Industrial Health 2007, **45**, 462–466

**Original Article**

# Analysis of Backward Falls Caused by Accelerated Floor Movements Using a Dummy

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*Received November 21, 2006 and accepted February 21, 2007*

**Abstract: This investigation used a standing dummy on slippery and non-slippery surfaces with accelerated movements of a floor to simulate falling backward events. The results revealed the duration of falling, head impact velocity, etc., which are valuable for guiding the development of personal protective equipment, such as wearable airbags. The mechanism, by which a dummy falls backwards due to abrupt accelerated movements of a floor, was studied. A small linear accelerator was designed to apply a series of 20 combinations of step-shaped accelerations of varying durations to cause a standing dummy to fall backwards. Two flooring surfaces, namely, a smoothed aluminum surface sprayed with mould lubricant and a surface with abrasive materials, were used. Ankle, knee and hip joints of the dummy were adjusted in fixed or unfixed positions. When the dummy fell backwards like a rigid body, the head impact velocities were almost constant at around 22 to 23 km/h, and the mean duration of falling to the ground was 0.83 s, when standing on a slippery surface, and 0.98 s when standing on a non-slippery surface. The duration of falling to the ground tended to converge at 0.8 s as the maximum velocity of accelerated movements of the floor increased, irrespective of the frictional properties of the flooring surfaces.**

**Key words:** Floor slipperiness, Floor acceleration, Standing dummy, Falls, Leg joints, Head impact velocity

## Introduction

Older people are most likely to lose balance when slipping, tripping or stumbling, and to be injured by hitting their heads, hips, wrists, etc. on the ground. In 2004, 3,530 people died from falls on level surfaces according to the vital statistics in Japan[1)]. Most fatalities in falls are elderly people aged 65 and over. The primary causes of death are head injuries and fractures of the lower limbs[2)]. When people fall and strike their heads on the ground, there seems to be characteristic differences in the falling mechanism due to the functions of lower limb joints or the frictional properties of the flooring surfaces. The authors have experimentally investigated the instability of human standing posture by fixing ankle, knee or hip joints[3)], and pointed out the importance of ankle joints in keeping an upright posture. In this study we measured head impact velocities and the duration of falling considering combinations of fixed or unfixed joints of the lower limbs and sliding surfaces when a dummy fell backwards in order to obtain fundamental data to develop a new protective device such as wearable airbags[4)] for older people or people with a gait disorder.

## Methods

A dummy was used to represent an average male Japanese (height 167 cm, weight 61 kg). Every experiment was performed with the dummy, not a human, in order to avoid experimental risks. A small linear accelerator with a servomechanical motor[5)] was designed to apply various accelerations to the suspended dummy as shown in Fig. 1. The dummy was suspended by an electromagnetic separator, which was synchronized with accelerated movements of the floor. The horizontal velocity of the floor was accurately

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measured by a laser beam.

According to the author's slip study[6)], foot movements just after slipping show linearly increased velocities, and at the same time they form step-shaped accelerations of certain durations. Generally speaking, a human will sequentially lose balance and fall down due to trigger like accelerated movements of the foot; however the values of accelerated movements of the floor disturbing human standing posture are rather lower than the values of accelerated movements of the foot[7)]. Referring to the previous study[7)] to give step-shaped accelerations to subjects standing on a moving floor of another long sized linear accelerator (length: 10.5 m), the critical curve in Fig. 2 was obtained and it shows the lowest combinations of step-shaped accelerations and durations which cause falling backwards. Twenty combinations of step-shaped accelerations and duration values above the critical curve were applied to trigger abrupt falls of the dummy as shown in Fig. 2.

As shown in Fig. 3, maximum velocities of accelerated movements of the floor can be derived from the multiplication of the values of the step-shaped accelerations by the durations of the accelerations. In this study, maximum velocities of the floor movements ranged from 0.90 to 4.46 km/h.

There were two types of flooring surface materials as shown in Fig. 4: a slippery surface of smoothed aluminum sprayed with a mould lubricant, dimethyl-silicone oil (The coefficient of friction (COF) between the surface of the aluminum floor and the foot-material of the dummy covered with socks was measured by a slip meter of the Floor Slide Control-FSC2000; COF=0.2) and a non-slippery surface with abrasive materials (COF=0.98). Ankle, knee and hip joints were adjusted to fixed or unfixed positions.

