2019 19th International Conference on Control, Automation and Systems (ICCAS 2019)
Oct. 15∼18, 2019; ICC Jeju, Jeju, Korea

Validation of trip-induction system on a treadmill by comparison with a walking lane

Hazuki Miyata[1] , Akiyama Yasuhiro[2*], Yoji Yamada[3] , and Shogo Okamoto[4]

[1]Department of Mechanical Systems Engineering, Nagoya University,
Nagoya, Japan (miyata.hazuki@b.mbox.nagoya-u.ac.jp) * Corresponding author
[2]Department of Mechanical Systems Engineering, Nagoya University,
Nagoya, Japan (akiyama-yasuhiro@mech.nagoya-u.ac.jp)
[3]Department of Mechanical Systems Engineering, Nagoya University,
Nagoya, Japan (yoji.yamada@mae.nagoya-u.ac.jp)
[4]Department of Mechanical Systems Engineering, Nagoya University,
Nagoya, Japan (okamoto-shogo@mech.nagoya-u.ac.jp)

Abstract: Trip-related falls, which account for a significant portion of falls by the elderly, often result in serious injury. A method to evaluate fall risk accurately will be increasingly required in the aging society. For this purpose, it is necessary to analyze the natural reaction motion against tripping. We therefore developed a device and method to induce tripping at an arbitrary time during walking on a treadmill. To evaluate the validity of that method, another experiment that induced tripping on a walking lane was conducted. The reaction motions in the two environments were then compared. In this study, we focused on the difference in the preferred walking speed between the ground and the treadmill. The results suggest that the joint patterns during the reaction motion become similar when the subjective velocities, not the physical velocities, become the same for the subject, whereas physical parameters such as the trajectory of the center of mass become similar when the physical velocities match. These results help to understand the reaction motion against tripping and to reproduce the natural reaction motion on the treadmill.

Keywords: Fall, Recovery motion, Trip, Treadmill

1. INTRODUCTION

A fall is one of the main events that decrease the quality of life and daily living activities of the elderly. A typical cause of a fall is tripping during walking. Therefore, estimating and preventing the risk of trips and falls is socially important. For this purpose, the measurement and analysis of the natural fall avoidance motion are essential.

Many researchers have attempted to understand the mechanism of falling by reproducing the fall experimentally. A typical method for causing tripping during walking uses an obstacle that is located or suddenly appears just in front of the swing leg [1]. As a result of this experiment, two fall recovery strategies, "elevating" and "lowering," have been observed. The elevating strategy was observed mainly when the subject was tripped during the early swing phase. When this strategy was used, the subject stepped over the obstacle using the tripped leg. In contrast, the lowering strategy was observed mainly when the trip occurred during the middle or late swing phase. The tripped foot was landed quickly in front of the obstacle and the other leg was stepped forward to prevent the forward fall.

The advantage of the gait and trip experiment conducted on the ground is that the experimental environment is physically the same as the actual situation. However, it is difficult to prevent subjects from expecting the tripping owing to the limited length of walking lane and size of recording space. Therefore, the responses may be different from natural fall motions unless anticipation is sufficiently prevented [2].

The treadmill is an option to solve the problem of such anticipation because the timing of the tripping can be controlled easily and randomly. However, treadmill walking differs from walking in an actual environment. For this reason, the difference between treadmill walking and ground walking has been examined by many researchers from various perspectives. With regard to time and distance factors, the rate of treadmill walking was often reported to be higher than that of ground walking. At the same time, stride length and stride time were shorter [3-6]. On the other hand, regarding the double support phase, results were not consistent among previous studies. As for the kinematic parameters, the joint angle patterns of the hip, knee, and ankle became similar between treadmill and ground. Although the angles were statistically different, they differed by at most 2° [7]. The ground reaction force (GRF) patterns also became similar under the two walking conditions. However, a difference in the peak value of the GRF between the walking conditions was reported. According to Reiley et al., the GRF peak value in three directions decreased at the beginning and end of the stance phase [7]. White et al. reported that the GRF peak value in only the vertical direction decreased in the middle and late stance phases [6].

