Analysis of Skip Motion as a Recovery Strategy after an Induced Trip

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***Abstract*—Falls are one of the main causes of decreased quality of life and activities of daily living among the elderly individuals. Because tripping is the most common cause of falls, some types of recovery motions have been reported after tripping induced by a flat plate or block. Common recovery strategies observed under these conditions included elevating and lowering strategies. Especially, in case that the swinging leg contacts an obstacle at its early phase, the elevating strategy has been considered as a typical recovery motion. In this study, we performed a tripping experiment using a crossbar in the early and middle of swing phase. As a result, a new recovery strategy, which differed from those previously reported, was observed. In the new strategy, referred to as the skip strategy, the subjects lifted and moved the standing leg forward after tripping. The subjects utilized this strategy to recover from an early phase trip. The participants had to exert enough knee flexion and ankle plantar flexion torques of recovery leg with the skip strategy and enough knee extension, hip extension, and ankle plantar flexion torques of recovery leg with the lowering strategy. Especially for the elderly who cannot perform large joint torques, physical assistant robots are required to compensate such joint torques in order to perform these recovery motions.**

***Index Terms*—Fall, Physical assistant robot, Recovery motion, Skip strategy, Trip**

I. Introduction

The elderly population is rapidly increasing around the world. Aging can cause many diseases and injuries, which can decrease the quality of life (QOL) and activities of daily living (ADL) of the elderly. Falls are one of the main reasons for injuries. In fact, approximately 10 to 30% of the elderly experience a fall, and 10% have severe injuries and limitations in daily activities [1]. Falls can also lead to death or to the individual becoming bedridden [2]. Even in cases in which these injuries could be avoided, the fear of falling also makes the elderly more inactive and decreases the QOL and ADL [3]. Thus, it is important to protect the elderly from falling.

More than 100 factors have been proposed to affect the risk of falling. These factors have been classified as internal (related to physical ability) or external (related to environmental conditions) [4]. These factors can influence each other and cause a fall.

In general, the elderly has less strength of muscle and joint torques [5] [6]. It is one of the factor of falling for the elderly. Physical assistant robots have been developed to support elderly to walk better [7]. However, it is difficult to assist fall avoidance motion because of the complexity of the motion. Thus, an investigation of the critical factors that cause falls is necessary to determine the timing, position, and torque of fall avoidance assists.

Tripping is the major reason for falls during gait motion [8]. Therefore, many studies have aimed to reveal the mechanism underlying recovery motion after triggering events. In these studies, tripping was induced using a flat plate or block that was fixed on the ground [9] [10]. Through these studies, two common recovery strategies were observed [11]. One strategy was referred to as the lowering strategy and was observed when the subjects tripped during the late swing phase. The tripped foot was placed immediately in front of the obstacle and the other leg was subsequently lifted over the obstacle and placed behind it. The second strategy, called the elevating strategy, was observed when the subject tripped during the early swing phase. The tripped leg was quickly lifted over the obstacle and then placed behind it [12].

However, the type of tripping in these experiments was limited. Only flat obstacles were used under conditions in which the toe hit the obstacle in all trials. In general, tripping does not always occur at the toe and can also occur at the shank and ankle. Thus, it is possible that different recovery strategies are used under different conditions. In particular, a trip at the ankle may have more of an impact because it might be difficult to absorb the reaction force using the ankle joint and overcome the obstacle because the foot may get stuck on the obstacle. However, tripping caused upon the impeded ankle has hardly been studied thus far. One specific condition was investigated by [13] where a rope transiently arrested ankle movement, which is still one limited cause of tripping.

Thus, measurement and analysis of recovery motions after a trip induced at the ankle under the more general conditions are required to understand the fall avoidance strategy. Such understanding will help to design assist strategy of physical assistant robots to prevent falls among elderly individuals.

II. Methods

A. Subjects

Two males who were 23 and 25 years old participated in the study. The weights of the patients were 60 and 70 kg and their heights were 165 and 170 cm, respectively. Neither participant had a history of impaired balance, falls, neurological disease, or visual deficits. The experiments were performed with the approval of the Institutional Review Board of Nagoya University. Written informed consent was provided by each subject.

