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Changes in Gait between Successful Balance Recovery and Fall after Unexpected Slip

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Abstract

This paper concentrates on the analysis of the human body of lower limb muscles and the effect of the gait motion. Eight human lower limb muscles are selected, containing: hip extensor: (semitendinosus and biceps femoris), hip flexor: (rectus femoris and vastus medialis), knee extensor: (vastus lateralis, rectus femoris, vastus medialis), knee flexor: (lateralis gastrocnemius, medialis gastrocnemius and semitendinosus), ankle plantar flexion: (lateralis gastrocnemius and medialis gastrocnemius), ankle dorsal flexor: (tibialis anterior). The Telemyo 2400 DTS and Vicon MX system is used to collect gait parameters and surface Electromyography (sEMG) of lower limbs when 10 healthy subjects walk on the oil trails recovery or fall from slipping during leg heel contacting trail moment to swing leg heel contacting trail moment (the first double support and single support phase). Moreover, this paper compares and analyzes the muscles reaction and gait parameters change about hip, knee and ankle after subjects suffer the interference and then slip or fall. The results indicate that increasing the stretching hip, the knee flexion and ankle dorsiflexion movement contributes to human recovery balance from unexpected slip. The results of this research will explore new ideas and provide a reference value for the formulation of anti-slip strategy, rehabilitation training and the development of lower limb walker.

Keywords: Recovery balance; Falls; Surface electromyography; Joint angle; Joint toque

Introduction

The most common interference causing human gait instability is slippery ground [1]. Falling caused by the interference of slippery ground is one of the serious security problems in the occupational environment [2]. Yamaguchi et al. pointed out that falling was the main accident in the industrial apartment and up to 50% of the occupational harm [3]. Therefore, a large number of researches have been conducted on gait instability. Cham et al. found that knee flexion movement and stretching the hip reduce heel slippage rate can maintain the stability of the body at the instant of the heel contact with smooth surface. Lockhart et al. [4] researched the differences of human gait biomechanics between sliding without falling and sliding to fall. They constructed the relation between biomechanics and slip or fall accident and provided a series of prevention strategies [5]. Chambers et al. used Electromyography to study the relationship between muscle activation patterns and sliding degree of slipper. Their research indicate that the effect of muscle after sliding and reaction time were reduced, and faster muscle reaction was beneficial for reducing the number of slip accidents. Based on the studies from Rectus Femoris, Tibialis Anterior and Gastrocnemius activation patterns and effort of joint motion, [6] Yang et al. suggests that the knee flexion and stretching hip could slow down the speed of base of support (BOS) interval change to ensure the center of mass (COM) projection on the ground in BOS to keep balance [7]. Xingda et al. compared the muscle reaction characteristics of calf after slipping when recovery or fall happened, and found that the calf of TA muscle response characteristics had the biggest differences [8]. Fui et al. focused on the influence of the muscle fatigue to muscle mechanical properties when falling. Their studies suggest that strengthening the awareness of body and the lower limb muscle strength could effectively prevent falling caused by sliding [9]. Li et al. concentrated on the relationship between muscular weakness and fall among community elders by comparing the muscle forces when subjects recover balance or falling after sliding and found that the muscle forces of knee when falling happened was lower than recovery balance. As slip severity increased, the reactive activation onset of the medial hamstring was significantly faster and there was a trend approaching significance for the onset of the vastus lateralis. Additionally, the peak magnitude and time-to-peak of the vastus lateral is increased with slip severity. No significant effects of age were found on any of the output variables [10]. The above studies have demonstrated that both human lower limb joints and muscles play important roles in recovery balance when slip happened.

In this paper, the reaction rule of main joints and sEMG of lower limbs in the situation of recovering balance or falling after unexpected slip were compared. The joint angle and joint moment from Vicon MX system (Vicon, Oxford Metric Ltd., Oxford, UK) in combination with sEMG were analyzed for the situation of recovering or falling after gait instability. The results show that the functions of hip extension, knee flexion and ankle dorsiflexion movement are more apparent when people want to control posture to keep balance after slipping. The consequence of study will exploit the new idea and provide a reference value in the field of preventing slip damage, rehabilitative training and developing of lower limb walker.

Methods

This section is, firstly, to explain the subject of the experimental test. Secondly, the instrument and procedures are described. Thirdly, experimental parameters and lastly statistical analysis is discussed.

