. A previous study employing the physical functioning scale of the SF36 amongst a group of independently ambulatory community dwelling older adults reported a mean of 74.7 ± 19.4 (Bohannon et al., 2010). No correlation was detected between scales of physical activity and physical functioning scale of the MOS36 ($r(17) = 0.05$, $p = 0.834$).

## 5.4 **Discussion**

The purpose of the present study was to investigate the age-related differences of subjects performing COSs and SSs to three different targeted step widths during forward locomotion. We hypothesized that we would see a significantly smaller hip abductor moment of older adults compared to younger adults at all step targets regardless of the step utilized. On average, the peak hip abduction moments of older adults were 30% greater than younger adults. Therefore, we reject the null hypothesis, and further, we were unable to provide support for the alternative hypothesis.

We also hypothesized that older adults would be less stable than younger adults particularly at the longer step targets. Surprisingly, older adults were more stable than younger adults while performing these laterally directed steps at all three distances (Long 30% larger, medium 23% larger, short 17% larger) although only the long and medium steps resulted in a statistically difference in the $MOS_{avg}$. Thus we reject the null hypothesis and, further, we were unable to provide support for the alternative hypothesis. .

### 5.4.1 **Age-related difference in hip abduction moment**

It was surprising that the laterally directed steps of older adults resulted in greater peak hip abduction moments than in younger adults for many reasons. It has previously been reported that peak frontal plane hip abduction moments during normal walking scales linearly with increasing forward walking velocity (Rutherford and Cheryl, 2009). However, the forward step velocity of younger adults was approximately 28 % greater than older adults, which, given the relationship between walking speed and hip abduction moments, would be expected to have resulted in a greater peak moment in younger adults (based on Rutherford and Cheryl, 2009). Further, peak lateral velocity of younger adults at all step targets was approximately 9% greater for younger adults than older adults in spite of similar step widths for all targets. Presumably, a greater lateral COM velocity would result in the need to perform greater negative work on the COM (Donelan et al., 2001), thereby, requiring a larger abductor moment to arrest the lateral velocity of the COM. Currently, it is unknown whether the increased moments generated by older adults were the result of greater muscular effort in an attempt to reduce the likelihood of becoming unstable or resulted from age-related differences in the orientation of the lower limb at heelstrike. It is possible that younger adults stepped in such a way to more closely align the resultant ground reaction force vector in the frontal plane to the hip joint center. This would impart a smaller external moment by reducing the moment arm between the resultant force vector and the axis of rotation, which would result in the need to generate a smaller muscular moment to counteract the external moments. Measuring the EMG of the gluteus medius of younger and older adults while performing laterally directed steps could provide some clarity regarding whether the greater moments observed in older adults relate to greater muscular activation.

### 5.4.2 **Age-related difference in dynamic stability**

Older adults established a stable $MOS_{avg}$ (i.e. greater than 0) despite the increased challenge this protocol provided to lateral stability. Performing these lateral steps required an increased displacement and velocity of the COM compared to normal walking. In fact, peak lateral velocity to the long, medium and short targets were approximately 5.3, 3.9 and 2.6 times larger than the peak lateral velocity experienced during normal walking. In spite of this, older adults were surprisingly more stable than younger adults for the long and medium step conditions. Similar to a previous investigation (i.e. chapter 3), utilizing a SS conferred greater stability than a COS. We previously suggested that increased stability of older adults may have resulted from a more cautious or deliberate execution of the lateral step (Chapter 3). Similar to the previous study, older adults performed these lateral steps with slower peak lateral vCOM and a slower forward step vCOM than younger adults, which suggests that older adults may have attempted to maintain greater control over COM kinematics. We have previously observed that a stronger relationship existed between trunk COM kinematics and step width of older adults compared to younger adults (chapter 1 Hurt et al., 2010). We surmised that the stronger relationship was related to increased control over COM kinematics to avoid a misstep off the treadmill belt. This potentially destabilizing event is one that older adults would likely avoid. Similarly, with the present study, an inability to arrest lateral motion of the COM would result in the COM extending beyond the lateral border of the BOS, a destabilizing event that older adults would likely avoid.

