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Gait Asymmetry and Variability in Older Adults during Long-distance Walking: Implications for Gait Instability

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Abstract

Background: Physical exercise, such as walking, is imperative to older adults. However, long-distance walking may increase walking instability which exposes them to some fall risks.

Objective: To evaluate the influence of long-distance walking on gait asymmetry and variability of older adults.

Method: Sixteen physically active older adults were instructed to walk on a treadmill for a total of 60 minutes. Gait experiments were conducted over-ground at the baseline (before treadmill-walk), after first 30 minutes (30-min) and second 30 minutes (60-min) of the walk. In addition to spatiotemporal parameters, median absolute deviation of the joint angular velocity was measured to evaluate gait asymmetry and gait variability.

Findings: There were significant differences in the overall asymmetry index among the three time instances (Partial $\eta^2 = 0.77$, $p < 0.05$), predominantly contributed by the ankle (Partial $\eta^2 = 0.31$, $p < 0.017$). Long-distance walking significantly increased the average and maximum median absolute deviation of the ankle at both sides ($W \geq 0.19$, $p < 0.05$), and knee at the non-dominant side ($W = 0.44$, $p < 0.05$).

Interpretation: At 30-min, the older adults demonstrated a significantly higher asymmetry and variability at the ankle, which implied higher instability. Continue walking for an additional 30 minutes (60-min) further increased variability of the

non-dominant limb at the knee joint. Walking for 30 minutes or more could significantly reduce walking stability.

Keywords: Prolonged walking; prolonged exercises; fatigue; kinematics;

1. Introduction

The advantages of physical exercise in older adults are well recognized (Lim and Taylor, 2005). However, more than half of the older adults reported that they did not have sufficient physical exercises (Lim and Taylor, 2005). Walking is regarded as one of the most accessible types of exercises for older adults, which occurs through activities of daily living without any equipment (Chastin et al., 2019). Older adults are recommended to walk 10,000 steps per day for improved health (Duncan et al., 2014). However, a majority of healthy older adults can walk 3,000 step a day only (Tudor-Locke and Bassett Jr, 2004). Blindly pushing older adults to achieve a generalized walking goal may do more harm than good. Older adults gradually decrease their muscle strength by 1.5% and 3.0% yearly after the age of 50 and 60, respectively (Van Kan, 2009). Muscle weakening and fatigue reduce walking stability, inducing higher chance of fall to older adults when they try to achieve some walking goals (Helbostad et al., 2010)

While some studies have successfully linked responses to perturbation to risk of falling (Bohm et al., 2015), some other studies have used gait variability which is often measured in laboratory settings to evaluate walking stability and predict risk of falling as reviewed in (Hamacher et al., 2011). High inter-limb asymmetry and gait variability could reflect some impaired motor control leading to errors in foot placement (Maki, 1997). Stride-to-stride and step-to-step variability of discrete gait variables, including step width and step stance, were found to be correlated with falls risk among active community dwelling older adults (Paterson et al., 2011). Variability of body sway has also been identified as a predictor of fall and imbalance (Greene et al., 2012; Jansen et al., 2014). Meanwhile, some studies focused on a continuous analysis of the variability of knee and hip joint angles and angular velocities throughout the stance phase, and associated their high variability with functional impairment, muscle fatigue, and poor coordination (Cortes et al., 2014; Fallah-Yakhdani et al., 2012; Smith et al., 2014). Increased gait asymmetry generally reflects poor coordination that disturbs gait stability increasing falls risk (Hausdorff, 2007).

There is an abundance of research studying gait stability of older adults as reviewed in (Hamacher et al., 2011). For example, the comparison between younger and older adults as well as fallers and non-fallers provided some understandings on the decline of walking functions and instability upon aging (Beauchet et al., 2009). However, there is limited research on the study of the changes in gait stability during prolonged physical exercises, such as long-distance walking. Such research is warranted as it allows better understanding of the walking limit of older adults. It may also aid in better design of physical training and rehabilitation regime given that physical training can improve motor control and improve gait stability (Falbo et al., 2016; Kao et al., 2018).

The main objective of this study is to investigate the effects of long-distance walking on variability and inter-limb asymmetry of joint angular velocities. We hypothesize that gait variability and inter-limb asymmetry increase after some instances of long-distance walking. This study would shed some light on the physical limit of the older adults in walking.

