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# EFFECT OF FALLING DOWN POSTURES ON HUMAN INJURIES BY MULTI-BODY DYNAMIC SIMULATION USING OPENSIM

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Abstract. *As most previous studies on human falling down have been executed by experimental dummy tests, expensive instruments and complex configurations of the research environments are required. To decrease the cost of these experimental tests, it is necessary to develop prediction method for the body injuries caused by falling down through computer simulation. The purpose of this study is to investigate the effect of falling down postures on human injuries by computer simulation. To analyze falling down, the biomechanical analysis software OpenSim was used to rebuild a human model by Gait2354 (bone and muscle) model. Since body tissue cannot be included in dynamic simulation in OpenSim, contact points were added into appropriate part of the body model to imitate the effect of cushion of body structure. The kinematic characteristics of head during falling backward and forward were finally obtained by OpenSim and head injuries were evaluated by the acceleration on center of head. It was concluded that the head injury characteristics of different falling postures can be evaluated by comparing the kinematic results of different falling.*
**Keywords:** Computer simulation, OpenSim, Falling down, Injury evaluation

1. **Introduction.** Falling down is a sudden, involuntary, and unintentional change in body position that hits the ground or a lower surface. As a common and inevitable phenomenon, falling down has become the second leading cause of accidental death. It is estimated that one out of every three older adult individuals report a fall at least once every year of which 20% have serious consequences [1].

In order to predict injury scientifically and have better-targeted treatment after falling down, it is important to study the damage caused by falling down. In previous studies related to the injury by falling down, Tarabini et al. [2] analyzed the fall kinematics by means of accelerometers placed on head and torso of a crash test dummy, which was used for fall experiments. However, expansive experiment equipment and effort to set up experiment conditions are needed for these experiments. Moreover, the dummy's posture was kept by the additional mechanical structure, and its variables are difficult to be controlled accurately. There are also many errors for operating the dummy's falling down. Compared with these traditional dummy experiments [2-7], the force and kinematic characteristics of the human body model for falling down can be obtained quickly by using biomechanical simulation software. Mortensen and Merryweather [8] applied the OpenSim to simulating a head impact dynamically caused by falling down on the compliant floor. And the HYOID model including hyoid muscles and head neck bone was used to investigate the protective effect of neck muscles on the acceleration and force of the head during the impact. Vieira et al. [9] used OpenSim for investigating the ankle injury of a model equipped with AFO (ankle-foot orthosis) when it falls to the platform. They used the model named "ToyLandingModel" including the head, torso and lower limbs. In

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their paper, OpenSim was used to investigate effects of passive AFO, muscle reflexes, and muscle synergistic activation during ankle varus on the risk of injury. The applicability of the OpenSim to obtain the biomechanical falling impact was validated. On the other hand, due to the lack of contact points and insufficient degrees of freedom of the model joints, the effects of the model's postures on the falling impact could not be evaluated well.

In order to better understand the biomechanical and kinematic characteristics of the human body when it falls, in this study, OpenSim was used to simulate whether the body structure impacts the ground earlier or later than the head during falling down, which simplifies the complex specific situations. In addition, the falling injuries such as HIC are evaluated by obtaining the force during the fall process, and they are compared with the previous experimental results using dummy for this validation.

This paper is composed of 4 sections starting with the introduction. The method of this study is mainly described in Section 2. The simulation results of kinematic characteristics of the human body model when falling with various postures by the above method are shown in Section 3. Consistencies of the simulation results with reality are also discussed in Section 3. Finally, the concluding remarks on this investigation on falling simulation by OpenSim are described in Section 4.

## 2. **Method of Multi-Body Dynamic Simulation for Falling Down.**

2.1. **Multi-body model.** Once the possible injury is predicted by the force value and the distribution obtained in the simulation results, comprehensive treatments can be done by the medical staff, and recovery guidance is given to patients more scientifically. There is much well-known biomechanics software such as LifeMOD, AnyBody and OpenSim, but most of them are expansive commercial package software except OpenSim, which is one of the practical open-source software for research on falling simulation [10,11].