It has previously been reported that older adults are vulnerable to medial-lateral instability. The results of the current investigation suggest that, at least with respect to executing targeted laterally directed steps, older adults perform these tasks with greater stability than younger adults. This is consistent with a previous study that also utilized a laterally directed stepping task during forward directed walking as an internal disturbance to lateral stability (Chapter 3). When utilizing external postural disturbances, older adults were significantly less dynamically stable than younger adults (Chapter 2). This may highlight the differences between utilization of internal and external balance disturbances to assess dynamic stability. The major limitation of the external disturbances is that subjects must start from a quasi-static standing posture. This is a somewhat contrived condition with which to assess dynamic stability. The strength of the current investigation is that dynamic stability was assessed while subjects performed a task that would challenge lateral-stability to a greater extent than normal walking, however, it would be of interest to provide external disturbances to subjects while they walk. Currently, only one investigation has delivered external disturbances to subjects while walking. However, these disturbances were quite small (only 0.06 m) and only delivered to younger adults (Hof et al. 2010).

5.4.3 **Limitations**

We recognize potential limitations of the current study. The conditions of this study were performed in the same order for all subjects potentially creating an ordering effect of our results. However, inherent differences between SSs and COSs may preclude transfer. Because these steps were taken with the dominant limb, the direction the subject executed the step was different (e.g. for a right-limb dominant subject, a COS would be directed to the left while a SS would be directed to subjects right). Further, the orientation of the lower limbs is quite different between a COS and a SS creating a different step condition. Also, the older adults utilized in this study were healthy and active. This sample of robust older adults may not be at an increased risk for laterally-directed falls or, more specifically, hip fracture. However, investigations that have suggested that older adults may be more laterally unstable have utilized a similarly healthy cohort of older adults as their subject population (Mille et al., 2005, Maki et al., 2000).

5.4.4 **Conclusions**

Age-related differences existed in the performance of targeted laterally-directed steps. The step widths of older and younger adults were the same, although, younger adults exhibited a significantly greater peak lateral vCOM that likely related to a smaller $MOS_{avg}$. Surprisingly, peak hip abduction moments were greater in older adults, but this may have related to the increase in $MOS_{avg}$. It was suggested that the difference in hip abductor moments may have related to greater muscular effort by older adults in an attempt to reduce the likelihood of becoming unstable. To the best of our knowledge, this was the first study to provide a scaled challenge to lateral stability of older adults. These results add further evidence that, contrary to results of external postural disturbances, the older adults utilized in this investigation did not appear to be more laterally unstable than younger adults while performing a task that transiently challenged lateral dynamic stability.

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# 6. **Conclusions**

The purpose of this dissertation was to investigate the effects of age on frontal plane dynamic stability. For each chapter of the dissertation the specific purpose and hypotheses are reiterated below.

## **Chapter 2**

The purpose of this study was to characterize the relationship between variations in frontal plane trunk center of mass (COM) kinematics during the swing phase and variations in the subsequent step width.

We hypothesized that frontal plane trunk COM kinematics during swing phase would explain a significant proportion of variance in the subsequent step widths.

We further hypothesized that the relationship between trunk kinematics and step width would be stronger in younger adults.

## **Chapter 3**

The purpose of this study was to investigate the lateral stepping responses of older and younger adults while recovering from similar laterally-directed postural disturbances that required a step in every trial.

We hypothesized that the compensatory stepping response of older adults would result in an increase in the relative frequency of sidestep (SS) sequence to crossover steps (COS) compared with younger adults.

We also hypothesized that older adults would be less dynamically stable than younger adults upon completion of the initial recovery step.

**<u>Chapter 4</u>**

The purpose of this study was to investigate the age-related differences to preplanned and cued COSs and SSs during forward locomotion.

We hypothesized that step widths of older adults in the cued lateral step conditions would be significantly smaller in magnitude than younger adults whereas no difference would be observed under preplanned conditions.

We also hypothesized that while performing these laterally-directed steps while walking, older adults would be less dynamically stable than younger adults.

**<u>Chapter 5</u>**

The purpose of this study was to investigate the age-related differences of subjects performing a COS and a SS to three different targeted step widths while walking.

We hypothesized that older adults would generate a significantly smaller hip abductor moment compared to younger adults at all step targets regardless of the type of step utilized.

We also hypothesized that older adults would be significantly less dynamically stable while performing a COS and a SS compared to younger adults, particularly at the longer step targets.

