

## Estimation of effects of recovery step length on severity of injuries caused by the trip and fall

Shuto Yamada<sup>1</sup>, Yasuhiro Akiyama<sup>1</sup>, Shogo Okamoto<sup>1</sup>, and Yoji Yamada<sup>1</sup>

**Abstract**—Forward fall is a major risk for the elderly. In the case of a trip and fall, it is known that the length of the recovery step affects the ability to avoid the fall. However, the effects of recovery step length on the severity of injuries are unclear. Therefore, this study was conducted with the objective of investigating the effects of the recovery step length on the contact velocity with the ground by estimating the natural fall motion using a motion simulator. In this study, we developed a simulator for estimating the fall motion which started from the motion obtained in an experiment. In the experiment, the recovery step of the participants was classified as a short-step case or long-step case. The simulation results showed that the contact velocity had a correlation with the fall velocity of the center of mass ( $r = 0.52$ ) and the simulation duration ( $r = -0.50$ ) in the short-step case, but no correlation was observed in the long-step case. It was suggested that a long recovery step could result in an increase in the types of fall motion and thus variations in fall injuries.

### I. INTRODUCTION

In recent years, the majority of developed countries are facing the problem of an aging society. In such a society, one of the most significant risks that the elderly face on a daily basis is the risk of a fall [1]. Tripping is known to be a major cause of a fall in the elderly [2]. In a trip and fall, if the recovery step is delayed, injuries such as wrist fractures caused by contact with the ground are more likely to occur. Although it would be ideal to conduct actual fall experiments to estimate the fall injuries, it is difficult to conduct such experiments for ethical reason. Thus, there has been many research on a fall, and they have tried to estimate the fall motion and fall injuries by partially reproducing or simulating a fall.

Mitsuoka et al. [3] conducted an actual trip and fall experiment and recorded the subject's fall motion; however, the subjects were supported by a harness that stopped their fall before ground contact occurred. The results of this study suggested that the recovery step length affected the fall motion. Lo et al. [4] used a 2D and seven-links model to simulate a forward fall and estimate the corresponding fall injury risk. They investigated the influence of each joint on the fall motion by simulating various initial joint angles. In this research, the subjects' hands contact velocities were reported to be in the range of 2.86 m/s to 3.10 m/s.

Most of studies about the fall have been either partial fall experiments with adequate safety precautions or measurements of fall avoidance motion in situations that do not lead to fall. Thus, it was difficult to estimate fall injuries directly

based on the results of actual fall experiments. In addition, the simulators used in the previous researches did not fully mimic the human body. For example, when simulator's joint angles were fixed, they could not fully reproduce the fall motion of a human.

Therefore, we developed a simulator that has a sufficient number of joints for estimating a human's fall motion based on the data obtained from an actual fall experiment. The objective of this study was to estimate the natural trip and fall motion using a simulator and investigate the effect of the recovery step length on fall injuries (contact velocity with the ground). Our hypothesis is that the fall injuries would be more severe in the case of short step length than those in the case of a large step length. This hypothesis is based on the results of Mitsuoka's research, according to which the step length of the recovery leg affects the fall motion. In order to assist people with wearable robots, it is necessary to clarify the motion of wearer, the human, and this research focuses on the fall motion.

### II. METHODS

We developed a fall simulator using numerical analysis software (MATLAB, MathWorks Corp.). This simulator makes use of data obtained from an actual fall experiment [3].

#### A. Experimental data

The experiment was conducted on seven healthy young males who had no neurological or musculoskeletal disorders. Their average age, height, and weight was  $21.4 \pm 1.2$  y,  $173.0 \pm 3.0$  cm, and  $61.1 \pm 6.9$  kg respectively. The experimental condition is presented in Fig. 1. A trip fall was induced in the late swing phase of the participants due to obstacles placed in their path. There were some strategies for avoiding a fall such as the "elevating strategy" and "lowering strategy" [5]. the elevating strategy is a motion in which a tripped leg that has collided with an obstacle and put it forward as a recovery leg and lowering strategy is a motion in which the tripped leg immediately touches the ground and the other leg is put forward as a recovery leg. The most common outcome was an elevating strategy of the swing leg in response to the early swing perturbation and a lowering strategy in response to the late swing perturbation [5]. In this experiment, the latter was focused on, and the 59 trials of lowering strategy was analyzed. By adjusting the length of the rope, the limitation of the recovery step was relatively large in the "Long step case" or "Short step case" in which the length of recovery step was strictly limited. In

