Protective Movements during Sideways Falls from Standing Height

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Abstract To examine the effect of protective movements during sideways falls from standing height (i.e., from the standing position), a two-step study was performed. In the first step, 80 young male and female volunteers freely fell onto a sport-mat. All falls were recorded on videotape, and replayed to analyze movements in response to the falls. Several protective movements were observed; forward flexion and lateral flexion were observed with a particularly high frequency. In the second step, impact velocities of the head and hip were measured by a three-dimensional motion analyzer regarding three types of falls: stiff falls, forward flexion falls and lateral flexion falls. Both types of flexion reduced impact velocities of the head, but not those of the hip. The reduction of the impact velocity on the head correlated with the lowering of the height of the head from the floor.

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1. Introduction

It is commonly predicted that fall-related injuries in the elderly will increase dramatically in an aging society. It is reported that over 90% of femoral fractures in the elderly occur as a consequence of a fall (Grisso et al., 1991; Cummings et al., 1990). According to a biomechanical model, the impact force at the fall is greater than the strength of the femur in the elderly (Coutney et al., 1995). However, only a few percent of falls actually result in a femoral fracture. One reason for this is thought to be that fall response movements during the descending phase of the fall may reduce the impact force, resulting in the prevention of fractures.

Although fall response movements may be important as protective strategies for fall-related injuries, it is not yet known how fallers reduce an impact force by protective movements during a fall. One of the protective movements is a flexion of the body, in either the forward or lateral direction, because it is thought that flexion in either direction (or both) can reduce the height of the head or hip from the ground.

The aim of this study is therefore to investigate the effect of flexion as protective movements during sideways falls by conducting a two-step study. In the first step, the frequency of the flexion response during free sideways falls was counted by motion analysis. In the second step, impact velocities of the head and hip during sideways falls were measured using three-dimensional motion analyzer.

2. Methods

Motion analysis of free falls

A total of 40 male and 40 female students participated in the study. They stood on a platform, and began to fall by application of a horizontal force on the right side of the hip. Subjects were prohibited from performing step reactions so that they begun to fall in the left-side direction onto a sport-mat with inherent movements responding to the fall (Fig. 1). All movements during the fall were recorded on videotape, and subsequently replayed for analysis of the protective

Fig. 1 Sideways free falls. Subjects stood on a platform (A), and began to fall onto a sport-mat (B) induced by horizontal force by experimenters.
movements. We focused on certain kinds of protective movements, such as hand breaking by outstretching the arms, forward flexion, lateral flexion, and rotation of the body. These movements were expected to generally occur from some previous studies (Coutney et al., 1995; Hsiao et al., 1998). Detected protective movements were compared with each other in order to obtain an observation rate.

Measurement of impact velocities

Ten male students participated in the study for measurement of impact velocity. Subjects stood on the edge of a platform of 40 cm in height, and leaned to the left side supported at their pelvis by a rope (Fig. 2). When the tensile force on the rope reached 10% of the subject's body weight, the rope was released by a releaser connected in series to the rope. Subjects were prohibited from performing stepping and hopping reactions to consistently ensure a fall, and fell on a sport-mat 40 cm thick. We considered the following three types of falls to test the effects of flexion. (1) Stiff fall: a fall from a standing upright position onto the mat keeping the same posture, regarded as the worst situation, (2) forward flexion fall: flexion of the knee and hip joint and a bending of the spinal column to form a crouching posture, which is expected to reduce the standing height, (3) lateral flexion fall: a bending of the spinal column directed to the right side in addition to the flexion of the knee and hip joints, which separates the head from the floor. If the subjects could not complete these planned movements of the fall, they had to try again until they succeeded.

To use a three-dimensional motion analyzer (FRAM DIAS II: DKH), seven reflective markers were attached on the vertex, acromion, elbow, wrist, greater trochanter, knee, and malleolus. All markers, except the head, were put on the left side of the body. All trials of the fall were recorded, from the release to the resting of the body on the mat, onto videotape with a three-camera system at 60 frames per second. Three-dimensional coordinates of the each point were calculated from two-dimensional data obtained through three cameras of the motion analyzer.

Three parameters were obtained from three-dimensional coordinates to indicate the characteristics of each configuration of the fall. First, a vertical velocity of each point was calculated at the moment of the contact on the mat surface. Second, an angle of the knee joint was obtained from three-dimensional coordinates of the greater trochanter, knee and malleolus. Third, a head-ankle distance was determined by measuring the distance between the head and malleolus.

Statistical analysis

Means and standard deviations of the impact velocity for 10 subjects were calculated in each fall type to analyze the effect of movements during falls. A variance analysis was used to find out the effect of the movements on the impact velocity. In the case that a significant effect was found by the variance analysis, a paired $t$-test was performed on the each item. To examine the relation of the impact velocity and posture during fall, correlation coefficients of the impact velocity versus the angle of the knee joint, the angle of the hip joint, and the head-ankle distance were calculated from the three-dimensional coordinates of each point. All statistical analyses were based on a significance level of $p=0.05$.