2. Methods

2.1 Participants

Twenty older adults aged over 65 were recruited in this study with convenient sampling. There were four participants dropped out from the study. Three of them stopped the experiment due to physical exhaustion. Another participant was unable to arrange another required gait test. The sample size of 16 produced statistical power of 0.75, assuming medium effect size and a level of significance of 5%. The participants were independent to walk without use of walking aids. Exclusion criteria included cardiovascular, pulmonary diseases, cancer, uncontrolled hypertension, diabetes, lower-limb pain or deformities. Participants were excluded if they had a history of fall in the past 12 months. The 16 participants (11 males, 5 females) had a mean age of 70 (SD: 5.0). Their mean height and mass were 163.5 cm (SD: 7.3) and 63.3 kg (SD: 9.2), respectively.

This experiment was approved by the institutional review board of the university (Ref. No.: HSEARS20151016007). All participants signed an informed consent statement after receiving the oral and written descriptions of the experimental procedure prior to the start of the experiment.

2.2 Equipment and Procedure

The participants were asked to walk on a treadmill at their self-selected comfortable speed for two consecutive 30-minute walking sessions. Gait assessments were conducted at three time conditions: prior to the walking session (baseline), after the first 30-minute walking session (30-min), and the second 30-

minute walking session (60-min). Before the gait assessments, the participants were given a 2-minute familiarization time to adapt environment changes from treadmill to over-ground walking.

Gait assessments were conducted over-ground in a 10-m gait laboratory equipped with the motion capture system (Vicon, Oxford Metrics Ltd., Oxford, UK) and force plates, which was sampled at 200 Hz and 1000 Hz, respectively. Twenty-four infrared reflective markers were placed over both limbs at the anterior and superior iliac spines and crests, greater trochanters, middle of thighs and shanks anteriorly, medial and lateral femoral condyles and malleoli, foot dorsum, and heels (Winter, 1991).

A trial with both left and right clean footfalls on separate force plates, which were located at the center of the runway, was regarded as a successful trial. The ground reaction force data were used to define the start and end of the gait cycle for subsequent analyses. Five successful trials were collected and only the second to the fourth trials were extracted to minimize irregularities due to gait initialization and termination (Wong et al., 2015). The angular velocities of the ankle, knee and hip joints at the dominant and non-dominant limbs in the sagittal plane were extracted from the Vicon Nexus Software and subsequently processed in Visual 3D (C-Motion Inc., USA) using a 4^{th} order Butterworth low-pass filter with cutoff frequency of 6 Hz. Spatiotemporal parameters, including walking speed, step length and stance time of the dominant and non-dominant sides were also extracted. The dominant limb was determined by asking the participants the side of the limb they would use to kick a ball (Chapman et al., 1987).

2.3 Data Management

The time-series of the data were normalized to 101 time-points that represented 0 to 100% gait cycle (Bruijn et al., 2013). Asymmetry index (ASI), which was calculated by the percentage ratio of the data difference to the data mean, was used to quantify the asymmetry between dominant and non-dominant limbs. The average ASI was calculated by averaging all ASIs across the time-series.

Median Absolute Deviation (MAD) is a commonly used variability index which is defined as the median of the deviations from the data median and was calculated using the three successful trials for each of the time conditions (baseline, 30-min, and 60-min) (Bruijn et al., 2013). The maximum MAD and mean MAD (i.e., averaging all MADs across the time-series) were extracted for analysis (Wong et al., 2015).

2.4 Statistical Analysis

MAD and spatiotemporal parameters, including walking speed, step length and stance time of the dominant and non-dominant sides were examined using the non-parametric Friedman test to compare among the baseline, 30-min, and 60-min conditions since some parameters violated the assumption of normality. Significance level (α) was set at $p = 0.05$. Post-hoc analyses with Wilcoxon signed-rank tests were conducted with a Bonferroni correction at $p < 0.017$.

Regarding ASI, a one-way multivariate analysis of variance (MANOVA) with repeated measures was conducted to determine the effect of walking time (baseline, 30-min, and 60-min) on the ASIs of the ankle, knee, and hip joints. The outcome of the MANOVA essentially combines these dependent variables in the analysis such that we named it as the overall SI. Significance level (α) was set at $p = 0.05$. Univariate and post-hoc analysis with Bonferroni correction would be subsequently conducted when significance was revealed.

