Role of Upper Limbs: Slip-induced Falls

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Abstract

The purpose of this study was to examine the upper limb motions after a slip event. The study focused on examining relationships between arm motions and a regain of stability. A slippery surface was introduced unexpectedly while participants (younger or older adults) were walking at their preferred pace wearing the safety harness. The synchronized ground reaction force and body position data were obtained while they were slipping and recovering. The focus of this study was to examine the upper limbs (arms) kinematics while slipping over a slippery floor surface. It was believed that the arm movements would be used to improve imbalance produced by the inadvertent slipping. In particular, it was hypothesized that the involuntary arm motions while slipping was created in attempt to move the body center of mass forward, resulting in an improvement in the imbalance. The upper limb kinematic data was used to calculate the center of mass and acceleration of the upper limb. Along with the role of the upper limb, the different phases of recovery after the slip was studied and characterized. The data was analyzed using Matlab and a statistical analysis tool (JMP). The results were discussed in light of the 3-D kinematics of the arm movements and recovery categorization. In conclusion, the present study suggested that the upper limbs' movements created during slipping contributed to an enhancement of individual's recovery possibility from an inadvertent slip.

Key words: slips and falls, control strategy, arm motion, Center of Mass, stability

1. Introduction

Although continuous efforts in reducing falls and fall-related injuries have been made by many investigators, falls and fall-related injuries continue to remain as the leading cause of injury death among older adults over the past decade (CDC 2008; Stevens, 2006). The annual direct cost from occupational injuries due to slips, trips and falls in the USA has been estimated to exceed $6 billion (Courtney et al. 2001). According to the Bureau of Labor Statistics (1999, 2000, and 2001), floors and walkways or ground surfaces were identified as the major sources of slip and fall accidents, causing over 86% of all fall-related injuries. In many cases, fall accidents lead to moderate to severe injuries such as bruise, hip or wrist fracture, or head injuries often resulting in permanent physical damages (Sterling et al. 2001) or deaths (CDC 2008). The elderly population is especially susceptible to slip and fall injuries (CDC, 2008). Physical injuries in older adults are more seriously problematic than that in younger adults because aging body cannot repair injured bones, tissues, and muscles as efficiently and timely as younger adults resulting in a longer recovery time. For that reason, many older adults fear falls and curtail their physical activities and imprison themselves within their home (Vellas et al. 1997).

Generally, studies in slips and falls used shoe-floor contact kinematics (Lockhart and Kim 2006) or shoe-floor kinetics (Grönqvist et al., 1989; Perkins, 1978) to analyze the human response processes to slips and falls; examples were heel velocity and slip distance for shoe-floor kinematics, and RCOF for shoe-floor kinetics. Although the previous studies (Lockhart and Kim, 2005; Grönqvist et al., 1989; Perkins, 1978) have well distinguished the slips and falls processes utilizing kinematics and kinetics, a study in evaluating human responses in terms of the upper limb movements responding to slip-induced perturbation has been lacked.

After a slip started, a chance of regaining balance was highly related to the individual ability to control or maintain his/her balance (Kejonen et al., 2003; Maki, 1997; Marigold et al, 2003; Marigold and Patla, 2002; Tang et al., 1998a &1998b; You, Chou, Lin, and Su, 2000).

Lower body reactions or movements have received much attention since lower extremity is suggested to play a dominant active role in terms of corrective response (Dingwell et al., 2001, Liu and Lockart, 2006; Lockhart and Kim, 2006). Meanwhile, the upper limb motions such as arm motions can be commonly seen after a slip starts. This response can be considered as to regain stability because the arm motions may change the COM (Center of Mass) position relative to the COP (Center of Pressure) position. For that reason, an understanding of the arm motions would be useful in improving fall prevention strategies. These arm motions could facilitate to shift the COM in close to the COP projection, thus, helping to regain balance (Orendurff et al., 2004; You et al., 2000). Close examination of upper limb motions may help increase an understanding of successful reactive-recovery mechanisms.