Five markers were attached to the dummy as shown in Fig. 1. The falling mechanism of the dummy was captured by a video camera and analyzed by picture analysis (sampling frequency: 30 Hz). The duration from the beginning of the falling of the dummy to the end of the fall as the head hit the ground was measured by picture analysis. The following two influences were mainly examined: (a) the influence of the frictional properties of the surfaces for each fixed lower limb joint, and (b) the influence of lower limb joints with one or two joints unfixed. The flexibilities of real human joints are probably in between those of joints unfixed and fixed. Various joint rotations comparable human joints in terms of rigidity or flexibility were not dealt with in this study.

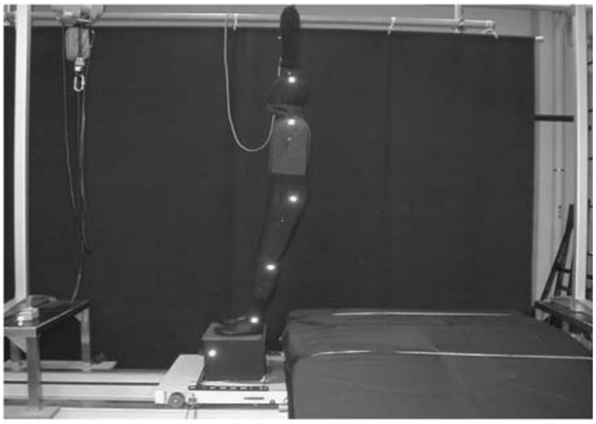


**Fig. 1. The dummy suspended on the moving floor and the linear accelerator.**

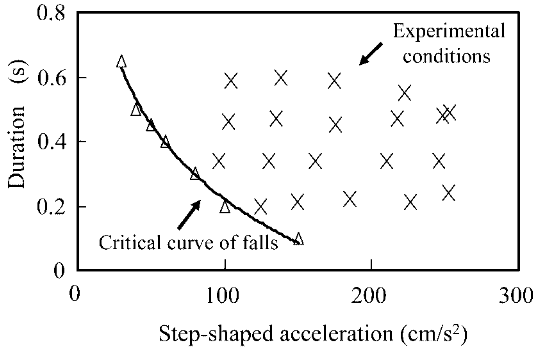


**Fig. 2. The twenty experimental conditions of accelerated movement of the floor, and the critical curve of falls derived from a previous study[7)].**

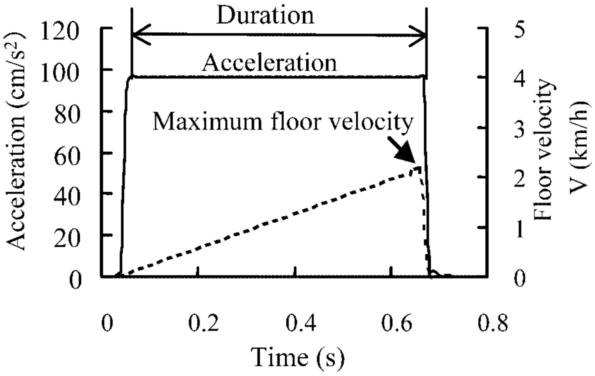
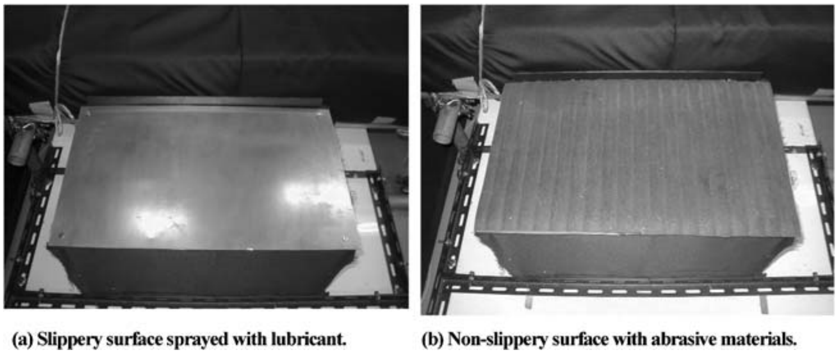
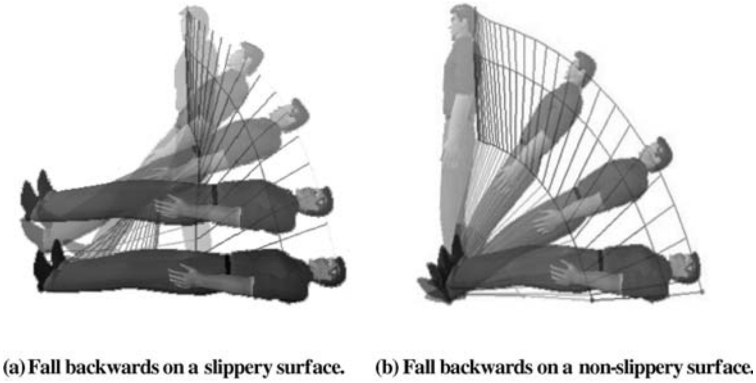


**Fig. 3. An example of accelerated movement of the floor: duration and value of step-shaped acceleration and maximum floor velocity.**



(a) Slippery surface sprayed with lubricant. (b) Non-slippery surface with abrasive materials.