Many of alternative hypotheses we tested were not fully supported by our results. A significant relationship was observed between trunk COM kinematics at midstance and the succeeding step width, however, this relationship was actually stronger in older adults, thus, our hypotheses were partially supported (Chapter 2). These results provide evidence that step width is adjusted, step-by-step, with respect to the COM kinematics at the preceding midstance. The stronger relationship in older adults may have suggested an increased voluntary control over frontal plane motion of the center of mass (COM) by older adults to avoid a foot placement partially off the treadmill belt, a potentially destabilizing event.

We also observed that, in response to laterally-directed postural disturbances, older adults were less dynamically stable than younger adults with respect to the initial stepping response, thus, supporting our hypothesis (Chapter 3). Further, for this investigation, we observed no statistical difference between the frequency of SSSs and COSs between older and younger adults, and therefore, this hypothesis were not supported. Collectively, older and younger adults utilized a SSS with a higher frequency than a COS. This suggested that older adults did not avoid performing a COS. For those older adults who did utilize a COS however, they were more likely to require extra steps compared to younger adults. The need for extra steps while performing a COS was likely due to the initial step being insufficient to restore lateral dynamic stability.

Older adults performing laterally-directed steps during forward locomotion were as dynamically stable or more so than younger adults (Chapter 4). No age-related differences existed while performing a SS, however, older adults performing a COS were more stable than younger adults, and thus, our hypothesis was not supported. The increased stability of older adults was surprising given that the step widths of younger adults were significantly larger than older adults, which also did not support our hypothesis. It was reasoned that older adults may have exerted greater control over COM motion while performing these laterally directed steps compared to younger adults. Evidence for the increased control of the COM was surmised by the significantly slower forward-directed step velocity of the COM of older adults and a significantly slower peak lateral COM velocity for the laterally-directed steps.

The final study controlled the step width of younger and older adults by asking them to step to targets at three different distances (Chapter 5). Similar to previously reported results (Chapter 4), older adults were more stable than younger adults, thus, our hypothesis was not supported. Surprisingly, the peak hip abductor moment of older adults was 30% larger in magnitude across all conditions, which also did not support our hypothesis. It is possible that the increased peak hip abductor moment of older adults helped to ensure that the kinematics of the COM remained medial to the lateral edge of the base of support. Performing large lateral steps substantially increased peak lateral velocity of the COM compared to normal walking conditions. Previously, we provided evidence that step width is modified relative to the kinematics of the COM (Chapter 2), presumably, to ensure that the kinematics of the COM can be arrested and reversed in preparation for the next step. However, in the present study, step width was fixed relative to the step target. Without the benefit of being able to adjust step width, the hip musculature is then primarily responsible to arrest the lateral motion. Thus, it is possible that compared to younger adults, the increased peak hip moment of older adults was an indicator of a more cautious approach to taking these steps compared to younger adults.

The results of these four investigations are, to the best of our knowledge, the first attempt to understand the age-related effects on the maintenance of frontal plane dynamic stability across multiple unique tasks. Further, the novelty in the approach of these investigations was the focus on how a given step can create conditions for frontal plane instability during normal walking while recovering from external disturbances applied during a quasi-static standing posture and while performing voluntary laterally directed steps during forward locomotion. This approach has merit considering that a misplaced step is a leading cause of falls behind trips and slips amongst healthy community dwelling older adults (Berg et al. 1997).

The current investigations provide evidence that the maintenance of frontal plane dynamic stability is context specific. This is based on our findings that older adults were more dynamically stable than younger adults while performing voluntary laterally directed steps while walking, but were less dynamically stable than younger adults while recovering from laterally-directed postural disturbances. Many of the investigations that provide evidence of frontal plane instability in older adults relate to laterally-directed postural disturbances (Maki et al. 2000, Mille et al. 2005, Hilliard et al. 2008), however, the majority of falls by older adults occur while walking (Berg et al. 1997).

To further understand deficits of older adults in maintaining frontal plane dynamic stability, more investigations will be needed that challenge dynamic stability under specific and varied conditions. It is important to identify specific modifiable risk factors that increase the likelihood of older adults becoming dynamically unstable within the frontal plane so that training paradigms can be developed that target these risk factors. These risk factors may relate to health status or functional abilities. For instance, the degree that peak strength and power of older adults' hip abductors-adductors negatively impacts their ability to effectively control COM kinematics under conditions that challenge frontal plane dynamic stability is of interest. Finally, given the results of this dissertation, it is important to consider if identified risk factors that increase the likelihood of dynamic instability within the frontal plane are context or task specific. Ultimately, this is important given that training paradigms may only be effective at reducing the risk of a laterally-directed falls when the conditions of the training closely match real-life conditions (i.e. task-specific training) that initiate the fall. For instance, training paradigms using laterally-directed platform-based or waist-pull disturbances delivered to subjects from a standing posture may not be effective at reducing laterally-directed falls that occur while walking.