TABLE I
NORMAL GAIT PARAMETERS

		Step length [m]	Step time [m]	Ratio of half gait [m]	Walking speed [m/s]
Subject A	During experiment	0.79 ± 0.02	0.51 ± 0.02	49.6 ± 1.90	1.51 ± 0.05
	After experiment	0.78 ± 0.02	0.52 ± 0.01	50.6 ± 0.48	1.50 ± 0.01
Subject B	During experiment	0.76 ± 0.04	0.50 ± 0.02	47.9 ± 1.14	1.52 ± 0.05
	After experiment	0.75 ± 0.04	0.51 ± 0.03	47.8 ± 1.42	1.48 ± 0.03

Notes : Values are mean ± SD

B. Apparatus

Full body kinematic data was recorded by the motion capture system (MAC3D System, Motion Analysis Corp.) consisting of 10 cameras with 25 reflective markers that were attached to the entire body. A movable foot force plate (M3D Force plate, Tec Gihan Corp.) was used to measure the ground reaction force. A load cell (RSCC-200kg, Unipulse Corp.) monitors applied force on the safety harness. All of the devices were synchronized and recorded with a sample frequency of 100 Hz. Three axis force sensors (USL-08-H6, Tech Gihan Corp.) were also attached to the obstacle to detect the timing of the trip perturbation. For safety, a harness was connected to the shoulders and waist, and a knee protector and ankle joint supporter were utilized.

An overview of the experimental setup is shown in Fig. 1. Tripping was induced to a leg using a stick-shaped, aluminum crossbar as an obstacle. The position of the obstacle was manipulated using a linear motor actuator (GLM25-CE, THK Corp.). A speed guide that moved in front of the subject along the walkway was used to control walking speed. The walking speed was set as 1.5 m/s for all subjects using a three-phase induction motor (TO-K, HITACHI Corp.). An electrical metronome was also used to control the walking cadence. The walking cadence was determined for each subject individually.

C. Protocol

The subjects wore tight sportswear and markers were put on the suits after agreement. The subjects were then instructed to walk continuously on the walkway to get used to walking with the speed guide and the electrical metronome and until the gait was stable. The position of the obstacle for each trip phase was decided based on the gait motion of the subject after stabilization.

After the completion of the practice trials, the trip experiment was initiated. During the experiment, the subject occasionally tripped at the ankle while walking. Trip perturbations were applied during the early and middle swing phases. These phases were defined based on the relative positions of the support and swing limbs. Perturbations that occurred behind the support limb were defined as early phase trips. In contrast, perturbations that occurred in front of the support limb were defined as middle phase trips. To avoid the

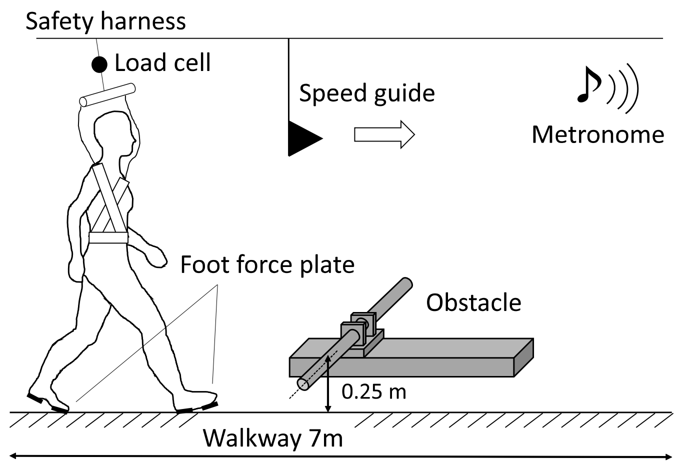


Fig. 1. Experimental setup

prediction of tripping, the order of the dummy and trip trials, the perturbed limbs, and the trip perturbation phases were randomized. In addition, half-covered glasses, which prevented the subject from visualizing what was below, were used to prevent prediction of the obstacle position.

