ASSOCIATION BETWEEN AGE AND BODY'S KINEMATIC RESPONSES TO UNPREDICTABLE GAIT PERTURBATION

Dongyual Yoo[1,4], Chihyeong Lee[2], Jooeun Ahn[2,3], and Beom-Chan Lee[1,3,4]

Department of Health and Human Performance, University of Houston, USA[1]
Department of Physical Education, Seoul National University, South Korea[2]
Institute of Sport Science, Seoul National University, South Korea[3]
Center for Neuromotor and Biomechanics Research, University of Houston, USA[4]

This study assessed the body's kinematic responses to unpredictable gait perturbations repeatedly induced by a fall-inducing technology platform in young and older adults. Ten young adults (young group) and ten older adults (older group) completed two trials with the gait perturbation (i.e., trip). Maximum trunk flexion angle, maximum right hip flexion angle, and minimum whole-body center of mass (COM) position quantified the body's kinematic responses for a pre-trip period and a recovery period. The results showed that both groups significantly increased maximum trunk flexion angle and maximum right hip flexion angle during the recovery period compared to the pre-trip period. The young group showed a significantly decreased minimum COM position during the recovery period compared to the pre-trip period. Our findings can inform perturbation-based gait training in young and older adults to improve the body's responses for fall reduction and prevention.

KEYWORDS: falls, gait perturbation, kinematics, young and older adults.

INTRODUCTION: Falls can occur during various activities. Walking and sports/exercise activities are fall-related activities throughout all ages (Talbot, Musiol, Witham, & Metter, 2005). Unpredictable gait perturbations (e.g., trips and slips) are the leading causes of falls. Notably, falls affect the quality of life due to physical injuries (e.g., fractures, concussion, etc.), loss of confidence, and fear of falling while performing daily activities.

Therapeutic regimens such as balance, gait, strength, resistance, and endurance training have been used to improve balance and decrease fall rates (Gillespie et al., 2003), although a few studies have noted no difference or change in fall rates (e.g., (McMurdo, Millar, & Daly, 2000)). Fall-inducing technologies using external mechanical obstacles, cables/pulleys, or a contaminated floor have been shown to improve the body's responses resulting in decreased rates of falls (McCrum, Gerards, Karamanidis, Zijlstra, & Meijer, 2017). Learning the recovery responses from unpredictable gait perturbations is an important skill for all ages (Shimada, Obuchi, Furuna, & Suzuki, 2004), and thus the use of a fall-inducing technology can facilitate task-specific learning for fall reduction and prevention (McCrum et al., 2017).

Fall-inducing technologies with external mechanisms, however, have practical limitations due to the required obstacles, cables, pulleys, or physical space. In 2017, we first developed a new fall-inducing technology platform using a commercially available programmable split-belt treadmill (Lee, Martin, Thrasher, & Layne, 2017). The results showed that kinematic responses to unpredictable gait perturbations (i.e., trips and slips) in healthy young adults were consistent with those induced by fall-inducing technologies with external mechanisms (Lee et al., 2017). A recent study also demonstrated the effects of a split-belt treadmill on understanding the mechanisms of falls and balance recovery in healthy young adults (Debelle, Harkness-Armstrong, Hadwin, Maganaris, & O'Brien, 2020). This study extends our previous findings by investigating whether our fall-inducing technology platform induces adequate gait perturbations (i.e., trips) in older adults compared to young adults and quantitatively compares the body's kinematic responses between young and older adults.

METHODS: Figure 1(a) shows our fall-inducing technology platform consisting of a programmable split-belt treadmill with force plates beneath treadmill belts (Bertec Corporation, Columbus, OH, USA) and custom software (Lee et al., 2017). The VICON motion capture system with 12 cameras and 35 reflective passive markers (Vicon Motion Systems Ltd., Oxford, UK) was used to measure the body's kinematic responses to unpredictable gait perturbations. The custom software consistently measured ground reaction forces (GRFs) from the force plates and ran an algorithm to detect gait phase parameters (e.g., heel strike, toe off, gait cycle, and loading response phase) at a rate of 100 Hz. The custom software induced trip perturbations at the loading response phase (i.e., initial double-limb support) by suddenly stopping one of the treadmill's belts at a rate of 10 m/s^2. The stopped belt returned to pre-perturbation speed after the compensatory limb's first heel strike because the stepping response of the compensatory limb (i.e., non-perturbed limb) is the general response to gait perturbations (Jensen, Brown, & Woollacott, 2001).

