Theoretical contribution of the upper extremities to reducing trunk extension following a laboratory-induced slip

Introduction

Falls by older adults are a direct cause of considerable mortality and morbidity, both of which exert a significant burden on the healthcare system in the United States. A prerequisite to developing fall-prevention interventions aimed at improving the execution of the recovery task is reliant on characterizing the modifiable biomechanical requirements of the task. When a slip occurs while walking forward, the overall body center of mass continues to translate forward while the body tends to rotate backwards as a pendulum. Rapid shoulder flexion may be a mechanism by which trunk extension velocity can be reduced. Limiting trunk extension may increase the potential distance between the center of mass and the recovery (non-slipping) foot, which determines the boundaries of the new base of support.

The purpose of this study was to quantify the biomechanical role of the upper extremities during the initial phase of a slip, that is, from the instant of heel strike on the slippery surface until the instant the recovery foot was placed on the ground. Two groups of adults were examined: older adults who fell and younger adults who avoided falling after slipping. We hypothesized that adults who slipped would use shoulder flexion to significantly reduce trunk extension velocity and that younger adults who avoided falling would use their upper extremities to reduce trunk extension velocity to a greater degree than older adults who fell.

Methods and Materials

The subjects included in this institutionally reviewed and approved study were a subset from a larger study who fell primarily in the sagittal plane. All provided written informed consent prior to data collection. In total, data from 12 young adults who recovered (5 males, mean±SD: 24±5 years, 168±11 cm, 66±11 kg) and 8 older adults who fell (1 male, 71±4 years, 162±9 cm, 70±11 kg) were analyzed.

Subjects wore a safety harness and were unexpectedly slipped on a lubricated Plexiglas sheet (1.22cm x 2.44m x 0.63cm), which was placed approximately mid-way along a 12.8 m walkway. Subjects were aware that they might be slipped, although they were unaware of how or when the slip would occur. The lubricant was either mineral oil or a water soluble lubricant. Only one slip was attempted for each subject. The motions of 23 passive reflective markers placed over selected anatomical landmarks were collected at 60 Hz using an eight camera motion capture system (Motion Analysis, Santa Rosa CA).

The slipping event was temporally bounded by the onset of the slip (heel strike) and recovery foot touchdown; both were identified manually from motion capture data by a single investigator (KLT).

To examine the possible contribution that rapid shoulder flexion could make towards reducing trunk extension, a three-segment sagittal plane model was developed. The three segments represented the head/neck/trunk and the right and left upper extremities. We assumed that the only external forces were gravity and the reaction force at the distal end of the trunk, that elbow flexion remained constant during the analysis period, and that angular momentum of the system about the shoulder center of rotation was conserved. The model was based on the equation \( I_{trunk} + I_e (\theta_e + \dot{\theta}_e) = constant \) where \( I_e \), \( m_e \) and \( \dot{\theta}_e \) are the moments of inertia and masses of the arms and trunk, respectively, and \( \theta_e \) is the angular velocity of the segment. The change in angular velocity of the trunk, \( \Delta \theta_{trunk} \), can be expressed as \( I_{trunk} + I_e (\dot{\theta}_e + \Delta \theta_{trunk}) = 0 \).

We assumed an initial (theoretical) condition in which the trunk was extending with some velocity \( \theta_{0,\theta} \) but that there was no arm motion. That is, \( \dot{\theta}_e(0) = 0 \) and \( \dot{\theta}_e(0) = 0 \). If the arms started at rest and moved to their peak, they would provide a maximum change to the angular momentum of the trunk, or \( \Delta \theta_{max} = \theta_{max} - \dot{\theta}_e(0) \) where \( \theta_{max} \) is the actual measured peak angular velocity for a segment. Thus, the maximum possible change in trunk angular velocity provided by moving the arms at their respective peak velocities would be: \( \Delta \theta_{max} = \theta_{max} - \dot{\theta}_e(0) \). Similarly, at any given time point \( t \), \( \Delta \theta(t) = \theta(t) - \dot{\theta}_e(0) \).

The model was used to estimate the maximum possible contribution of upper extremity motion to reducing the trunk extension velocity for each subject during the slip trial, \( \Delta \theta_{max} \), and the theoretical reduction in trunk extension velocity at the instant of recovery, \( \Delta \theta_{recovery} \). An independent sample t-test was used to compare \( \Delta \theta_{max} \) between groups.

Results and Discussion

The mathematical model indicated that young adults who avoided falling backwards were no more effective at using their upper extremities to reduce trunk extension velocity than older adults who fell. However, one older subject was identified as a statistical outlier. This subject’s percent reduction in peak trunk extension velocity, 25.7%, was more than five times greater than that of the next nearest subject. After this subject was excluded from the analysis, the mean percent reduction in trunk extension velocity (\( \Delta \theta_{max} \)) for young adults was 7.2±6.7%, compared to only 2.9±2.4% in older adults (p<0.050; Figure 1). \( \Delta \theta_{max} \) was significantly different than zero for both younger and older adults (p<0.004), indicating that rapid flexion of the shoulders could effectively decrease trunk extension velocity following a slip.

Younger adults may have been more capable of reducing trunk extension velocity because of their ability to rapidly flex the shoulders. The largest single shoulder peak flexion velocity achieved by a young subject was 599 deg/s and the largest mean velocity was 394 deg/s. In contrast, the largest single shoulder peak flexion velocity for an older adult was 356 deg/s and the largest mean velocity was 237 deg/s.

Our results indicate that upper extremity motion can contribute to the recovery effort after a sagittal plane slip, that subjects implemented this as a strategy, and that younger adults who avoided falling were over twice as effective at reducing trunk extension velocity as most older adults who fell. Due to differences in strength, power, reactive response, or other factor(s), the young adults in our study were able to more effectively use shoulder flexion moments than older adults to reduce trunk extension velocity following a slip. If one of these factors contribute to the poor performance of older adults, these may represent potential areas for clinical intervention as they are modifiable.

Clearly, factors other than upper extremity use contributed to the observed slip outcomes (fall versus recovery). The degree to which trunk extension velocity is reduced through rapid shoulder flexion does not determine the outcome of the slip. All but one older adult used their upper extremities to reduce trunk extension velocity by less than 5% and all older subjects fell. However, half the younger adults, all of whom recovered, also had reductions in trunk extension velocity of 5% or less due to upper extremity use. Given the potential degree to which trunk extension velocity can be reduced with rapid shoulder flexion, fall prevention interventions focused on slip-related falls may benefit from including upper extremity motion as an outcome whether through conventional or innovative strategies.