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Limits of recovery against slip-induced falls while walking

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ABSTRACT

Slip-induced falls in gait often have devastating consequences. The purposes of this study were 1) to select the determinants that can best discriminate the outcomes (recoveries or falls) of an unannounced slip induced in gait (and to find their corresponding threshold, i.e., the limits of recovery, which can clearly separate these two outcomes), and 2) to verify these results in a subset of repeated-slip trials. Based on the data collected from 69 young subjects during a slip induced in gait, nine different ways of combining the center of mass (COM) stability, the hip height, and its vertical velocity were investigated with the aid of logistic regression. The results revealed that the COM stability (s) and limb support (represented by the quotient of hip vertical velocity to hip height, S_{hip}) recorded at the instant immediately prior to the recovery step touchdown were sufficiently sensitive to account for all (100%) variance in falls, and specific enough to account for nearly all (98.3%) variability in recoveries. This boundary ($S_{hip}=-0.22s-0.25$), which quantifies the risk of falls in the stability–limb support quotient (s–S_{hip}) domain, was fully verified using second-slip and third-slip trials (n=76) with classification of falls at 100% and recoveries at 98.6%. The severity of an actual fall is likely to be greater further below the boundary, while the likelihood of a fall diminishes above it. Finally, the slope of the boundary also indicates the tradeoff between the stability and limb support, whereby high stability can compensate for the insufficiency in limb support, or *vice versa*.

1. Introduction

Falls are a major cause of injury in older adults (Kannus et al., 2005). Falls initiated by slip account for about 25% of all falls (Luukinen et al., 2000). Accurate understanding of the causes of falls and assessing the risk of falls are critical to reducing the incidence of falls. As illustrated in our previous research, both center of mass (COM) stability and limb support against gravity play a critical role in determining a fall during slip in gait. It is still unclear, however, whether these two factors or their combinations can quantify the boundary (i.e. the limits of recovery) that can clearly separate the falls from recoveries.

At a global level, the failure in the control of a person's COM stability may cause falls. The limits of stability (thick line in Fig. 1), which differentiate backward balance loss and no balance loss in the COM state space (i.e., its position and velocity), have been recently established (Pai and Iqbal, 1999; Pai and Patton, 1997; Yang et al., 2007; 2008). This stability measure could accurately predict that a backward balance loss must occur when COM motion state locates below the limits of stability (Bhatt and Pai, 2008b; Pai, 2003). Subsequently, however, a recovery step can often rapidly reverse slip-induced instability, and avert actual falls. Therefore, while instability leads to falling, it cannot in itself fully account for falls (Yang et al., 2008). The limits of recovery against risk of falls are yet to be established.

Besides controlling one's stability, providing sufficient limb support to prevent limb collapse (in the vertical direction) is another important factor (or determinant) to avoid a fall (Pavol and Pai, 2007; Pijnappels et al., 2008; Yang et al., 2009). The hip height correlates highly with the magnitude of the vertical impulse generated by the stance limb(s), and hence has been used to approximate and characterize subject's vertical limb support against gravity (Yang et al., 2009). It has been reported that when instability combines with poor limb support at the instant prior to the recovery step touchdown some 300 ms following the slip onset, a subsequent fall incidence becomes nearly (88.9%) inevitable ~500 ms later (Yang et al., 2009). Therefore, limb support must also play an essential role.

The purposes of this study were (1) to select the determinants that can best differentiate the outcomes (recoveries or falls) of an unannounced slip induced in gait (and to find their corresponding threshold, i.e., the limits of recovery, that can clearly separate these two outcomes), and (2) to verify these results in a subset of repeated-slip trials. By combining the COM stability and the hip height, and its vertical velocity, nine different ways of determining falls were investigated. We expected that one of these

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