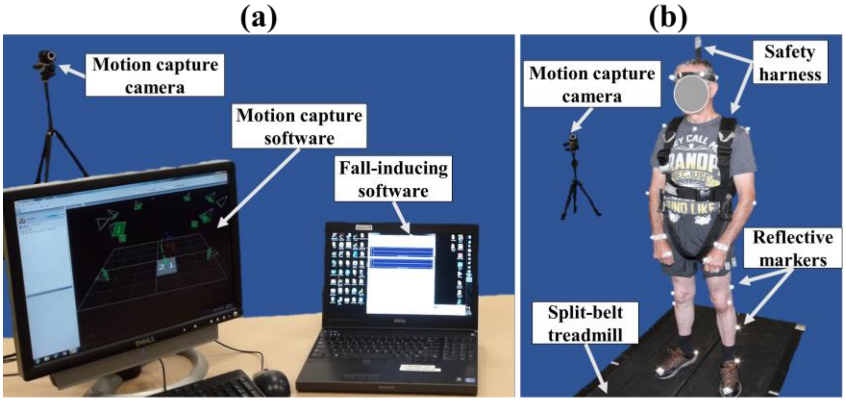

Figure 1: Experimental apparatus. (a) Fall-inducing technology platform and motion capture system. (b) Reflective markers placed on the body, split-belt treadmill, and safety harness.

Ten healthy young adults (young group (YG); age: 24.40 ± 2.84 years; stature: 166.8 ± 9.50 cm; mass: 64.15 ± 8.94 kg) and ten healthy older adults (older group (OG); age: 70.90 ± 3.84 years; stature: 171.42 ± 7.74 cm; mass: 76.25 ± 15.59 kg), who were naïve to the purpose of the study, participated in this study. Exclusion criteria included neurological disorders (e.g., stroke, Parkinson's disease, etc.), musculoskeletal dysfunctions, peripheral sensory diseases, and major operations that can negatively impact balance and walking performance in the past 6 months. The University of Houston Institutional Review Boards approved the study protocol in accordance with the Helsinki Declaration. Prior to the study, all participants reviewed and signed the informed consent.

All participants were attached with 35 reflective passive markers and wore a safety harness as shown in Figure 1(b). Then each participant chose a comfortable walking speed by changing the treadmill's speed. All participants completed 2 trials with gait perturbations (i.e., trips) because a previous study found that reactive motor adaptation occurred at trial 3 compared to trial 1 after repeated exposure to trip perturbations (Wang, Bhatt, Yang, & Pai, 2012). Each trial included four consecutive periods: standing (15 s quiet standing), pre-trip (normal walking), gait perturbation, and recovery (defined as the period from the gait perturbation in an instant to return to baseline gait (i.e., normal walking) based on the GRF's profile (Lee et al., 2017)). In each trial, our fall-inducing technology platform randomly induced the gait perturbation to the participant's left limb between 31st and 40th steps. Each trial lasted approximately 2 min, and each participant had a 20s rest period.

The full body Plug-in-Gait model (Vicon Motion Systems Ltd., Oxford, UK) processed the position data of the 35 markers and computed three outcome measures (i.e., maximum trunk flexion angle in the sagittal plane, maximum hip flexion angle of the compensatory limb (i.e., right hip flexion angle) in the sagittal plane, and minimum whole-body center of mass COM position in the transverse plane) based on the previous work (Lee et al., 2017). The three outcome measures were computed for standing, pre-trip, and recovery period. For normalization, each outcome measure during the pre-trip and recovery periods was subtracted from the corresponding outcome measure during the standing period. Each outcome measure for two trials was averaged as a function of the three periods for each participant.

SPSS (IBM Corp., Armonk, NY, USA) was used to perform statistical analysis for the three outcome measures. Two-way ANOVA was performed for the outcome measures to assess the main effects of the group and period (pre-trip and recovery periods), and their interactions (group x period). Statistical significance was defined at the $p < 0.05$ level.

