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Lower extremity kinematics during forward heel-slip

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Abstract.
BACKGROUND: Most fall intervention studies attempted to improve the mobility, range of motion of upper and lower extremities, or all major muscle strengths. Yet, there has been little effort to identify movements or actions that may be mainly responsible for recovering from a slipping. It was imperative to link lower extremity kinematics in conjunction with the functional anatomy of lower extremity muscles during forward heel-slipping to identify what muscles should have been activated substantially if a person would have recovered from forward heel-slipping.
OBJECTIVE: The present study investigated lower extremity movements, such as the ankle, knee, and hip rotations, which could contribute to falls from forward heel-slipping. Determining changes in positions of foot, shank, and thigh during slipping would provide information to develop the optimal training regimen or interventions that may be effective for improving a chance to recover from the postural disturbance.
METHODS: Twenty healthy adults (24–68 years old) participated in this experiment. Among twenty participants, only eight participants' data were analyzed in this study. The 3D position data were used to compute the sagittal foot, shank, and thigh angles and frontal thigh angle.
RESULTS: The study results indicated that, during the period of slipping, the angles of the segments of the slipping leg were different from that of the foot, shank, and thigh when walking ordinarily over the dry surface in the present study.
CONCLUSIONS: The characteristics or differences in the angular kinematics of lower extremity during unexpected slips in the present study demonstrate possible causes for slip-induced falls.

Keywords: Forward heel slip, leg kinematics, segment angles, fall

1. Introduction

Slips and falls are a main cause of accidents in the home and workplace accounting for 30% of all injuries [1,2]. According to the Liberty Mutual Workplace Safety Index, falls on the same level were the major sources of slip and fall accidents leading to time-loss injuries and ranked second with direct cost of $11.23 billons accounting for 19.2 percent of the total injury burden [2]. Often, slip or fall accidents result in the bruise, hip or wrist fracture, or head injuries causing permanent physical damages or deaths [3,4]. Despite constant attempts to decrease falls/fall-related injuries, falls and fall-related injuries constantly stay in the leading cause of injury death for the elderly [4–6]. People start exhibiting a

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tendency of falling with advancing age because an aging body is constantly to lose its ability to integrate neuro-musculo-skeletal systems resulting in an imbalance. Lower body reactions or reactive movements have received much attention since lower extremity was suggested to play a dominant active role in terms of corrective response [5–8]. Although kinematics analyzes movement patterns without the forces that cause the movement, the acquisition of limb kinematics during walking and slipping should provide significant information about limb control and insight into muscle performance.

Most falls related to walking are initially provoked by environmental factors such as the uneven surface, slippery surface, height, slopes, vibration, etc. However, whether a person falls or not depends upon one's physical ability to recover from the initial environmental factors that trigger instability [9–12]. For a person to regain their stability when one loses balance, the person must be able first to detect postural disturbances through the central nervous system or peripheral nervous system [13]. Then, one must be able to produce smooth and coordinated movements across the body joints to overcome the instability and regain balance [5,9–11]. Thus, an intact neuro-musculo-skeletal system is a key factor in producing such movements.

Poor mobility and health status have been suggested as the leading cause for the decrease in physical abilities such as strength attenuation contributing to fall-related accidents among older adults [14] due to impaired postural control [9,13,15,16] or deterioration in motor control [13,17].

Furthermore, many studies [5,9,13,15,16,18,19] proposed that strength training and balance training among older adults developed an improved mobility and health status. Most studies attempted to improve the range of motion of upper and lower extremities and to strengthen all major muscle. Yet, there has been little effort to identify movements or actions that may be mainly responsible for recovering from a slipping.

In the present paper, authors were challenged to investigate lower extremity movements, such as the ankle, knee, and hip rotations, which could contribute to falls from a forward heel-slipping. The study endeavored to link lower extremity kinematics in conjunction with the functional anatomy of lower extremity muscles during forward heel-slipping to identify what muscles should have been activated substantially if a person would have recovered from forward heel-slipping. Determining changes in positions of foot, shank, and thigh during slipping would provide information to develop the optimal training regimen or interventions that may be effective for improving a chance to recover from the postural disturbance. This study further tried to establish proper strategies for trainers as to what muscles should be strengthened to recover from forward hill-slipping.

