Trunk Angular Kinematics during Slip-Induced Falls and Activities of Daily Living – Towards Developing a Fall Detector

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The purpose of the current study was to investigate the trunk angular kinematics (i.e., angle and angular velocity) during slip-induced falls and activities of daily living (ADLs), with the aim to facilitate the development of a new fall detector. Ten elderly participated in a laboratory experiment, composed of normal walking, slip-induced falls, and 5 types of ADLs. Sagittal trunk kinematics was measured from optical motion analysis system. Angular phase plots were utilized to characterize falls from ADLs.. Results indicated that backward falls were characterized by a simultaneous occurrence of a slight increase in trunk extension angle (average peak = 11°) and a dramatic increase in extension angular velocity (average peak = 139.7°/s). It was concluded that trunk angular kinematics could be used to design an effective fall detector.

INTRODUCTION

Slip and fall accidents have been recognized as a major threat to the safety of industrial workers. Falling on the same level was found to be one of the five leading causes of loss in productivity (e.g., 5 or more days away from work), and in 2002 alone, result in $4.6 billion direct cost of disabling work place injuries (Liberty Mutual Research Institute for Safety, 2002). It is certainly desirable to avoid the fall accidents altogether through developing a comprehensive fall prevention program (Bell, et al., 2008). However, in case of unavoidable falls, an effective injury-prevention technology is critical to minimize/reduce fall-related physical injuries. Recently, the concept of wearable airbag (Fukaya & Uchida, 2008) emerged as one viable and promising injury-prevention approach.

Being able to detect fall events unambiguously and reliably is the key for the practical implementation of wearable airbag technology. Consequently, fall event detection has attracted several research attentions since early 2000s. Doughty et al. (2000) designed a fall detector (combination of impact sensor and tilt sensor) and evaluated on mannequin with five different types of falls. Noury et al. (2003) developed an accelerometer-based fall detector and tested with younger adults with three types of falls. Since then, MEMS-based ambulatory sensors (e.g., accelerometers, gyroscope, etc.) have been widely used in fall detection research (Bourke, O'Brien, & Lyons, 2007; Karantonis, Narayanan, Mathie, Lovell, & Celler, 2006; Lindemann, Hock, Stuber, Keck, & Becker, 2005; Nyan, Tay, Tan, & Seah, 2006) due to their appealing features in terms of portability and power consumption.

Despite the continuous efforts, existing fall detection technology still requires much research. First of all, previous fall detection methods have been exclusively evaluated with falling from a static posture (i.e., standing). It is unknown whether and to what extent these methods can be applied to more realistic scenarios (i.e., falls during dynamic movement). Second, previous methods have been tested with the younger adults only. Considering the age-related motion feature differences, fall detection performance evaluation has to involve the elderly who are the most likely users for this type of technology. To address these two issues, it is desirable to develop and evaluate the fall detection methods with the elderly during walking. Even before that, a natural research question arises as to whether there are unique human motion features which can unambiguously distinguish falls during motion from activities of daily living (ADLs), and which can be readily measurable by current ambulatory sensing technology.

Therefore, the purpose of the current study was to investigate the trunk angular kinematics (i.e., angle and angular velocity) during slip-induced falls and ADLs. Trunk segment was selected for its superior user compliance as a site of sensor attachment (Karantonis, et al., 2006; Nyan, Tay, Tan, et al., 2006). Angular kinematics was chosen because they can be measured directly by inertial measurement unit (IMU). It was hypothesized that trunk angular kinematics during the backward falls would be significantly different from those during ADLs.

METHODS

Participants

Ten elderly participants (> 65 years old) were recruited from the local community for this study. Their anthropometric information was summarized as: age (mean = 75 years, SD = 6.0 years), weight (mean = 74.1 kg, SD = 9.1 kg), height (mean = 1.74 m, SD = 0.08 m). They were required to be in generally good physical health and deemed suitable by the study physician. Informed Consent (Virginia Tech IRB #07-628) was approved by the IRB committee at Virginia Tech and obtained from the participants prior to any data collection.