Subjects

Ten healthy young men (mean age: 24.5 ± 0.5 years old; height: 175.3 ± 5.4 cm; weight: 72.78 ± 8.6 kg), who have relatively strong lower

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limbs muscle groups, no history of musculoskeletal and neurological diseases, cardiovascular disease, volunteered for the experiment. The subjects have no strenuous exercise, muscle strain or muscle fatigue before test. Meanwhile, participants read and signed the informed consent, and all test procedures were approved by Mechanical Engineering Ethics Committee, Tianjin University of Science and Technology.

Instruments and procedures

Subjects were required to wear shorts and testing shoes to walk on the testing platform. Briefly, walking trials were conducted on a linear walkway (0.8 m × 3 m) embedded with two force-plates at 1000 Hz (OR6-6-1, AMTI Corp., Newton, MA, USA) as shown in Figure 1. To reduce the errors of data, the two pieces of AMTI load were embedded in platform and fixed, and smooth marble was placed on the AMTI to ensure it's highly consistent with the experimental platform. Subjects may slide or fall in the process of walking. In order to protect the subjects, the protection device was placed on the test platform (Figure 2). The device was fixed on the roof, and moved on the orbit through the motor driving the chain and connected with subjects through seat belts.

The safety belt can protect the subjects during a falling impact, but will not affect the normal gait patterns of the human body. The speed of motor can be manually adjusted to adapt to each subject's normal pace. The seat belts can move with subjects to guarantee the subjects when subjects fall in the process of walking.

All subjects need to accomplish two trails as follows:

(1) Walking 10 times on dry ground in a normal speed.

(2) Walking 10 times on oil ground in a normal speed without consciousness.

All participants experienced the same experimental conditions and wore the same plastic and smooth soles of shoes based on their own sizes. Before the trials, this trials need subjects to wear tight pants, remove body hair on the leg, and use professional hairdressing paper to burnish thigh skin and use the medial alcohol to wipe and make skin smooth as much as possible to reduce the impact for surface electricity sensor. During the trials subjects need to wear the belts that connect slide through the elastic rope, and walk more times in experimental environment to adapt to the body of the additional equipment before the trials. To reduce the impact of safety protection device for the participants' psychological, test conditions will be changed randomly for different subjects, including smear grease on anyone or adjust the order of ordinary walking trails and grease trails. At the same time, subjects will have a rest or listen to music to relax for a few minutes after each test. It is important for them to be unaware of the random change of test conditions during the trials.

Experimental parameters

The research gathers the joint moment and joint angle in one gait cycle through a ten-camera Vicon MX system by defining 0% moment as the heel of slip leg contacting ground firstly, 50% moment as the heel of swing leg touching ground, 100% moment as the heel of slip leg contacting ground secondly. Meanwhile, "joint torque" defines as a force multiply the vertical distance between the center of joint and related force. SEMG will be obtained using the Telemyo 2400 DTS. The patch way is implemented as follows (Figure 3).

The study mainly compared the variables of sEMG including muscular activation latency time, time-to-peak and muscular peak amplitude. As shown in Figure 4, muscular activation latency time Δt_1 is from the moment of slip t_1 to the moment of muscular activation starting t_2 ($\Delta t_1 = t_2 - t_1$).

Muscular peak amplitude is the first signal peak after the muscular activation. Time-to-peak Δt_2 is from the moment of muscular activation starting t_2 to the moment of muscular peak amplitude t_3 ($\Delta t_2 = t_3 - t_2$), which can reflect the muscle activity duration and intensity of reaction.

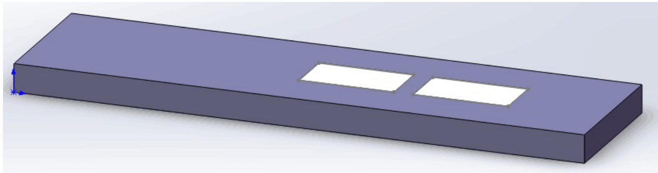

Figure 1: Picture of the rendering of simulating the gait test rig.

