Kinematics of the Compensatory Step by the Trailing Leg Following an Unexpected Forward Slip while Walking

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Abstract In this study, we described the joint angle changes of the trailing leg during the compensatory step used to recover balance following a forward slip while walking. Fifteen healthy young males walked on a walkway which incorporated a movable platform to simulate a forward slip while walking. In 12 out of the 15 subjects, the trailing leg was rapidly lowered during the swing phase and was placed on the ground behind the slipping foot following the onset of the slip. Time taken for the onset of the slip to the placing of the trailing foot was 0.28±0.03 s. The amount of hip flexion lessened after 52% of the normalized time, with 0% being the onset of the platform movement and 100% representing the placing of the trailing foot on the ground. The flexed knee began to extend at 72% of the normalized time, which continued until the foot was firmly placed. The plantarflexed ankle began to dorsiflex at 56% of the normalized time, the angle of which peaked at the moment the toe made contact with the walkway again—the end of the movement. These findings aided us in understanding the mechanism underlying the compensatory step to recover the loss of balance caused by a forward slip while walking. J Physiol Anthropol 27(6): 309–315, 2008 http://www.jstage.jst.go.jp/browse/jpa2 [DOI: 10.2114/jpa2.27.309]

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Introduction

Slipping is one of the most common causes of falls and fall-related injuries (Berg et al., 1997; Björnstad et al., 1997; Campbell et al., 1990; Luukinen et al., 2000). Especially among elderly people, fall-related injuries pose serious problems such as higher morbidity, mortality, and healthcare costs. As lifespans continue to lengthen, preventing falls is becoming more of an important issue. Therefore, developing interventions for preventing slip-related falls is required in our society.

Most slips that lead to falls occur after heel-strike while walking. There are two biomechanical aspects of the causes of the slips and falls. First, shear force reaches a peak at this period in normal walking. As slips arise when friction force at the foot/floor interface is less than the shear force of the movement of the foot, the slips are most likely to occur at this moment (Redfern et al., 2001). Second, the body weight is being transferred to the front foot at this moment. Additionally, the center of mass (COM) of the whole body is behind the front foot; i.e., it creates potential instability because the COM is outside the base of support (BOS) (Gao and Abeyesekera, 2004). Under such conditions, shifting the front foot more anteriorly relative to the COM due to slipping might result in a backward fall of the body.

Once the slip occurs, corrective responses are essential to avoid a backward fall of the body. One explanation for why elderly people frequently fall could be their difficulty with generating effective corrective responses once they have lost balance caused by the slip (Tang and Woollacott, 1998). Some researchers (Bhatt et al., 2005; Redfern et al., 2001) indicate that improving the ability of generating corrective responses may be one effective intervention for avoiding such falls.

Knowledge of the mechanisms underlying corrective responses is important for the purpose of developing effective interventions to improve the ability to generate corrective responses. Previous studies (Bhatt et al., 2005; Cham and Redfern, 2001; Ferber et al., 2002; Marigold et al., 2003; Marigold and Palta, 2002; Tang and Woollacott, 1998, 1999; Tang et al., 1998) have reported that several parts of the body, such as legs (leading and trailing), upper body, and arms, contribute to recovering balance following a forward slip while walking. Of all the corrective responses, recent studies (Bhatt et al., 2005; Marigold et al., 2003; Marigold and Palta, 2002) have focused on the importance of the corrective responses of the trailing leg following a slip while walking. The main reason is that the trailing leg can quickly react to ensure dynamic stability because of its freedom, i.e., the trailing leg has almost unloaded the body weight and is preparing for the
swing phase when the slip occurs. Marigold et al. (2003) investigated the corrective responses of the trailing leg from this viewpoint and found that a majority of the subjects used a compensatory step, in which their trailing leg was rapidly lowered during the swing phase and the trailing foot was briefly placed on the ground behind the foot that slipped. They suggested that the compensatory step widens the BOS and increases stability. Bhatt et al. (2005) also examined the relationship between the COM of the whole body and the BOS when the trailing foot is placed on the ground following a slip while walking. The results demonstrated that the body’s COM was located within the BOS once again by placing the trailing foot on the ground following the slip. They concluded that the compensatory step is used to relocate the perturbed COM within the re-established BOS, and that the corrective response plays a major role in preventing the body from suffering a backward fall.