2. Method

2.1. Subjects

Sample size calculation [20] was performed and a sample of 8 were sufficient to satisfy Type I error of 0.05 and Type II error of < 0.2 (Power > 0.8). Eight participants (19–27 years old) participated in this study. In order for experimenters to compare lower extremity kinematics while walking on dry surface and on a contaminated surface, participants who slipped forward more than five cm during slip trials were drawn for data comparison. The young adults or older adults were respectively recruited from the local university or the local community. Each participant completed an inform consent procedure approved by the University's Institutional Review Board (IRB). Participants were excluded from the study if they indicated any physical problems (i.e. hip, knee, ankle problems).

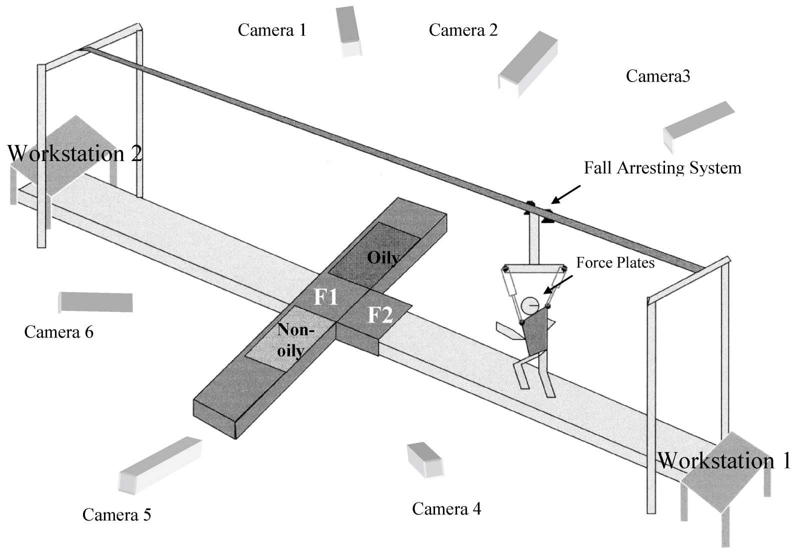

Fig. 1. Field layout of the experiment including Fall Arresting System, Infra-red cameras (6), Linear Slide Floor Changer (LSFC) with force plate (F2) and hidden oily and non-oily test floor surfaces, fixed force plate (F1), and workstations.

2.2. Apparatus

A vinyl tile (Armstrong) was installed on the top of a walking track (Fig. 1). To create a realistic slippery environment, the vinyl tile surface was sprayed with a soap and water mixture (2:3) resulting in the dynamic coefficient of friction (COF) of 0.07. The available dynamic COF (ADCOF) of the vinyl surface was measured by a standard 4.54 kg (10 lb.) horizontal pull slip-meter with a rubber sole material on the floor. An overhead fall arresting harness system was used to prevent fall injuries during walking (Fig. 1). In order to provide unexpected slippery condition, each subject's eyes were always fixed on a TV located 1.5 m high. A fall-arresting harness was designed to permit a subject's body to drop approximately 15 cm. A six-camera system (Qualysis) collected three-dimensional position data at 120 Hz.

2.3. Procedure

A set of 26 markers were placed on the anatomically significant landmarks to present a whole body. Among them, twelve markers such as right and left heels (2), medial malleolus (2), lateral malleolus (2), medial epicondyle (2), lateral epicondyle (2), and ASIS (2) were used for data analysis of the current study. Within a 20-min session, experimenters introduced a slippery surface while the participant's postural data were recorded (Fig. 1). One slip trial was performed for each subject since the subjects would alter their walking characteristics once they were exposed to a slippery surface. That effect did not allow the study to collect multiple slip trials for each subject. To conceal any sound of the floor changing, a Walkman was provided and played old comedy routines.

2.4. Data analysis and statistics

The 3D kinematics data from the cameras were collected for calculating the sagittal foot, shank, and thigh angles and frontal thigh angle. The data were recorded for five seconds at 120 Hz and low-pass filtered (4^{th} order, Butterworth, cutoff =12 Hz).