The present study examined upper limb motions and their contribution to the role in regaining postural balance while subjects were slipping. The study examined the effects of the arm motions on COM position. The major assumption for the present study was that human maintained their body COM stability when walking. Based on the assumption, the study developed two hypotheses; 1) whole body COM stability while slipping would be poorer without arm motions. 2) the base of support, which was characterized by the distance between two feet, would get larger during the slips/falls conditions.

2. *Methods*

2.1. Participants

A total of 21 participants' data was used for this study. The 21 participants included 11 younger adults and 10 older adults. The participants' anthropometric data were listed in table 1.

2.2. Procedure

The procedure for data collection was primarily based on the methods developed by researchers at the Locomotion Research Laboratory (Lockhart et al., 2003).The participants were instructed to walk across a linear walkway (1.5m × 15.5m) embedded with two force plates (BERTEC # K80102, Type 45550-08, Bertec Corporation, OH 43212, USA) at their preferred gait speed (Figure 1). The walkway was covered with baseline vinyl tile. Twenty-six small spherical reflecting markers were placed over bony landmarks of participants according to the marker configuration described by Lockhart et al. (2002). A six-camera ProReflex system (Qualysis) was used to collect three-dimensional posture data of the participants while walking. Kinematic data was sampled at 120 Hz, while force-plate data was sampled and recorded at 1200 Hz. Both kinematic and force-plate data were digitally low-pass filtered by a zero-phase fourth order Butterworth filter with a cut-off frequency of 6 Hz and 12 Hz, respectively. A fall arresting rig was used to prevent participants from hitting the ground except their feet (Lockhart et al., 2002).

The participants were dressed in a tight shirt and shorts and provided uniform experimental shoes to minimize shoe sole differences. Participants walked naturally for a period of more than ten minutes prior to introducing slipper floor surfaces (Lockhart et al., 2002). There were two surface conditions, dry and slippery. Slippery surface were covered with soap and water mixture (2:3) to reduce the coefficient of friction (COF) (dynamic COF was 0.07). While walking, subjects were distracted by several moderate cognitive tasks (Kim and Lockhart, 2005). After collecting normal gait data, slippery surface was introduced without participant's awareness.

2.3. Data Analysis

2.3.1. Normal body COM range

A whole body COM and a half body COM (without upper limbs) for each individual were calculated by identifying positions of 26 markers in 3D (x, y, z). The position data obtained for the two COMs for different individuals were normalized using their heights (in unit of COM coordinates (x or z) / height), and plotted as a function of percent stance phase. The position data corresponding to the stance phase (both feet in contact with floor) were used for analysis.

The mean position data across individuals were captured in a sixty-frame window with the first frame representing the point of heel contact. Also, only the data collected along upward and forward directions were used for analyses, with forward direction representing motion in the forward direction and upward direction in the vertical direction. The data for each frame were averaged across all the subjects, and the standard deviation was also obtained.

2.3.2. The body COM with or without upper limbs

For the analysis, the recovery start and end frames were identified. The instant, when the heel velocity reached the peak after a slip start, was defined the recovery start (Kim and Lockhart, 2010). At the recovery start, the upper extremity corrective response following a slip began with a slight delay. The instant, when the body COM velocity reduces to zero after the heel velocity peaked, was identified for the recovery end.

To test if arm motions contributed to regaining postural balance (1st hypothesis) during the recovery period, the progressive body COMs without the arm contribution were calculated and they were compared to the normal body COMs (with the arm contribution). The effects were observed in the upward and forward directions. The mean COM position for each participant calculated and one-way ANOVA was performed to test differences between the two conditions. A significant value of $p \leq 0.05$ was used throughout the analyses.

2.3.3. The role of arm COM acceleration in the corrective response

To test if the arm COM accelerations were associated with regaining balance (1st hypothesis), the right and left arm COM accelerations were calculated using the COM position data during the recovery period. The peak COM acceleration during recovery was compared to the normal range of COM acceleration during normal walking. The effects were observed in the upward and forward directions. One-way ANOVA was performed to observe the results of the arm COM acceleration in the recovery period. A significant value of $p \leq 0.05$ was used throughout the analyses.

2.3.4. Base of support

To determine the base of support, the difference between the individual's heel data (e.g. $D_x = X_{R\_Heel} - X_{L\_Heel}$ (forward to back) and $D_y = Y_{R\_Heel} - Y_{L\_Heel}$ (side to side)) was calculated. The maximum D_x and D_y in a step represented the anteroposterior and mediolateral distances between two feet during normal walking, respectively.