Although the results of previous studies have indicated the role of the trailing leg concerning the compensatory step in recovering loss of balance due to a slip, the movement of the joints of the trailing leg throughout the compensatory step remains unclear. Marigold et al. (2003) found that the different muscle activities of the trailing leg appeared in slip-induced walking compared with those in normal walking. Although this result suggests that joint movements for achieving the compensatory step are evoked while walking following occurrence of a slip, no studies have focused on the joint movements of the trailing leg. Since health professions often assess the quality of human performance using a biomechanical model to determine appropriate therapeutic interventions in clinical settings, expanding knowledge concerning the kinematics of the compensatory step would be helpful in assessing dynamic stability in the event of a slip.

The purpose of this study was to clarify the movements of the joints of the trailing leg during the compensatory step used to recover balance following a forward slip while walking.

Methods

Subjects

Fifteen healthy males participated in this study. Their mean (SD) age, height, and weight were 24.33 (2.82) years, 1.71 (0.05) m, and 60.27 (5.90) kg, respectively. All subjects were right-leg dominant, as determined by their preferred kicking leg. The subjects had no history of musculoskeletal or neurological problems. All subjects gave informed consent prior to their participation in the study.

Slip apparatus

A movable platform (length, 1.0 m; width, 0.6 m; height, 0.1 m) was used to simulate a slip while walking. The movement of the platform was generated by a hydraulic servomotor. The platform was incorporated into the center of a 7-m wooden walkway on the right side. For this study, the platform translated 0.15 m anteriorly for 0.40 s at a maximum speed of 0.75 m/s (the maximum speed was attained 0.20 s after the onset of platform movement) to simulate a forward slip while walking. The platform movement was triggered by a signal from an electric switch mat (length, 0.43 m; width, 0.59 m; Tapeswitch Japan Corporation, Tokyo, Japan) mounted on the platform. The trigger signal was generated when the vertical force load on the mat exceeded 26.4 N threshold, because of which the platform movement occurred during the early stance phase of the gait cycle. To prevent a fall during the experiment, each subject wore a safety harness that was attached to the overhead suspension frames via two ropes. The safety system

![Schematic diagram of the experimental set-up.](image-url)
allowed the subject to walk on the walkway with minimal restrictions. The experimental set-up used in this study is illustrated in Fig. 1.

Protocol
During the experiment, all subjects were the same designed shoes and walked at their own comfortable pace on the walkway while looking straight ahead. For each trial, they were asked to step on the mat with their right foot on their fourth step from the starting point. Each subject was also instructed to walk as naturally as possible and not to stop while walking. Prior to data collection, the subjects underwent several practice trials to adjust their starting positions. However, during these trials, the platform did not move although the subjects stepped on the mat.

A total of 63 trials were conducted for each subject. The first 60 trials were divided into three sessions. Each session consisted of 20 trials because such trials were required to get steady gait state from our pilot study. In each session, the first 10 walks were dummy trials (i.e., the slip was not generated even if the subjects stepped on the mat); the 10 trials that followed included random 9 dummy and 1 slip-induced trials. The subjects were blinded to the slip-induced trial. Prior to data collection, we did not provide the subjects with any information concerning the apparatus on the walkway. They were therefore unaware that while walking on the walkway during the first slip trial an unexpected slip would occur. A 10-min rest period was provided to each subject after every session. After 3 sessions, 3 control trials were conducted to collect normal walking data, which were used as reference. During the control trials, the subjects were informed that the platform would not move despite foot placement on the mat.

Data collection
Kinematic data were collected from a three-dimensional motion analysis system (Vicon Motion System, Oxford Metrics Ltd., UK). Six infrared cameras were set up around the walkway. The plug-in-gait marker set was used for measuring full body kinematics. In addition, two markers were placed on the platform to record the platform movement. The position data for the markers were synchronized with the signal data of the mat and sampled at a rate of 120 Hz.

Data analysis
Based on previous studies (Bhatt et al., 2005; Marigold et al., 2003), we defined the compensatory step as a step in which the trailing leg was briefly lowered while in the swing phase and the toe was placed on the ground posterior to the slipping foot. The relationship of the positions in the horizontal direction between the slipping toe and the trailing toe was measured to determine whether the compensatory step was performed. It was calculated by subtracting the horizontal position of the slipping toe marker from that of the trailing toe marker. A negative value indicated that subjects had performed the compensatory step to recover balance.