Apparatus and Procedures

Normal walking and slip-induced backward falls. A detailed description of the experiment protocol has been published previously (Liu & Lockhart, 2005). Briefly, participants were instructed to walk at a normal pace on a linear walkway (1.5m × 15.5m) with the protection of an overhead harness system. Unexpected slips were induced by changing the dry floor surface into slippery surface (covered with 3:1 KY-Jelly and water mixture) without participants' awareness. Two force-plates (BERTEC # K80102, Type 4550-08, Bertec Corporation, OH) and a six-camera optical motion analysis system (ProReflex, Qualysis, Sweden) were synchronized to collect kinetic and kinematics at a sampling rate of 100Hz. A biomechanical model (Lockhart, Woldstad, & Smith, 2003) using 27 marker-set was adopted in the current study. One additional marker was placed close to the sternum.

Given the slip perturbation, participants' reactions may be classified into either recovery or fall. Fall was identified as the trial in which the participant had to rely on external assistances (i.e. overhead harness) other than floor support to regain their balance. Quantitatively, falls were considered as those trials in which the participant's vertical shoulder position (as measured by the shoulder marker) dropped more than 20 cm from normal shoulder height after a slip. All other trials were considered as recovery trials.

The slippery surface was introduced repeatedly until three slip perturbation trials were obtained from each participant. After each trial with the slippery surface, participants were encouraged to walk continuously as normal as possible at a normal pace for 5 to 10 minutes before the next slippery trial. The participants had no knowledge regarding the exact timing of the floor surface change.

Activity of daily living (ADLs). A six-camera optical motion analysis system (ProReflex, Qualysis, Sweden) was used to collect the kinematics data at a sampling rate of 100Hz. The same biomechanical model (Lockhart, et al., 2003) using a 27 marker-set was adopted in this study. A gait analysis laboratory with regular living furniture (bed, chair, desk, etc) was used as the experimental setting.

Each participant was instructed to perform 5 types of daily activities according to the order specified by a balance Latin square. For the sitting down activity (SN), the participant was asked to sit onto a regular office chair which is about the knee height (individual adjusted), wait 1 or 2 seconds, and then stand up. For the sitting in to a rocking chair activity (SR), after sitting down, the participant was free to move his/her body in a relaxed way as allowed by the rocking chair. For the sitting into a bucket seat activity (SB), the participant sat into a chair about half of the knee height to mimic the sitting motion of getting into a car. For the lying down activity (LD), the participant lied down on his/her back from a sitting posture on a medical bed. For the bending over activity (BD), the participant bent over from a standing posture to pick up an object (e.g., a roll of duck tape), which was located one foot in front of the participant, from the floor.

Data acquisition was performed by a custom-designed program in Labview (Labview 8.2, National Instruments, TX).

Data Reduction

Kinematics data from the motion analysis system was first low-pass filtered (Butterworth, 4^{th} order, 6Hz cut-off frequency) before further processing. The trunk sagittal angle and angular velocity was calculated using the kinematics data of reflective markers placed on the acromions and sternum. The trunk angles were reported with the vertical direction being the reference of zero.

To facilitate the description of the fall dynamics, the following events were defined:

Fall initiation: an event same as the definition of slip start (for details, see Lockhart, et al., 2003) when the forward heel velocity occurs after heel contact.

Fall completion: the event when the trunk COM reaches its lowest vertical position.

To facilitate the description of the ADL activity, the start and end point of each trial of activity were determined as the following. First, the mean and SD (standard deviation) of trunk angular velocity during the initial 1 second of each trial of activity were analyzed. Then, the start point of an activity was defined as whenever the trunk angular velocity deviates over 2 SD from the mean during the initial 1 second (Giansanti & Maccioni, 2006). Similarly, the end point for that activity was defined as whenever the trunk angular velocity deviates more than 2 SD from the mean during the last 1 second.