Descriptive and inferential statistical analyses were performed (JMP package, SAS Institute Inc. Cary, NC, USA). One-way ANOVA was used to test the group differences. The results were considered as statistically significant when $p \leqslant 0.05$.

2.5. Dependent variables

The definitions of lower extremity segmental orientations in this study were similar to ISB recommendations [21]. Specifically, the segmental coordinate systems were first constructed in the following manner:

For the foot segment, the origin was defined as the inter-malleolar point located midway between markers at medial and lateral malleoli. The Z axis was defined as a line connecting the heel marker and the origin, and pointing cranially. The YZ axis was defined as a line connecting the medial and lateral malleolus markers, and pointing to the right. With the Gram-Schmidt orthogonalization process [22], the X and Y axes were then determined. The X axis was a line perpendicular to the plane spanned by YZ and Z axes, pointing anteriorly, while the Y axis was the common line perpendicular to both X and Z axes.

For the shank segment, the origin was defined as the same origin of the foot segment on the same side. The Y axis was defined as a line connecting the medial and lateral condyle markers, and pointing to the right. The YZ axis was defined as a line connecting the origin and the midpoint between medial and lateral condyle markers, and point cranially. With the orthogonalization process, the X and Z axes were determined as the line perpendicular to the plane spanned by Y and YZ axes, pointing anteriorly, and the common line perpendicular to both X and Y axes, respectively.

For the thigh segment, the origin was coincident with the hip joint, which was defined based on left and right ASIS markers [23]. The Z axis was defined as a line connecting the origin and the midpoint between medial and lateral condyle markers. The YZ axis was defined as a line connecting medial and lateral condyle markers, and pointing to the right. With the orthogonalization process, the X and Y axes were determined as a line perpendicular to the plane spanned by Z and YZ axes, pointing anteriorly, and the common line perpendicular to both X and Z axes, respectively.

After the segmental coordinate systems were established, the segmental 3D Euler angles were calculated using XYZ convention [23]. The following conventions were exercised: +X represents abduction and adduction for left and right side, respectively; +Y represents flexion for both sides; +Z represents external and internal rotation for left and right side, respectively.

2.5.1. Sagittal foot, shank, and thigh angle

Right and left sagittal foot, shank, and thigh angles were assessed to evaluate differences in angle changes (flexion or extension) between walking-on-slippery-surface trials and walking-on-dry-surface trials. Vectors of foot, shank, and thigh were defined as Fig. 1. These vectors and ground X vector were used to calculate angles (Fig. 2). Slip-start (SS) and slip-end (SE) points [24] were identified for data normalization. SS was defined as the point where non-rearward positive acceleration of the heel after heel contact (HC), equivalently where the first minimum of the horizontal heel velocity after HC [8,24]. SE for SDI was defined as the point where peak horizontal heel acceleration occurred after SS point [8,24]. The continuous foot, shank, and thigh angles were normalized from HC to SS and from SS to SE [8,24]. First, every angle at 20, 40, 60, 80, 100% of the first normalized phase (HC to SS) was evaluated. Second, every angle at 20, 40, 60, 80, 100% of the second normalized phase (SS to SE) was compared between normal walking data and slipping data.

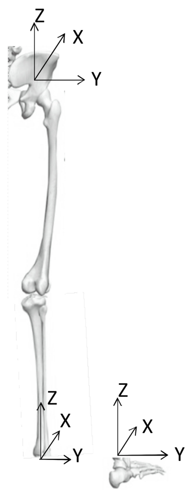

Fig. 2. Vectors of foot, shank, and thigh.

2.5.2. Frontal thigh angle

Frontal thigh angle was calculated to determine if thigh angle deteriorates in the frontal plane; frontal thigh deteriorations assisted to identify rotation of the thigh segment during events. Transverse thigh angle was not assessed since there was almost no rotation occurred at longitudinal axis. Ground Z vector and thigh were used to calculate the frontal thigh angle while slipping or walking. As same as sagittal angle, SS and SE points were identified for data normalization [24]. The continuous frontal thigh angles were normalized from HC to SS and from SS to SE. Since there was no difference between the dry and slippery surface, up to 50% of a gait cycle, basic information was statistically assessed at 10, 30, 50%. Afterward, information was statistically assessed at every 10%. Every angle at 10, 30, 50, 70, 90% of the first normalized phase (HC to SS) and the second normalized phase (SS to SE) was evaluated while slipping and walking.

