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Exploring the Biomechanics of Double Slips

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Abstract
Background: Biomechanics of slips and falls have been explored by several researchers over the past decade. However, none of the researchers have explored the concept of double slips that occur as a result of a slippery perturbation.

Purpose: The question explored in the study was: what happens if individuals slip multiple times? The purpose of the study was to better understand double slips and also to establish relevant variables in understanding the biomechanics of double slips as they relate to fallers and non-fallers

Methods: Twenty-eight individuals (14 young and 14 elderly) with equal numbers of males and females participated in the study. Out of the 84 gait slip trials in the study, only 25 trials were used for analysis in this paper as only 25 trials resulted in double slips. Individuals were required to walk along a circular track and they were exposed to an 'unknown' slippery floor condition. The gait trials were monitored using an 8-camera motion capture system.

Two new variables were introduced while exploring recovery effort as it relates to double slips in individuals, namely slip distance ratio and step length ratio. Slip distance ratio was defined as the ratio of the distance slipped during the first slip to the distance slipped during the second slip. Similarly, the step length ratio was defined as the ratio of the step length just prior to the first slip to the step length just prior to the second slip.

Results: The results indicated that individuals with smaller slip distance ratio and higher step length ratio were able to recover better when compared to individuals with higher slip distance ratio and lower step length ratio. This suggests that individuals who slipped a greater distance during the second slip when compared to the first slip were more likely to fall. Also, individuals who took a shorter step after the first slip were more likely to fall.

Conclusion: Findings from this study provide new insight into double slips. Simple variables such as slip distance ratio and step length ratio could be used to predict falls and recovery from double slips. In terms of recovery effort, individuals could benefit from attempting to slip less the second time if they do encounter a double slip and more importantly take a larger step and place the foot safely and gently to reduce the likelihood of a fall resulting from a double slip.

Keywords: Double slips, slip distance ratio, step length ratio

1. Introduction

A significant body of research has explored biomechanics of slips and falls in the elderly (Chambers & Cham, 2007; Moyer, 2006; Lockhart, Smith & Woldstad, 2003; Cham & Redfern, 2002; You et al., 2001) but none of the studies have attempted to study the effects of double slips on recovery. In other words, when individuals slip multiple times, does it increase their likelihood of falling. Also, what are there any variables that can be used to distinguish fallers from non-fallers as a result of the double slip?

In the current study 25 of 84 slip trials resulted in double slips. Individuals slipped with one foot and in an attempt to recover, then slipped again using the other or same foot. So, this idea of exploring double slips seemed important. A study by Yang, Espy, Bhatt & Pai (2012) did look at double or bilateral slips, but the slips were forced in that rollers were unlocked once the leading leg started slipping to introduce a second slip in the trailing leg.

Regardless, the authors pointed out that when one takes a longer step during recovery of stability after slip onset, the recovery limb is more likely to experience a slip as well, resulting in a bilateral slip. That may not be true in the real world slip scenario as it is possible that individuals can use their trailing leg to take a large enough step to avoid a second slip. Yang et al. (2012) also pointed out that, a shorter recovery step would more likely lead to the trailing foot landing behind (posterior to) the slippery surface area. That would be true if rollers were used to unlock slips. Once again, in a real world slip scenario it is possible that the trailing leg lands on a contaminated floor area where the leading leg made contact by taking a small step. Thus step length could be an important factor in deciding if a slip ends up being a double slip or not. An additional factor could be the amount slipped after initial contact. For instance, if an individual slipped a large distance after initial contact is it less likely that the individual would have a double slip.

With these two variables in mind, namely, step length and slip distance the concept of double slips was explored in this paper. The purpose of this paper was to explore double slips. The specific questions asked were: (1) How does double slip effect fall and recovery, (2) Are there relevant variables to better understand double slips. It was hypothesized that double slips would result in higher rate of fall incidences reported in slip and fall studies. It was also hypothesized that new variables related to step length and slip distance could be introduced to better understand double slips.

2. Methods

2.1 Experiment location and approval.

The research study was conducted at the Ergonomics Laboratory in the Industrial Engineering Department at Texas Tech University (TTU). All procedures for this study were conducted upon approval from the Texas Tech University Institutional Review Board for the protection of human subjects.