Phase plots of trunk angular kinematics were generated with trunk angle as the X axis and trunk angular velocity as the Y axis for each activity. During normal walking, the phase plots were generated during one stance phase. During falling, the phase plots were generated from fall initiation to fall completion. During ADLs, the phase plots were generated between the activity start and end points.

All of the data analyses were performed using a custom-designed MATLAB program (MATLAB R2007b, MathWorks, USA).

RESULTS

Normal Walking and Slip-Induced Backward Fall

In the current study, participants always walked with a slight trunk flexion (mean = 5.6° / SD = 2.9°) during normal walking, with peak flexion and peak extension occurring approximately at heel contact and toe off, respectively. The trunk angular velocity profile was characterized by two extension velocity peaks occurring at about 10% and 90% of stance phase, and one flexion velocity peak at about 50% of stance phase.

Totally, 30 perturbation trials were collected; including 13 backward falls, 15 successful recovery trials, 1 forward fall, and 1 sideway fall. For the purpose of the current study, only the 13 backward fall trials were analyzed.

Slip-induced backward falls were characterized by a simultaneous rapid increase of both trunk extension angle and trunk extension angular velocity, with peak angle and angular velocity reaching, on average, 11° and 139.7°/s, respectively. The trajectories from slip end to fall completion were mainly located within a narrow band of 1st and 2nd quadrants on the phase plot diagram (Figure 1-c).

During Activities of Daily Living

The bending over activity can be divided into two phases: an initial phase characterized by trunk flexion angular velocity and increasing trunk flexion, and a later phase characterized by trunk extension angular velocity and decreasing trunk flexion. The peak trunk flexion and extension angular velocities were comparable, with an average of 131.6°/s and 118.7°/s, respectively.

The trunk angular kinematics during lying down were characterized by a dramatically increasing trunk extension and an extension-dominant angular velocity. The peak trunk extension occurred at the end of lying down, with an average of 142.7°, while the peak extension velocity reached an average of 90°/s.

Similar to that of bending over, the trunk angular kinematics of the sitting down activity can be divided into two phases: an initial phase characterized by trunk flexion angular velocity and increasing trunk flexion angle, and a later phase characterized by extension angular velocity and decreasing flexion angles. Compared to bending over, however, sitting down was characterized by lower average peak flexion (53.6°/s), lower average peak flexion velocity (85.4°/s), and lower extension velocity (84.7°/s).

The activity of sitting into a rocking chair was analyzed from the start of sitting down to the end of standing up. No distinguishable pattern of the trunk angular kinematics can be observed during sitting into a rocking chair. Sitting into a rocking chair was dominated by a trunk flexion angle (average peak flexion = 56.5°).