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## APPENDIX

### Approval Notice

UNIVERSITY OF ILLINOIS
AT CHICAGO

Office for the Protection of Research Subjects (OPRS)
Office of the Vice Chancellor for Research (MC 672)
203 Administrative Office Building
1737 West Polk Street
Chicago, Illinois 60612-7227

**Initial Review (Response to Modifications)**

May 13, 2011

Christopher Hurt, MS
Department of Kinesiology and Nutrition
1919 W. Taylor Street, Room 648
M/C 994
Chicago, IL 60612
Phone: (312) 413-9432 / Fax: (312) 996-3532

**RE: Protocol # 2011-0254**
**"The Use of Treadmill Disturbances as a Surrogate to Study Sideways Balance in Older Adults"**

Dear Dr. Hurt:

Your Initial Review (Response to Modifications) was reviewed and approved by the Expedited review process on May 6, 2011. You may now begin your research

Please note the following information about your approved research protocol:

| | |
|---|---|
| **Protocol Approval Period:** | May 6, 2011 - April 4, 2012 |
| **Approved Subject Enrollment #:** | 30 Total |
| **Performance Sites:** | UIC |
| **Sponsor:** | None |

**Research Protocol(s):**

a) The Use of Treadmill Disturbances as a Surrogate to Study Sideways Balance in Older Adults, Version 2.0, 5/3/2011

**Recruitment Material(s):**

a) "Research Subjects Needed 65 Years or Older" Flyer, Version 2.0, 3/5/2011

b) Older Adults Balance Study (Internet Advertisement), Version 2.0, 5/3/2011
c) Older Adults Balance Study, Telephone Script, Version 2.0, 5/3/2011

**Informed Consent(s):**

a) Older Adults Balance Study, Version 2.0, 5/3/2011
b) Waiver of Documentation of Consent for Telephone Screening Only, granted under 45 CFR 46.117(c)

**Additional Determinations for Research Involving Minors:** These determinations have not been made for this study since it has not been approved for enrollment of minors.

**Please note the Review History of this submission:**

| Receipt Date | Submission Type | Review Process | Review Date | Review Action |
|---|---|---|---|---|
| 03/22/2011 | Initial Review | Convened | 04/06/2011 | Modifications Required |
| 05/03/2011 | Response To Modifications | Expedited | 05/06/2011 | Approved |

Please remember to:

→ Use your **research protocol number** (2011-0254) on any documents or correspondence with the IRB concerning your research protocol.

→ Review and comply with all requirements on the enclosure,
"**UIC Investigator Responsibilities, Protection of Human Research Subjects**"

**Please note that the UIC IRB has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.**

**Please be aware that if the scope of work in the grant/project changes, the protocol must be amended and approved by the UIC IRB before the initiation of the change.**

We wish you the best as you conduct your research. If you have any questions or need further help, please contact OPRS at (312) 996-1711 or me at (312) 355-1404. Please send any correspondence about this protocol to OPRS at 203 AOB, M/C 672.

Sincerely,

Sheilah R. Graham, BS
IRB Coordinator, IRB # 1
Office for the Protection of Research Subjects

Enclosure(s):

1. **UIC Investigator Responsibilities, Protection of Human Research Subjects**
2. **Informed Consent Document(s):**
    a) Older Adults Balance Study, Version 2.0, 5/3/2011
3. **Recruiting Material(s):**
    a) "Research Subjects Needed 65 Years or Older" Flyer, Version 2.0, 3/5/2011
    b) Older Adults Balance Study (Internet Advertisement), Version 2.0, 5/3/2011
    c) Older Adults Balance Study, Telephone Script, Version 2.0, 5/3/2011
4. **Data Security Enclosure**

cc: Charles B. Walter, Department of Kinesiology and Nutrition, M/C 517
Mark D. Grabiner, Faculty Sponsor, Department of Kinesiology and Nutrition, M/C 994

UNIVERSITY OF ILLINOIS
AT CHICAGO

Office for the Protection of Research Subjects (OPRS)
Office of the Vice Chancellor for Research (MC 672)
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**Approval Notice**
**Continuing Review (Response To Modifications)**

November 9, 2011

Christopher Hurt, MS
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1919 W. Taylor Street, Room 648
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Phone: (312) 413-9432 / Fax: (312) 996-3532

**RE: Protocol # 2008-0967**
**"Compensatory Stepping Responses of Young Adults to Sideways Disturbances"**

Dear Mr. Hurt:

Your Continuing Review (Response To Modifications) was reviewed and approved by the Expedited review process on November 8, 2011. You may now continue your research.