3. Results

3.1. Whole Body COM Position - Normal Walking

The whole body COM position (normalized) along the upward direction as a function of percent stance phase, along with the corresponding standard deviations for each frame, was presented in Figure 2. The overall mean COM position during the entire stance phase was 0.5417 or 54.17 % of body height (averaged across all subjects), with a standard deviation of 0.53%. The movement of the COM along upward direction ranges from a maximum of 0.5485 (54.85%) to a minimum of 0.5337 (53.37%). The overall mean COM position for the entire stance phase along the forward direction was 44.29% of body height with a standard deviation of 10.71%. The range of movement along forward direction was found to be (0.6297 - 0.2668) or (62.97% - 26.68%) expressed as a percentage of body height.

3.1.1. Body COM Position - Normal Walking vs recovery period

The COM position during the slip event was compared with COM range during normal walking. Figure 3 displayed the body COM position during normal walking and the recovery period. It was observed that there was significant variation. Most of the COM position points for a slip event existed outside the standard deviation range for COM position during normal walking.

3.1.2. Left Upper Limb COM Acceleration - Normal Walking

The left upper limb COM acceleration along the upward and forward direction was shown in Figures 4 and 5 as a function of percent stance phase for a single individual, in order to reveal the trend.

3.1.3. Right Upper Limb COM Acceleration - Normal Walking

The figure 6 depicted the right upper limb COM acceleration trend for a single individual across upward direction. The upper limb COM acceleration trend along the forward direction was depicted in Figure 7 for a single individual.

3.2 Contribution of arms in the corrective response by balancing the body COM

One-way ANOVA (condition) was conducted to test significant differences between the participants' body COM with and without arms.

The body COM with arms (*M* = 52.42, *SD* = 5.15) was significantly higher (*p* = 0.02) than the body COM without arms (*M* = 46.01, *SD* = 4.99). The results of the ANOVA indicated that there was a significant effect of the arms during the slip recovery period. With arms, the participants were closer to the normal body COM range (54.85 - 53.37). These results implied that the arm motions played a role in maintaining or bringing back the participants' balance during slip recovery. Figures 8 and 9 displayed the comparison between the body COM position in the upward direction, the comparison between the body COM position in the forward direction.

The right and the left upper arm accelerations were plotted during the recovery period for the upward and forward directions in Figure 10. It was observed that the arm acceleration pattern along the upward direction was more consistent with participants as compared to the forward direction. The Figure 10 provided the trend of the arm acceleration for both the right and the lower arm during the recovery period. The acceleration was rapidly increased at the beginning of the recovery period and dropped thereafter. The maximum acceleration ranges for all participants were compared with their normal acceleration range while walking. It was observed that the acceleration for the right arm was significantly increased during the recovery from the slip (p= 0.0007) in the upward and (p=0.0145) in the forward direction as compared to the left arm acceleration.

3.3 Base of Support

To test hypothesis three, the maximum values during the slips and falls condition were compared to the values from the normal walking condition. In normal walking conditions, the distance was relatively stable. D_x and D_y were calculated based on the definition defined in the data analysis section of this paper. Figure 11 illustrated the common pattern of D_x and D_y during recovery period.

Tables 2 displayed the study results. For anteroposterior distance, the null hypothesis could not be rejected ($p > 0.05$); but, we had every reason to reject the null hypothesis for mediolateral distance ($p < 0.01$). As such, Hypothesis 3 was partially supported by the data.

3.4 Categorizations of slips and falls

Table 3 summarized the categorization of all the slip and fall trials in the current study. Majority of the participants (63.6%) increased their bases of support by using widen-support motion, while some of the participants (36.4%) retracted their slipping foot leading to a smaller base. =In terms of the arm motion on the unperturbed side, almost all the participants (96.7%) adopted the raise-up motion. On the contrary, more than half of the participants (54.5%) did not show clear reactive arm motion on the perturbed side.