3. Results

While slipping, sagittal left foot angle continuously became smaller until SE. This reduction in foot angle indicated that, while slipping, the supporting leg's knee joint dropped close to the floor surface quickly. The supporting foot keeps rotating forward after SS compared to normal walking. Such forward rotating foot angle was found to be significantly lower during slipping than during normal walking (Table 1). It indicates that instead of completing the swing phase, the supporting foot rapidly rotates to bring the toe down to the ground, which is a typical toe-touch strategy to establish a wider base-of-support. Overall, while slipping, the slipping leg's sagittal foot angle became smaller (Figs 3 and 4). The sagittal angle of the slipping foot after SS was significantly lower during slippery trials than during normal walking. It indicates that the slipping foot reached foot flat condition faster while slipping. The sagittal angle of the supporting shank keeps rotating forward even after SS during the slipping trials (Fig. 5). Together with the increasing sagittal thigh angle, the knee joint of the supporting side was found to flex more during slipping compared to that during normal walking (Table 1). Both the thigh segments on both supporting side and slipping side adducted more during slipping than during normal walking (Table 1).

Table 1
Descriptive statistics of segment angles during gait cycle and HC to SE

Dependent variables	Mean (standard deviation)		*p*-value
	Dry	Slippery	
Sagittal left foot angles			
10% gait cycle	174.31 (3.32)	174.34 (4.48)	0.99
30% gait cycle	165.23 (2.60)	165.09 (2.67)	0.91
50% gait cycle	159.60 (3.32)	159.35 (4.45)	0.90
60% gait cycle	145.81 (7.18)	145.91 (7.94)	0.97
70% gait cycle	106.65 (13.68)	107.27 (11.90)	0.92
80% gait cycle	102.58 (7.02)	102.60 (6.77)	0.99
90% gait cycle	134.31 (8.93)	130.15 (18.64)	0.58
10% HC-SS	182.08 (3.74)	182.09 (5.30)	0.99
30% HC-SS	166.38 (2.31)	166.43 (2.48)	0.97
50% HC-SS	165.31 (2.56)	165.16 (2.62)	0.91
70% HC-SS	163.05 (2.48)	163.00 (2.71)	0.97
90% HC-SS	157.77 (3.66)	157.91 (4.45)	0.95
10% SS-SE	148.29 (7.06)	146.23 (8.06)	0.60
30% SS-SE	147.09 (7.49)	135.80 (12.82)	0.05*
50% SS-SE	145.81 (7.92)	121.87 (19.31)	0.006*
70% SS-SE	144.46 (8.36)	108.56 (24.22)	0.001*
90% SS-SE	143.02 (8.81)	105.04 (20.90)	0.0003*
Sagittal right foot angles			
10% gait cycle	138.56 (8.47)	137.08 (10.34)	0.76
30% gait cycle	107.69 (3.77)	109.56 (4.53)	0.38
50% gait cycle	183.77 (5.17)	184.50 (4.09)	0.76
60% gait cycle	179.56 (5.16)	180.37 (5.48)	0.76
70% gait cycle	165.88 (1.60)	169.97 (5.50)	0.05*
80% gait cycle	164.86 (1.67)	171.85 (6.60)	0.01*
90% gait cycle	163.35 (1.85)	169.85 (6.94)	0.02*
10% HC-SS	147.17 (7.04)	145.90 (8.21)	0.74
30% HC-SS	102.50 (11.10)	102.92 (12.18)	0.94
50% HC-SS	106.60 (3.53)	108.07 (5.34)	0.52
70% HC-SS	147.97 (5.06)	149.43 (6.24)	0.61
90% HC-SS	189.46 (5.56)	190.03 (4.00)	0.81
10% SS-SE	183.41 (4.88)	181.16 (4.67)	0.36
30% SS-SE	181.81 (4.64)	174.33 (5.57)	0.01*
50% SS-SE	180.21 (4.42)	172.25 (5.92)	0.009*
70% SS-SE	178.64 (4.23)	172.49 (6.66)	0.04*
90% SS-SE	177.08 (4.07)	172.64 (7.16)	0.15
Sagittal left shank angle (degree)			
10% gait cycle	105.64 (2.47)	105.24 (2.13)	0.74
30% gait cycle	86.60 (4.07)	86.179 (4.22)	0.84
50% gait cycle	73.54 (2.70)	73.62 (2.92)	0.95
60% gait cycle	59.92 (4.46)	60.23 (3.81)	0.88
70% gait cycle	41.91 (5.89)	41.68 (4.30)	0.92
80% gait cycle	38.04 (7.02)	35.46 (3.20)	0.15
90% gait cycle	60.59 (5.63)	46.56 (11.96)	0.001*
10% HC-SS	108.88 (2.31)	108.52 (1.60)	0.72
30% HC-SS	93.80 (1.27)	93.76 (4.38)	0.98
50% HC-SS	86.82 (4.23)	86.36 (4.22)	0.83
70% HC-SS	80.50 (2.94)	80.63 (3.21)	0.93
90% HC-SS	70.99 (3.27)	80.63 (0.13)	0.81
10% SS-SE	61.91 (4.78)	60.56 (3.94)	0.54
30% SS-SE	61.04 (4.85)	54.75 (5.48)	0.03*
50% SS-SE	60.16 (4.92)	48.30 (7.93)	0.003*
70% SS-SE	59.27 (4.99)	42.87 (9.33)	0.0006*
90% SS-SE	58.36 (5.06)	39.95 (8.99)	0.0002*