<sup>1</sup>Department of Mechanical Systems Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8603, Japan  
yasuhiro.akiyama@mae.nagoya-u.ac.jp

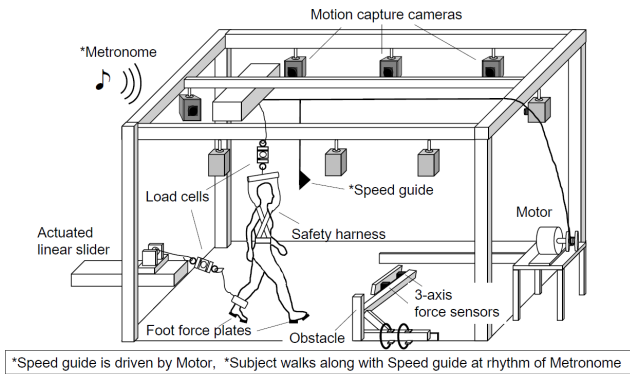


Fig. 1: Experimental condition

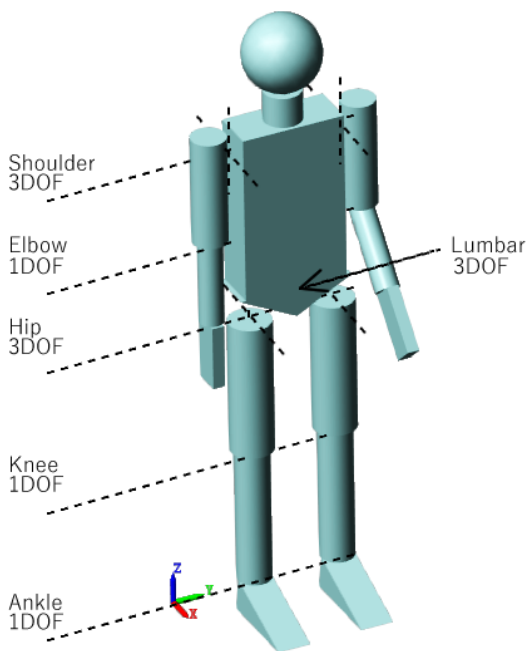


Fig. 2: 17-link rigid body model

more detail, the length of the rope was adjusted so that the recovery leg was not in front of the support leg in the short step case. On the other hand, the length of rope was adjusted so that the recovery leg was no more than 20 cm in front of the support leg in the long step case. The experiment was conducted under the two step conditions. Motion capture system (MAC3D System, Motion Analysis Corp.) comprising 10 cameras and 29 reflective markers was used to measure the fall motion. The participants were made to wear a safety harness to prevent their heads, shoulders and elbows from coming into direct contact with the ground, thus preventing the occurrence of injuries. The Institutional Review Board of Nagoya University approved all the experiment protocols, and all the participants provided written consent.

### B. Fall motion simulator

The human model used in the simulator comprised 17 links: head, neck, trunk, abdomen, pelvis, (the left and right)

upper-arms, forearms, hands, thighs, shanks, and feet. This human model comprised shoulder, elbow, hip, knee, and ankle joints. The shoulder, lumbar, and hip joints have three degrees-of-freedom (DOFs) and the other joints have one DOF. Fig. 2 shows an overview of the human model. At the beginning of the simulation, the human model is scaled from the subject's height and weight based on anthropometrics [6][7].

For estimating the fall injuries caused by collision with the ground, contact detection was used at both hands and knees and the ground in order to obtain the contact speed at the time of contact with the ground.

### C. Simulation condition

The joint torque is calculated using the inverse kinematics method with the input of the joint angle, angular velocity, and angular acceleration obtained from the experiment. In the experiment, the observed motion of the lower-limb joints and lumbar under the condition of the support of the harness probably differed from the actual fall motion because the subject was supported by the harness in the terminal phase of the fall. Therefore, in this study, the simulation was started from the posture and velocity at which the harness started to support the subject during the experiment. The lower-limb joints and lumbar in the sagittal plane were not actuated while estimating the most severe fall condition. The other joints were driven by trajectory control, using the same joint motion as that in the experiment. In this manner, a more natural fall motion could be reproduced in the simulator. In this simulator, Simscape Multibody was used as a solver. The simulation ended when the hands or knees contacted with the ground.