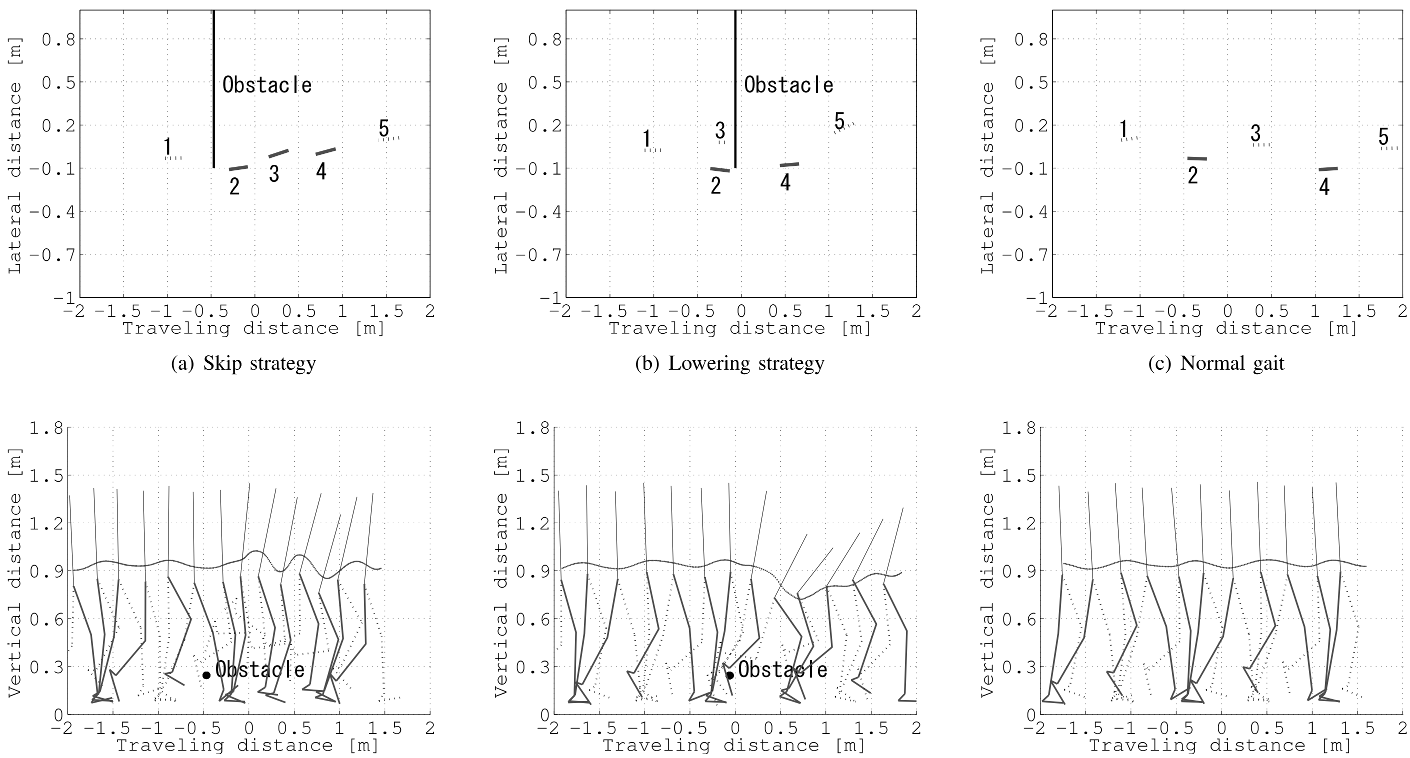
In total, 30 trials that included 20 dummy trials (in which trip perturbation did not occur), five early phase trip trials and five middle phase trip trials were performed. After all the trials were completed, an additional five trials were recorded under conditions in which the subjects knew that no obstacle existed on the walkway. As described later, by this method, early and middle phases at which the ankle contacts the obstacle were clearly discerned.

D. Data Analysis

All data was filtered using a 6 Hz Butterworth filter. Falls were detected based on a force that was applied to the safety harness, with a threshold value that corresponded to 5% of the body weight. Heel contact and toe-offs were detected when the ground reaction force exceeded 10 N. To calculate internal joint torque, the Software for Interactive Musculoskeletal Modeling (SIMM, Mulsculographics Inc., CA) was used.