3. Results

3.1 Spatiotemporal Parameters

As shown in Table 1, there were no significant differences in walking speed, step length of both limbs and stance time of the non-dominant side among the three time conditions. The stance time of the dominant side significantly decreased with time ($\chi^2(2) = 19.27$, $p < 0.05$). Post-hoc test showed that all pairwise comparisons demonstrated statistical differences (baseline vs 30-min: Z= -3.44; 30-min vs 60-min: Z= -2.59; baseline vs 60-min: Z= -3.46, $p < 0.017$).

3.2 Asymmetry Index

Pre-hoc test using the Shapiro-Wilk test revealed that all the data were normally distributed ($p > 0.05$); and Pre-hoc test using Pearson correlation revealed that there was no multi-collinearity ($0.2 > r > 0.6$); there were linear relationships among the asymmetry data of the three joints, as observed on the scatterplots.

MANOVA indicated that the significant difference among the time conditions in the overall ASI, F (6, 10) = 5.47, $p < 0.05$; Wilks' $\Lambda = 0.23$; partial $\eta^2 = 0.77$ (Table 2). Follow-up univariate test showed that statistically significance only appeared at the ankle angular velocity, F (1.31, 19.61) = 6.58, $p < 0.017$; partial $\eta^2 = 0.31$). Post-hoc analysis revealed that the ASI of the ankle was significantly increased after the first 30-minute walking session, 11.88, $p < 0.017$ (95% CI, 4.87 to 18.89), as shown in Figure 1.

3.3 Maximum and Average MAD

In Figure 2, there were statistically significant differences in the average MAD of the ankle joint at both non-dominant ($\chi^2(2) = 6.13$, W = 0.19, $p < 0.05$) and dominant limbs ($\chi^2(2) = 10.13$, W = 0.32, $p < 0.05$), and the knee joint at the non-dominant limb ($\chi^2(2) = 14.00$, W = 0.44, $p < 0.05$) among the three time conditions. Post-hoc analysis on the ankle joint at the non-dominant limb showed no significance among the pairwise comparisons, despite that significance was demonstrated ($\chi^2(2) = 6.125$, $p = 0.047$). For the ankle joint of the dominant limb, there was a statistically significant increase in 30-min compared with the baseline ($Z = -3.52$, r = 0.88, $p < 0.001$). Similarly, there were a significant increase in the non-dominant sided knee joint after the first 30-minute walking session($Z = -3.52$, r = 0.88, $p < 0.001$).

In Figure 3, there were statistically significant differences in the maximum MAD of the ankle joint at both non-dominant ($\chi^2(2) = 8.38$, W = 0.26, $p < 0.05$) and dominant limbs ($\chi^2(2) = 6.50$, W = 0.20, $p < 0.05$), the knee joint at the non-dominant limb ($\chi^2(2) = 11.38$, W = 0.36, $p < 0.05$), and the hip joint at the dominant limb ($\chi^2(2) = 9.13$, $p < 0.05$). Despite overall significance determined in the ankle and hip joints, there were no significance differences among the time points for both limbs in the post-hoc comparison tests. On the other hand, the knee joint at the non-dominant side showed significant increases at 30-min (Z = -2.48, r = 0.62, p = 0.013) and 60-min (Z = -2.59, r = 0.65, p = 0.010), when compared to the baseline condition.

4. Discussion

The present study showed that after 30 minutes of walking the participants significantly increased 1) asymmetry between limbs at the ankle joint, 2) variability of the ankle joint at the dominant limb, and 3) variability of the knee joint at the non-dominant limb. The increased variability at the ankle joint aligned with the findings of previous studies, which indicated that plantarflexors of the dominant limb were more vulnerable to fatigue (Yeung et al., 2012) and that long-distance walking significantly reduced dominant-sided ankle power during push-off phase of the gait (Elhadi et al., 2016). This study also found that stance time of the dominant side was significantly reduced after both 30 and 60 minutes of walking, which could be induced by the altered kinematics of the ankle. Meanwhile, the significantly higher variability of the non-dominant sided knee joint after 30 minutes of walk could be explained by a previous study (Elhadi et al., 2016), which showed that the knee joint at the non-dominant side appeared to compensate for the fatigued plantarflexors at the dominant side.