Although three slip trials were conducted for each subject, data only for the first slip trial was used in the current study because of the possibility that repeated exposure to the slip induced changes in postural strategies. Kinematic data were extracted for time intervals between the onset of the platform movement and placing the trailing foot on the ground. A 15-linked-segment model of the whole body was used for the analysis. Ankle, knee, and hip angles of the trailing leg in the sagittal plane were determined throughout the movement. The ankle, knee, and hip joint angles were defined as the angle between the foot and shank segments, the angle between the shank and thigh segments, and the angle between the pelvic and thigh segments, respectively. The time taken for the compensatory step was used as the normalized time, with 0% being the onset of the platform movement and 100% representing the placing of the trailing foot on the ground. Mean joint angle patterns during the compensatory step for all subjects were represented by averaging the joint angle data in the normalized time. Furthermore, normal walking data for the trailing leg were referenced to clarify the deviation in the joint movements associated with the compensatory step. Normal walking data were derived from the average values of the control trials for all subjects. To compare both data, the averaged joint angle data were re-sampled at a rate of 120 Hz, and were plotted in real time with a custom-written program using LabVIEW software (National Instruments Co., Japan).

First, the joint angle patterns of the ankle, knee, and hip during the compensatory step were analyzed in this study. We then identified the timings and joint angles of the events during the compensatory step. The timings of the events during the compensatory step were compared with those during normal walking.

Statistical analysis
The mean and standard deviations for all variables were calculated. A paired t-test was used to compare the timings of the events between two conditions. The statistical significance level was set at $p < 0.05$. All statistical procedures were performed using SPSS 11.0 (SPSS Japan Inc., Japan).

Results
In the first slip trial, all subjects were able to regain their balance. Two movement patterns of the trailing leg were observed in the slip trial. In 12 out of the 15 subjects, the trailing leg was rapidly lowered during the swing phase and was placed on the ground behind the slipping foot in the first slip trial (Fig. 2B). The horizontal position of the trailing toe relative to the position of the slipping toe at placing was $-0.38 \pm 0.17 \text{ m}$. The remaining 3 subjects advanced the trailing leg in front of the slipping foot without taking the compensatory step following the slip, i.e., the horizontal position of the trailing toe relative to the position of the slipping toe at placing was $0.38 \pm 0.18 \text{ m}$ (Fig. 2C). Hence, the data for the 12 subjects were used in further analysis.
subjects showed that the angle of the hip peaked (10.7±9.2° extension position) at the end of the movement and then remained almost steady.

**Knee joint kinematics**

The knee initially flexed following the onset of the slip and reached the maximum angle (53.2±8.7° flexion position) at 71.5±8.1% of the normalized time. The knee flexion increased rapidly as compared to normal walking. Next, the knee began to extend and it continued until placing of the trailing foot. The initiation of the knee extension occurred earlier than that during normal walking (0.20±0.03 s in the first slip trial and 0.30±0.03 s in the control trial, p<0.001). The excursion of the extension movement was approximately 7.8±7.1°.

**Ankle joint kinematics**

Following the onset of the slip, the ankle initially plantarflexed. The increase in plantarflexion tended to be steeper when compared to normal walking. The plantarflexed ankle changed its direction toward dorsiflexion at 56.1±6.0% of the normalized time. The timing occurred earlier than that during normal walking (0.15±0.02 s in the first slip trial and 0.20±0.03 s in the control trial, p<0.01). Then, the ankle rapidly increased dorsiflexion and reached the maximum angle (5.6±13.6° dorsiflexion position) at the end of the movement.

**Discussion**

This study investigated joint angle changes of the trailing leg during the compensatory step used to recover balance following a forward slip while walking. Similar to previous studies (Bhatt et al., 2005; Marigold et al., 2003), we have confirmed that the majority of the subjects showed the compensatory step following the onset of the slip. The kinematic outcomes indicated that joint angle changes deviated from the normal trajectories on the hip, knee, and ankle of the trailing leg following the onset of the slip, especially after the toe-off event.

**Methodology**

In this study, the corrective response of the trailing leg for recovering loss of balance due to a slip while walking was drawn from a platform translation procedure, which simulates a slip by moving the support floor surface. Pai and Iqbal (1999) investigated whether forced sliding from a movable platform and natural slipping produce the same perturbing effects on stability. The results demonstrated that these two types of perturbation have similar effects on stability. Therefore, they suggested that forced sliding from a movable platform can be used to investigate the effects of slipping on stability in experimental or clinical settings. However, they also indicate the possibility of a distinctive perturbing effect in forced sliding in which the braking force is generated by an external source during deceleration. Since the braking force acts in the counter direction, it may help to recover the loss of balance.
evoked during the acceleration of forced sliding. In the current study, there was a deceleration period after 0.20 s although the platform translated for 0.40 s. Consequently, the platform translation procedure could simulate the perturbing effect on stability as compared to a natural slip, but there is the possibility that the distinctive effect resulting in movement strategies may be different from a natural slip to recover balance.