TABLE II
TRIAL DETAIL

	Early phase trip		Middle phase trip		Dummy trial		
	Fall	Recover	Fall	Recover		Missed data	Total
Subject A	0	4	2	3	20	1	30
Subject B	0	4	1	4	20	1	30



(a) Skip strategy (b) Lowering strategy (c) Normal gait

(d) Skip strategy (e) Lowering strategy (f) Normal gait

Fig. 2. Approximate foot contact trajectory and recovery motions of the skip strategy, the lowering strategy, and the normal gait. (a), (b), and (c) are the foot contact trajectory with step number, and (d), (e), and (f) are the motions of each strategy. In this figure, left leg (dotted line) was tripped by obstacle and right leg (solid line) was used as recovery leg. In each strategy, the first recovery step was step number 3 in fig. 2(a) and step number 4 in fig. 2(b).

III. RESULTS

A. Recovery motions

The gait timing for the two subjects is shown in Table I. As a result of the speed guide and metronome, the gait timing varied only slightly and did not differ significantly during the experiment. This indicated that the existence of an obstacle did not affect the gait motion of the subjects. Thus, when analyzing the data, it was not necessary to modulate the gait motion of the subjects during the experiment.

As shown in Table II, 18 trip data sets were successfully recorded; 8 of them were early phase and 10 were middle phase trips. Additionally, three trials were classified as falls. Early phase trips were induced an average of 0.29 $\pm$ 0.09 m behind the position of the support limb. Middle phase trips were induced an average of 0.25 $\pm$ 0.09 m in front of the support limb. Two different recovery strategies, the lowering and skip strategies, were observed in this experiment. The approximate motions for the recovery strategies and normal walking are shown in Fig. 2.

The lowering strategy was used after an middle phase trip. In the lowering strategy, the tripped leg was placed on the ground immediately after the trip and the other leg was subsequently lifted over the obstacle and placed behind of it as the recovery leg. Instead of the elevating strategy, which was reported previously, the skip strategy was used after early phase trips. In the skip strategy, the standing leg which is opposite to tripped leg, was lifted to the front and used as the recovery leg immediately after the trip.

TABLE III
FIRST RECOVERY STEP PARAMETERS AFTER TRIPPING

		Lowering strategy		Skip strategy
		Fall	Recover	Recover
Subject A	First recovery step length [m]	1.01	0.90 ± 0.10	0.52 ± 0.04
	First recovery step time [s]	0.55	0.58 ± 0.02	0.38 ± 0.01
Subject B	First recovery step length [m]	0.81 ± 0.07	0.83 ± 0.04	0.33 ± 0.05
	First recovery step time [s]	0.31 ± 0.11	0.47 ± 0.04	0.26 ± 0.01

TABLE IV
COM MAXIMUM HORIZONTAL, VERTICAL, AND ABSOLUTE VELOCITY AFTER TRIPPING

		Horizontal velocity [m/s]	Vertical velocity [m/s]	Absolute velocity [m/s]
Subject A	Skip strategy	0.99± 0.08	0.67 ± 0.09	1.42 ± 0.04
	Lowering strategy	1.17 ± 0.04	1.22 ± 0.10	2.18 ± 0.05
	Normal gait	1.36 ± 0.09	0.24 ± 0.03	1.69 ± 0.10
Subject B	Skip strategy	0.94 ± 0.09	0.99 ± 0.09	1.54 ± 0.02
	Lowering strategy	1.11 ± 0.02	1.40 ± 0.11	2.23 ± 0.11
	Normal gait	1.33 ± 0.05	0.26 ± 0.05	1.70 ± 0.07

TABLE V
MAXIMUM KICKING AND BRACING FORCES AFTER TRIPPING

		Tripping	1^{st} recovery step		2^{nd} recovery step
		Kicking force [N]	Bracing force [N]	Kicking force [N]	Bracing force [N]
Subject A	Skip strategy	28.8 ± 24.3	166 ± 32.0	61.5 ± 32.4	296 ± 25.9
	Lowering strategy	192 ± 30.5	245 ± 30.1	157 ± 52.4	253 ± 54.0
Subject B	Skip strategy	102 ± 22.2	149 ± 78.4	75.8 ± 49.1	203 ± 40.3
	Lowering strategy	205 ± 14.7	248 ± 32.7	122 ± 32.7	195 ± 76.2

Notes : Values are mean ± SD

B. First recovery step

The recovery step time was defined as the duration between the time when the recovery leg was lifted and when it was placed on the ground after the trip. The recovery step length was defined as the distance between the heel position of the recovery leg when lifted and the heel position of the recovery leg when it was placed on the ground after tripping. The recovery step time and the duration of each strategy are shown in Table III. The recovery step time and the length after the trip were significantly different. Both were much shorter for the skip strategy compared to the lowering strategy for both subjects. In all cases involving falls, the subjects utilized the lowering strategy for recovery. In the case of a fall, the recovery step was not significantly different from the cases involving recovery.