To simulate the falling process of the human body model as realistically as possible, the musculoskeletal Gait2354 model including the head, torso and lower limbs was used in the previous study [12]. As this Gait2354 model has only muscles, bones and internal force settings, it is difficult to investigate real falling postures by OpenSim. In this investigation, to take account of the effect of interaction between the model and ground during falling, more contact points should be added by using our proposed model. Figure 1 shows the comparison between the Gait2354 and our proposed model. From this figure, it is easily found that our proposed model has additional points on head, neck, chest, back, hip, knee and foot.

In the previous study, the markers in the musculoskeletal model are usually served as the reference coordinate when the motions are imported. In addition, the three-dimensional position is recorded by another function of markers during simulation. In this paper, kinematic characteristics of the model can be obtained by adding markers on every part of the model. Especially the marker for the kinematic characteristic of head is located on the mass center of the head.

2.2. **Falling simulation using multi-body model.** The falling from a standing state is caused by instability of human body and gravity. In the OpenSim simulation, the instability of human body can be represented by inactive muscles, which will not be actively contracted or expanded. Usually, there are no external forces during the falling caused by instability. The angle between the standing human body and the ground is preset to simulate the instability of the human body.

The proposed model contains 23 degrees of freedom. Various initial postures can be changed by adjusting the degrees of freedom. During falling, the human body's head is the main contact point for the impact of the ground, and the injury occurs. Moreover, the posture of falling can be set up by adjusting the configuration of degrees of freedom.

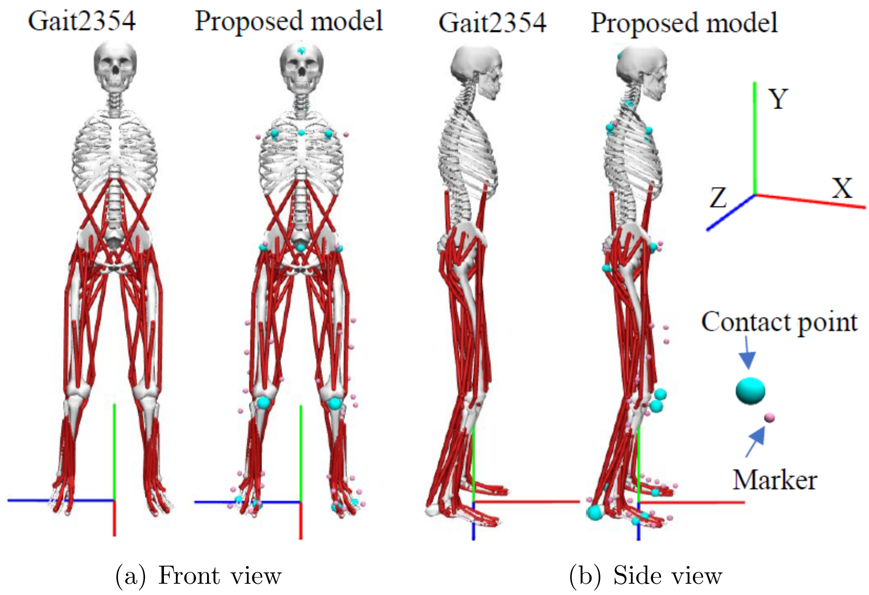


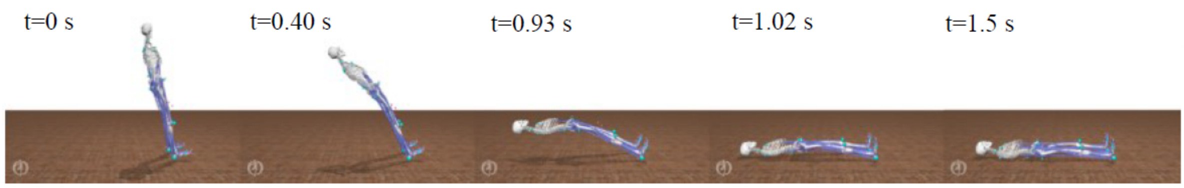

FIGURE 1. Comparison between the Gait2354 and the proposed model

For example, if the degrees of freedom of the hip are locked when falling backward, the head will directly impact the ground without a hip bent. Otherwise, the hip may hit the ground firstly and partly absorb the impact.