**Comparisons with previous studies**

Marigold et al. (2003) stated that 80% of the subjects showed the compensatory step to recover the loss of balance caused by a slip while walking. Likewise, Bhatt et al. (2005) examined the influence of gait speed on the compensatory step and noticed that all the subjects recovered by taking the compensatory step except those walking at slow speed. In this study, we judged the compensatory step by assessing whether the trailing toe was placed on the ground behind the slipping foot following the onset of the slip based on previous studies. Consistent with previous studies, the present result demonstrated that the majority of the subjects recovered their balance by taking the compensatory step following the onset of the forward slip.

**Joint movements during the compensatory step**

The time taken for the compensatory step from the onset of a slip was 0.28 s. Of this time, the toe-off event of the trailing leg occurred at 0.14 s, approximately 50% of the normalized time. Runge et al. (1998) indicated that only passive joint movements occur during the first 0.15 s following applied perturbation. Likewise, Cham and Redfern (2001) reported that the corrective joint movements to recover balance from a slip are initiated at approximately 0.19 s after heel-strike on the leading leg. The EMG study (Marigold et al., 2003) also showed that the muscles of the trailing leg are activated at 0.14 s following the onset of the slip. Based on their results, the angle changes observed after the toe-off event can be regarded as corrective joint movements generated to recover loss of balance due to a slip during the compensatory step.

The hip joint kinematics showed that the flexion pattern was similar to that found during the swing phase in normal walking. However, the flexion movement observed during the compensatory step reduced gradually after approximately 50% of the normalized time and deviated from its normal trajectory. The function of the hip flexion movement is interpreted as the limb advancement for preparing the next stance during normal walking (Perry, 1992). The result suggests that limb

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**Fig. 3** Joint angles for the hip, knee, and ankle during the compensatory step in the first slip trial. Time represents normalized time, with 0% being the onset of the platform movement and 100% being the placing of the trailing leg on the ground. Positive values indicate flexion and dorsiflexion, and negative values indicate extension and plantarflexion. The solid line represents the ensemble average, and the dash line represents one standard deviation of the 12 subjects.
Kinematics of Compensatory Step

In normal walking, the knee is rapidly flexed, beginning at the end of terminal-stance to a maximum at the mid-swing phase. Perry (1992) indicated that this knee flexion allows limb advancement without dragging the foot. In the present study, the initial knee flexion was observed at the end of terminal-stance during the compensatory step. However, the knee began to extend before the trailing foot passed the leading leg at about 70% of the normalized time and the timing occurred earlier than that during normal walking. The knee extension then increased until placing. Thus, the results suggest that the trailing leg lowers the foot for placing on the ground by extending the knee joint as quickly as possible.

The rapid ankle dorsiflexion was observed immediately after the toe-off event. The ankle reached the maximum dorsiflexion angles at the end of the movement and remained steady until placing. During normal walking, the ankle begins to dorsiflex in the initial-swing phase. It is explained that this function secures floor clearance for leg advancement in the subsequent mid-swing phase (Perry, 1992). However, as mentioned above, leg advancement would not be needed on the compensatory step because the strategy is used to widen the BOS by placing the trailing foot on the ground behind the leading leg. It rather seems that the result relates to the weight transfer in the trailing leg after placing it on the ground. At the toe-off event, the ankle angle was approximately 10° plantarflexion. If the trailing foot is in the position at placing, it presumably is difficult to touch the sole to the ground behind the leading leg.

As a result, the body could neither transfer the weight to the trailing leg nor control balance. For this reason, rapid ankle dorsiflexion might occur to facilitate subsequent weight transfer immediately after the toe-off event during the compensatory step.

We focused on the compensatory step of the trailing leg used to recover balance following a forward slip while walking in this study. Consequently, 3 out of the 15 subjects who regained their balance without taking the compensatory step were excluded. One possible explanation for this finding is that these subjects were less disturbed compared to the others during the slip. Therefore, they might have been able to recover their balance without the compensatory step following the slip. Another explanation could relate to the differences in the postural control of other parts of the body following the slip. Because multi-limb postural controls involving the leading leg, the upper body, and both arms have been previously observed following the slip, the strategy of the trailing leg might be coordinated with those of the other limbs. Future studies on multi-limb coordination for recovering loss of balance might be required to understand the mechanism underlying the compensatory step of the trailing leg following a forward slip while walking.

Our study provided normative data describing the kinematics of a compensatory step used to recover loss of balance caused by the forward slip during the early-stance phase while walking, taken from a sample group of healthy young adults. This kinematic data can be used as a basis for
establishing a biomechanical model to assess the quality of the compensatory step. We believe that such a model would aid in identifying difficulties in generating a compensatory step in the elderly who frequently fall, as well as determining appropriate interventions to improve their difficulties in clinical settings.

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References


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