2.2 Subjects.

Twenty-eight individuals were recruited for the study. Specifically, 14 young (7 male and 7 female) and 14 elderly (7 male and 7 female) individuals were selected from the university and elderly community in Lubbock, Texas to participate in the study. The age, height and weight statistics of the younger and elderly individuals are presented in *Table 1* below. All the individuals were in good health and passed the screening procedures required for participation. Individuals were screened for heart problems, blood pressure, shortness of breath, dizziness, fatigue, discomfort in hip, knee and/or ankle joints, difficulty in walking, difficulty with cognition and history of prior falls. Further, individuals were required to do a practice gait trial while wearing a whole body fall protection harness. If individuals indicated difficulty in walking, they were not included in the study. It is important to note that no monetary benefits were provided to the subjects for their participation in the study. Only trials from individuals resulting in double slips were used for the analysis in this paper.

Table 1: Age, Height and Weight statistics for individuals in the study

	Age (yrs)		Height (m)		Weight (kg)	
	Avg.	SD	Avg.	SD	Avg.	SD
Young	25.29	3.17	1.70	0.08	65.31	17.61
Elderly	72.86	4.49	1.68	0.11	75.51	18.02

Avg. - Average, SD - Standard Deviation

2.3 Experimental set-up and protocol.

Gait trials were performed on a circular track equipped with a fall arrest rig system. Subjects walked at their preferred walking pace. Motion data were captured using an 8-camera motion capture system from Motion Analysis Corporation (Santa Rosa, California, USA). The sampling rate used for the motion capture of the 3-D (dimensional) position data using reflective markers was 120 Hz. During the post-process the data were smoothed using a Butterworth filter (cutoff frequency of 6 Hz). Nineteen (19) reflective markers were placed on each individual at various palpable locations. However, for this paper, only the heel marker that was placed on the shoe was used for the analysis.

Individuals were required to walk several trials for 'dry', 'known' and 'unknown' slippery conditions for the study under different arm restriction conditions. From these the three 'unknown' slippery trials where individuals were not aware of the slippery surface and slipped were considered. Out of the 84 'unknown' slippery trials (28 subjects *3 trials/subject) only the 25 trials that resulted in double slips were analyzed.

2.4 Calculation of slip distance ratio and step length ratio.

For all the 25 double slip trials, the ratio of the second slip distance to the first slip distance was then calculated to come up with the slip distance ratio. Similarly, the step length of individuals after the first slip (and before the second slip) was divided by the step length prior to the first slip to come up with step length ratio.

2.5 Classification of the outcome of the unknown slippery trials.

The outcomes of the 25 double slip trials were classified as 'recovery' or 'fall'. A trial was classified was a 'fall' if the resulting vertical load exceeded 100N as detected by the fall-arrest-rig (FAR) system which would cause the machine to shut down and support the individual fully using the full-body-harness system attached to the FAR. If the machine did not shut down when individuals attempted to recover, implying that they did not exert a vertical force greater than 100N on the FAR the trial was classified as 'recovery'. In terms of individuals who fell, they were classified as 'fallers', where as individuals who recovered were classified as 'non-fallers'.

2.6 Statistical Analysis.

Independent t-tests were carried out to test differences between faller and non-fallers. A significance level of 0.05 was used.

3. Results

Out of the 25 double slip trials, only six (6) resulted in a fall and 19 trials resulted in a recovery. It was observed that the slip distance ratio was much smaller for the 'recovery' trials when compared to the 'fall' trials. The mean slip

distance ratio for the 'fall' and 'recovery' trial is shown in *Figure 1* below. When a t-test was carried out for slip distance ratio, it was found that there was a significant difference between the fallers and the non-fallers. The t-test (one-tail with equal variance) results along with the mean and standard deviation (stdev) for the fall and recovery trials for slip distance ratio are presented in *Table 1* below.
Next, the mean step length ratios for the fall and recovery trials are presented in *Figure 2* below. In contrast to the slip distance ratio, it was found that the step length ratio was much smaller for the 'recovery' trials when compared to the 'fall' trials. The t-test (one-tail with equal variance) results along with the mean and standard deviation (stdev) for the fall and recovery trials for step length ratio are presented in *Table 2* below. The results for step length ratio do show statistically significant differences between fallers and non-fallers.