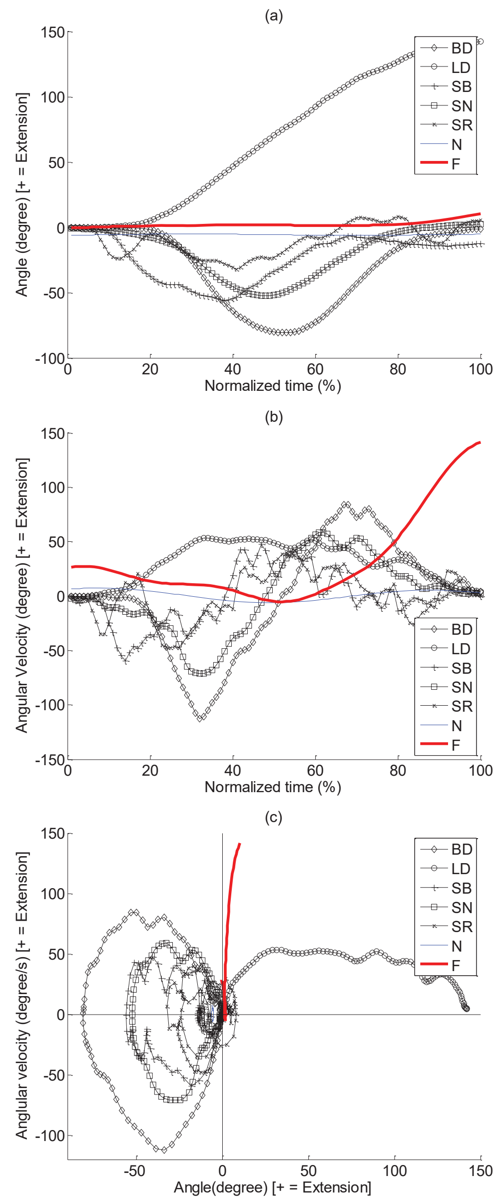

Figure 1 – Trunk angular kinematics during ADLs and falls; (a) and (b) ensemble average profiles; (c) ensemble average angular phase plots

The trunk angular velocity during SB, however, was highly irregular, which was different from the smooth two phase pattern during SN and BD. With peak flexion angle, peak flexion velocity and extension velocity to be 73.1°, 100.5°/s and 112.1°/s, respectively, the peak trunk angular kinematics were slightly higher than that of the other two types of sitting activities (SN and SR).

Comparison of Trunk Kinematics during ADLs and Falls

Ensemble average profiles of trunk angular kinematics were shown in Figure 1 for all the ADLs and backward falls. Peak trunk sagittal angular kinematics were summarized in Figure 2.

In terms of trunk sagittal angles, three types of sitting down (SN, SB and SR) and bending over were all flexion dominant, while lying down was clearly extension dominant. Compared to ADLs, trunk sagittal angular range of motion were limited for both normal walking and slip-induced backward falls. The two ADLs that had peak extension velocities close to that during falls were bending over and sitting down into a bucket seat (Figure 2).

From the perspective of angular phase plot, the backward falls were clearly distinguishable from ADLs (Figure 1-c). The trunk angular kinematics of all the ADLs except lying down was mainly located within the 2nd and 3rd quadrants of the phase plot diagram. On the contrary, the trunk kinematics during backward falls was uniquely located in a narrow region close to the positive vertical axis and within the 1st quadrant of the phase plot.

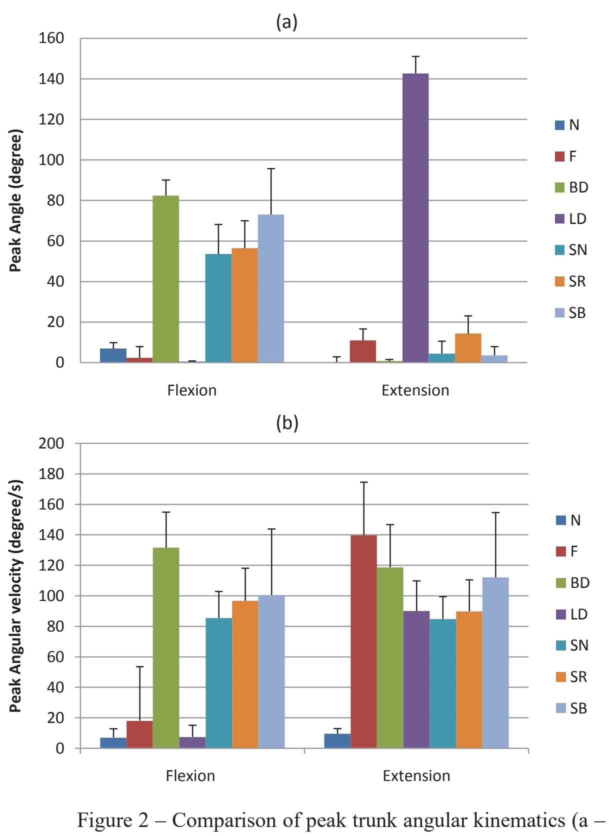

Figure 2 – Comparison of peak trunk angular kinematics (a – angle; b - angular velocity) during ADLs and slip-induced backward falls (error bar indicates 1SD)

DISCUSSIONS AND CONCLUSIONS

The purpose of the current study was to explore the feasibility to differentiate slip-induced backward falls from ADLs. Obtaining such knowledge is the first step towards developing a new trunk-based fall event detector. The findings from the current study indicate there exist unique trunk angular motion features associated with backward falls.