3. Results

(1) Motion analysis of protective movements during sideways falls

Table 1 shows observation rates of each protective movement during free sideways falls. Forward flexion was frequently observed as well as body rotation and hand breaking. The observation rate of forward flexion was 90%, which was the highest rate among all of the falls. The hips of all fallers contacted the surface of the mat, which was placed at the floor level, while the heads of the fallers contacted the mat in only 31% of cases.

<table>
<thead>
<tr>
<th>Protective movement</th>
<th>Observation rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand touching the floor</td>
<td>76</td>
</tr>
<tr>
<td>Frontal flexion</td>
<td>90</td>
</tr>
<tr>
<td>Lateral flexion</td>
<td>76</td>
</tr>
<tr>
<td>Body rotation</td>
<td>58</td>
</tr>
</tbody>
</table>

(2) Effect of the type of the fall on impact velocity

Figure 3 shows means and standard deviations of impact velocities for the head and hip in each type of fall. For the head, the impact velocity was highest in the stiff fall, followed by the forward flexion fall, and lowest in the lateral flexion fall. The effect of falling type was statistically significant by variant analysis ($p<0.05$). On the other hand, there was no significant difference in the velocity of the hip among the three types of falls.
(3) Relationship between impact velocities and posture during falls

The impact velocity of the head decreased in proportion to the reduction in the head-ankle distance. Figure 4 shows the relationship between impact velocities of the head and (A) the angle of the knee joint, and (B) the angle of the hip joint. The correlation coefficients between them were 0.35 ($p < 0.05$) on the knee joint and 0.39 ($p < 0.05$) on the hip joint. Figure 5 shows the relationship between impact velocity and the head-ankle distance. The correlation coefficient was 0.43 ($p < 0.05$). On the other hand, none of the correlation coefficients between impact velocities of the hip and joint angles were significant.

4. Discussion

In the first step, expected protective movements during free falls from standing height were observed in many cases. Forward flexion and lateral flexion were observed with an especially high frequency. Forward and lateral flexions are thought to lower the falling height from the floor, and consequently reduce the impact velocity. Furthermore, lateral flexion is believed to keep the head from impacting the floor during falls. These are considered to be largely unconscious movements, and in our study they may have been partly induced by fear of falling. Because all falls were performed in a laboratory, they are different from actual falls in daily life. In an actual fall, the faller cannot anticipate when, where and how a fall might occur. And in general falls occur in an instant: less than 1 second. Hence, it is impossible for fallers to accurately simulate actual falls in the laboratory, especially those of the elderly. However, fallers seem to perform nearly natural movements, despite the fact that they knew they were about to fall. One reason for this may be that fallers felt a fear of falling, and performed the expected responses described in previous studies.

In the second step, the actual effects of forward and lateral flexion on the severity of falls were examined by measuring impact velocities in three types of falls. Both the forward flexion and lateral flexion falls reduced impact velocities of the head compared to of the stiff fall, which is not thought to entail any protective movements. On the other hand, the impact velocity of the hip was not affected by falling conditions. It can
be concluded from these results that reactive movements during falls perhaps protect the head rather than the hip. It is thought that protective movements occur as a reflex in fallers, because injury to the head is more serious than to the hip to survival.

Impact velocities of the head were related to body postures during falls. During forward flexion, the vertebral column and joints of the leg are bent, resulting in a reduction in the height of the head and hip. Our results similarly showed that the reduction of impact velocities of the head corresponded to the head-ankle distance and angles of the hip and knee joints. However, our results did not show a reduction in impact velocity of the hip. It is supposed for this reason that the knee joint did not bend sufficiently. This means that the upper part of the body is mainly bent during forward flexion and lateral flexion falls in our experiments. It may be difficult for fallers to bend the whole body when they are conscious of the flexion. There was no difference in influence between forward and lateral flexion on reduction of the impact velocities. Although lateral flexion is assumed to moderate a fear of falling, the actual effect as a protective movement is probably not larger than forward flexion.

The present study has some limitations. First, although the ultimate purpose of the study was to examine falls in the elderly, our results were obtained from young men and women. However, it is not possible for the elderly people to participate in fall experiments because of the inherent danger of injury. Second, our experiments were performed in a laboratory, which is quite different from actual falls because of the presence of a mat and the anticipation of the fall. However, it is impossible to accurately and completely reproduce actual fall conditions in a laboratory. Hence we planned an experimental that was to obtain basic biomechanical data to ascertain what sort of falling conditions might result in more serious injury in the elderly.

**Conclusions**

1. Flexion is commonly observed during sideways free falls.
2. Flexion reduces the impact velocity of the head, but not of the hip.
3. Impact velocity of the head is related to the crouching posture of the body.

**References**