Please note the following information about your approved research protocol:

**Protocol Approval Period:** November 12, 2011 - November 10, 2012
**Approved Subject Enrollment #:** 25 (17 enrolled to date; Limited to Data Analysis)
**Additional Determinations for Research Involving Minors:** These determinations have not been made for this study since it has not been approved for enrollment of minors.
**Performance Sites:** UIC
**Sponsor:** None
**Research Protocol(s):**

b) Compensatory Stepping Responses of Young Adults to Sideways Disturbances, Version 1.0, 10/01/2008

**Recruitment Material(s):**

d) N/A; Research Limited to Data Analysis

**Informed Consent(s):**

c) N/A; Research Limited to Data Analysis

Your research meets the criteria for expedited review as defined in 45 CFR 46.110(b)(1) under the following specific categories:

**(4)** Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving X-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.).,

**(6)** Collection of data from voice, video, digital, or image recordings made for research purposes.

**Please note the Review History of this submission:**

| Receipt Date | Submission Type | Review Process | Review Date | Review Action |
|---|---|---|---|---|
| 10/31/2011 | Continuing Review | Expedited | 11/02/2011 | Modifications Required |
| 11/04/2011 | Response To Modifications | Expedited | 11/08/2011 | Approved |

Please remember to:

→ Use your **research protocol number** (2008-0967) on any documents or correspondence with the IRB concerning your research protocol.

→ Review and comply with all requirements on the enclosure,
"**UIC Investigator Responsibilities, Protection of Human Research Subjects**"

**Please note that the UIC IRB has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.**

**Please be aware that if the scope of work in the grant/project changes, the protocol must be amended and approved by the UIC IRB before the initiation of the change.**

We wish you the best as you conduct your research. If you have any questions or need further help, please contact OPRS at (312) 996-1711 or me at (312) 413-7323. Please send any correspondence about this protocol to OPRS at 203 AOB, M/C 672.

Sincerely,

Jennifer Joaquin, MPH
IRB Coordinator, IRB # 1
Office for the Protection of Research Subjects

Enclosure(s):

5. **UIC Investigator Responsibilities, Protection of Human Research Subjects**

cc: Charles B. Walter, Department of Kinesiology and Nutrition, M/C 517
Mark D. Grabiner, Faculty Sponsor, Department of Kinesiology and Nutrition, M/C 994

UNIVERSITY OF ILLINOIS
AT CHICAGO

Office for the Protection of Research Subjects (OPRS)
Office of the Vice Chancellor for Research (MC 672)
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**Approval Notice**
**Initial Review – Expedited Review**

November 24, 2010

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1919 W. Taylor Street, Room 648
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Chicago, IL 60612
Phone: (312) 413-9432 / Fax: (312) 413-3532

RE: Protocol # 2010-0980
"The Maintenance of Balance of Younger Adults After Performing a Sideways Step While Walking"

Dear Mr. Hurt:

Members of Institutional Review Board (IRB) #3 reviewed and approved your research protocol under expedited review procedures [45 CFR 46.110(b)(1)] on November 15, 2010. You may now begin your research.

Your research meets the requirement for Expedited Review under the following categories:
(4) Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving X-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.)
Examples: (a) physical sensors that are applied either to the surface of the body or at a distance and do not involve input of significant amounts of energy into the subject or an invasion of the subject's privacy; (b) weighing or testing sensory acuity; (c) magnetic resonance imaging; (d) electrocardiography, electroencephalography, thermography, detection of naturally occurring radioactivity, electroretinography, ultrasound, diagnostic infrared imaging, doppler blood flow, and echocardiography; (e) moderate exercise, muscular strength testing, body composition assessment, and flexibility testing where appropriate given the age, weight, and health of the individual.

(6) Collection of data from voice, video, digital, or image recordings made for research purposes.