**Fig. 4. Experimental surfaces.**



(a) Fall backwards on a slippery surface. (b) Fall backwards on a non-slippery surface.

**Fig. 5. Illustrations of falling patterns to the ground.**

## Results

### *Influence of frictional properties on the two experimental flooring surfaces*

Every joint of the dummy was fixed in these experiments. As the floor on the linear accelerator was accelerated with step-shaped accelerations, falling patterns of the standing dummy were different from each other due to the frictional properties of the flooring surface as shown in Fig. 5. In the case of standing on a non-slippery surface, the center of rotation of the dummy's fall was always at the foot position. On the other hand, in the case of standing on the slippery surface, the foot of the dummy just after falling backwards lost physical contact with the surface. The dummy rotated in the air and falls down as illustrated in Fig. 5 (a).

As shown in Fig. 6, the duration of falling also depended on frictional properties: the mean duration was 0.83 s for falls on the slippery surface and 0.98 s, a longer time, for falls on the non-slippery surface. The duration of falling decreased as the maximum floor velocity increased.

Duration of falling to the ground tended to converge at 0.8 s as the maximum velocity of the floor increased irrespective of the frictional properties of the flooring surfaces. The relatively shorter falling periods for the slippery surface indicate that people would have less time to grasp handrails or to protect themselves from impact on the ground.

Figure 7 shows head impact velocities on the ground when falling backwards. The mean head impact velocity was 22.3 km/h when the dummy fell backwards on the slippery surface, and 23.3 km/h on the non-slippery surface, showing no clear difference between the two cases. The head impact velocity remained almost constant as the maximum velocity of the floor movements was increased.

### *Influence of lower limb joints*

Figure 8 plots the duration of falling to the ground against the velocity of floor movements for falls in which one joint was unfixed. The duration of falling to the ground decreased as the maximum velocity of the floor was increased. In the case of unfixed hip joints, the duration was longer than in other cases. The head impact velocity in the case of unfixed hip joints (mean value: 18.5 km/h) was less than the other