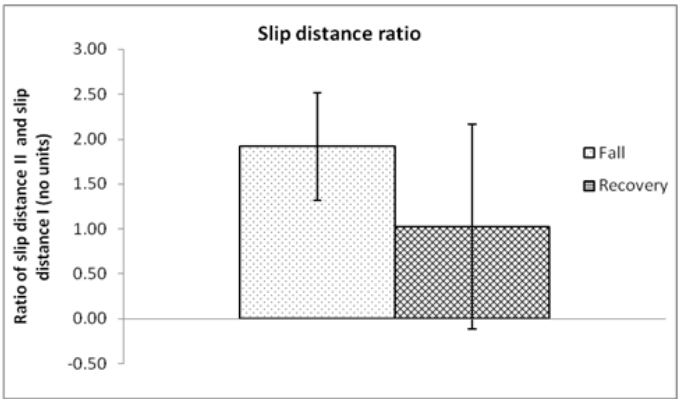

Fig. 1: Slip distance ratio for 'fallers' and 'non-fallers'

Table 1: t-test result along with mean and standard deviation (stdev) values for slip distance ratio for the fall (n = 6) and recovery (n = 19) trials

	Fallers	Non-fallers
Mean	1.92	1.02
Stdev	0.60	1.14
p-value	0.01	

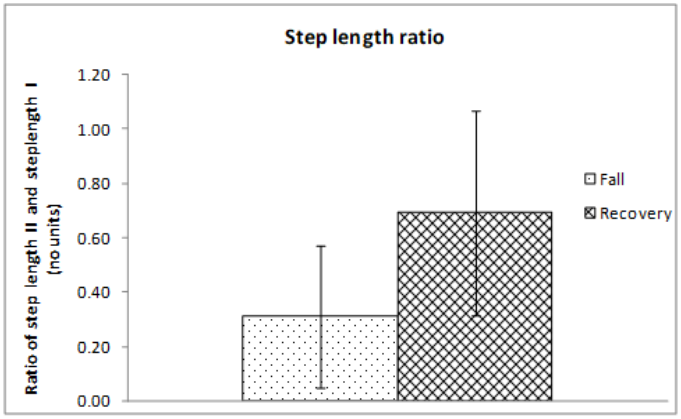

Fig. 2: Step length ratio for 'fallers' and 'non-fallers'

Table 2: t-test result along with mean and standard deviation (stdev) values for step length ratio for the fall (n = 6) and recovery (n = 19) trials

	Fall	Recovery
Mean	0.31	0.69
Stdev	0.26	0.38
p-value	0.008	

4. Discussion

The findings from the study suggest that if individuals slipped multiple times and they slipped a larger distance for their second slip when compared to their first slip they were more likely to fall. This finding has yet to be reported in 'the biomechanics of slips and falls' literature. In terms of step length ratio, it could be inferred from the results that when individuals slipped multiple times, individuals who took a larger step prior to their second were less likely to fall when compared to individual who took smaller steps. This could be because the individuals who took smaller steps had a larger area of contaminated floor surface yet to clear. Another possibility is that individuals who took a larger step propelled their upper body center of mass (UBCOM) forward through a quick reactive protective step forward. This variable does need further exploration but it seems like an interesting start to a new approach to better understanding double slips and recovery mechanisms as they relate to double slips.
One thing the study did point out is that, it is not necessary that fall incidence is higher under double slip scenario. Only six (6) out of the 25 trials, resulted in falls. Thus there is a possible strategy used by individuals to reduce their likelihood of fall even under the double slip scenario.
One of the limitations of the study was the area of the contamination. In this study, the area was limited to the width and length (0.60m x 0.40m) of the force plate. It might be interesting to note if the findings from this study hold good for larger areas of contamination. Another limitation in the study was that age was not taken into account since there were only six trials that resulted in falls under the double slip scenario. In future studies it might be interesting to see if there are differences between young and older fallers and non-fallers.

5. Conclusion

When analyzing slip distance ratio (slip distance of the second slip to the slip distance of the first slip) between fallers and non-fallers it was found that there was a significant difference between fallers and non-fallers with the fallers resulting in higher slip distance ratio values. This approach is novel and has not been reported in previous literature. In addition to the slip distance ratio, it was also found that the step length ratio was significantly different between fallers and non-fallers. In this case, the fallers took a smaller significantly step and thus ended up putting themselves at higher risk of falling by having a greater distance of slippery surface to navigate especially with both feet over the slippery surface for a longer time. Once again, this has not been reported in the past and needs further exploration in the future.

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