Please note the following information about your approved research protocol:

**Protocol Approval Period:** November 15, 2010 - November 14, 2011
**Approved Subject Enrollment #:** 25
**Additional Determinations for Research Involving Minors:** These determinations have not been made for this study since it has not been approved for enrollment of minors.
**Performance Sites:** UIC
**Sponsor:** None
**Research Protocol:**

c) The Maintenance of Balance of Younger Adults After Performing a Sideways Step While Walking, Version 1.0, 11/01/2010

**Recruitment Materials:**

e) Telephone Script, Version 1.0, 11/01/2010
f) Flyer, Version 1.0, 11/01/2010

**Informed Consents:**

d) The maintenance of balance..., Version 1.0, 11/15/2010
e) Alteration of informed consent granted under 45 CFR 46.116(d) for the telephone screening process

**Please note the Review History of this submission:**

| Receipt Date | Submission Type | Review Process | Review Date | Review Action |
|---|---|---|---|---|
| 11/09/2010 | Initial Review | Expedited | 11/15/2010 | Approved |

Please remember to:

→ **Use only the IRB-approved and stamped consent document(s) enclosed with this letter when enrolling new subjects.**

→ Use your **research protocol number** (2010-0980) on any documents or correspondence with the IRB concerning your research protocol.

→ Review and comply with all requirements of the,
"**UIC Investigator Responsibilities, Protection of Human Research Subjects**"

**Please note that the UIC IRB has the right to ask further questions, seek additional information, or monitor the conduct of your research and the consent process.**

**Please be aware that if the scope of work in the grant/project changes, the protocol must be amended and approved by the UIC IRB before the initiation of the change.**

We wish you the best as you conduct your research. If you have any questions or need further help, please contact the OPRS office at (312) 996-1711 or me at (312) 413-3788. Please send any correspondence about this protocol to OPRS at 203 AOB, M/C 672.

Sincerely,

Rachel Olech, B.A., CIP
Assistant Director, IRB # 3
Office for the Protection of Research Subjects

Enclosures:

6. **UIC Investigator Responsibilities, Protection of Human Research Subjects**
7. **Informed Consent Document:**
   b) The maintenance of balance..., Version 1.0, 11/15/2010
8. **Recruiting Materials:**
   d) Telephone Script, Version 1.0, 11/01/2010
   e) Flyer, Version 1.0, 11/01/2010

cc: Mark D. Grabiner, Faculty Sponsor, Kinesiology and Nutrition, M/C 994
Charles B. Walter, Department of Kinesiology and Nutrition, M/C 517

**Vita**
**Christopher P. Hurt, M.S.**
3224 N. Hoyne Ave.
Apt. 2F
Chicago, IL 60618

| | |
|---|---|
| **BUSINESS ADDRESS** | University of Illinois at Chicago<br>Department of Kinesiology and Nutrition<br>1919 W. Taylor Street<br>650 AHSB, M/C 994<br>Chicago, IL 60612<br>Phone: 312.413.9432<br>Fax: 312.996.3532<br>e-mail: churt2@uic.edu |


## Education:

**Doctor of Philosophy Candidate**
Department of Kinesiology and Nutrition
Concentration: Biomechanics and motor control
University of Illinois at Chicago, IL, Spring 2012

**Master of Science**
Department of Integrative Physiology
University of Colorado, Boulder, CO, *May 2006*

**Bachelor of Science**
Department of Health Physical Education and Recreation
Concentration: Exercise Science
University of Nebraska, Omaha, NE, *May 2004*

**Associates of Applied Science in Business Marketing and Management**
Southeast Community College, Lincoln, NE, *September 1999*

### Research Experience:

**Graduate Student Researcher, Univ. of Illinois, Chicago, Clinical Biomechanics and Rehabilitation Laboratory**

Mentor: Mark Grabiner, Ph.D.
Dissertation Project:
The influence of age on the maintenance of frontal plane dynamic stability

**Other Projects:**

- Polestriding versus walking for PAD Rehabilitation
  Responsibilities included data collection, data processing and analysis
- Fall prevention training program for older adults

Responsibilities included data collection

**Graduate Student Researcher, Univ. of Colorado, Locomotion Laboratory**
Mentor: Rodger Kram, Ph.D.
Master's Thesis: *The interaction between preferred walking speed and attentional demand*

**Projects:**

- The interaction between performance on a cognitive task and the regulation of preferred walking speed
- The development of a passive exoskeletal load-carrying assistive device for walking

**Undergraduate Biomechanics Laboratory Intern, Univ. of Nebraska, Omaha**
Mentor: Nicholas Stergiou Ph.D.

- Assisted in data collection, data processing, and gait analysis.