RESULTS: Two-way ANOVA of the three kinematic outcome measures as a function of the group and period, and group x period interactions as reported in Table 1 indicated a significant main effect of the period for the maximum trunk flexion angle, significant main effects of group and period for the minimum COM position, and a significant main effect of the period and group x period interactions for the maximum right hip flexion angle.

Table 1: Statistical analysis results of all outcome measures for group (G), period (P), and interaction (G × P). * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.0001$.

Dependent variable	Effects	*p*-value
Maximum trunk flexion angle (deg)	G	0.193
	P	< 0.0001***
	G × P	0.090
Minimum COM position (mm)	G	< 0.0001***
	P	0.002**
	G × P	0.071
Maximum right hip flexion angle (deg)	G	0.398
	P	< 0.0001***
	G × P	0.014*

As shown in Figure 2, the maximum trunk flexion angle and maximum right hip flexion angle significantly increased, and the minimum COM position significantly decreased in the recovery period compared to the pre-trip period for the YG. The maximum trunk flexion angle and maximum right hip flexion angle significantly increased in the recovery period compared to the pre-trip period for the OG. For the YG compared to the OG, the maximum trunk flexion angle and maximum right hip flexion angle were significantly higher in the recovery period, and the minimum COM position was significantly lower in the pre-trip and recovery periods.

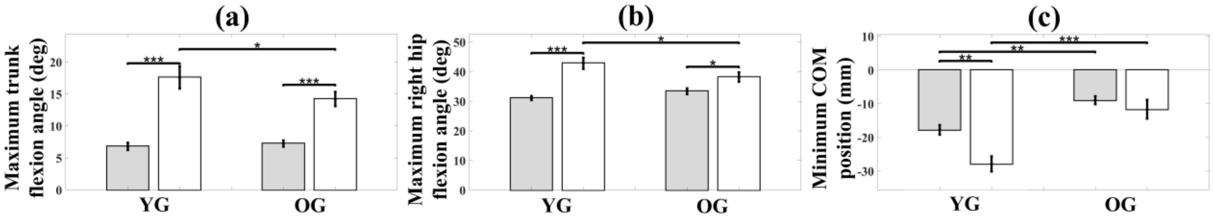

Figure 2: The body's kinematics as a function of the group (YG and OG) and period. (a) Maximum trunk flexion angle. (b) Maximum right hip flexion angle. (c) Minimum COM position. Gray and white bars indicate pre-trip and recovery periods, respectively. Error bars indicate standard error of the corresponding average (* $p < 0.05$, ** $p < 0.01$, and *** $p < 0.0001$).

DISCUSSION: Both groups showed significantly increased maximum trunk flexion angle and maximum right hip flexion angle, and decreased minimum COM position in the recovery period compared to the pre-trip period, with the exception of minimum COM position for the OG. The results aligned with previous studies which have found that maximum trunk and hip flexion angles and vertical changes of COM significantly increased after trip perturbations induced by external mechanical obstacles (McCrum et al., 2017).

The YG showed higher maximum trunk and right hip flexion angles and lower minimum COM in the recovery period compared to the OG. Previous studies indicated that maximum trunk flexion angle and lumbar flexion significantly correlated with faster pre-trip walking speeds (McCrum et al., 2017). We infer that the slower walking speeds of older adults observed in this study may affect both walking performance and responses to unexpected gait perturbations.

We also attribute the insignificant change in minimum COM position between the pre-trip and recovery periods for the OG and the significant difference in minimum COM position in the pre-trip period between both groups to participants' walking speeds. Previous studies have indicated that the range of COM position increased more in the vertical direction as walking speed increased in healthy adults (Gard, Miff, & Kuo, 2004; Orendurff et al., 2004). In our study, the relatively slower walking speeds in the OG did not significantly change the minimum COM position in the recovery period compared to the pre-trip period in the OG.

CONCLUSION: This study quantified the body's kinematic responses following unpredictable gait perturbations (trips) induced by our fall-inducing technology platform. The results showed increased maximum trunk flexion, maximum right hip flexion, and decreased minimum COM positions in older and young adults following unexpected trip perturbations. Only young adults showed significant changes in minimum COM positions. Our findings suggest that the devised fall-inducing technology platforms can be used to train both young and older adults and athletes to facilitate recovery responses from unpredictable gait perturbations, which can inform perturbation-based gait training for fall reduction and prevention.

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