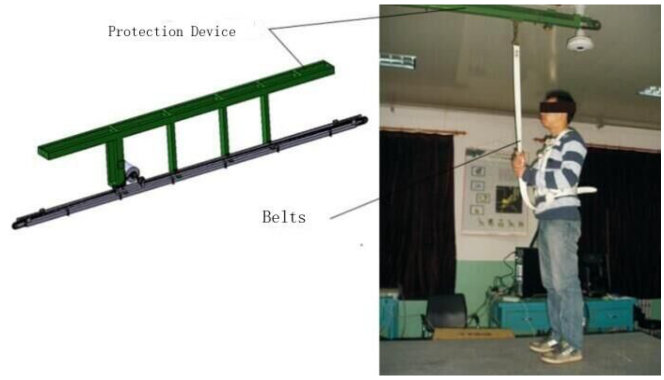

Figure 2: Protection device used to protect subjects during the trails.

Figure 3: Picture shows the place where the electrodes are.

Statistical analysis

The research used one-way repeated measures analysis of variance (ANOVA) to analyze the results in the situations of recovery and falling, respectively in order to meet Homogeneity of variance test. For eight muscle group of lower limb (Table 1), the sEMG will be pretreated through a series of ways including rectifier, filter, standardization and so on to calculate the muscular activation latency time, time-to- peak and muscular peak amplitude. All calculation processes are conducted in Telemyo 2400 DTS. Then, SPSS22.0 program is used to analyze the results using the ANOVA method. The significance test standard is sig <0.05.

Results

The results of gait parameters

During the period of sliding leg heel contacting trail moment to swing leg heel contacting trail moment, the hip joint angle and knee joint angle in the group of fall (group I) are higher than those in the group of recovery balance (group II), when unexpected slip happened. In the same condition, there is less ankle joint angle in the period of 0% to 20% and greater in remaining time period for the group I, in comparison with the group II (Figure 5).

During the period of sliding leg heel contacting trail moment to swing leg heel contacting trail moment, when unexpected slip happened, comparing with the group II, the hip joint toque of group I and group II have the same change trend basically, but group I needs greater flexion moment based on the comparison between the two groups (Figure 6). And the knee joint toque has the same trend, but group I changed slowly. Before the 20% of the period of gait cycle, ankle joint toque has the same trend and magnitude basically. After the 20% time period, group I needs greater ankle joint moment.

The results of sEMG

Analyzed by the method of ANOVA, the muscular activation latency time of eight muscle groups when the body is disturbed all shows significant level more than 0.05 (Table 2). This implies that the mean values for muscular activation latency time of perturbed leg have no significant difference in both recover and fall status.

When the body was disturbed and then slips, group I is compared to group II (Table 3). The result shows that significance value of VM is 0.03, less than 0.05. It suggests that its muscular peak amplitude has significant difference between recovery and fall status. And the others have no significant difference (sig<0.05).

Table 4 shows the mean, the standard deviation and the significance of time-to-peak. The result reveals that the sig value of TA and ST from group I and group II are 0.0038 and 0.03, respectively. They are less than 0.05 and have significance difference.

Discussion

This study focuses on the change of joint angle, joint moment and

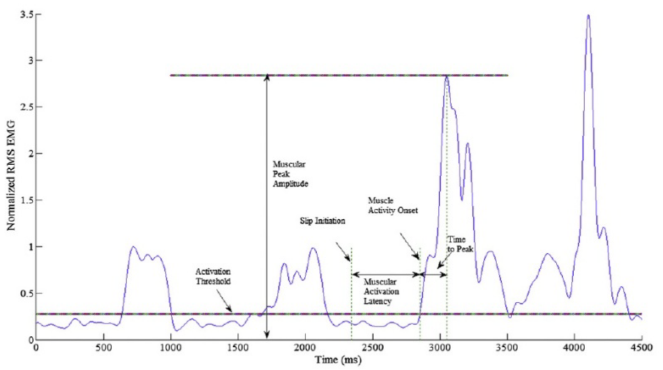

Figure 4: It shows variables of sEMG.

Joint		Muscle
Hip	Extensor	Semitendinosu (ST) Biceps Femoris (BF)
	Flexor	Rectus Femoris (RF) Vastus Medialis (VM)
Knee	Extensor	Vastus Lateralis (VL) Rectus Femoris (RF) Vastus Medialis (VM)
	Flexor	Lateralis Gastrocnemius (LG) Semitendinosu (ST) Medialis Gastrocnemius (MG)
Ankle	Extensor	Lateralis Gastrocnemius (LG) Medialis Gastrocnemius(MG)
	Flexor	Tibialis Anterior (TA)

Table 1: The selected muscles for the motion of each joint in sagittal plane.