**Project:**
The run to sprint gait transition

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**Assistantships**:

**Research Assistantship**
2007-2011 University of Illinois at Chicago
**Project:** Polestriding versus walking for PAD rehabilitation
Responsibilities included data collection, data processing and analysis

Spring 2006 University of Colorado, Boulder
**Project:** Development and testing of a portable swing assist device used in conjunction with gait re-training for but not exclusive to stroke and spinal chord injury

**Teaching Assistantship**
Fall 2006-Spring 2007 University of Illinois at Chicago
*Courses*: Advanced Exercise Physiology
Responsibilities: Provide students with the knowledge and guidance to create and execute a research project
Human Aging and Performance
Responsibilities: Grading

Fall 2004-Spring 2006 University of Colorado, Boulder
*Courses:* Biomechanics
Responsibilities: Lead the laboratory section of the class and help students develop a research project for the course
Neurophysiology,
Responsibilities: Lead the laboratory section of the class
Statistics,
Responsibilities: Attend the laboratory portion of the class and assist students with questions they may have of the course material
Introduction to Integrative Physiology,
Responsibilities: Writing test questions and grading

Lower Division Scientific Writing,
Responsibilities: Grading
Upper Division Scientific Writing
Responsibilities: Grading

## Scientific Presentations:

**Hurt CP,** Earnest L, Grabiner MD. Adaptation and form of the unconstrained lateral compensatory stepping response. American Society of Biomechanics Annual Meeting, Providence RI, 2010, Podium Presentation

**Hurt CP,** Roseblatt N, Grabiner MD. *Are feedback related adjustments to step width affected by performance of the Stroop Test?* American Society of Biomechanics Annual Meeting, State College PA, 2009, Podium Presentation

Rosenblatt N, **Hurt CP**, Grabiner MD. *Quantifying coordination during recovery from a tripping task.* American Society of Biomechanics Annual Meeting, State College PA, 2009, Podium Presentation

**Hurt CP**, Hamstra-Wright K, Roseblatt N, Troy K, Grabiner M. *Variance in Step Width Suggests a Link to Variance in Step Width* North American Congress of Biomechanics, Ann Arbor MI, 2008, Poster Presentation

Hamstra-Wright K, **Hurt CP**, Grabiner M. *The Influence of an Attention Demanding Task on Trunk Control and Step Width During Treadmill Walking in Older Adults* Great Lakes Athletic Trainers Association Annual Meeting Winter, 2008

**Hurt, CP**, Kram, R,. *Conscious control of preferred walking speed: are we paying attention?* American College of Sports Medicine 53rd Annual Meeting, Denver, 2006.

**Hurt CP**, Kurz M, Stergiou, N, *Is there a gait transition from run to sprint?* International and American Societies of Biomechanics, Cleveland, 2005.

**Hurt CP**, Kram R, *Cognitive demand affects preferred walking speed*. Coleman Institute for Cognitive Disabilities Conference, Boulder, 2005.

## Manuscripts:

**Hurt CP,** Rosenblatt N, Grabiner MD. *Form of the compensatory stepping response to repeated laterally directed postural disturbances*. Exp Brain Res 2011,214:.557-66 http://dx.doi.org/10.1007/s00221-011-2854-1

Rosenblatt N, **Hurt CP,** Grabiner MD. Maintenance of MOS while walking on a dual belt treadmill. J App Biomech. (Accepted September 2011)

Crenshaw J, Rosenblatt N, **Hurt CP,** Grabiner MD. *Dynamic stability during successful and failed compensatory stepping responses.* J Biomech 2012, 45:129-133. DOI http://dx.doi.org/10.1016/j.jbiomech.2011.09.022

**Hurt CP**, Rosenblatt N, Crenshaw J, Grabiner M. *Variation in Trunk Kinematics Influences Variation in Step Width during treadmill walking by Older and Younger Adults*. Gait Posture 2010, 31. 2010. 461-4. http://dx.doi.org/10.1016/j.gaitpost.2010.02.001

Collins EG, O'Connell S, McBurney, C, Jelinek C, Butler J, Reda D, Gerber BS, **Hurt CP**, Grabiner MD. *Comparison of walking with poles and traditional walking for PAD rehabilitation.* J Cardio Rehab Preven. (Submitted January 2012)