C. COM maximum absolute velocity

According to the center of mass (COM) trajectory, which is shown in Fig. 2, the vertical displacement of COM was largest in case of lowering strategy. Table IV showed recorded COM maximum horizontal, vertical, and absolute velocity after tripping. The maximum absolute velocity of COM after trip was different with skip strategy and lowering strategy. Compared with the normal gait and lowering strategy, the velocity of COM for skip strategy was smaller than that for the

TABLE VI
ESTIMATED MAXIMUM JOINT FLEXION AND EXTENSION TORQUES OF THE HIP, KNEE, AND ANKLE OF RECOVERY LEG

Flexion torques (Dorsal flexion torque for ankle)		Tripping to 1^{st} recovery step			1^{st} recovery step to 2^{nd} recovery step		
		Hip [Nm]	Knee [Nm]	Ankle [Nm]	Hip [Nm]	Knee [Nm]	Ankle [Nm
Subject A	Skip strategy	6.06± 20.9	97.7 ± 15.1	4.32 ± 0.78	16.9 ± 23.3	45.7 ± 5.91	4.18 ± 0.9
	Lowering strategy	51.4 ± 3.51	32.0 ± 4.90	9.55 ± 1.25	32.0 ± 20.4	86.7 ± 16.8	3.13 ± 1.7
	Normal gait	19.8 ± 26.7	47.4 ± 10.3	6.24 ± 2.19	16.3 ± 8.97	56.6± 20.3	2.30 ± 0.8
Subject B	Skip strategy	21.8 ± 12.3	88.7 ± 15.6	5.36 ± 0.72	2.37 ± 24.9	70.2 ± 26.2	1.16 ± 2.3
	Lowering strategy	51.2 ± 15.7	35.2 ± 6.21	6.44 ± 2.31	48.8 ± 39.8	67.6 ± 34.6	0.08 ± 6.8
	Normal gait	47.8 ± 20.1	17.4 ± 3.90	13.4 ± 1.96	4.15 ± 14.6	33.8± 4.12	0.63 ± 0.6

Extension torques (Plantar flexion torque for ankle)		Tripping to 1^{st} recovery step			1^{st} recovery step to 2^{nd} recovery s		
		Hip [Nm]	Knee [Nm]	Ankle [Nm]	Hip [Nm]	Knee [Nm]	Ankle
Subject A	Skip strategy	167± 22.9	26.9 ± 8.33	102 ± 23.6	195 ± 41.2	33.8 ± 8.56	150 ±
	Lowering strategy	73.8 ± 11.6	51.5 ± 2.34	79.0 ± 7.86	349 ± 56.2	98.5 ± 9.78	146 ±
	Normal gait	190 ± 38.6	11.6 ± 14.3	81.6 ± 7.41	169 ± 28.3	14.5± 7.82	93.2 ±
Subject B	Skip strategy	185 ± 16.5	24.2 ± 2.86	106 ± 5.84	343 ± 43.1	11.1 ± 25.72	100 ±
	Lowering strategy	82.3 ± 13.9	42.1 ± 6.98	73.3 ± 8.01	425 ± 54.2	24.4 ± 21.8	96.0 ±
	Normal gait	123 ± 30.6	34.9 ± 3.59	68.9 ± 5.02	189 ± 8.40	19.0± 10.7	74.7 ±

Notes : Values are mean ± SD

normal gait and lowering strategy. In contrast, the maximum absolute velocity of COM of lowering strategy was larger than normal gait.