Muscular activation latency: Mean (SD) Unit (ms)			
	Recovery	Fall	Sig
RF	692.8 (30.7)	702.8 (20.7)	0.563
VL	645.2 (38.2)	673.4 (15.8)	0.166
VM	-166.6 (37.5)	-170.4 (120.7)	0.948
TA	-242.4 (110.8)	-140.6 (79.8)	0.134
BF	1234.2 (38.7)	1265.6 (46.3)	0.278
ST	1257.4 (45.4)	1278.2 (53.9)	0.528
LG	154.6 (30.3)	173.6 (56.3)	0.525
MG	130.4 (17.0)	110.2 (22.0)	0.145

"*" is shown significant difference.

Table 2: Mean and significance of muscular activation latency of sliding leg.

Muscular peak amplitude: Mean (SD)			
	Recovery	Fall	Sig
RF	66.2 (8.3)	71.8 (16.6)	0. 519
VL	84.2 (9.3)	98.6 (14.0)	0.092
VM	70.2 (9.8)	89.0 (12.7)	0.030*
TA	232.8 (23.9)	271.0 (84.0)	0.357
BF	193.0 (37.9)	257.2 (102.7)	0.226
ST	198.0 (39.5)	204.4 (60.0)	0.861
LG	91.4 (17.6)	109.4 (27.3)	0.251
MG	170.4 (26.8)	158.6 (15.9)	0.423

"*" is shown significant difference.

Table 3: Mean and significance of muscular peak amplitude of sliding leg.

Time-to-peak: Mean (SD) Unit (ms)			
	Recovery	Fall	Sig
RF	106.0 (19.0)	111.6 (37.4)	0.773
VL	249.4 (63.8)	161.4 (92.5)	0.118
VM	369.8 (50.8)	321.6 (129.0)	0.460
TA	450.4 (128.6)	258.8 (115.4)	0.038*
BF	175.6 (99.17)	67.6 (50.4)	0.062
ST	178.8 (95.8)	65.6 (5.8)	0.030*
LG	135.2 (22.8)	118.4 (47.4)	0.469
MG	105.0 (14.9)	102.8 (23.6)	0.864

"*" is shown significant difference.

Table 4: Mean and significance of time-to-peak/valley of sliding leg.

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sEMG of sliding leg, when the body slipped and then recovered balance or fell, during the period of slipping leg heel contacting trail moment to swing leg heel contacting trail moment (the first pair of support and single support phase). The conclusion from the above results is that group I and group II have the basically same trend in the whole and show difference in the magnitude of each data.

At present, when people walk and keep balance, the theory of balance shows that only keeping the COM in the area of BOS can keep the body balance [11]. And the previous literature [12] Cara et al. shows that the wrong location of COM would not produce the necessary joint toque when the unexpected slip happened. Hip is a key joint to connect upper with lower limb and control posture in the situation of unexpected slip. When the body slips and then recoveries balance or falls, during the period of slipping leg heel contacting trail moment to swing leg heel contacting trail moment (the first double support and single support phase), hip joint ankle shows the flexion angle and performs greater flexion angle when the body recovers balance (Figure 5). Because of the instant of slipping, the COM of body moves to backward and down. In order to recover balance (or no slipping), hip flexion angle will decrease continuously to maintain the COM in BOS. Hip flexion toque appears smaller fluctuation and presents the downward trend, namely the stretching torque increasing (Figure 6). That is why the movement changes from flexion to extension so that COM go upward and forward to maintain the body in the upright position. The result is consistent with the conclusion from Winter [13]. Muscular activation latency time, time-to-peak, muscular peak amplitude of the extensor (ST, BF) in sliding leg all have no significant difference (Tables 2 and 3). Qu found that there is no significant difference of muscular activation latency time between recovery balance and falling. Qu's result agreed with this study. Because in the instant of slipping, hip angle and moment both appear the downward trend and the extensor muscle groups are activated, which can make hip produce the extensor angle and toque to resist the flexion movement. And in the two situations, the body's autonomic balance selection strategy should be the same. These results show that the extensor movement is helpful to recover balance. The muscular peak amplitude of VM from the flexion muscle group (BF and VM) has significant difference, whereas its muscular activation latency time and time-to-peak have no significant difference. In the process of sliding, the COM moves to backward and downward continuously to make the force that works on hip gradually greater. In the case of recovery balance, the COM falls down to the specific position and then the COM due to the muscle activity begins to move upward. While in the case of falling, the COM vertical projection is not in the scope of BOS, and the COM has declined until the hip strike the ground. In the both processes, hip keeps flexion, while flexors have been always active.

