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Effect of Age on the Ability to Recover from a Single Unexpected Underfoot Perturbation during Gait: Kinematic Responses

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Abstract

A sudden underfoot perturbation can present a serious threat to balance during gait, but little is known about how humans recover from such perturbations or whether their response is affected by age. We tested the hypothesis that age would not affect the stepping responses to a nominal 10 degree inversion or eversion of the stance foot during gait. Twenty-three healthy young (22.7 ± 3.35 yrs) and 18 healthy old adults (68.0 ± 7.19 yrs) performed 60 walking trials along a 6-m level walkway at a normal gait speed. In 16 of these trials, a single medial (MP) or lateral (LP) perturbation was randomly administered once under the left or right foot. Recovery step width (SW), step length (SL), trunk kinematics and walking speed were measured optoelectronically. Repeated-measures analysis of variance and post-hoc t-tests were used to test the hypotheses. The results show that a MP or LP altered the recovery SL ($p = 0.005$) and age affected the number of recovery steps ($p = 0.017$), as well as the first recovery SW and SL ($p = 0.013$ and $p = 0.031$, respectively). Both MP and LP caused young adults to have wider SW ($p < 0.02$) and shorter SL ($p < 0.005$) without changing trunk movement during their first recovery step. Older adults, however, significantly changed lateral trunk inclination during the first recovery step, decreased their fourth recovery SL ($p < 0.001$). We conclude that young adults adjust the step kinematics of as many as four recovery steps following this perturbation, a response that was delayed and significantly weaker in older adults who instead exhibited an immediate torso inclination consistent with a hip response strategy.

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1. Introduction

Ambulatory individuals often have to walk across uneven surfaces. Such surfaces characteristically cause stance foot orientation to vary in the frontal and sagittal planes, thereby altering the anticipated trajectory of the center of pressure (COP) beneath the stance foot [1] and therefore its relationship to the whole-body center of mass [2, 3]. One can speculate that the ability to compensate for underfoot perturbations is essential for crossing such surfaces reliably without stumbling or falling. So it is not surprising that in older adults, at least, walking on uneven surfaces is associated with an increased risk of falls [4, 5].

While the width of each step is adjusted when walking across a smooth surface in order to maintain dynamic balance [6], step width (SW) and step length (SL) variabilities increase on uneven surfaces by about 20% in healthy young adults and 35% in their healthy older counterparts [7]. While increased variability in step kinematics is a marker of elevated fall risk on a flat surface [8], whether the same is true on uneven surfaces is not known, and it is of particular interest in older individuals.

While kinematic analyses of serial stepping on an irregular surface have been conducted [7, 9–11], carryover effects from a prior underfoot perturbation can theoretically confound the kinematic analysis of the next step recovery. So, as a result such studies provide limited insight to the nature of the response to any single underfoot perturbation. The responses of young adults to stepping on a single raised object have demonstrated marked changes in recovery step kinematics, including cross-over steps, an extreme case of step width (SW) reduction [3]. However, a limitation of that experiment was the nature of the perturbation. For example, where the perturbation acted under the foot was not controlled nor was the nature of perturbation: whether it was in- or eversional in nature, for example. Furthermore, subjects could see the surface protuberance from afar and gauge when they might step on it.

In order to overcome these shortcomings we developed a pair of custom instrumented shoes. These shoes can simulate a swing limb midfoot unexpectedly landing on an unseen medially-located (MP) or laterally-located (LP) protuberance, like a pebble, while walking across a flat hard surface [12]. Because Nnodim et al. found neither medial nor lateral underfoot perturbations had a significant effect on the first post-perturbation step kinematics in young adults, in the present study, we used these shoes and test method to assess the effects of perturbation type (MP vs LP) and advancing age on recovery step and trunk kinematics [1]. We tested the hypotheses that (a) medial and lateral perturbations would have similar effects on recovery step kinematics, and (b) age would not affect recovery step or trunk kinematics following these perturbations.

2. Methods

2.1 Subjects

A total of 41 healthy adult subjects (23 young adults: 22.7 (18~29) yrs, 18 older adults: 68.0 (52~84) yrs) participated in this research. The older subjects (HO) were recruited from University of Michigan Older Americans Independence Center (OAIC) Human Subjects Core and young subjects (HY), from the University of Michigan clinical studies volunteer network. Both groups were screened by telephone for neurological or musculoskeletal pathologies. Test procedures and devices were approved by the Institutional Review Board of the University of Michigan and all subjects completed a written informed consent form. Before the gait tests began, a neuromuscular system examination was performed on each participant to screen out abnormalities of the peripheral and central nervous system, or distal sensation and lower extremity muscle strength.