Differences in subjective perception were also reported. Sabetian et al. displayed a background image in front of the subject and moved this image in pace with the walking speed during treadmill walking to ease the con-

This paper was supported by JSPS KAKENHI Grant Number 26750121.

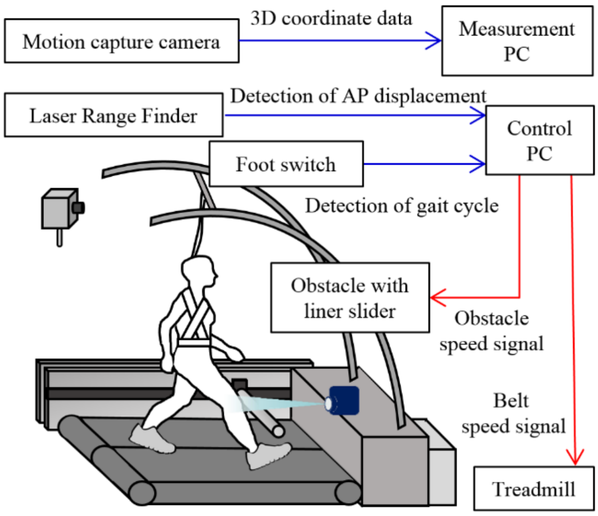


Fig. 1 Experimental overview; Based on the walking cycle detected by the foot switch and the Laser Range Finder, the linear slider with the obstacle moves toward the lower limb of the subject at the set timing

tradiction of visual information [8]. Treadmills were also used to simulate falls. Sessoms et al. simulated tripping by rapidly accelerating the treadmill belt [9]. Schillings et al. reproduced tripping physically by placing an obstacle on the belt. However, the similarity between the fall motions simulated on the treadmill and those on the ground requires further discussion because the measured parameters to date are limited [10].

In this study, we developed an experimental system that could induce tripping during walking on a treadmill. The reaction motions against tripping on the treadmill and ground condition were then compared. The purpose of this experiment was to evaluate how the physical and subjective speeds affect the reaction motion against tripping. The study also contributed to reproducing the natural fall motion when the experiment involves a treadmill.

2. METHODS

2.1 Subjects

Two healthy males aged 19 and 24 participated in the experiment. Their heights were 171 and 173 cm and their weights were 60 and 65 kg, respectively. The experiments were performed with the approval of the Institutional Review Board of Nagoya University. Written informed consent was provided by each subject.

2.2 Apparatus

We developed an experimental system that induced tripping at arbitrary times during walking on a treadmill. An overview of this system is shown in Fig. 1. A speed command signal that was input to the treadmill (Ohtake Root Co., Ltd.) controlled the speed of the belt located under the right and left foot. At the same time, the obstacle used to trip the subject was moved toward the subject using a tripping machine (e-Valley Co., Ltd.).

The tripping machine consisted of a tripping plate, an aluminum cylinder, and a linear slider. The tripping plate was fixed to the cylinder such that the height was 15 cm from the surface of the treadmill belt. The cylinder was fixed to the linear slider, which moved in a front-to-back direction. The speed of the linear slider was set to the same speed as the treadmill belt.

A laser range finder (LRF) (UST-20LX, Hokuyo Automatic Co., Ltd.) was installed in front of the treadmill to measure the distance between the tripping plate and the subject's leg. Furthermore, pressure sensors (FSR400, Interlink Electronics Inc.) were attached to the heel and toe of the insoles of the subject's shoes to detect the timing of the gait. The heel contact of the left foot was used as the reference of the gait cycle.

When 30 to 60 s had passed since the subject started walking on the treadmill and the gait had become stable, a trip occurred at a random time. However, the timing of the trip was controlled such that the tripping plate collided with the toe of the subject during the preset gait phase using an algorithm that estimated the timing of collision from the signal of the foot switch and the LRF. The reaction motion against the tripping was measured using an optical motion capture system (OptiTrack, NaturalPoint, Inc.).

Furthermore, to prevent the subject from anticipating the obstacle collisions, the subject wore goggles whose lower half was covered. We also prevented the fluctuation of gait by placing a mark at the center of the walking direction. For safety, the subject was supported by a safety harness to prevent contact with the surroundings. Furthermore, the subject wore protectors on his extremities.