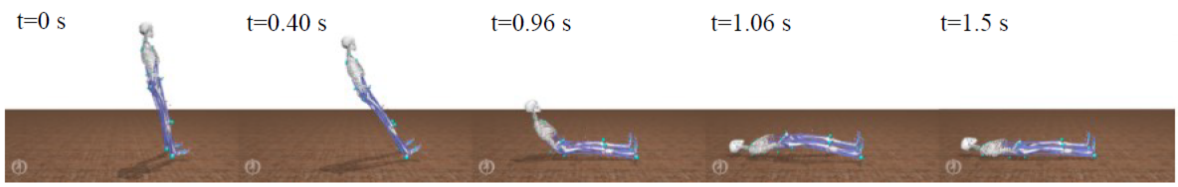
When the falling simulation starts, the model will start falling under gravity by the preset angle between the model and the ground. In the falling process, the bones, muscles and joints of the body in the musculoskeletal model will be computed by the falling simulation with adjusting the mutual position and mechanical relationship in the model. Due to the human body structure, there are tendencies to fall forward or backward when losing stability. As the most life-threatening injuries caused by falling are falling forward craniocerebral injury or backward one, they are two cases. And there are only two possibilities of head landing first or head landing later. Then, four cases of motions in this study were proposed in order to simplify the complicated situations, and they are falling backward without (Case A-1)/with (Case A-2) rotation on hip, and falling forward without (Case B-1)/with (Case B-2) rotation on the knee. These four models correspond to the actual fall situation and the biomechanical characteristics of the model.

3. **Results and Discussion.** Figure 2 shows two situations of falling backward without and with rotation/band in the hip. The state of falling backward without (Case A-1) rotation/bend in the hip is shown in Figure 2(a). Since all the structures of this model are designed and connected by the pelvis, the initial pelvic inclination angle of this posture is set to be 7°, and the degree of freedom of lumbar extension is locked. The state of falling backward with (Case A-2) rotation/bend in the hip is shown in Figure 2(b). The initial pelvic inclination angle of the standing posture is also set to be 7°. Considering that it is necessary to simulate the situation in which the hip may firstly hit the ground during realistic falling, the initial value of the lumbar extension is set to be 0° with allowing the lumbar extension.

Figure 3 shows two situations of falling forward without and with rotation/band in the knee. The state of falling forward without (Case B-1) rotation/bend in the knee is shown in Figure 3(a). To simulate falling forward, the initial pelvic inclination angle of the falling posture is set to be −15°. Since the head directly impacts the ground, the degree of freedom of the knee is locked. The state of falling forward with (Case B-2) rotation/bend in the knee is shown in Figure 3(b). The initial pelvic inclination angle of this fall posture is also set to be −15°. Since it is necessary to simulate the situation in

