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Ageing Effects on Medio-lateral Balance During Walking With Increased and Decreased Step Width

H. Nagano, R. Begg, and W.A. Sparrow

Abstract—**The current study used falls direction to categorize falls and explore age-related effects on the biomechanics of medio-lateral balance control. Minimum lateral margin (MLM) was defined as the critical swing phase event where the medio-lateral length between center of mass (CoM) and stance heel became minimum and accordingly, any lateral balance perturbation at MLM was considered to increase the risk of balance loss lateral to the stance foot. Lateral center of pressure (CoP) displacement from toe-off to MLM was also monitored to assess the risk of medio-lateral balance perturbation. Gait testing involving 30 young and 26 older male subjects was conducted under the three step width conditions: preferred and ±50% wider and narrower. For an overall description of gait, spatio-temporal parameters were also obtained. Typical ageing effects on spatio-temporal parameters such as lower step velocity, shorter step length and prolonged double support time were found, emerging most clearly in narrower, followed by wider and least in preferred width walking. MLM and CoP lateral displacement were not differentiated between the two age groups, but older adults demonstrated significantly more variable MLM and CoP in their non-dominant limb when walking with non-preferred widths. Variability of step width reduced in increased and decreased step width conditions while MLM and CoP variability increased, suggesting less consistent medio-lateral CoM control despite consistent foot control in altered width conditions. In summary, older adults were found to have less consistent control of CoM with respect to the non-dominant stance foot when walking with narrower and wider widths possibly due to more variable medio-lateral CoP control.**

I. INTRODUCTION

Falls among older adults is a serious issue, which deserves attention due to the demographically ageing in developed countries. Gait biomechanics has been utilized to improve understanding of falls during locomotion, required for prevention strategies. For falls to be analyzed in detail, categorization of falls is essential, and by classifying different falls types based on direct causes, the biomechanical understanding of falls has been greatly advanced. For example, up to 78% of falls are found to be attributable to either tripping or slipping [1-3], and the mid-swing phase event, minimum foot clearance (MFC) [4] and the terminating swing phase event, heel contact [5] were extensively investigated for the risk of tripping and slipping, respectively.

In addition to direct causes, another categorization method is based on falls direction. Smeesters et al. [6] reported that tripping mainly induces falls in the anterior direction while posterior falls is most frequently caused by slipping after heel contact. In relation to sideway (lateral) falls, investigations have not been yet sufficient, and the purpose of the current study is first, to identify the critical gait event in regards to lateral balance loss and second, to explore the mechanism and effects of ageing on medio-lateral balance control.

Sideway falls has been considered as a result of balance loss in the lateral direction, defined as center of mass (CoM) dislocated laterally from the base of support [7], [8]. In this sense, the risk of lateral balance loss can be considered highest when medio-lateral length between CoM and stance foot is minimum and this point is defined as minimum lateral margin (MLM) [9]. Due to the closest distance to stance foot, unexpected lateral balance perturbation at MLM (e.g. lateral push) can lead to balance loss more easily than any other part of gait cycle. Greater MLM may, for this reason, protect against lateral balance loss.

As single support phase is more vulnerable than relatively stable double support time, the critical temporal period in relation to medio-lateral balance can be considered from toe-off to MLM. During this period, lateral deviation of centre of pressure (CoP) was also recorded in the current study to assess the risk of lateral balance loss. While the typical CoP path takes the slight lateral curve to redirect CoM medially, any lateral CoP deviation exceeding the functional requirement can increase the risk of lateral balance loss [10-12]. Therefore, lateral CoP displacement from toe-off to MLM reflects the status of medio-lateral balance.

To further explore MLM characteristics, the current study conducted gait testing under the three distinctive step width conditions: preferred and ±50% narrower and wider. Older adults are known to take larger step width to compensate for age-related loss of medio-lateral balance [13], [14] and from the perspective of the base of support, greater step width provides additional lateral margin for CoM to travel before balance loss [7], [8]. Healthy older adults are often capable of hiding age-associated gait impairment under the least obstructed walking conditions, but under more challenging walking conditions, ageing effects on balance impairment tends to appear more visible [17]. Step width manipulation as experimental conditions was accordingly, to extract age-unique adaptations to secure medio-lateral balance in response to altered-width walking.

While narrower walking seems to provide functionally more challenging walking conditions, wider walking may elicit the functional advantage for medio-lateral balance as widening of the base of support can secure medio-lateral

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balance [13], [14], possibly reflected in greater MLM and minimized CoP lateral deviation. For overall description of gait patterns between young and older adults, spatio-temporal parameters including step velocity, step length and double support time in addition to step width used for designing experimental conditions were also recorded.