While the asymmetry of the ankle joint significantly increased after 30 minutes of walking, there was a trend that it slightly improved after 60 minutes although statistically insignificant. This aligned with a previous study which suggested that the asymmetry and variability improved with further physical exercises and attributed this to the ability of using a compensatory walking mechanism attempting to restore postural balance (Wong et al., 2015). However, there are questions regarding when exactly and how this compensatory walking mechanism is triggered by older adults. Our finding was contrary to the study conducted by Hamacher et al.(2016) which suggested that based on self-reported submaximal exhaustion levels, physical exhaustion increased dynamic stability in young people only but not in older adults. One possible explanation is that gait variability has not always been linked to perceived balance ability according to dynamical system theory. The theory suggests that behaviors in human systems are generally non-linear and only extremely high levels of variability could be self-noticed by older adults (van Emmerik et al., 2014). More investigations regarding the relationship between age and the compensatory mechanism are needed.

Both within-subject and between-subject variations, as demonstrated by the MADs and data outliers, were not small in our study. Walking stability depends on individual fitness, musculoskeletal conditions, cognition, neural control and reflex (Krasovsky et al., 2012). In the present study, all our participants were able to walk independently without any diseases which may affect walking. However, variations among participants still existed as some participants had less stable gait in the baseline. Three participants were dropped out in the study due to exhaustion. This could be one limitation of this study as this potentially excluded some participants who might be at risk of falling. While a universal method to classify the frailty of elderly was lacking (Paw et al., 2001), a larger population study enabling the categorization of subject groups according to their level of baseline performance of physical or functional activities is warranted. The association between the baseline performance and intrinsic factors, such as physical fitness and cognitive level, should also be addressed.

The long-distance walking was mostly facilitated by a treadmill as it allowed indoor monitoring and cross-study comparison. It should be noted that treadmill walking might produce different walking patterns compared with over-ground walking, although some studies suggested that treadmill walking was very similar to over-ground walking in terms of kinematic and kinetic gait parameters (Watt et al., 2010). In this study, the participants were given time to get accustomed to change of the walking modes from the treadmill (walking intervention) to over-ground (gait experiment). Further studies can consider the use of instrumented treadmills (i.e. with embedded force platform) to assess the variability continuously without the need of changing between treadmill and over-ground walking modes.

Future studies can use feedback questionnaires, such as the Borg perceived exertion scale (Garnacho-Castaño et al., 2018) and fatigue assessment scale (Marcellis et al., 2015), to evaluate the level of physical fatigues. In addition, Floquet theory (Bruijn et al., 2013) can be used to identify a level of physical fatigue which is linked to significantly reduced gait stability. Future studies can also use wearable sensing and feedback devices to continually assess gait changes and provide biofeedback in an attempt to control any detected walking instability (Ma et al., 2015; Wan et al., 2016).

5. Conclusion

After 30 minutes of walking (30-min), the older adults demonstrated a higher inter-limb ASI, which was predominantly contributed by the ankle joint. Their joint motion was less stable at the knee of the non-dominant side and the ankle of the dominant side, as indicated by the average MAD of the joint angular velocities. Continued walking for an additional 30 minutes (60-min) further deteriorated the stability of the knee joint at the non-dominant limb, as demonstrated by the maximum MAD. Although statistically insignificant, ASI and MAD of the ankle and hip joints tended to improve after 60 minutes of walking, which could be due to some compensatory walking responses to maintain balance in gait.

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Figures Legends

Figure 1. The ASI of the ankle, knee, and hip angular velocities under baseline, 30-min (30m) and 60-min (60m). Bracket denotes statistically significance in the post hoc analysis with Bonferroni correction at $p < 0.017$.

Figure 2. Average MAD of the ankle, knee, and hip joints between the non-dominant and dominant limbs under baseline, 30-min (30m) and 60-min (60m). Significance levels and Chi-square refer to Friedman test comparing average MAD among time points. o denotes outliers; * denotes outliers of extreme values; bracket denotes statistically significance in the post hoc analysis with Wilcoxon signed-rank test and Bonferroni correction at $p < 0.017$.

Figure 3. Maximum MAD of the ankle, knee, and hip joints between the non-dominant and dominant limbs under baseline, 30-min (30m) and 60-min (60m). Significance levels and Chi-square refer to Friedman test comparing maximum MAD among time points. o denotes outliers; * denotes outliers of extreme values; bracket denotes statistically significance in the post hoc analysis with Wilcoxon signed-rank test and Bonferroni correction at $p < 0.017$.