## III. RESULTS

Two of the fall motions estimated using this simulator are shown in Fig. 3a and Fig 3b as examples. Fig. 3a shows an example of a hand contact with the ground on the opposite side of the support leg, which was the most frequently observed, and Fig. 3b shows an example of a knee contact. The red area in these figures indicates the area at which the contact detection was applied.

In this simulator, a total of 51 fall motions of seven subjects were estimated. Eight trials, during which the first ground contact of the body did not occur at the hands or knees, were omitted from the analysis. The results of the part that contacted with the ground were shown in Table I. The side of the support leg before the contact with the ground was referred to as the "supported side" and the opposite side was referred to as the "opposite side". The contact of the knee with the ground only occurred on the supported side and occurred during approximately 8% of all the trials. However, the hand contacted with the ground, on supported side during 12 trials and on the opposite side during 35 trials, which corresponds to approximately 23% and 69%, respectively, of the total number of trials. Half of the 12 trials on the side of the support leg was brought into contact with the same participant.

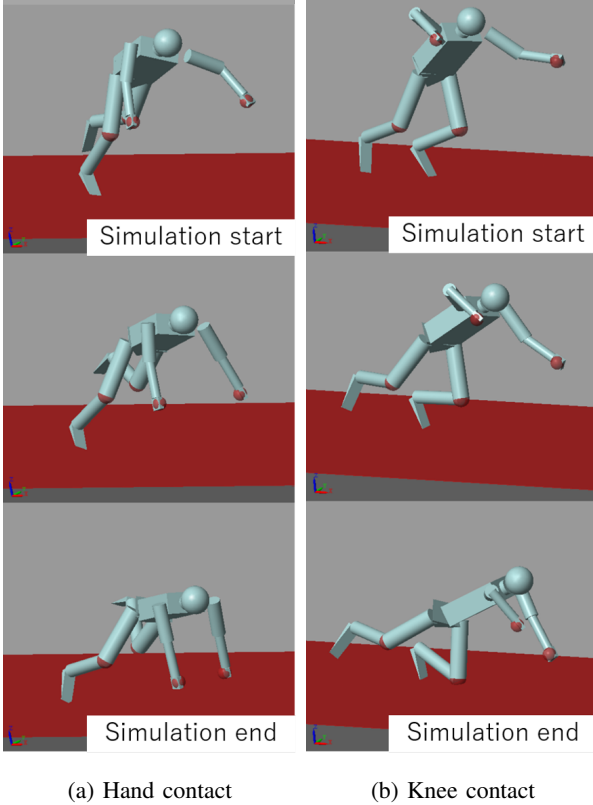


Fig. 3: Simulated fall motion

TABLE I: Contact parts for each condition

Contact part	Number of the case [times]		Total
	Short step case	Long step case	
Supported side hand	5	7	12
Opposite side hand	19	16	35
Supported side knee	2	2	4
Opposite side knee	0	0	0
Total	26	25	51

Notes : Supported side means the side of support leg

The results of the contact velocity for each part are shown in Table II. Although there were some differences in contact velocity between the short-step case and long-step case depending on the part that contacted with the ground, no significant difference was observed between the two conditions overall as a result of *t*-test ( $p$ -value = 0.82).

Fig. 4 showed the relationship between the contact velocity and the center-of-mass (COM) fall velocity at the beginning of the simulation (at the beginning of the support by the harness), and Fig. 5 showed the contact velocity with respect to the simulation duration, which is the time period of the simulated fall. In addition, the correlation coefficients of the contact velocity with the COM fall velocity and the simulation duration for each condition are shown in Table III. A positive correlation ( $r = 0.52$ ) between the COM fall velocity and contact velocity at the beginning of the simulation was found in the short step case, but no correlation was found in the long step case. Similarly, a negative correlation ( $r = -0.50$ ) between the contact velocity

TABLE II: Contact velocity for each condition

Contact part	Contact velocity [m/s]	
	Short step case	Long step case
Supported side hand	$2.62 \pm 0.82$	$3.32 \pm 0.52$
Opposite side hand	$3.66 \pm 1.25$	$3.44 \pm 0.94$
Supported side knee	$2.98 \pm 0.06$	$4.29 \pm 0.12$
Total	$3.41 \pm 1.20$	$3.48 \pm 0.84$