Various fall event detection algorithms have been proposed over the years (Karantonis, et al., 2006; Lindemann, et al., 2005; Nyan, Tay, Seah, & Sitoh, 2006). Until now, however, little research has been conducted on the characteristics of fall activities that differ from ADLs from a biomechanics perspective. Wu (2000) studied the linear velocity characteristics of the trunk during three different types of falls and several different ADLs. It was suggested that both horizontal and vertical trunk velocity could be used for automatic detection of fall events. Such findings, however, have not been utilized to develop an ambulatory fall detection algorithm, possibly due to the current technical limitations of inertial sensors in measuring the linear velocity directly. In the author's opinion, it is beneficial to build the knowledge regarding the unique motion features of falls before designing a new fall detection algorithm. Meanwhile, the potential motion features should be easily measurable by the current ambulatory sensors. With these considerations, the current study investigated the possibility to differentiate falls from ADLs utilizing trunk angle and angular velocities, which can be directly measured by an inertial measurement unit (IMU).

As expected, the slip-induced backward falls exhibited a unique feature in trunk angular kinematics compared to ADLs. As illustrated in Figure 1-c, the kinematic measurements of backward falls were clearly distinguishable from those of ADLs in an angular phase plot. The majority of kinematic measurements of ADLs were dispersed within the 2nd and 3rd quadrants, and a flattened region close to the positive x axis within the 1st quadrant of the angular phase plot. On the contrary, the kinematic measurements of the backward falls were mainly located in a flattened region close to the positive y axis within the 1st quadrant of the angular phase plot. That is, the trunk kinematics of the backward falls were unique in terms of the simultaneous occurrence of an extremely high extension angular velocity and extension angle.

The trunk angular kinematics obtained from the current study was generally comparable to the findings in the literature. During normal walking, the average trunk angular velocity and flexion angle were found to be 7~9.5°/s and 6.8° in the current study. As a comparison, Syczewska et al. (1999) found a forward leaning of the whole spine of 4~5°. Mc Gibbon et al. (2001) found that for healthy young adults, the range of trunk angular velocity was within 34°/s. During ADLs, in the current study, the average peak angular velocity was 118.7°/s for bending over and 84.7~112.1°/s for three types of sitting down. Similarly, Nyan et al. (2006) found the peak angular velocities being ~125°/s for bending over, and ~100°/s for sitting down.

During backward falls, however, the results from the current study were substantially different from those in literature. Nyan et al. (2006) observed an average peak extension angular velocity to be ~450°/s, much higher than that (139.7°/s) measured in the current study. Because the measurements of the same motion agreed well between motion analysis system and inertial sensors in the current study, the above discrepancies were likely to be due to the differences in study designs. More specifically, the backward falls in the current study were stopped by the overhead harness in the middle of the fall dynamics while in the previous study the participants were allowed to impact the ground (covered by mattress). Therefore, it is likely that those high angular velocities observed in the previous study occurred in the latter phase of the fall dynamics, which was not measured by the current study.

In conclusion, the slip-induced backward falls was characterized by a simultaneous occurrence of an extremely high trunk extension angular velocity and a slight trunk extension angle. Such motion features of falls were found to be clearly distinguishable from those of ADLs. The discriminant analysis indicated that the quadratic form of the discriminant function, with higher fall detection performance in terms of ROCa, was suitable for developing the new fall detection algorithm.

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