D. Kicking and Bracing force

The differences between the recovery strategies were also apparent in terms of the ground reaction force in the traveling direction. The force that pushed the body in the direction of travel was defined as the kicking force. The force exerted in the direction opposite to travel, which decelerated forward motion, was defined as the bracing force. The maximum kicking and bracing forces for the three phases, which are defined as the time between the trip and the first recovery step and the time between the first and second recovery steps, are shown in Table V. During the time between the trip and the first recovery step, the kicking force was larger with the lowering strategy than with the skip strategy. This indicated that the force, which accelerated forward motion, was larger with the lowering strategy. It also occurred at the phase between the first and second recovery steps. The bracing force for the lowering strategy was larger during the time between the trip and the first recovery step than that observed for the skip strategy. These results indicated that the subjects tried to decelerate forward motion with a large bracing force, but that a step was not enough to achieve deceleration. Therefore, the kicking force was still large during the time between the first and second recovery steps.

E. Estimated joint torques of recovery leg

Table VI showed the estimated maximum joints torque of recovery leg. The ankle plantar flexion torque at the time between the first and second recovery steps was larger in the skip and lowering strategies than in the normal gait for both subjects. The knee and ankle plantar flexion torques at the time of the first recovery step after the trip with the skip strategy were larger than those with the lowering strategy and normal gait. The joint torque for the lowering strategy had two different characteristics. The knee extension torque at the time of the first recovery step after the trip was larger for the lowering strategy than for both the skip strategy and normal gait. The hip extension torque at the time between the first and second recovery steps was larger for the lowering strategy than those for the other strategies.

IV. DISCUSSION

To avoid the obstacle at the middle phase of the swing phase, we observed the lowering strategy, which is in line with the previous studies. In contrast, for the obstacle at the early phase of the swing phase, the participants performed the skip strategy whereas the previous studies reported the elevating strategy as the most typical avoidance action. The most plausible cause for this new strategy was the shape of the obstacle used in the experiment. Previously, the elevating strategy was observed after early phase trips induced by a flat plate or block. Under these conditions, the tripped leg was able to overcome the obstacle. However, in our experiments, it was not easy to overcome the obstacle because the crossbar disturbed the motion of lifting tripped leg. Thus, the skip strategy might have been utilized instead of the elevating strategy.

The skip strategy was characterized by a hopping motion and a decrease in the velocity of the COM after the trip, as shown in Fig. 2. During this motion, large knee flexion and ankle plantar flexion torques were observed. The data suggested that the estimated knee flexion torque was more than twice that of the normal gait (Table VI). The estimated ankle plantar flexion torque was almost 25% larger than that of normal gait. It is likely that the knee flexion torque was mainly important for the success of the skip strategy.

Furthermore, from the point of the ground reaction force, when the subject used the skip strategy, the kicking force on the horizontal plane was always lower than that of the lowering strategy (Table V). This indicated that the kicking force was directed more vertically in the skip strategy compared to the lowering strategy. On the other hand, the kicking force of the lowering strategy was predominantly in the horizontal direction. In other words, the COM was accelerated as a result of the large kicking force. This also resulted in a difference in the COM velocity between the skip and lowering strategies.

The main factor that determined which strategy was selected was the tripping phase. The subjects selected the lowering strategy in all trials when they tripped in the middle phase. In contrast, the skip strategy was selected in all trials in which the trip occurred in the early phase. In addition, falls only occurred when the lowering strategy was utilized. This could be explained by differences in the horizontal position of the COM when the subject tripped. In cases of a middle phase trip, the COM had already moved forward compared to the early phase trip (Fig. 2). Thus, the COM velocity for the skip strategy was smaller than that of the lowering strategy. It was also caused by the initial position of the COM when the trip occurred. When a middle phase trip occurred, the COM was already in a forward position compared to an early phase trip (Fig. 2). Thus, the velocity of the COM was difficult to decelerate when the lowering strategy was utilized. This explains why the lowering strategy was only utilized after falls, and not with the skip strategy.