When forming hypotheses about ageing effects on medio-lateral balance, gait pattern changes due to ageing can be separated into 1) safety adaptations and 2) age-related functional declines. Older adults would possibly employ gait adaptations to secure medio-lateral balance including greater MLM and lower CoP lateral displacement. In contrast, the second type of ageing effects can appear in the examined parameters as increased step-to-step variability or lower limb asymmetry [15], [16].

II. METHODS

A. *Participants*

The participants included 30 young (18-35 yrs.) and 26 older male adults (> 60 yrs.) with identical physical characteristics including height (young: 1.77 ± .06m, older: 1.74 ± .07m) and mass (young: 75.7 ± 3.5kg, older: 76.7 ± 7.9kg). Five from the young and four from the older groups were classified as left limb-dominant, determined by the established procedure [18]. Older adults were limited to vigorous and healthy individuals who maintained independent lifestyles and were capable of walking actively longer than for 30 minutes without a break. They also reported no falls in the past two years and no traumatic injuries that would affect their gait. All participants provided informed consent using procedures approved and mandated by the Victoria University Human Research Ethics Committee.

B. *Protocol*

Gait testing was conducted under three step-width conditions: preferred, narrow and wide walking. All participants began with preferred walking, in which they walked straight at preferred speed above the 8m walkway. The following two conditions were performed in randomized order. Narrow and wide walking conditions were ±50% relative to average step width in preferred walking. In both width-controlled walking conditions, the two parallel lines were drawn on the walkway to indicate target step width and subjects were instructed to contact the line with their heels. In each condition, 60-90 gait cycles were recorded per subject from both limbs.

Both heels and toes in addition to estimated CoM based on pelvis segment [19], [20] were sampled by three Optotrak (Optotrak®, NDI, Canada) cameras constantly at 100Hz. Pelvis segment CoM was based on the dynamic locations of anterior superior iliac crests, posterior inferior iliac spines and greater trochanters, modeled by the Visual 3D convention. At the middle of the walkway, two AMTI force plates were implemented to obtain CoP data. A 4^{th} order zero-lag Butterworth Filter with a cut-off frequency of 15Hz was applied to all the obtained data prior to analysis.

C. *Events Definition*

Minimum lateral margin (MLM) was defined as the mid-swing phase event where medio-lateral distance between CoM and heel of stance foot is minimum (Fig. 1) and the dominance of MLM follows the stance foot.

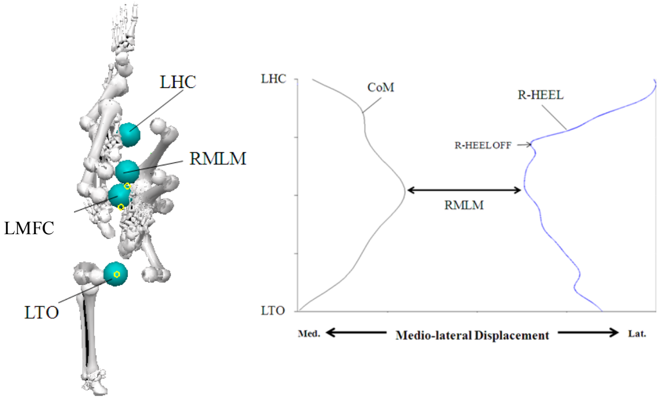

Figure 1. (Left) Minimum Lateral Margin (MLM) illustration in the transverse plane during left limb swing phase. Trajectory of CoM. Abbreviations: L/R = left/right, TO = toe-off, HC = heel contact; (Right) MLM defined as minimum medio-lateral distance between CoM and right heel in the transverse plane.

Swing phase was determined as the period from toe-off to heel contact following the kinematic convention [21]. Step length and width are displacements between two consecutive heel contacts in anterior-posterior and medio-lateral directions, respectively. Double support time was recorded from heel contact of one limb to contralateral toe-off, when both feet are on the walking surface. Step velocity is average horizontal velocity of foot during the swing phase.

A. *Statistical Analysis*

A 2 x 3 x 2 (age x width x limb) repeated measures mixed model analysis of variance (ANOVA) design was applied to show how ageing, step width and limb dominance would cause different MLM characteristics. Examined parameters included MLM and lateral CoP displacement. P-values lower than .05 was accepted as statistically significant.

III. Results

Results of spatio-temporal parameters including step width, step velocity, step length and double support time under three width conditions are summarized in Fig. 2 below. The three step width conditions were statistically distinguished (F (2, 53) = 272.0, p < .01) as preferred (9.9cm), narrow (5.4cm) and wide (14.8cm). Width control was relatively matched with the targeted 50%. Age-related increase in step width was by 1.3cm but statistically not differentiated. Step width variability in preferred width, narrow and wide walking was 3.0cm, 2.2cm and 2.1cm, respectively, such that SD reduced when step width was controlled (F (2, 53) = 13.8, p < .01).