2.3 Protocol

In this study, the reaction motions against tripping on the treadmill and on the ground lane at different walking speeds were compared. Three conditions were tested for each subject. In the first experiment, the tripping trial was conducted on the treadmill, whose speed was adjusted to a comfortable speed for the subject. The second experiment was conducted on the ground lane at the self-selected speed of the subject. The third experiment was also performed on the ground lane; however, the gait timing of the subject was controlled to match the one obtained in the first experiment using a metronome or similar device.

By comparing the reaction motion on the treadmill and ground lane at the same subjective speed (first and second condition) and the same physical speed (first and third condition), it becomes clear which is the important factor to reproduce the fall avoidance motion on the ground using the treadmill. In the first experiment on the treadmill, the subject's comfortable walking speed was acquired during a pilot trial for approximately 5 min. In the second and third experiments on the ground lane, the self-selected speed was determined in the same manner. In addition to the use of the metronome to stabilize and control the gait timing on the ground lane, targets of step position were placed at the height of the subject's face.

Table 1 Normal gait parameters

	Condition		Stride length [m]	Gait cycle [s]	Walking speed [m/s]
Subject A	Experiment 1	Treadmill	1.40 ± 0.09	1.19 ± 0.08	0.97
	Experiment 2	Overground	1.40 ± 0.05	1.04 ± 0.04	1.35 ± 0.09
	Experiment 3	Overground	1.43 ± 0.09	1.30 ± 0.08	1.06 ± 0.05

	Condition		Stride length [m]	Gait cycle [s]	Walking speed [m/s]
Subject B	Experiment 1	Treadmill	1.44 ± 0.03	1.15 ± 0.04	0.97
	Experiment 2	Overground	1.41 ± 0.05	1.05 ± 0.02	1.36 ± 0.05
	Experiment 3	Overground	1.43 ± 0.07	1.28 ± 0.08	1.00 ± 0.05

Notes : Values are mean ± SD

Moreover, to suppress the subject's adaptation to the trip perturbation, the trials in which the right and left feet were tripped were randomly conducted. Finally, dummy trials in which the subject was not tripped were randomly inserted in the ground experiments.

In this study, control of the gait phase at the trip moment was important. Therefore, for the first subject, tripping occurred during the early swing phase (65% of the subject's gait cycle) or the middle swing phase (80% of the gait cycle). For the second subject, the trip timing was set at the early swing phase to focus on the elevating strategy, whose reaction motion can be represented by few parameters for simpler analysis.

2.4 Data processing

All acquired data were processed using a 6 Hz Butterworth filter. The coordinates of each marker in three-dimensional space were projected on the sagittal plane. The hip joint angle was defined as the angle between the line connecting the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS) and the line connecting their midpoint and the knee. The knee joint angle was defined as the angle formed by the line connecting the greater trochanter and knee and the line connecting the knee and heel. In addition, the inclination of the upper body was defined as the angle formed by the line connecting the acromion midpoint and the midpoint between the ASIS and PSIS with the vertical line.

Heel contact was detected based on the time series change of the vertical position of the heel marker. Determination of stance phase and swing phase was performed with the timing of heel contact as the boundary.

The center of mass (COM) velocity was calculated using the Software for Interactive Musculoskeletal Modeling (SIMM, Musculographics Inc.)

3. RESULTS

3.1 Recovery motions

Table 1 shows the parameters of normal walking that were obtained from dummy trials on the ground lane or from the gait before the trip on the treadmill. Comparing experiments 1 and 2 in which the self-selected speed was applied, the speed of the ground walking was 1.39 times (subject A) and 1.38 times (subject B) greater than that of the treadmill walking. In experiment 3, for which the self-selected speed of experiment 1 on the treadmill was applied to the ground, the walking speed was successfully reproduced.

Table 2 shows the number of trials. In experiment 1 on the treadmill, subject A selected the elevating strategy in two trials that aimed to trip during the early swing phase (65% of the walking cycle); the actual collision occurred at 72.5±3.5%. In contrast, in two trials that aimed to trip during the middle swing phase (80% of the walking cycle), the actual collision timing was 83.5±2.9%, and the lowering strategy was selected. However, in experiments 2 and 3 on the ground lane with subject A, the lowering strategy was selected significantly less often even when the trip occurred during the middle swing phase. In addition, in experiment 1 with subject B, in which the subject's self-selected speed was applied to the treadmill, the elevating strategy was selected against the collision at 70.4±4% of the cycle.