## Invited Lectures

- Muscle Function During Human Locomotion, KN 251 Human Physiological Anatomy I, Fall 2011, Fall 2010, Fall 2009
- Mechanical Properties of tendons, KN 465 Biomechanicsof the neuromusculoskeletal system. Spring 2008
- Organization and Control of Circulation to Skeletal Muscle, KN 452 Advanced Exercise Physiology, Spring 2007
- Gait Analysis and Human Walking, *Schwab Rehabilitation Institute, Chicago, Il* 2008
- Ancova in statistical analysis. IPHY 2800 Introduction to Statistics Fall semester 2005.
- Anova vs. t-test in statistical analysis, IPHY 2800 Introduction to Statistics, Spring Semester 2005.
- Biomechanics, a broad overview. IPHY 1010 Introduction to Integrative Physiology. Fall Semester 2004

## Technical Experience:

Force/Timing Measurement
- 3D Force Measuring Treadmill
- AMTI force platform
- Photo-electronic Timers

Muscle Function and Electrophysiology
- Biodex Isokinetic Dynamometer
- Delsys Bagnoli 2 EMG System
- Noraxon telemetered electromyography system

Video Equipment
- Peak Performance Technologies Motus Motion Measurement System
- Motion Analysis Systems (Cortex and Orthotrak software)
- Basler Pilot high speed digital camera

Software
- MATLAB software
- Labview software
- Microsoft Office software

Exercise Physiology Related Instrumentation

- Indirect Calorimetry
- Graded Exercise Testing
- Treadmill/Cycle Ergometer
- Electrocardiograph
- Body Composition- Skinfold Calipers, Submersion tank-Chatillon Scale
- Pulmonary Function- Spirometer with Kymograph, Neumochek

Machine Shop Experience

- Certification to use lathe, milling machine, CNC rapid prototyping machines in Physics and Engineering Departments. University of Colorado, Boulder

## Undergraduate Students Mentored:

Undergraduate Project Mentoring: Along with Mark D. Grabiner, advised students in data collection, data processing, data interpretation, writing an abstract, and presenting a scientific poster.

Laura Earnest
*Form of uncontrained stepping response in younger adults* University of Illinois, Chicago Undergraduate Research Symposium, Spring, 2010

Carrie Griffin
Dual belt treadmill gap affects step width in younger adults while treadmill walking University of Illinois, Chicago Spring 2009

Katie Stephanie
*Comparison of Step Width and its Variability During Treadmill and Overground Walking* University of Illinois, Chicago Undergraduate Research Symposium, Spring, 2008
2$^{nd}$ place finish in the Physical Sciences/Engineering/Computer Science/Mathematics

Giovani Beradi
*The effect of fatigue on step kinematics.* University of Illinois, Chicago Undergraduate Research Symposium, Spring, 2007

Kris McKinney
*The effect of backward walking practice on step width variability*. University of Illinois, Chicago Undergraduate Research Symposium, Spring 2007

## Professional Organizations:

- American Society of Biomechanics 2004-present
- American College of Sports Medicine 2006-2007
- AAPHERD 2004-2005

## Honors and Awards:

- Graduated Cum Laude from the University of Nebraska, Omaha
- Graduated with distinction from Southeast Community College-Lincoln
- Dean's List, U.N.O. Fall of 2002, Spring of 2003, Fall 2003
- Dean's List, Southeast Community College, Lincoln
- Who's Who Among Students in American Universities & College
- NASPE Outstanding Physical Education Major of the Year Award from the Exercise Science Concentration at U.N.O.

**Service:**

- Chicago Public Schools Science Fair Judge A.N. Pritzker School 2007, 2008, 2009
- Chicago Public Schools Area 6 Science Fair Judge 2007, 2008, 2009
- Chicago Public Schools Science Fair Judge West Ridge School 2010

**References:**

Mark Grabiner, Ph.D.
Professor
University of Illinois Chicago
650 AHSB MC 994
Chicago, IL 60612-7249
E-mail: **grabiner@uic.edu**

Karen Troy, Ph.D.
Assistant Professor
University of Illinois Chicago
650 AHSB MC 994
Chicago, IL 60612-7249
E-mail: **klreed@uic.edu**

Charles Walter, Ph.D.
Professor
University of Illinois Chicago
650 AHSB MC 994
Chicago, IL 60612-7249
E-mail: **cwalter@uic.edu**