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Original Article

Stability against backward balance loss: Age-related modifications following slip-like perturbations of multiple amplitudes

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ABSTRACT

Falls are one of the most serious problems in the elderly. Although previous studies clearly link the increased risk of falls with ageing, the mechanisms responsible for the modifications of reactive motor behaviours in response to external perturbations are not yet fully understood. This study investigated how the stability against backward balance loss is affected by aging and intensity of perturbations. The Margin of Stability (MoS) was estimated while eight young and eight elderly adults managed three slip-like perturbations of different intensities while walking at the same normalized speed. A compensatory step was necessary to regain stability. The forward swing phase of the trailing leg was rapidly interrupted and reversed in direction. Results have shown that ageing significantly affects the time required to select the most appropriate biomechanical response: even if the characteristic of the backward step was similar between groups, elderly subjects took more time to reverse the movement of their swinging limb, thus achieving a less efficient action to counteract the backward balance loss (lower MoS both during and at the end of the early compensatory reaction). In addition, young and elderly subjects scaled their reactions with respect to the perturbations intensity in a similar way by increasing the length of their backward step, thus revealing a context-dependent tuning of the biomechanical response that was not affected by aging. These behavioural features can be helpful in identifying the causes of increased fall risk among the elderly in order to define more suited intervention in fall prevention programs.

1. Introduction

Falls and fall-related injuries remain one of the most serious causes of problems in the elderly [1,2]. Slips account for 25% of falls in community-dwelling older adults [2]. Literature agrees with the evidence that the age-related modification of neural, sensory and musculo-skeletal systems make the corrective motor responses of elderly people in response to external perturbations less effective [3,4], thus increasing the risk of falling. In spite of this, the mechanisms involved in the underlying corrective motor responses and their dependence on the intensity of the perturbation are not fully understood.

The effectiveness of the countermeasures enabled to maintain stability are critically dependent on the subject's ability to regulate the relationship between their body's Centre of Mass (CoM) and Base of Support (BoS) [5–7]. After an unexpected perturbation, the reactive biomechanical response must be appropriately directed, timed, and executed to achieve a fast expansion of the BoS and a shift of the body CoM away from the direction of the perturbation. In case of a slip of sufficient intensity, a compensatory step will be necessary to regain balance [8,9]. After lift-off, a successful reaction will rapidly interrupt the forward swing phase of the compensatory (trailing) leg, reverse its direction and land posteriorly with respect to the CoM. The CoM will then be anterior to the most posterior edge of the BoS, thus compensating for the backward balance loss induced by the forward movement of the slipping foot. An analysis of the compensatory step, distinguishing the forward

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and backward swing phase, would help to further research the age- and amplitude-related differences of its characteristic [8–13] in order to finally define more suited intervention targets in fall prevention programs.

Compensatory step length and relative CoM position are altered as a function of gait speed, indicating that the motor program for gait regulation may play a role in modulating the compensatory step [9]. Despite the fact that elderly adults usually walk with lower speed and step length than younger ones [14,15], age-related differences of the recovery responses are usually studied without control for similar dynamical conditions. Accordingly, it is difficult to understand if the obtained outcomes are due to alterations of the initial dynamical conditions between groups rather than the aging differences of the reactive response per se and to what extent the intensity of the perturbation alone can make the elders' motor responses less effective.

The aim of this study was to compare the effectiveness of the motor responses of young and elderly people while managing unexpected slip-like perturbations of different intensities, delivered while all subjects walked at similar dynamical conditions. Our hypothesis was that elderly and young people would show differences in their compensatory performance and would produce context-dependent responses based on the intensity of the perturbation.

2. Materials and methods

2.1. Participants

Eight young (Y: 24 ± 2.7 years old, 4 males) and eight elderly subjects (E: 65 ± 4.8 years old, 5 males) with comparable body mass (Y: 64.9 ± 10.9 kg, E: 67.6 ± 12.0 kg) and height (Y: 1.69 ± 0.07 m, E: 1.67 ± 0.09 m) volunteered to participate in this study. Participants were selected according to the following inclusion criteria: living autonomously, able to walk without any assistive device, no falls experienced within 1 year before testing, not reporting any significant neuro-muscular-skeletal diseases, not practicing competitive sports and not taking medical drugs which can affect balance control. Subjects were informed about the research procedures and signed a written consent form approved by the Local Ethics Committee of Fondazione Don Gnocchi, Firenze, in agreement with the ethical standards of the declaration of Helsinki.