Table 1, continued

Dependent variables	Mean (standard deviation)		p-value
	Dry	Slippery	
Sagittal right shank angle (degree)			
10% gait cycle	55.74 (4.40)	55.37 (5.44)	0.88
30% gait cycle	42.67 (3.09)	43.25 (4.54)	0.77
50% gait cycle	109.31 (5.50)	109.64 (5.04)	0.90
60% gait cycle	108.63 (3.35)	108.64 (2.54)	0.99
70% gait cycle	93.65 (3.66)	101.90 (5.71)	0.004*
80% gait cycle	86.50 (3.40)	106.73 (8.93)	< 0.0001*
90% gait cycle	82.45 (2.48)	98.93 (11.64)	0.001*
10% HC-SS	60.91 (4.06)	60.47 (4.98)	0.85
30% HC-SS	40.00 (4.86)	40.38 (5.66)	0.88
50% HC-SS	42.00 (3.06)	42.32 (4.36)	0.86
70% HC-SS	74.13 (5.11)	74.70 (6.24)	0.84
90% HC-SS	114.26 (4.22)	114.26 (3.28)	0.99
10% SS-SE	110.29 (3.61)	108.91 (2.71)	0.40
30% SS-SE	109.54 (3.53)	105.77 (3.42)	0.04*
50% SS-SE	108.83 (3.48)	103.97 (4.44)	0.03*
70% SS-SE	108.14 (3.46)	104.48 (5.30)	0.12
90% SS-SE	107.48 (3.46)	105.92 (4.95)	0.48
Sagittal left thigh angle (degree)			
10% gait cycle	109.59 (4.05)	109.94 (5.84)	0.89
30% gait cycle	94.16 (5.28)	94.18 (5.35)	0.99
50% gait cycle	77.86 (5.04)	77.89 (4.32)	0.99
60% gait cycle	74.85 (4.30)	74.87 (3.67)	0.99
70% gait cycle	83.27 (1.63)	83.33 (3.00)	0.96
80% gait cycle	101.04 (1.30)	100.48 (4.16)	0.72
90% gait cycle	112.47 (2.40)	104.24 (6.88)	0.006*
10% HC-SS	110.60 (3.55)	110.94 (4.96)	0.87
30% HC-SS	106.04 (4.52)	106.27 (6.90)	0.94
50% HC-SS	94.39 (5.22)	94.71 (5.16)	0.90
70% HC-SS	84.66 (4.84)	84.62 (4.48)	0.98
90% HC-SS	76.61 (4.96)	76.73 (4.06)	0.96
10% SS-SE	74.91 (4.42)	74.92 (3.69)	0.99
30% SS-SE	74.90 (4.35)	76.13 (3.50)	0.54
50% SS-SE	74.92 (4.20)	79.54 (4.51)	0.05*
70% SS-SE	74.98 (4.20)	84.70 (7.36)	0.006*
90% SS-SE	75.06 (4.12)	90.13 (10.13)	0.002*
Sagittal right thigh angle (degree)			
10% gait cycle	74.29 (4.32)	74.46 (4.49)	0.94
30% gait cycle	105.25 (4.02)	104.37 (3.87)	0.66
50% gait cycle	109.94 (4.19)	109.78 (4.57)	0.91
60% gait cycle	109.32 (4.62)	108.99 (4.65)	0.89
70% gait cycle	106.67 (5.87)	105.84 (5.88)	0.78
80% gait cycle	97.18 (6.04)	105.17 (5.49)	0.01*
90% gait cycle	87.03 (5.51)	117.19 (10.12)	< 0.0001*
10% HC-SS	73.57 (4.09)	73.58 (5.51)	0.99
30% HC-SS	84.52 (4.86)	84.42 (5.51)	0.97
50% HC-SS	104.67 (4.21)	103.73 (4.19)	0.66
70% HC-SS	114.25 (3.66)	113.43 (3.50)	0.65
90% HC-SS	108.60 (3.84)	108.52 (4.22)	0.97
10% SS-SE	109.25 (4.37)	108.99 (4.41)	0.90
30% SS-SE	109.32 (4.41)	108.01 (5.01)	0.58
50% SS-SE	109.34 (4.46)	106.77 (5.40)	0.32
70% SS-SE	109.31 (4.51)	106.77 (5.40)	0.17
90% SS-SE	109.26 (4.59)	105.29 (6.03)	0.16