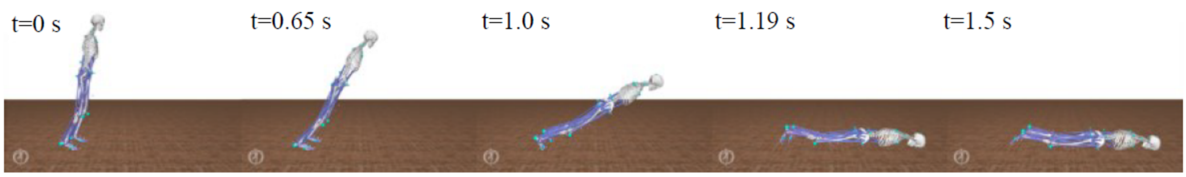



(a) Case A-1: Falling backward without rotation/bend in hip

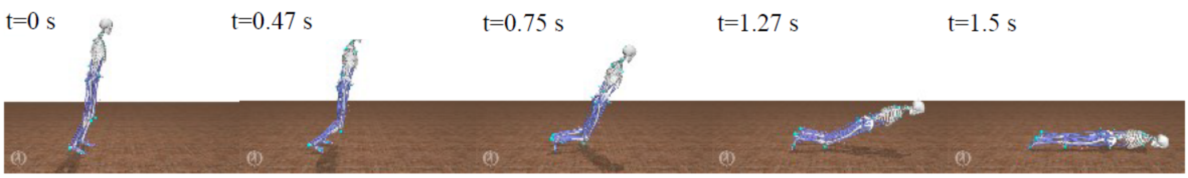



(b) Case A-2: Falling backward with rotation/bend in hip

Figure 2. Process of falling backward




(a) Case B-1: Falling forward without rotation/bend in knee




(b) Case B-2: Falling forward with rotation/bend in knee

Figure 3. Process of falling forward

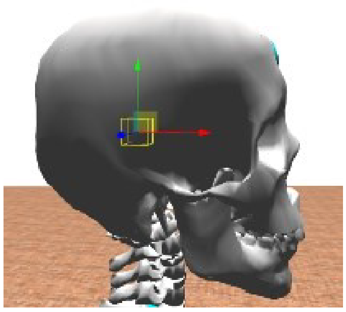


Figure 4. Marker in the center of head

which the knee may firstly hit the ground during real falling, the initial angle of the two knees is set to be 15° with allowing the knee to bend.

When using OpenSim to simulate falling with various postures, the kinematic characteristics of each part of the model can be obtained by markers in the corresponding part. In this study, the position of the head is tracked by added markers.

Figure 5 shows the location of the head center during falling simulation. By this location history, the acceleration of the center of the head in Case A and Case B can be calculated.

Figure 6 shows two acceleration situations of the head center during falling backward with/without bend in hip. The figure shows that head impact's time in the case of Case