Older adults showed lower step velocity (F (1, 54) = 37.6, p < .01) with shorter step length by 11.7cm (F (1, 54) = 30.7, p < .01) than the young. Significant age x width interactions were obtained for older adults showing step velocity (F (2, 53) = 18.7, p < .01) and length (F (2, 53) = 10.0, p < .01) greatest in preferred width walking, followed by wider and lowest in narrower walking.

Older adults had longer double support time by 0.05s than young adults (F (1, 54) = 21.7, p < .01). Effects of step width were seen only in the older adults for longest double support time in narrow and shortest in preferred width walking, validated by age x width interaction (F (2, 53) = 7.0, p < .01). Variability of double support time was, in general, greater in older adults but this effect did not reach the significant level (F (1, 54) = 4.0, p = .053).

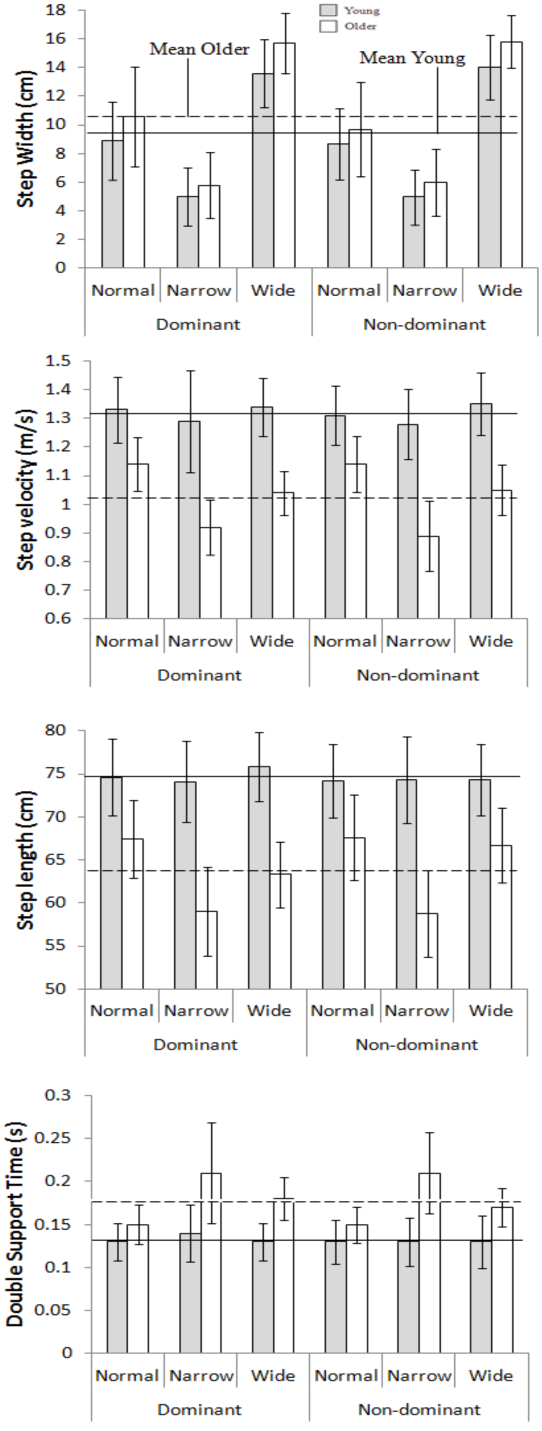

Figure 2. Spatio-temporal parameters: step width, step velocity, step length and double support time.

Parameters indicating medio-lateral balance, MLM and lateral CoP displacement are described in Fig. 3. MLM was not differentiated between the two age groups. Non-dominant MLM was found to be 1.5cm greater than the dominant side (F (1, 54) = 21.9, p < .01). Width effect (F (2, 54) = 8.7, p < .01) was obtained for MLM due to greatest MLM in wide walking (3.4cm) followed by narrow (2.2cm) and preferred width walking (2.1cm). Less steady MLM control was found in the older group (F (1, 53) = 35.5, p < .01) in response to narrow and wide walking, reflected in width x age interaction (F (2, 53) = 6.1, p < .01).

Ageing and step width effects were not discovered for lateral CoP displacement from toe-off to MLM. CoP displacement was found to be greater in the dominant limb by 0.9cm on average than the non-dominant limb (F (1, 54) = 21.9, p < .01). SD of lateral CoP displacement was significantly higher in the older group (F (2, 53) = 4.5, p < .05) and in the non-dominant stance foot (F (1, 54) = 6.5, p < .05). As clearly visualized in Fig. 3, both limb x age (F (1, 54) = 6.5, p < .05) and age x width interactions (F (2, 53) = 3.8, p < .05) clarified that only older adults increased non-dominant SD during narrow and wide walking.