2.2 Perturbing Shoes

The custom instrumented sandals designed to perturb gait during a single stance phase have been described in detail elsewhere [12], so only a brief account will be given here. Each sandal is equipped with two electronically-controlled hinged flaps concealed within the medial and lateral aspects of the shoe sole near the base of the metatarsal bones. During the ensuing stance phase, the unloaded midfoot is abruptly inverted (MP) or everted (LP) through an initial angle of 16°, an angle that is soon reduced to about two-thirds of that value under weightbearing, due to shoe sole compliance (Figure 1).

2.3 Experiment and instrumentation

Wearing a pair of the perturbing shoes, each subject performed a total of 60 walking trials along a 6-m level walkway at purposeful walking speed - “as though you were crossing a busy street”. Eight each of the medial and lateral perturbation trials were presented in random order among 44 unperturbed (UnP) dummy trials. Subjects were informed that the perturbation would happen only once per gait trial. Because the presentation was randomized by the computer, they could not know if, when or where (right foot vs left foot; medial vs lateral) a perturbation might occur. In a perturbed gait trial, a flap was covertly deployed during the latter part of the swing phase. As the stance foot began to roll towards foot-flat for weight acceptance, the subject would have to counter the sudden and unexpected effect of the perturbation when the flap contacts the support surface. The flap was then immediately retracted after toe-off and not deployed again for the rest of that gait trial. The subject practiced several times without the perturbation to familiarize themselves with wearing the shoes and the experimental environment before the trials began. For their safety in each gait trail, subjects wore a full-body safety harness connected to a rail in the ceiling by mountain climbing rope, backed up by a slightly longer multistrand steel aircraft cable. One optoelectronic camera system (Optotrak Certus, Northern Digital Inc., Waterloo, Ontario, Canada) sampled three-dimensional kinematic data at 100 Hz from a total of 28 infrared-emitting diode markers secured on the mid-section of each foot, the anterolateral aspects of each lower and upper leg, and over the pelvis midway between the anterior superior iliac spines, and over the mid-sternum on the thorax. The two foot switches, sampled at 2 kHz, were used to detect each heel strike. All data were post-processed to calculate walking speed (WS), SW, step length (SL), the timing of the heel strike and flap ground contact, using a custom Matlab algorithm (Matlab 2011a, The Mathworks, Inc., Natick, MA).

2.4 Data Analysis

Step kinematics (SW & SL) were calculated at every heel strike. Walking speed (WS) was calculated with respect to the position of the pelvis marker. The change (or delta) in kinematics was defined as the mean within-subject difference between the recovery kinematics and the unperturbed (UnP) kinematics as shown in (1).

$$\Delta X = \overline{X}_{\text{recovery step kinematics}} - \overline{X}_{\text{unperturbd step kinematics}} \quad (1)$$

X : step or trunk kinematics

For each subject, we calculated the mean unperturbed step kinematic parameters based on at least 20 normal steps from dummy (UnP) trials occurring after a subject experienced the first underfoot perturbation. These steps were all selected during steady gait [6]. Mean recovery kinematics for each type of perturbation were based on four consecutive post-perturbation steps in the four left MP, four right MP, four left LP and four right LP trials, respectively. Because no significant difference was found between kinematic responses to a left and right limb perturbation, the responses were pooled for MP and LP, respectively.

Similarly, the displacement of waist and sternum markers during each of the above steps enabled the calculation of changes in maximum trunk rotation (*trunk*) and maximum lateral pelvic displacement (*LPD*) in the frontal plane, which are among the major determinants of normal and pathological gait [13].

Single-factor repeated measures analyses of variance (ANOVA) were run (see Table 2) to assess the between-subjects effect of age (young, old), within-subjects effect of perturbation type (LP vs MP), and the number of recovery steps (1st, 2nd) on recovery SW and SL, with $p < 0.05$ being considered significant. Two-sided post-hoc t-tests were used to study directional effects. Matlab (Matlab 2011a Statistics Toolbox™, The Mathworks, Inc., Natick, MA) was used for all statistical analysis [14].

3. Results

There was no significant difference in the recovery step kinematics between the first trial and the rest of trials in each subject or in the unperturbed step kinematics before and after the first perturbation trial.

There were no significant group differences in subject demographic characteristics except for age (Table 1). Whereas a significant age effect on walking speed was noted, there was no effect of perturbation on that parameter across the subject groups. Walking speed decreased by 2.98 cm/s in the HY group but increased by 1.20 cm/s in its HO counterpart after medial perturbation. A similar pattern of change was observed after lateral perturbation (HY: -1.75 cm/s, HO: +0.49 cm/s).

3.1 Rm-ANOVA results for the two primary outcome measures: SW and SL (Table 2)

SL but not SW was significantly different between the age groups ($p = 0.005$) and there was significant interaction between perturbation and age in relation to SW ($p = 0.049$). SW and SL were unaffected by perturbation type (MP vs LP). There was a significant effect of age on both SW ($p = 0.031$) and SL ($p = 0.013$). Age did not interact with perturbation type.