When the body slips and then recoveries balance or fall, during the period of sliding leg heel contacting trail moment to swing leg heel contacting trail moment (the first double support and single support phase), knee joint angle is flexion. When the heel just strikes the ground, knee showed the extension (Figure 5). And at the moment of slipping, the COM suddenly moves back and down, making knee appear flexion state. At the moment of slipping, knee joint moment still keep extensor state (Figure 6). However, with the body using knee flexion movement to keep COM's vertical projection in the range of BOS, knee flexion torque increases, at the 20% time period, knee begins to show the extension torque. Combining with the hip extension, subject makes the COM move upward and forward constantly and then maintains the body in the upright position. At the same time, group I had shown greater knee joint torque in this process. When unexpected slip happen, body takes the same measures to resist body fall, (Figures 5 and 6), so whether recovering balance or falling, the muscular activation latency time, time-to-peak of knee extensor muscle group (VM, VL and RF) and flexor muscle group (MG, LG and ST) in slipping leg have no significance. Qu et al. found that it was of no significant difference of muscular activation latency time between recovery balance and falling. Qu result agrees with this study. Muscular peak amplitude of VM has significant difference, and the result from group II is greater than group I (Table 3). That suggests that body does not produce the force to overcome the muscular force from VM making knee extend and flexor movement will be not successful and fall will appear.

Time-to-peak of ST has significant difference (Table 4). This means the duration activate time from group II is lower obviously than the result from group I. As hip extensor muscle and knee flexor muscle, the effect of BT is extending hip and flexing knee. When recovery balance appears, BT has a long time to keep activated state to promote hip extension and knee flexion. While fall happened, the duration activate time of BT is shorter and can-not make hip reach the corresponding position, and knee flexion degree is insufficient. These movements can-not make the COM remain in the range of BOS. With the hip flexion and the knee extension, the COM is always down and then fall.

Comparing to group II, in the top 20% time, the dorsiflexion angle in group I is smaller and becomes greater after the initial 20% time. At the moment of 17%, dorsiflexion angle and moment begin to increase in group (Figure 5). When the heel of sliding leg just strikes the trail, the ankle is in dorsiflexion form. And when slip occurs, the COM moves back and down to make the ankle plantar flexion move.

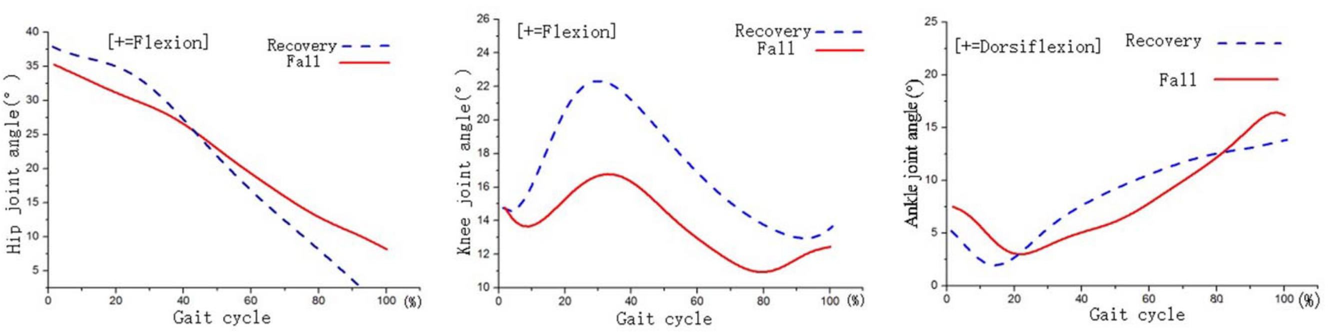

Figure 5: Comparison of ankle, knee and hip joint angle between recovery and fall after unexpected slip (The first subplot shows the change of hip joint angle, the middle subplot shows the change of knee joint angle and the last subplot shows the change of ankle joint angle).