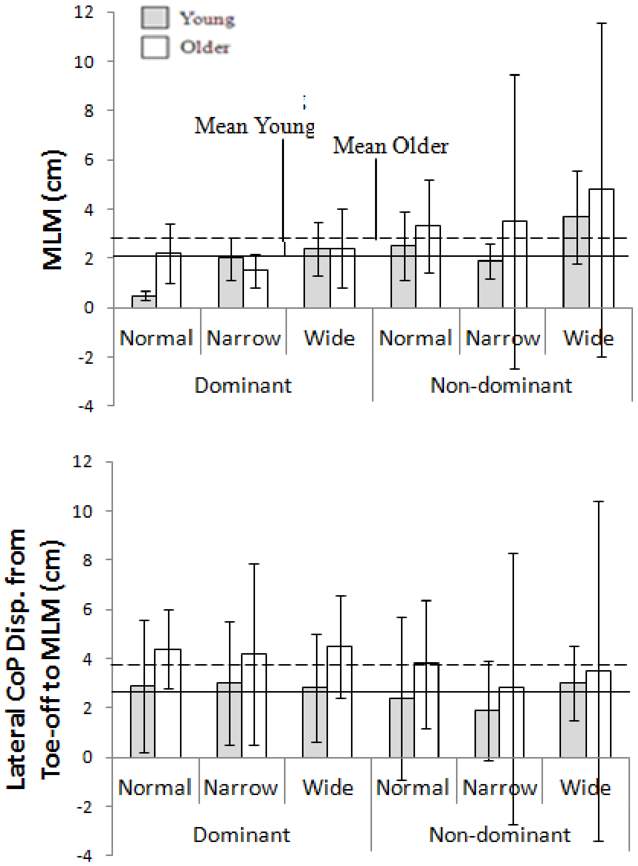

Figure 3. (Top) MLM; (Bottom) Lateral CoP displacement.

IV. DISCUSSION

Overall ageing effects on spatio-temporal parameters include reduction in step velocity due to shorter step length and prolonged double support time, consistent with the previous reports [14], [22]. These ageing effects tend to be accentuated in challenging walking conditions [17], [23] and accordingly, narrow-width walking seemed most challenging, less in wider walking but still more challenging than preferred-width walking. Young adults, on the contrary, were free from any width effects on spatio-temporal parameters. Greater step width in the older group was also observed, but the effect was not statistically significant. SD of step width decreased in narrower and wider walking probably due to the two parallel lines assisting the foot targeting task.

Except Lugade et al. [8] MLM characteristics and associated lateral CoP displacement have been little investigated. The current research explored effects of ageing, step widths and limb dominance on medio-lateral balance. Although older adults were expected to employ safety adaptation such as greater MLM and smaller lateral CoP, no main ageing effects to support these hypotheses were found. Evidence for age-related decline in medio-lateral balance was, however, characterized in higher step-to-step variability in MLM and lateral CoP displacement especially in their non-dominant limb during altered-width walking conditions.

High variability in these parameters indicates that both MLM and lateral CoP displacement often take negative values (< 0). Accordingly, CoM frequently travels beyond the medio-lateral location of stance heel and CoP at MLM is often more medial compared to toe-off, both of which are considered atypical in preferred width walking [8], [11]. From the medio-lateral heel location to the very lateral edge of the base of support, there still is the small margin and therefore, CoM lateral from stance heel does not necessarily define balance loss. Yet, it is apparent that negative MLM is very close to lateral balance loss initiation. In summary, older adults showed impaired medio-lateral balance control in their non-dominant limb if enforced to adopt unusual step widths.

It is interesting to focus on reduced variability in step width despite increased variability in MLM and CoP lateral displacement when older adults walked with altered step widths. Although width-control assisted in the consistent foot targeting task, medio-lateral CoM control became inconsistent because MLM, medio-lateral distance between CoM and stance heel, was more variable. Inconsistent medio-lateral CoM movement was likely to be attributable to more variable medio-lateral CoP displacement [10-12]. Thus, older adults impaired medio-lateral CoM control in the non-dominant side during altered width walking conditions despite more consistent medio-lateral foot control.

Consistent in both age groups, the results revealed that the dominant limb took lower MLM and greater lateral CoP displacement. Possible interpretation could be the dominant limb's relatively greater involvement in the medio-lateral balance controlling task or reduced load in the more vulnerable non-dominant limb. In terms of the functional advantage in taking larger step width on medio-lateral balance [13], [14], the current study detected increased MLM when walking with wider step, possibly explaining why older adults tend to enlarge step width. It is, however, important to note that lateral CoP displacement was not affected by step width. Age-associated medio-lateral balance impairment during controlled width walking was detected in more variable MLM and CoP lateral displacement in the non-dominant limb.

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