Between HY and HO, the first and second recovery steps were significantly different in both SW ($p = 0.005$) and SL ($p = 0.002$). There was no significant interaction between perturbation and age in relation to the kinematics of the first or second recovery steps.

3.2 Effect of age on recovery step kinematics (Figure 2)

Post-hoc testing showed that older adults did not significantly alter the kinematics of their first recovery step following MP or LP. They did decrease the width of the second recovery step after LP. There was no significant change in the third recovery step, but SL of the fourth step was significantly reduced after both MP and LP. In contrast, young adults increased the SW and decreased the SL of the first recovery step after both MP and LP. The SW of the 2nd recovery step also increased while the SL of the 3rd and 4th recovery steps decreased.

There was stronger concordance between first and secondary step kinematics in the HO than in the HY. For example, in the HO group, 69.6% of those who increased the SW of their first recovery step (i.e., 7 out of 18 subjects) after a MP also increased their second recovery SW. In the HY, 56.2% among the 14 of 23 subjects with a similar response did so. In the HO 84.2% of those who narrowed their first recovery SW in response to an LP also narrowed their second recovery SW; but in the HY the 52.6% of those who narrowed their SW after the LP did not narrow their second SW.

3.3 Effect of age on the first recovery step body kinematics (Figure 3)

The torso (*trunk*) and waist (*LPD*) kinematic responses during the first recovery step are shown in Figure 3. In the HY group, trunk rotation during the first recovery step after either MP or LP was similar to that during UnP gait. However, in the HO group, the trunk rotated significantly less laterally in response to MP ($p = 0.019$), and significantly more laterally in response to LP ($p = 0.004$). Similarly, the waist displacement of HY adults remained unchanged after MP, whereas that of HO adults decreased significantly ($p = 0.0001$). With LP, both HY and HO subjects shifted their waist more laterally than during UnP gait (HY:P < 0.001, HO:P = 0.017).

4. Discussion

This is the first study of age effects on responses to an unpredictable, yet standardized, eversional or inversional mid-stance underfoot perturbation during gait on a smooth and level surface. The results show an age effect on the recovery step kinematics after a medial or lateral underfoot perturbation. When a discrete challenge to balance was presented, healthy young adults changed their 1st recovery step immediately but healthy older adults did not. However, healthy young adults largely did not change their trunk kinematics during the 1st recovery step whereas healthy old adults did significantly respond by changing them.

No subjects lost their balance, fell, or required support from their safety harness as a result of the sudden eversional or inversional perturbation, so we deem the perturbations safe for challenging the stability of gait in these subjects.

It is perhaps not surprising that the young subjects were able to respond quickly by altering the kinematics of their first recovery step following a single underfoot perturbation. But we found it surprising that healthy young subjects continued to adjust their recovery step kinematics for as many as four steps after the underfoot perturbation in what one might characterize as an underdamped response. One might have expected them to recover in the first step or two given the capacities of youth.

On the other hand, the healthy older adults either would not or, more likely, could not alter the kinematics of their first step after an underfoot perturbation. Furthermore, when older adults did adjust their stepping pattern, it was on the second and fourth post-perturbation steps, but interestingly not the third step. However, older adults responded rapidly with their upper body on the first post-perturbation step, less laterally for an MP, and more laterally for an LP, compared to the unperturbed trials. This would require a stance limb hip response consistent with a classic ‘hip response’ for larger postural perturbations as noted by Horak & Nashner (1986) [15]. It is also consistent with the stance hip muscles playing an effective role in righting the torso in the frontal plane [16]. Healthy adults of all ages do respond to a proximal perturbation, such as a tug on the torso, with a ‘hip strategy’ [17, 18]. And in older adults, Manchester and colleagues showed that a distal perturbation such as platform sway, also evoked a ‘hip strategy’ [19]. So, the torso response of the older adults in the present study is consistent with responses to a sudden perturbation described in the literature.

A factor which favors the hip response strategy is the considerably shorter reflex pathways of hip muscles compared to ankle muscles. A stance limb hip strategy has been shown to be a highly effective biomechanical response to restore frontal plane balance [16]. Our results indicate that this response was indeed adopted by the healthy older adults during the first recovery step. Then, they continued their balance recovery by altering the kinematics of the second post-perturbation step, perhaps by employing a swing limb hip response.

A novel result in the present study was that a small underfoot perturbation during gait resulted in significant carryover effects on the kinematics of foot placement in both younger and older adults for up to four steps after withdrawal of the perturbation. The source of the carryover effect is presently unknown, but warrants further investigation. The differential nature of the healthy old response demonstrates that they too correctly sensed the direction of the foot perturbation. But their use of a hip strategy during the first recovery step is logical from a biomechanical perspective both because it minimizes loop delays by utilizing shorter neural pathways than exists for the ankle, and also because it utilizes the most biomechanically effective response strategy [16]. Such a response strategy seems reasonable given the slower muscle rate of strength development in older adults [20] and age-related changes in the neurosensory and musculoskeletal systems [21].