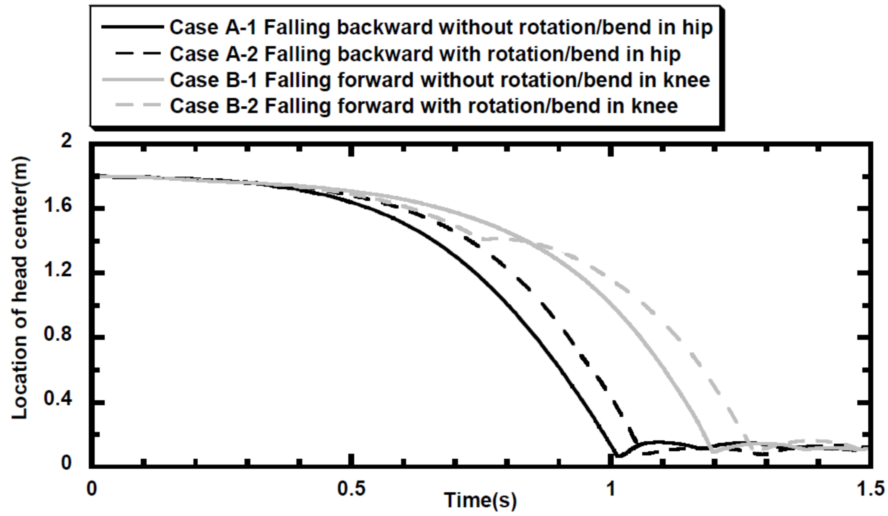



Figure 5. Location of head center during falling simulation

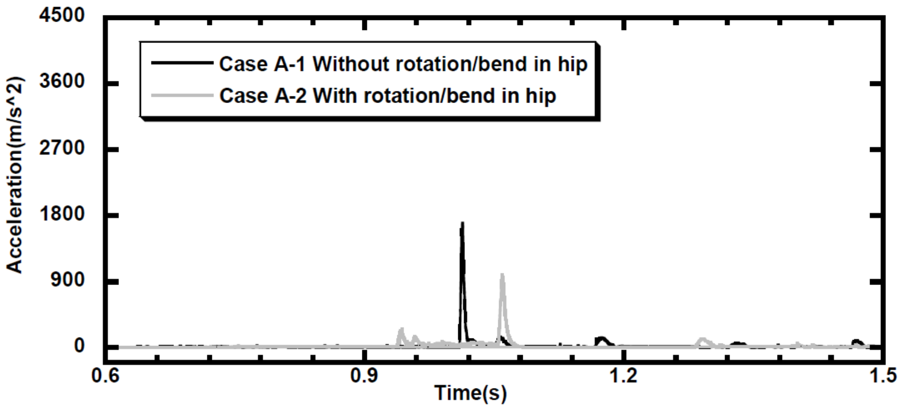



Figure 6. Acceleration of the head center during falling backward with/without bend in hip (0.6 s ∼ 1.5 s)

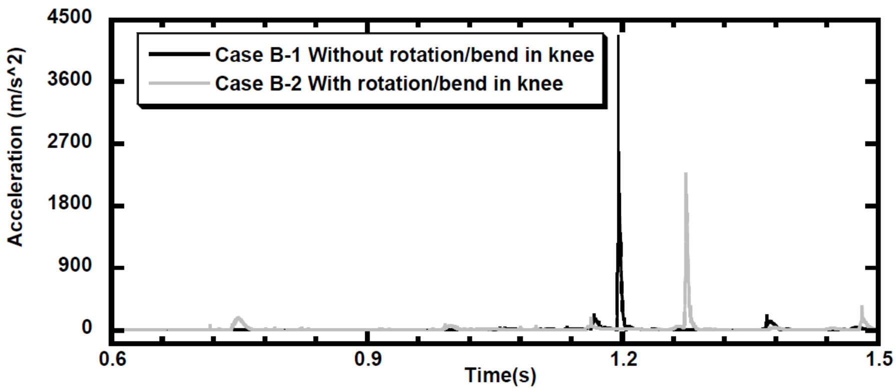



Figure 7. Acceleration of the head center during falling forward with/without bend in knee (0.6 s ∼ 1.5 s)

A-2 is 0.047 s later than that in the case of Case A-1, and the peak acceleration of the head was about half of that in Case A-1. In other cases, Figure 7 shows two situations of acceleration of the head center during falling forward with/without bend in knee. From this figure, it is found that head impact's time in the case of Case B-2 is 0.08 s later than that in the case of Case B-1, and the peak acceleration of the head was about half of that in Case B-1.