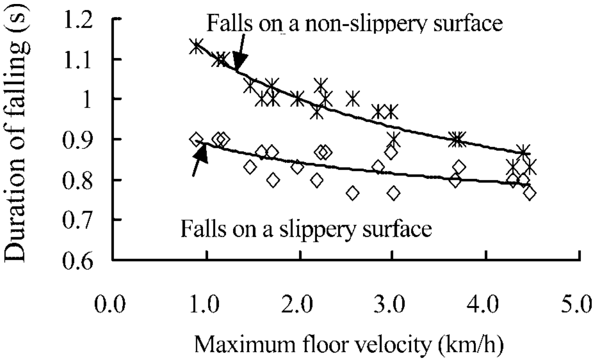


**Fig. 6. Maximum floor velocity and duration of falling with each joint fixed.**

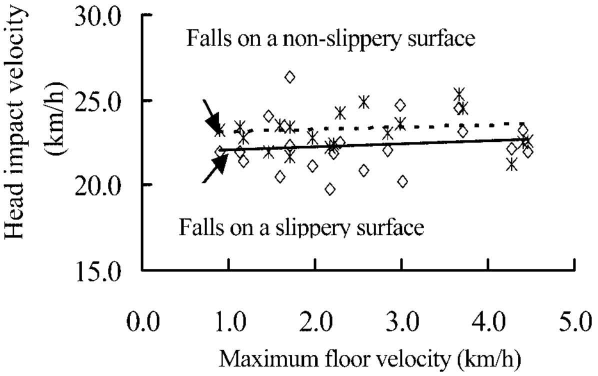


**Fig. 7. Head impact velocity and floor velocity with each joint fixed.**

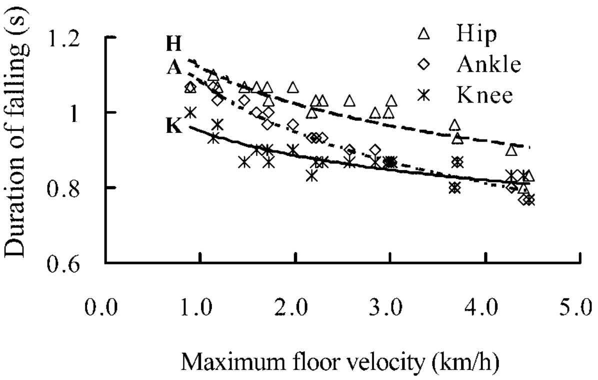


**Fig. 8. Maximum floor velocity and duration of falling of the dummy with one joint unfixed.**

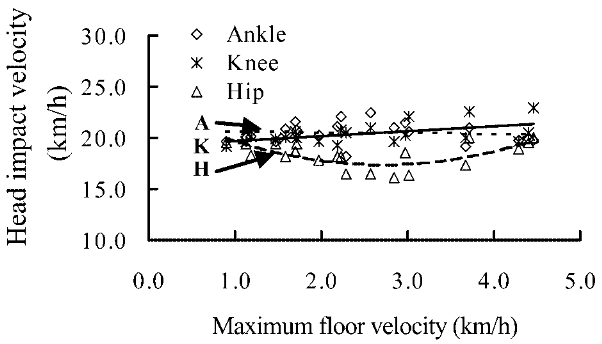


**Fig. 9. Maximum floor velocity and head impact velocity with one joint unfixed.**

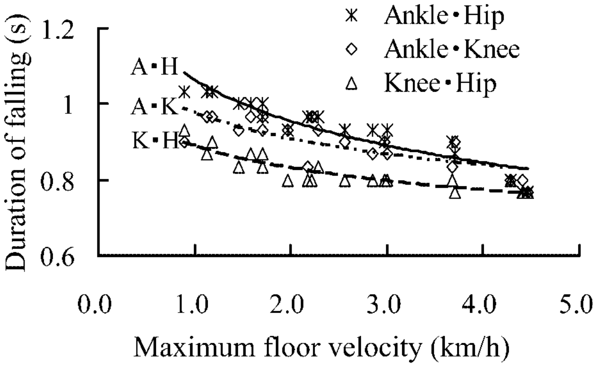


**Fig. 10. Maximum floor velocity and duration of falling with two joints unfixed.**

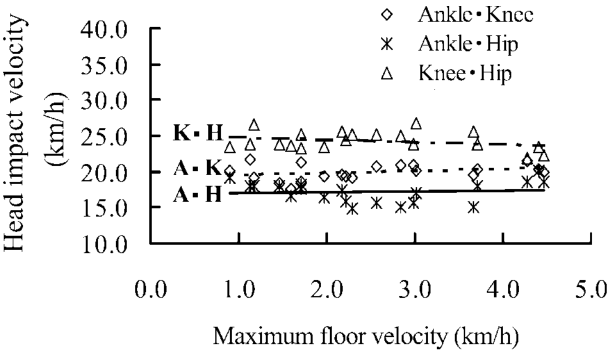


**Fig. 11. Maximum floor velocity and head impact velocity with two joints unfixed.**

cases, as shown in Fig. 9, but no significant difference was found as the maximum velocity of the floor was increased.

Figure 10 shows the duration of falling and maximum velocity of the floor for falls in which two joints were unfixed. The duration decreased as the maximum velocity of the floor was increased. The head impact velocity in the case of unfixed ankle and hip joints was the least (mean value: 17.2 km/h) as shown in Fig. 11. On the other hand, the velocity in the case of unfixed knee and hip joints with fixed ankles was the highest (mean value: 24.3 km/h). No clear tendency was found as the velocity of the floor was increased, which means that the fastest head impact velocities and shortest durations of falling were measured when the ankles were fixed.

## Discussion

Rotations of ankle and hip joints play important roles in protecting the head from impacts on the ground by decreasing the head impact velocity and by extending the time, in which people can protect themselves by reflex actions against head impacts on the ground. Head impacts are mitigated because the body bends forward due to rotations of the ankle and hip joints. However, older people find it difficult to protect themselves by their own reflex actions within a second, and so they tend to fall backwards like a rigid body with fixed joints. When applying these results to the development of protective devices like wearable airbags for older people or people with a gait disorder, it will be necessary to consider a duration of falling below 0.8 s and a head impact velocity of around 23 km/h as demonstrated by falls of the dummy with fixed joints.

## Conclusions

When a dummy falls backwards like a rigid body with fixed joints, the head impact velocity is almost constant at around 22 to 23 km/h, and the mean duration of falling is 0.83 s when standing on a slippery surface, and 0.98 s when standing on a non-slippery surface. When a dummy falls backwards, the mean head impact velocity in the case of unfixed ankle and hip joints has the smallest value, around 17.2 km/h, and the duration of falling is around 0.94 s. The mean duration of this condition was the longest seen in the experiments.

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