According to these results, a middle phase trip has more risks than a early phase trip. In addition, lager joint torques are required to achieve these recovery strategies than normal walking. Especially, enough knee flexion torque and ankle plantar flexion torque at the time of first recovery step after the trip, and ankle plantar flexion torque at the time between the first and second recovery steps are needed to succeed in skip strategy. To perform lowering strategy, larger knee extension torque at the time of the first recovery step after the trip, and hip extension torque and ankle plantar flexion torque at the time between the first and second recovery steps are required. However, it might be difficult for elderly to perform those larger torques because of weakened strength of muscle. Thus, physical assistant robots might be helpful to decrease risks of fall if they can assist such joint torques at suggested timings.

V. CONCLUSIONS

In this study, we measured recovery motion after ankle tripping induced by a crossbar. As a result, a new recovery strategy, which was named the skip strategy, was observed whereas the elevating strategy was thought to be a major recovery motion against the contact with an obstacle during the early swing phase. With the skip strategy, the subject lifted the stance leg forward just after tripping and used the leg as a recovery leg. We analyzed the internal joint torques needed to perform observed recovery motions using a muscleskeletal software, and found that during this motion, the subject had to exert larger knee and ankle plantar flexion torques by the time of the first recovery step, compared with the other strategies. On the other hand, to achieve lowering strategy, the subject had to perform larger hip and knee extension torques and ankle plantar flexion torque. Furthermore, we have suggested joint torques and timings which are required to perform such recovery motions. It might be helpful for physical assistant robots when they assist such fall avoidance motions.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number 26750121.

REFERENCES

[1] K.M. DeGoede,J.A. Ashton-Miller,A.B. Schultz, gFall-related upper body injuries in the older adult: a review of the biomechanical issuesh *Journal of Biomechanics*, Vol.36, 1043-1053, 2003

[2] H. Luukinen,M. Herala,R. Honkanen,P. Laippala and S.L. Kivela, gFracture risk associated with a fall according to type of fall among the elderlyh *Osteoporosis International*, Vol.12, 631-634, 2000

[3] Cynthia L. Arfken, Helen W. Lach, Stanley J. Bridge, and J. Philip Miller, gThe prevalence and correlates of falling in elderly persons living in the communityh *Am J Public Health*, Vol.84, 87-101, 1994

[4] Nevitt MC,Cummings SR,Hudes ES, gRisk factors for injurious fallsh *Journal of Gerontology: Biological Science and Medical science*, Vol.46, pp.164-170, 1991

[5] Susan V. Brooks, and John A. Faulkner, gSkeletal muscle weakness in old age: underlying mechanismh *Medicine and Science in Sports and Exercise*, Vol.26, pp.432-439, 1994

[6] Darryl G. Thelen, Albert B. Schultz,Neil B. Alexander, and James A. Ashton, gEffects of age on rapid ankle torque developmenth *Journal of Gerontology*, Vol.51, pp.226-232, 1996

[7] Robert Bogue, gExoskeletons and robotic prosthetics: a review of recent developmentsh *Industrial Robot: An International Journal*, Vol.36, pp.421-427, 2009

[8] Blake AJ, Morgan K, Bendall MJ et al., gFalls by elderly people at home: prevalence and associated factors.h *Age Ageing*, Vol.17, pp.365-372, 1988

[9] Michael J.Pavol,Tammy M.Owings, Kevin T.Foley, and Mark D.Grabiner, gMechanisms leading to a fall from an induced trip in healthy older adultsh *Journal of Gerontology: Medical Sciences*, Vol.56, pp.428-437, 2001

[10] Mirjam Pijnappels, Maarten F. Bobbert, and Jaap H. van Dieen, gContribution of the support limb in control of angular momentum after trippingh *Journal of Biomechanics*, Vol.37, pp.1811-1818, 2004

[11] A. M. Schillings, B. M. H. Van Wezel, TH. Mulder, and J. Duysens, gMuscular responses and movement strategies during stumbling over obstaclesh *Journal of Neurophysiology*, Vol.83, pp.2093-2102, 2000

[12] Janice J. Eng., David A. Winter, and Aftab E. Patla, gStrategies for recovery from a trip in early and late swing during human walkingh *Experimental Brain research*, Vol.102, pp.339-349, 1994

[13] Cecile Smeesters, Wilson C. Hayes, Thomas A. McMahon, gThe threshold trip duration for which recovery is no longer possible is associated with strength and reaction timeh *Journal of Biomechanics*, Vol.34, pp.589-595, 2001