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Influence of gait speed on stability: recovery from anterior slips and compensatory stepping

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Abstract

Falls precipitated by slipping are a major health concern, with the majority of all slip-related falls occurring during gait. Recent evidence shows that a faster and/or more anteriorly positioned center of mass (COM) is more stable against backward balance loss, and that compensatory stepping is the key to recovering stability upon balance loss. The purposes of this paper were to determine whether walking speed affected gait stability for backward balance loss at slip onset and touchdown of compensatory stepping, and whether compensatory stepping response resembled the regular gait pattern. Forty-seven young subjects were slipped unexpectedly either at a self-selected fast, natural or slow speed. Speed-related differences in stability at slip onset and touchdown of the subsequent compensatory step were analyzed using the COM position-velocity state. The results indicate that gait speed highly correlated with stability against backward balance loss at slip onset. The low COM velocity of the slow group was not sufficiently compensated for by a more anteriorly positioned COM associated with a shorter step length at slip onset. At touchdown of the compensatory step, the speed-related differences in stability diminished, due to the continued advantage of anterior COM positioning from a short compensatory step retained by the slow group, coupled with an increase in COM velocity. Compensatory step length and relative COM position altered as a function of gait speed, indicating the motor program for gait regulation may play a role in modulating the compensatory step.

Keywords: Gait stability; Balance loss; Stepping response; Level walking; Fall prevention

1. Introduction

Falls, injurious or non-injurious have a significant health impact, often causing deterioration in mobility and performance of activities of daily living. Falls precipitated by slipping are a major concern, accounting for about 25% of falls among older adults [1]. Backward falls commonly result from slips [2] and are often associated with hip fracture [3], which is not only costly to manage medically [4], but also a precursor to mortality among older adults [5].

One intervention strategy to reduce backward falls might be to improve one's dynamic stability (operationally defined as the ability to resist and prevent backward balance loss upon a slip during movement). Recent findings indicate that dynamic stability may play a major role in reducing slip-related falls induced during the braking phase of a sit to stand among individuals of different ages [6,7]. In these cases, subjects used feedforward control to increase their forward center of mass (COM) velocity and anteriorly shift their COM position to improve their dynamic stability during the sit to stand [6]. A faster or a more forwardly positioned COM can enable the COM to quickly catch up with the forward slipping foot, thus avoiding a backward loss of balance (operationally defined as the necessity of taking a step that lands posterior to the heel of the slipping foot) and a fall. Such empirical evidence lends support to the outcomes of mathematical model simulations that have determined the theoretical threshold for a backward balance loss in the event of a slip [8]. The model results predicted the amount of increase in forward COM velocity or anterior shift of COM position required in order to avoid a backward balance loss. While the threshold values that define stability have been applied to predict the likelihood of backward balance loss in slips induced during a sit to stand [7], they are yet to be applied in assessing gait stability.

It is well known that preferred gait speeds for older adults are slower than preferred speeds for the young [9]. It is generally believed that an age-related decrease in gait speed, with a longer double support phase improves stability and reduces the likelihood of falling [10]. However,

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epidemiological studies involving both community-dwelling and institutionalized older adults have reported conflicting results concerning the relationship between walking speed and falling. Some studies report no association between walking speed and risk of falling [11,12]. Others report the slowed gait speed of older adults and its associated characteristics as predisposing factors for falling [13–15]. During slips induced in a laboratory setting, no relationship was found between walking speed and likelihood of balance loss, although this study tested natural and fast but not slow gait speeds [16]. Other laboratory findings indicate that slow walking speeds could increase the likelihood of balance loss upon a slip [17], whereas fast walking speeds could prevent the occurrence of a backward balance loss [18]. Speed-related differences in gait stability are still unclear.