Notes : Supported side means the side of support leg

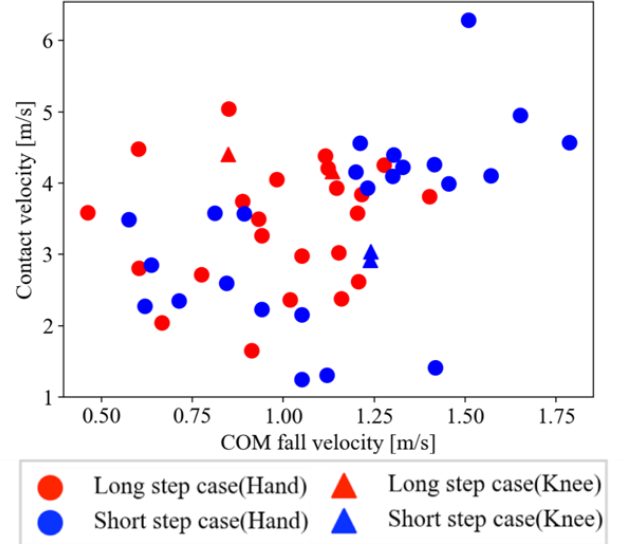


Fig. 4: Scatter plot of contact velocity against vertical velocity at simulation start (n=51)

and the simulation duration was found in the short step case, but no such correlation was found in the long-step case.

#### IV. DISCUSSION

In the short-step case, a positive correlation was found between the COM fall velocity at the beginning of the simulation and the contact velocity, which indicates that the contact velocity increases as the COM fall velocity increases. Furthermore, a negative correlation was found between the simulation duration and contact velocity, which indicates that the shorter the simulation duration is, the larger contact velocity. These two correlations are intuitively understandable, but the same results were not obtained in the long-step case. This may be because it was possible to mitigate the fall impact before the ground contact in the long-step case as compared to that in the short-step case. Therefore, there were more types for fall strategies in the long-step case. This result suggests that the difference in the recovery step length will affect the severity of fall injuries caused by tripping.

In this study, no torque was applied to the lower limb joints until the end of the simulation, which is the most severe condition of a fall. However, in the case of an actual fall, it is expected that joint torque will be generated in the support leg which will be used for the recovery motion. Therefore, it is necessary to develop a method for estimating the reaction

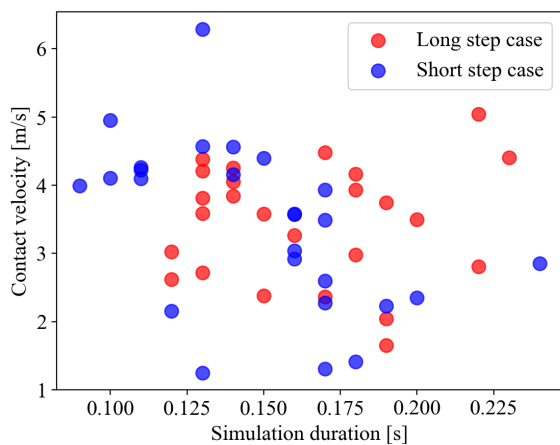


Fig. 5: Scatter plot of contact velocity against simulation duration (n=51)

TABLE III: Correlation coefficients the contact velocity with the COM fall velocity and the simulation duration for each condition

	Short step case	Long step case
COM fall velocity		
-Contact velocity(in Fig. 4)	0.52	0.11
Simulation duration		
-Contact velocity(in Fig. 5)	-0.50	0.044

motion of the subject in order to estimate the actual fall motion, and further research is needed in this respect as well.

## V. CONCLUSIONS

The objective of this study was to investigate the effect of the recovery step length in the lowering strategy on the contact velocity with the ground by estimating the natural fall motion using a simulator. A sufficiently human model was used in the simulator to estimate a more natural fall motion than that observed in the experiment.

In conclusion, it was found that when the step length of the recovery leg during a fall is not sufficiently long, the possible fall motion is limited and the simulation duration and COM fall velocity at the start of the simulation affect the impact velocity. In addition, it was suggested that the faller will be able to react before the ground contact and choose a wider range of fall motions if the step length of the recovery leg is long. This may have been the why the contact velocity in the long step case was not affected by parameters such as the simulation duration and COM fall velocity.

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