Table 1, continued

Dependent variables	Mean (standard deviation)		p-value
	Dry	Slippery	
Frontal left thigh angle (degree)			
10% gait cycle	96.80 (2.26)	95.94 (1.70)	0.40
30% gait cycle	91.67 (2.37)	91.27 (2.85)	0.76
50% gait cycle	94.12 (1.53)	93.84 (1.86)	0.75
60% gait cycle	96.37 (1.40)	96.34 (1.82)	0.97
70% gait cycle	96.89 (1.31)	96.52 (2.34)	0.70
80% gait cycle	96.86 (1.21)	93.74 (2.90)	0.01*
90% gait cycle	96.99 (1.31)	91.70 (2.58)	0.0001*
10% HC-SS	97.30 (2.05)	96.65 (2.51)	0.47
30% HC-SS	93.47 (2.32)	92.86 (2.51)	0.62
50% HC-SS	91.77 (2.32)	91.20 (2.82)	0.66
70% HC-SS	92.85 (2.47)	92.61 (2.53)	0.85
90% HC-SS	94.52 (1.69)	94.17 (1.77)	0.69
10% SS-SE	95.99 (1.68)	96.27 (1.91)	0.76
30% SS-SE	96.13 (1.62)	96.66 (2.16)	0.59
50% SS-SE	96.28 (1.56)	96.64 (2.32)	0.72
70% SS-SE	96.40 (1.51)	96.27 (2.35)	0.90
90% SS-SE	96.50 (1.46)	95.44 (2.39)	0.30
Frontal right thigh angle (degree)			
10% gait cycle	79.18 (4.94)	79.32 (5.15)	0.96
30% gait cycle	81.34 (4.07)	81.21 (4.13)	0.95
50% gait cycle	81.43 (4.02)	81.03 (4.54)	0.86
60% gait cycle	82.09 (3.85)	82.00 (5.07)	0.97
70% gait cycle	83.42 (4.11)	83.65 (5.41)	0.93
80% gait cycle	82.46 (4.04)	83.64 (5.25)	0.62
90% gait cycle	80.54 (4.56)	84.62 (7.10)	0.20
10% HC-SS	78.51 (4.86)	78.65 (5.00)	0.95
30% HC-SS	81.18 (4.66)	80.92 (5.07)	0.91
50% HC-SS	81.30 (4.14)	81.17 (4.10)	0.95
70% HC-SS	81.62 (4.28)	81.27 (4.19)	0.87
90% HC-SS	81.65 (4.01)	81.17 (4.48)	0.82
10% SS-SE	81.86 (3.80)	81.17 (4.48)	0.97
30% SS-SE	81.92 (3.81)	82.65 (5.49)	0.76
50% SS-SE	81.99 (3.82)	83.26 (5.79)	0.61
70% SS-SE	82.07 (3.83)	83.49 (5.71)	0.57
90% SS-SE	82.16 (3.85)	83.42 (5.43)	0.60

