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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.

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 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

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(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 (Fig. 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 toward 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, SW, 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 and SL) were calculated at every heel strike. Walking speed 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

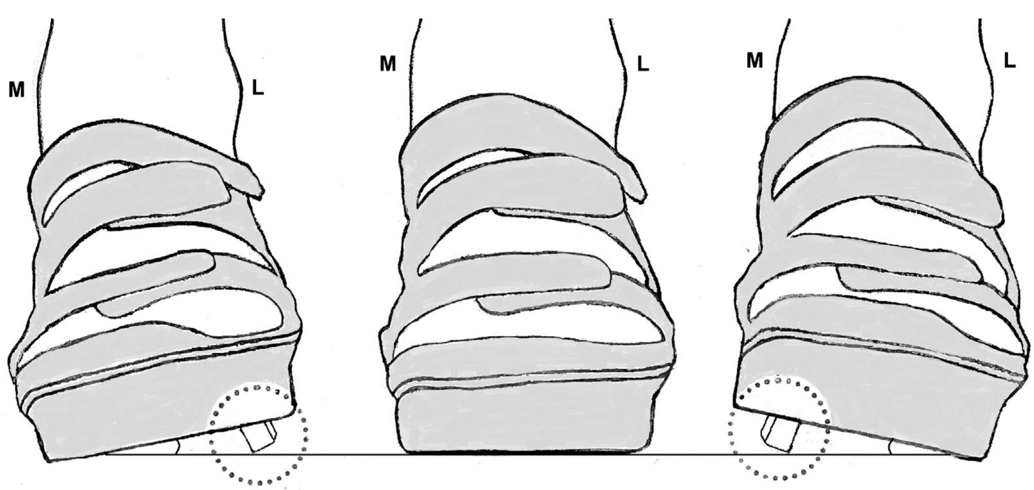

Fig. 1. Anterior view of the modified 11 ½-sized men's sandal showing shoe orientation with flap undeployed (middle illustration). A 18.4 mm high medial flap (dotted circle) is deployed in the parasagittal plane such that during midstance the foot is inverted (right illustration; dotted circle) or everted (left illustration; dotted circle). Figure is reproduced from [12].