2.2. Experimental setup and protocol

Subjects were asked to walk on SENLY, a custom-made instrumented treadmill which belts can be independently moved both longitudinally and transversally to impose slip-like perturbations [16–18]. The walking speed (v) was normalized for each subject in accordance with the principle of dynamic similarity described by the Froude number (Fr) [19]:

$$v = \sqrt{Fr \cdot g \cdot L}$$

where g is the gravitational acceleration and L is the leg length from the prominence of the greater trochanter external surface to the lateral malleolus. In this study Fr = 0.15 was chosen.

The protocol accounted for 3 perturbations (i.e., P1, P2, and P3) of different amplitudes delivered once for each subject while steadily walking. Perturbations consisted of a sudden and unexpected forward movement of the right belt when the right heel strike was detected by SENLY. Please refer to Fig. 1 for more details.

Subjects were told they could rest at any time during the experiment if they felt tired and wore a safety harness to prevent them from falling without restricting their movements.

2.3. Data analysis

The 3D trajectory of 40 reflective body markers was collected at 100 Hz using a 6-camera Vicon motion capture system.

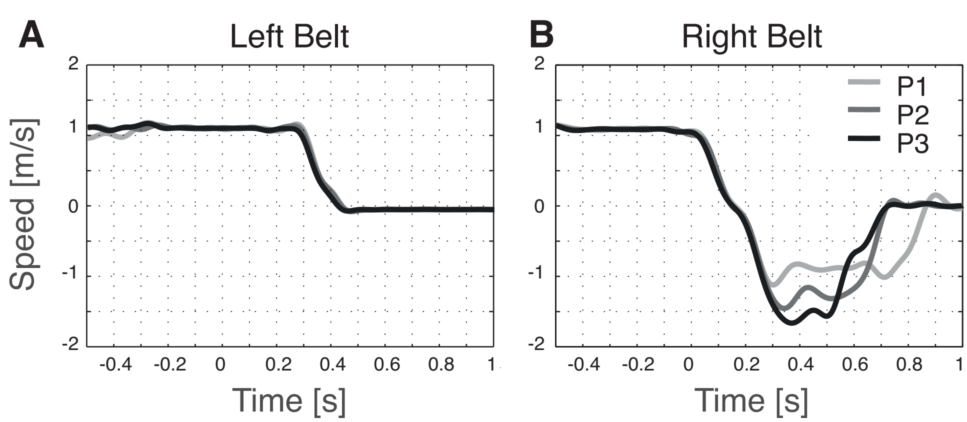

Fig. 1. Experimental Setup and Protocol.
SENLY is a custom-made instrumented treadmill which belts can be independently moved both longitudinally and transversally to impose slip-like perturbations. It is equipped with two sensorized force plates, one for each foot: they allow for evaluating the distribution of load between the feet at run time. The control strategy leading SENLY automatically identifies a heel strike based on the distribution of load between the two force plates.
Perturbations were delivered along the Antero-Posterior (AP) direction while participants were steadily walking and consisted of a sudden and unexpected forward movement of the right belt when the right heel strike was detected by SENLY. Fr and L were used to normalize the amplitudes of the perturbations (i.e., P1, P2, and P3). Specifically: (i) the velocity of the right belt was brought to the maximum speed and then to zero with an acceleration of 8 m/s2 in order to cover a total displacement equal to 60% of L; (ii) three different values for the belt's maximum speed were defined according to a Fr equals to 0.10, 0.20 and 0.30. The speed on the contralateral belt was maintained at the walking speed for 0.40 s and then brought to zero in 0.15 s. In order to obtain unbiased results: (i) perturbations with different kinematic characteristics were delivered to both the right and left feet; (ii) five further trials, in which no perturbation was supplied, were included in the experimental protocol; (iii) participants did not know whether they were going to be perturbed or not; and (iv) perturbations were supplied in random order.
Perturbations amplitude was measured by the encoders embedded in the brushless motors that drive the Antero-Posterior (AP) movement of the belt. The speed profiles depicted in the plot refer to a typical subject with L = 0.81 m (i.e., walking speed equal to 1.09 m/s, maximum speed obtained during P1, P2 and P3 equal to 0.89 m/s, 1.26 m/s, and 1.54 m/s, respectively). Light, medium and dark grey speed profiles of the right belt represent P1, P2 and P3 perturbations, respectively. Noticeably, during the first part of the perturbation, the belt is slowing down. The actual forward movement of the belt started after approximately 0.15 s.