3.2 Time and distance parameters

The recovery motion was defined as the motion between the tripping and the landing of the tripped leg. The time interval between them was defined as the recovery time. The stride length of this recovery motion was determined as the footstep distance of the tripped leg between the tripped foot leaving the surface and the foot landing on the surface. This distance was measured using the position of the heel marker attached to the tripped leg in the travelling direction. These parameters are shown in Table 3. The stride length and step time differed slightly among the three experiments in the case of subject A. In contrast, for subject B the parameters of experiment 1, which was performed on the treadmill, were significantly larger than those of the ground experiments.

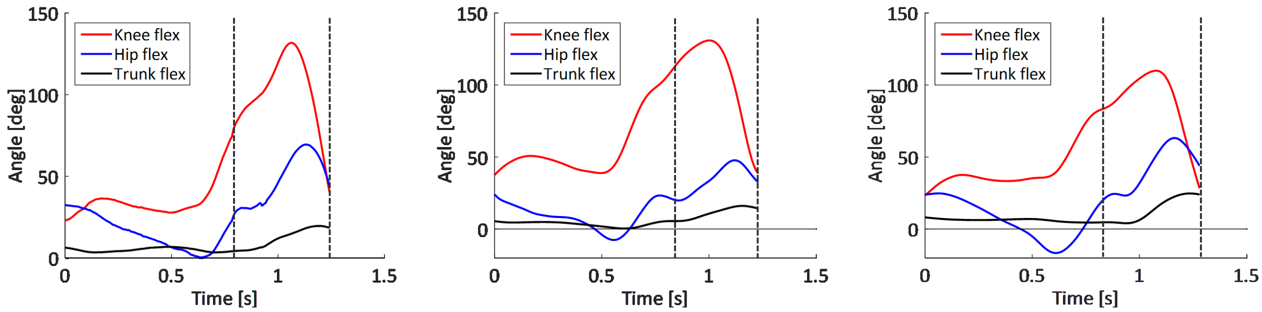
3.3 Joint angles and trunk inclination

Fig. 2 shows the transition of the knee, hip joint angle of the tripped leg, and trunk inclination angle during recovery motions of subject B whose tripping phases were close. The dashed lines in this figure indicate the trip

Table 2 Trial detail

	Condition		Elevating strategy	Lowering strategy	Dummy trial	Missed data	Total
Subject A	Experiment 1	Treadmill	2	2	5	1	10
	Experiment 2	Overground	12	2	5	4	23
	Experiment 3	Overground	11	0	10	2	23

	Condition		Elevating strategy	Dummy trial	Missed data	Total
Subject B	Experiment 1	Treadmill	8	10	4	22
	Experiment 2	Overground	8	10	4	22
	Experiment 3	Overground	10	10	2	22



(a) Experiment 1: Treadmill (b) Experiment 2: Overground (fast) (c) Experiment 3: Overground (slow)

Fig. 2 The transition of the knee, hip joint angle of the tripped leg, and trunk inclination angle during recovery motions of subject B whose tripping phases were close; The dashed lines in this figure indicate the trip timing and recovery step timing, respectively. The results of the experiment 1 and 2 were similar for the maximum knee joint angle.

timing and recovery step timing, respectively. Through experiments 1 to 3, the knee and hip were significantly flexed after tripping and the trunk inclined forward. Compared with the ground experiment results shown in Figs. 2 (b) and (c), the flexion angle of the knee joint of the treadmill experiment shown in Fig. 2 (a) increased sharply during the recovery motion and the knee flexion started late.

According to Fig. 2, the maximum knee flexion angle became similar between experiments 1 and 2 whereas it decreased by approximately 20° in experiment 3. Therefore, from the viewpoint of the reproducibility of the joint pattern of reaction motion against tripping on the treadmill, matching the subjective speed seems more important. In contrast, there was no significant difference between the three experiments in terms of hip joint angle and maximum upper body angle.