There are several strengths to our experimental approach. First, the perturbing shoes allow within-subject comparisons between unperturbed steps and recovery steps taken in response to an unpredictable underfoot perturbation of standardized onset and magnitude. The onset of the perturbation is at the same angle of inversion or eversion on every occasion, an arrangement that cannot be guaranteed on any uneven surface [6, 9]. Second, neither the foot nor the step to be perturbed could be predicted by a subject. The fact that 44 dummy trials were randomized among the 16 perturbation trials lessened the likelihood of subjects walking in a guarded fashion. Third, the current experimental paradigm allowed us to explore the effects of age safely, as already mentioned. Lastly, the changes in step kinematics were analyzed as a change score, normalized to each subject's own unperturbed gait kinematics and based on an average of eight MP or LP recovery steps and more than 20 UnP steps at steady-state walking speed. This recovery step kinematic analysis strategy has proven reliable [12].

Even though midfoot perturbations were used in this study, the method is generalizable to other underfoot locations. The method can also be used to perturb more than one step during gait, whether sequential or not, but use of a single perturbation did facilitate the study of carryover effects in the present study. We chose not to control walking speed because we wanted each subject to feel comfortable with their walking speed, given that a perturbation might occur. However, we gave a participant feedback before the next trial if their prior trial had varied unduly from their demonstrated comfortable speed. Although a little faster than comfortable gait speed, it lay well within the range of normal gait speed [22, 23].

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Highlights

- We investigated the age effect in responses to an unexpected underfoot perturbation.
- Healthy young altered at the first and up to the fourth recovery step kinematics.
- Healthy old kept unchanged in the first recovery step kinematics.
- Healthy old changed trunk angle and lateral pelvic movement during the perturbation.
- Healthy young did not change frontal body kinematics during the first recovery step.

Figure 1.

Anterior view of the modified 11 ½-sized men's sandal showing shoe orientation with flap undeployed (middle illustration). A 18.4 mm high medial flap (dotted circle) is deployed in the parasagittal plane such that during midstance the foot is inverted (right illustration; dotted circle) or everted (left illustration; dotted circle). Figure is reproduced from [12].

Figure 2.

Box- and scatter- plots of changes in recovery step width (SW; first row) and step length (SL; second row) after medial (MP; first and second columns) and lateral (LP; third and fourth columns) perturbation for young (HY; first and third columns) and old (HO; second and fourth columns) subjects. ($\Delta X = \bar{X}_{1st recovery step} - \bar{X}_{unperturbed step}$). MP_n and LP_n denotes the n th recovery step after perturbation, where n can take a value of 1–4. *: significant change ($p < 0.05$) in recovery step parameter, compared to unperturbed gait.

Figure 3.

Box- and scatter- plots of changes in peak torso inclination ($\Delta\theta_{trunk}$) and lateral pelvic displacement (ΔLPD) in the frontal plane during the first recovery step.

+ denotes more than during unperturbed gait. * denotes a significant difference ($p < 0.01$) compared with unperturbed joint kinematics.

Table 1

Subject demographics.

M denotes male, F denotes female, and BMI denotes body mass index.

	HY (n = 23)	HO (n = 18)
Gender (M/F)	13/10	7/11
Age (yr)	22.7 (3.35)	68.0 (7.19)
Age range (yr)	18 ~ 29	52 ~ 84
Weight (kg)	70.0 (14.0)	74.0 (16.7)
Height (cm)	172.9 (8.47)	169.8 (6.64)
BMI (kg/m ²)	23.3 (3.65)	25.7 (6.11)

Single-factor repeated-measures ANOVA results: the effects on absolute step width (SW) and step length (SL) of age and the interaction of age on the presence of perturbation (unperturbed vs perturbed: UnP/Ptb), perturbation type (medial vs lateral: MP/LP), and recovery steps (first vs second:RS1/RS2). Asterisk indicates the effect was significant. Ho denotes null hypothesis.

Table 2

Effects	SW		SL	
	F	p	F	p
Presence of Perturbation (H ₀ : UnP = Ptb)	Age	3.10 0.086	8.85	*0.005
	Perturbation Presence × Age	3.13 *0.049	1.18	0.311
Perturbation Type (H ₀ : MP ₁ = LP ₁)	Age	4.98 *0.031	6.74 *0.013	
	Perturbation Type × Age	1.08 0.305	1.45	0.235
Recovery Step (H ₀ : RS ₁ = RS ₂)	Age	8.18 *0.005	9.75 *0.002	
	Recovery Step × Age	0.11 0.744	1.90	0.172

* p < 0.05