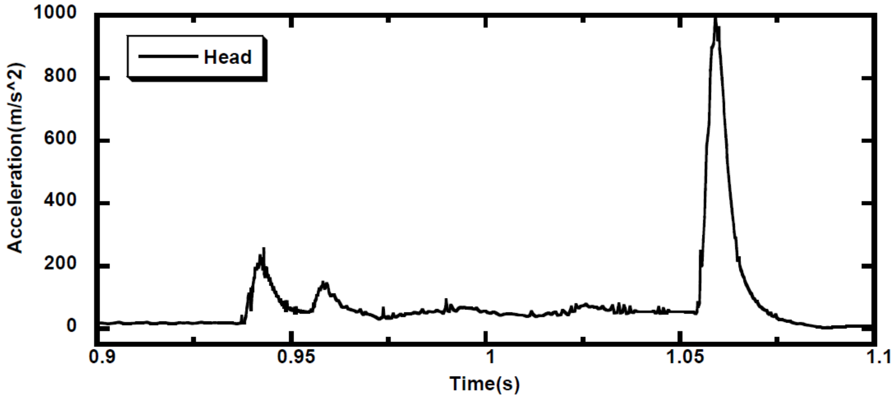



FIGURE 8. Acceleration of head 0.9 s ∼ 1.1 s in Case A-2

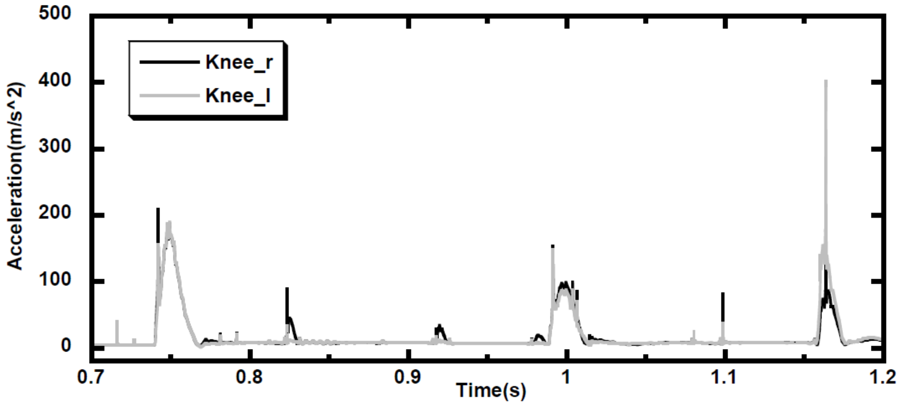



FIGURE 9. Acceleration of two knees 0.7 s ∼ 1.2 s in Case B-2

TABLE 1. HIC of various falling postures (10 ms)

| Falling cases | HIC |
|---|---|
| Case A-1 | 468 |
| Case A-2 | 255 |
| Case B-1 | 1009 |
| Case B-2 | 515 |

Figure 8 shows the acceleration of head 0.9 s ∼ 1.1 s in Case A-2. It is found that the torso absorbs the impact force and the acceleration of the head after the hip's first touch of the ground at 0.94 s. Besides, Figure 9 shows the acceleration of two knees 0.7 s ∼ 1.2 s in Case B-2. It is found that there are several reboundings, which release part of the impact to the head, after the knee hits the ground for the first time in 0.74 s.

Generally, head injury is the biggest damage to life in falling accidents. Head Injury Criteria (HIC) [13] is usually used to evaluate the damage of head impact, which can be obtained by using the linear acceleration of the head center. A reduction in HIC means a reduction in the risk of head injury. According to Figure 6 and Figure 7, the HIC of falling backward and falling forward (various falling postures) are calculated as shown in Table 1.

The effectiveness of OpenSim investigating falling in different postures was indicated because the peak acceleration when the head impacts the ground was comparable to the values in previous studies. Fanta et al. [14] used a dummy experiment in their study and found that the head's peak acceleration is between 1176 $m/s^2$ and 3175.2 $m/s^2$ when the model falling backward. The accelerations of the head when falling backward in our study are 943.6 $m/s^2$ and 1613.9 $m/s^2$. The relatively lower value can be attributed to the variation of initial postures and the stiffness of the ground. As for the case of falling forward, the acceleration is generally higher than that in the case of falling backward. When falling backward, a part of the impact can be absorbed by the hips and the entire back. However, when falling forward, only two knees can partly absorb the impact with a slight range rebound. Additionally, the trends of HIC agree with that in previous dummy experiments, and the difference between the values may be caused by time step. OpenSim has better performance for a single impact when falling, but multiple impacts are difficult to be accurately simulated. The reason may be that mechanical properties of human tissue cannot be considered by OpenSim. In this paper, several contact points on the torso (mainly on the back and chest) were added to simulate the effect of human tissue in absorbing impact during multiple impact situations. Then the problem of accuracy in multiple impacts was solved by our newly proposed model.

4. **Conclusions.** In this study, a human musculoskeletal model with biomechanical characteristics was used for falling simulation by OpenSim. Falling simulations in various postures were well simulated by adjusting the degrees of freedom of the different joints of this model. The following matters are concluded.

1) To make the falling effect more accurate, several contact points were added to the torso with confirming the cushioning effect of the body structure during falling.
2) The biomechanical and kinematic characteristics of the model when falling with changing postures were obtained by simulation on four types of falling motion. The results agree with the one in the previous investigation and actual situation, and the effectiveness of falling simulation by OpenSim can be suggested.

This study supports OpenSim as a promising tool for investigating the effects of posture changes during falling. In the future, the effects of the wide range of postures on older adult, and the risk of injury will be predicted by this proposed method. In addition, the detailed behavior of stress and strain in the brain for falling down will be analyzed with actual geometry and mechanical properties by Finite Element Method (FEM).

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