Furthermore, for subject A the hip and knee angles and trunk inclination became similar between experiments 1 and 2 in which the subject's self-selected speed was used on the treadmill and ground lane. The maximum angle of these parameters decreased slightly in experiment 3 although the trend of joint patterns was similar.

3.4 COM velocity

Fig. 3 shows the horizontal and vertical velocities of the COM at the time of landing of the recovery leg, which should be the tripped leg in the elevating strategy and the opposite leg in the lowering strategy. The filled area of the bar represents the belt speed of the treadmill. According to Fig. 3 (a), which shows the COM vertical velocity for subject A, the values of experiments 1 and 3, for which the subject's self-selected speed on the treadmill was used, were approximately equal in the case of the elevating strategy. In contrast, the COM vertical velocity became larger in experiment 2, where the subject walked on the ground with the self-selected speed of the lane. However, Fig. 3 (d), which represents subject B, shows that the COM vertical velocity became high in experiment 1. This difference may be caused by the difference in the treadmill experience between subjects.

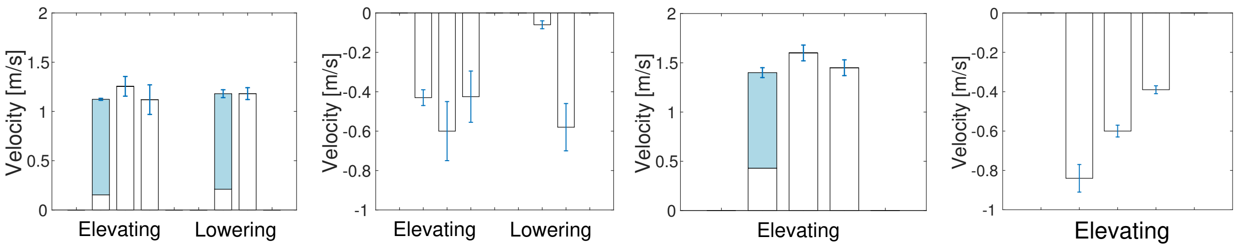
4. DISCUSSION

During the recovery motion, the maximum knee angle became similar between experiments 1 and 2, which were conducted on the treadmill and ground lane with the subject's self-selected speed for each condition. This was a common trend for both subjects. On the other hand, with

Table 3 Recovery motion parameters

Condition		Subject A		Subject B	
		Stride length [m]	Recovery time [s]	Stride length [m]	Recovery time [s]
Experiment1	Treadmill	1.46 ± 0.11	0.68 ± 0.04	1.54 ± 0.10	0.97 ± 0.05
Experiment2	Overground	1.45 ± 0.05	0.65 ± 0.05	1.45 ± 0.15	0.71 ± 0.06
Experiment3	Overground	1.40 ± 0.08	0.70 ± 0.04	1.36 ± 0.14	0.74 ± 0.10

Notes : Values are mean ± SD



(a) Horizontal COM velocity: Subject A
(b) Vertical COM velocity: Subject A
(c) Horizontal COM velocity: Subject B
(d) Vertical COM velocity: Subject B

Fig. 3 COM velocity at recovery step; The horizontal and vertical center of gravity velocities at the timing of recovery step for two subjects are shown. The bar graphs represent Experiment 1 on the treadmill 1 and Experiment 2 and 3 on the ground, respectively, from the left. In (a-c), the results of experiments 1 and 3 were similar for the elevating strategy. On the other hand, there was a different tendency in (d).

regard to the COM velocity at the time of the recovery step, experiments 1 and 3, which used the same speed on both treadmill and ground lane, had similar results. The result for experiment 2, which used a greater speed than the other experiment on the ground lane, became large as shown in Figs. 3 (a), (b), and (c). However, as shown in Fig. 3 (d), for subject B the COM vertical velocity with the treadmill in experiment 1 became larger than the velocity with the ground.

Considering the similarity of the maximum flexion angle of the knee joint, from the viewpoint of joint pattern, the leg and trunk motions of the reaction motion probably become similar when the subjective speed is matched between the treadmill and ground walking. On the other hand, when the physical speed of both treadmill and ground walking are matched, the COM velocity at the time of the recovery step on the sagittal plane probably becomes the same. However, unlike the COM horizontal velocity, the vertical velocity differs between subjects.