In preferred gait, there is a coupling relationship between velocity and step length. The speed-related effect of the relative position between the COM and the base of support (BOS) further complicates the issue of stability in gait. During fast walking, a high COM velocity is usually associated with a longer step length, and therefore a more posterior COM position with respect to the leading foot at touchdown (or slip onset when it occurs) [19]. This could reduce stability and increase the likelihood of backward balance loss upon a slip [8]. Conversely, during slow walking, a slower traveling COM is usually associated with a shorter step length, and therefore a more anterior COM position with respect to the heel of the leading foot. This benefit could mitigate the associated destabilizing effect of a slow COM velocity and decrease the likelihood of balance loss. Nevertheless, it is still possible that the net effect of a slower gait speed predisposes a person to a less stable condition against backward balance loss when the benefit of a shorter step cannot sufficiently offset the disadvantage of a slower horizontal COM velocity. The extent to which this competing relationship in stability (at slip onset) between the gain in anterior COM position and the loss in COM velocity associated with slow gait is currently unknown.

Once a forward slip initiates backward balance loss, a compensatory step is required to recover balance. A successful compensatory step will land posterior to the COM such that the COM is substantially anterior of the most posterior edge of the BOS [20]. This implies that the shorter the compensatory step, the more advantageous is the resulting COM position for preventing a backward fall. If the compensatory step resembles gait as controlled by the central pattern generator, then slips at fast walking speeds will produce longer compensatory steps than slips at slow speeds. A sufficiently long compensatory step may result in a COM position that is posterior relative to the BOS and any advantage from the fast walking speed is lost. In this case, the backward balance loss continues and a fall occurs. Conversely, the short compensatory step resulting from a slip during slow gait may provide enough advantage to outweigh the disadvantage to stability of a slow COM velocity. This competing relationship between compensatory step length (COM position) and velocity is still largely uncharacterized.

The purposes of this paper were to determine whether walking speed affected gait stability for backward balance loss at slip onset and touchdown of the compensatory step; and whether the compensatory stepping response resembled the regular gait pattern. Three specific hypotheses were tested. (1) Gait stability at onset of an unexpected slip is inversely related to speed, with slow speed being least stable due to a slow COM velocity that is not sufficiently compensated for by a greater anterior COM position. (2) The compensatory step will increase stability against further backward balance loss, and this increase in stability will be independent of the degree of stability at slip onset. (3) The compensatory step will resemble the regular gait pattern such that step length and thus relative COM position will be altered as a function of gait speed.

2. Methods

2.1. Subjects

Forty-seven healthy young subjects (28.1 $\pm$ 5.98 years, 26 males and 21 females) participated in the study after being screened for exclusionary factors such as neurological (e.g. stroke, Parkinson's disease, spinal cord injury), musculoskeletal (e.g. osteoarthritis, rheumatoid arthritis, fractures onset $<$6 months), cardiopulmonary (e.g. angina, emphysema, lung cancer), other systemic disorders (e.g. diabetes), and selected drug usage (e.g. sedatives, anti-anxiety, anti-histamines). Prior to participation, all subjects gave informed consent as approved by the Institutional Review Board.

2.2. Experimental set-up and protocol

Slips were induced using a sliding device consisting of a low-friction, non-motorized moveable platform (dimensions: 29 cm $\times$ 40 cm long, 3.85 kg) mounted to a supporting frame with linear ball bearings. The device was embedded in a 7 m walkway and was camouflaged by surrounding it with stationary decoy platforms. The supporting frame of the sliding device was bolted to a force plate (OR6-5-1000, AMTI, Newton, MA) to measure ground reaction forces (GRF). Three additional force plates were placed such that GRF from the steps before and after contact with the moveable platform (including the compensatory step) could be recorded (Fig. 1). Slips were induced by a computer controlled release mechanism that unlocked the moveable platform when the ratio of the horizontal to vertical forces, measured in real time by the corresponding force plate after heel strike, exceeded a preset threshold comparable to a low coefficient of friction of 0.02. Once released, the moveable platform slid freely on linear bearings and locked upon reaching a maximum travel of 44 cm. Fig. 2 shows the kinematics of