Mean (SD) of foot, shank, and thigh angles during walking on dry surface or slippery surface. HC (Heel Contact), SS (Slip-Start), SE (Slip-End). For example, 10% HC-SS indicates during a period from heel contact to slip-start. $^*p$-value < 0.05.

4. Discussion

The objective of the current study was to compare the lower extremity angular kinematics during unexpected forward heel-slipping with that during normal dry surface walking. As hypothesized, statistically significant floor surface condition effect was found between the two different surfaces.

In the results from the present study, authors were challenged to link lower extremity rotational kinematics in conjunction with functional anatomy of lower extremity muscles. This association between the two would assist trainers to identify specific muscles that should be trained in order for a person to recover from a postural disturbance during slipping. The results found in the present study, such as relatively smaller left and right foot angles, smaller left and right shank angles, and larger left thigh angles

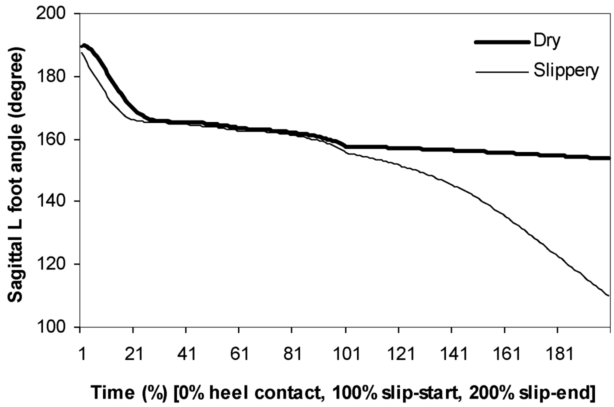

Fig. 3. Sagittal left foot (supporting foot) angle.

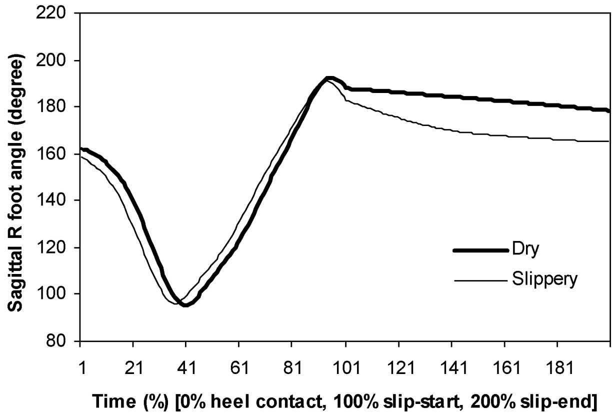

Fig. 4. Sagittal right foot (slipping foot) angle.

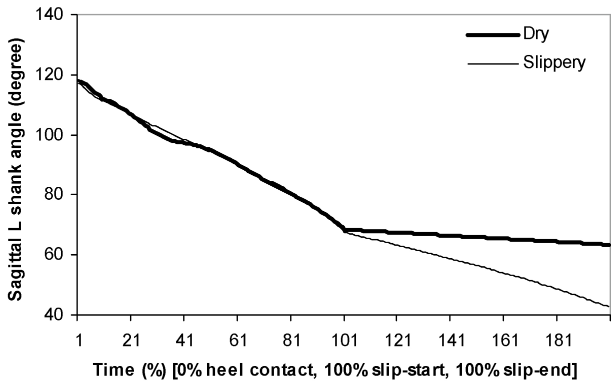

Fig. 5. Sagittal left shank angle.