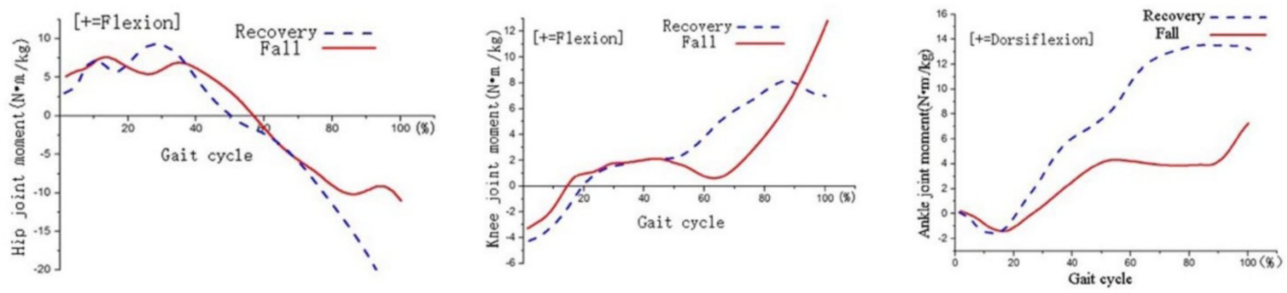

Figure 6: Comparison of hip, knee and ankle joint moment between recovery and fall after unexpected slip (The first subplot shows the change of hip joint moment, the middle subplot shows the change of knee joint moment, and the last subplot shows the change of ankle joint moment).

Then dorsiflexion angle begins to decrease and ankle joint torque performs as plantar flexion torque. Because subjects take autonomic balance strategy at the time of 17%, the hip and knee flexion movement promote COM to move forward. And then ankle dorsiflexion angle starts to increase and plantar flexion moment begins to decrease. After the time period of 20%, the dorsiflexion torque appears. Dorsiflexion torque is used to increase the contact area on the surface of the foot and trails and increase the foot - contact force, to ensure that the sliding velocity decrease or stop the slide. They show that ankle dorsiflexion angle and moment from group I are greater the results from group II (Figures 5 and 6). This suggests that ankle dorsiflexion movement is helpful to recover balance. The result of this study is consistent with the result of study from Cham in which they found that the greater dorsiflexion muscles shrink is beneficial to decreasing the risk of walking. Combining with sEMG, MG and LG can make not only the knee flexion but also the ankle plantar flexion. The result of analyzing the sEMG parameters has no significant difference (Tables 2-4). Because the knee flexion is helpful to recover balance, when LG and MG promote knee flexion, the ankle plantar flexion movement would be reduced. Hence, the active role of ankle dorsiflexion muscles becomes stronger. The time-to-peak of ankle dorsal flexor muscles (TA) has significant difference and the time-to-peak from group II is far less than group I. Because the time of ankle dorsiflexion angle and torque starting to increase from group II is slower than group I and the maximum of ankle dorsiflexion torque from group I is far greater than the maximum from group II, the ankle dorsiflexion muscle activation time is longer and more intense reaction.

When gait occurs to slip after interference by external conditions, gait disorder during the second half of the gait cycle causes large difference. Hence, this study adopts the change of slipping leg during the period of the first double support and single support phase to research. In later study, the change of swing leg should be investigated in detail. If the condition of trails is good, the change in the whole cycle should be studied thoroughly.

Liu's studies [14] suggest that when the unexpected slip happens, young man mainly relies on the knee and ankle torque coming from sagittal plane, while elderly man mainly relies on torque from frontal plane. We will analyze three planes (sagittal plane, frontal plane and horizontal plane) in the future research.

Conclusion

This paper suggests that there are some differences in slipping lower limb when the unexpected slip happens under both the condition of body restoration and slip during the period of slipping leg heel contacting trail moment to swing leg heel contacting trail moment (the first pair of support and single support phase). The conclusions are as follows:

(1) The characteristics of hip extension, knee flexion and ankle dorsiflexion movement are obviously helpful for the recovery balance of body posture after unexpected slipping occurs. And the changing characteristics of the torque, angle and sEMG from these movements are closely related to restore balance.

(2) In order to resist falling and succeed recover balance, the activity of hip extensor (ST and BF) and knee flexor (LG, MG and ST) should be increased and the time-to-peak of ankle dorsiflexion (TA) should be decreased.

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