Adaptation to the treadmill experiment is suggested as a cause of the difference of the vertical COM velocity between subjects. Before this experiment, subject A had experience in treadmills, whereas subject B did not have such experience. Therefore, the experience of the treadmill experiment probably affected the reaction motion. Therefore, when considering a treadmill as an alternative method for reproducing the fall reaction motion on the ground, individual differences between the subjects should be considered.

In addition, the difference in the hip joint pattern of some treadmill trials in the normal gait motion suggested that subjects perhaps anticipated the timing of the trip. Sufficiently preventing this anticipation of tripping is necessary.

5. CONCLUSIONS

Although a treadmill is useful for gait analysis, the gait motion on the treadmill differs from that on the ground to some extent. Therefore, in this study, a series of tripping experiments on a treadmill and a walking lane was performed to compare and analyze the difference between them to reproduce the reaction motion on the ground using the treadmill.

We developed an experimental system that induced tripping on a treadmill. The timing of the tripping was controlled using an algorithm that monitored and estimated the gait timing of the subject. This study focused on the difference in subjective and physical speeds on the reaction motion. Therefore, the tripping experiment was conducted on the treadmill and ground lane at different speeds.

The results suggest that the COM velocity becomes similar between the treadmill and ground when the physical speeds are the same rather than the subjective speeds. On the other hand, the joint pattern tends to become similar when the subjective speeds are matched. However, differences between individuals, especially the experience of treadmill walking, should be considered for further analysis.

REFERENCES

[1] Janice J. Eng, David A. Winter, and AE Patla. Strategies for recovery from a trip in early and late swing during human walking. *Experimental brain research*, 102:339–49, 02 1994.

[2] Ting-Yun Wang, Tanvi Bhatt, Feng Yang, and Yi-Chung Pai. Adaptive control reduces trip-induced forward gait instability among young adults. *Journal of Biomechanics*, 45(7):1169 – 1175, 2012.

[3] Jaclyn R Watt, Jason R Franz, Keith Jackson, Jay Dicharry, Patrick O Riley, and D Casey Kerrigan. A three-dimensional kinematic and kinetic comparison of overground and treadmill walking in healthy elderly subjects. *Clinical biomechanics*, 25(5):444–449, 2010.

[4] M P Murray, G B Spurr, S B Sepic, G M Gardner, and LA Mollinger. Treadmill vs. floor walking: Kinematics, electromyogram, and heart rate. *Journal of applied physiology (Bethesda, Md. : 1985)*, 59:87–91, 08 1985.

[5] F. Alton, L. Baldey, S. Caplan, and M.C. Morrissey. A kinematic comparison of overground and treadmill walking. *Clinical Biomechanics*, 13(6):434–440, 1998.

[6] White Scott C, Yack H. John, Tucker carole A., and Lin Hsin-Ying. Comparison of vertical ground reaction forces during overground and treadmill walking. *Medicine & Science in Sports & Exercise*, 30:1537–1542, 1998.

[7] Patrick O. Riley, Gabriele Paolini, Ugo Della Croce, Kate W. Paylo, and D. Casey Kerrigan. A kinematic and kinetic comparison of overground and treadmill walking in healthy subjects. *Gait & Posture*, 26(1):17–24, 2007.

[8] P. Sabetian and J. M. Hollerbach. A 3 wire body weight support system for a large treadmill. In *2017 IEEE International Conference on Robotics and Automation (ICRA)*, pages 498–503, 5 2017.

[9] Pinata H. Sessoms, Marilynn Wyatt, Mark Grabiner, John-David Collins, Trevor Kingsbury, Nancy Thesing, and Kenton Kaufman. Method for evoking a trip-like response using a treadmill-based perturbation during locomotion. *Journal of Biomechanics*, 47(1):277–280, 2014.

[10] A.M. Schillings, B.M.H. Van Wezel, and J. Duysens. Mechanically induced stumbling during human treadmill walking. *Journal of Neuroscience Methods*, 67(1):11–17, 1996.