4. Discussion

The purpose of this study was to evaluate the contribution of arm movements to the corrective response by humans to a slip-induced perturbation from the COM positioning perspective. The study's findings indicated that the progressive arm motions following a slip event played a significant role in maintaining the whole body COM. Also, increase in the base of support was the common strategy adopted by the most participants while recovering from slips.

The present study examined the region of stability for the whole body center of mass during normal walking and slipping. Every person maintains his/her body center of mass (COM) within a particular range to maintain proper balance (Wu and Essien, 1998). During normal walking, whole body COM position along the upward direction increased and fell in a sinusoidal fashion, but stayed within a particular range. However, the position along the forward direction increased almost linearly as the body moved forward at almost a constant speed (speed of walking). Hence, the region of stability could be associated with the upward direction. This region of stability was found to exist between ranges of approximately 1.5% of the subject body height, the range being centered at approximately 54% of body height in the present study. Additionally, a person could cover distance (along forward direction) equaling approximately 36% of body height, though this would vary with walking speed.

The whole body COM position in the upward and forward direction was reported to be shifted to bring the body back to the normal COM range and hence recover balance (You, Chou, Lin, and Su, 2000). The present study examined the range of movement of the body COM *without upper limbs*, in order to compare this with the position data for whole body COM with both limbs intact, and gain further insight into the effect of upper limbs (arms) on consequent body COM stability.

In the present study, there was a significant contribution of arms in shifting the whole body COM in the upward direction but not in the forward direction. These results suggested that the lower limbs and the torso prevailed in bringing the whole body forward as a corrective reaction to the slip to the arms. Whereas, the results from the present study suggested that the arms contributed to an enhancement of the capability to recover from the slip by bringing the whole body COM upward to the normal balance range.

The present study also examined the trend of left or right arm accelerations during dry surface trials in order to compare them with those during a slip event. The left and right arm acceleration in the upward direction was parallel within participants, indicating that they used similar strategies to bring their body COM to normal stable range by raising their arms upward to bring their body COM. However, the patterns were not similar in the forward direction, which could be attributed to individual differences. The right arm acceleration was significantly increased during the recovery as compared to left arm. The lower right limb was perturbed and hence this could induce a greater corrective response by the upper right limb, even if the left upper limb acceleration was increased at the same time.

The base of support was another important aspect in the series of corrective reactions taken by the body in response to a slip induced perturbation. It was evident from the results that individuals increased their mediolateral base of support during the recovery period. But anteroposterior base of support was quite variable, which may be contributed to various recovery mechanisms. These findings were consistent with Wu (1996) and Tang et al. (1998b). Maki et al. (1997) reported that "change-in-support" reactions were not just strategies of last resort, but were often initiated well before the center of mass was near the stability limits of the base of support. The increase in the base of support along with the arm upward acceleration were believed to be the driving mechanism towards restoration of the normal body COM position and hence prevented participants from falling. Furthermore, it was observed that for the trials in which participants fell, they couldn’t bring their whole body COM back to the normal range.

The various strategies utilized by the participants in the slip- recovery process and slip-fall process were categorized based on their kinematic responses. The motions of three unperturbed limbs were used to describe human reactive motion during slips and falls. All the data trials would fit into the combinations of these motion sets. For the unperturbed leg, there were two types of responses: catch-up and widen-support. Catch-up was used to describe the leg motion after slip initiation, where the unperturbed foot quickly moved forward and contacted the floor surface very close to the location of the perturbed foot. Widen-support was used to describe the leg motion after slip initiation. Widen-support was when the unperturbed foot quickly landed on the floor surface far away from the location of the perturbed foot. The base of support increased by the widen-support of unperturbed leg, which improved chance of successful balance recovery.

In terms of the arms on both unperturbed side and perturbed side, there were also two types of motions, raise-up and no-raise-up, during slip process. Raise-up was used to describe the motion that after slip initiation, the entire arm was raised upward and laterally. No-raise-up was used to describe the motion that after slip initiation, the range of arm motion was within the range of normal swing.

The study concluded that the arms movement and increased base of support had a significant effect in regaining the normal body COM leading to a recover from a slip. The future studies should incorporate a larger sample size and further investigate kinetic and EMG parameters associated with the slip event in order to further delineate the reason behind the motion that we have seen in this study.

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