during a period from heel-contact to slip-end, may have suggested that knee extensor muscles, ankle plantar flexion muscles, and hip extensor muscles could be functionally involved in recovering from postural disturbances after a slip would start. In order to actively recover from a slipping, knee extensor muscles such as vastus lateralis, medialis, and intermedius and rectus femoris should actively contract to stabilize the knee joint of the support leg and ankle plantar flexion muscles such as gastronemius, soleus, and Plantaris muscles. Proper strengthening of any of these muscles could improve one's ability to plantar-flex the foot increasing the chance to recover from a slip. In addition, hip extensor muscles, such as hamstring muscles (biceps femoris, semimembranosus, semitendinosus), gluteus maximus and medius, and adductor magnus, should actively contract to stability hip joint of the slipping leg.

Overall, the study results revealed the role of the unperturbed limb in response to slip perturbations. After slip starts, the unperturbed limb (non-dominant) demonstrated a strategy quickly to land on the floor surface with decreased sagittal foot angle and shank angle, and increased sagittal thigh angle. This finding is consistent with literatures [25–28]. Employing the landing strategy, the subjects could quickly establish a stable base-of-support with the slipping limb. A controlled base-of-support was important for subjects to regain balance after postural perturbation such as a slipping. Martelli et al. [28] suggested that the unperturbed limb should be better suited for keeping balance in response to perturbations. The reactive control of stability of the unperturbed limb had an impact on recovery of the whole body because the non-dominant limb preferentially provided support to propulsion provided by the dominant limb [28,29]. The results from the present study also agreed to that the reactive joint motions of the unperturbed limb during slipping were essential for maintaining balance or stability or supporting body weight. Similar kinematic pattern was observed for the perturbed limb while slipping in the present study. Towards the end of a slip, the perturbed limb was characterized by a decreasing sagittal foot angle, shank angle, and thigh angle (not statistically significant), the supporting limb was characterized by increasing sagittal thigh angle. Together, such characteristic was consistent with the effort to maintain body center-of-mass over the perturbed limb while slipping. Apparently, lower extremity functional capability (e.g., joint torque production) could play an important role in the success of such strategy [14–16]. Again, proper strengthening program would be essential in improving the chance of recovery during a slipping or a postural disturbance.

Moderate reductions in falls risk (15–20%) were found in healthy older adults after exercise intervention such as strength, balance, or aerobic exercise [30,31]. However, general exercise interventions for falls risk reduction demonstrated the lack of effectiveness and consistency for some special population [32–34]. A possible cause of these results was alleged to be the lack of task specificity to the recovery actions during a postural disturbance [35,36]. Like results shown in the present study, to counteract to the change in lower extremity movements during slipping, rotations of lower extremity segments should be actively executed [37,38]. It was suggested that interventions that stimulate such recovery movements or mechanisms should be more effective than general exercise interventions [39–41]. Accordingly, task-specific training such as perturbation-based balance training (PBT) has been shown to improve reactive balance control after postural disturbances in some laboratory studies [15,18,40–43]. These studies [15,18,40–43] proposed that older adults' reactive locomotor adaptation potential could be augmented by employing task specific stimuli such as PBT.

As a pilot study, the current research had several limitations that should be addressed in the future. Due to limited sample size, the study results should be generalized with caution. Walking over a slippery surface typically would result in either a balance recovery or a fall. But, the slip outcome of each perturbation trial was not considered in the current study. Future studies are needed to pinpoint the relationship between lower extremity angular kinematics with slip outcomes. Potential interaction effect with aging or clinical populations could also greatly expand one's understanding of slip-induced fall mechanism.

5. Conclusion

In conclusion, the characteristics or differences in the angular kinematics of lower extremity during unexpected slips in the present study demonstrate possible causes for slip-induced falls and appear to be a practical approach to relate exercise intervention to reduce a slip-induced fall accident. Based on the current evidence, it appears that task specific training interventions such as PBT might be the most effective methods in improving reactive balance control through active control of muscle contraction at the joints in realistic situations. To better determine the linkage between the functional anatomy and rotational kinematics, more controlled studies of lower extremity kinematics during postural disturbance should be required.

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Conflict of interest

The authors declare that they have no competing interests.

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