Longitudinal Rollover Strategy as Effective Intervention to Reduce Wrist Injuries During Forward Fall

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***Abstract*—Strategies for reducing fall-related injuries have been assessed through biomechanical studies and employed in robotics. A better understanding of the mechanism of such fall arresting methods can help fall prevention programs to reduce injuries and help robots to prevent damage to themselves. Rollover about the longitudinal axis is an effective strategy to reduce the impact force experienced by the hand and consequently reduce the associated injuries; however, neither biomechanical researchers nor roboticists have studied this useful fall arresting strategy. This study was designed to investigate the impact force experienced by the human hand during a forward fall using the longitudinal rollover strategy. We designed a series of fall experiments in which the subjects were instructed to arrest a forward fall using longitudinal rollover and bimanual strategies. The experimental results showed that during a forward fall, longitudinal rollover considerably reduces the impact force and the risk of injuries. The kinematic data of motion were measured and presented. A comparison of our method with various forward fall arresting methods reported so far in the existing literature showed that our proposed fall arresting strategy is one of the most efficient techniques. Our study results are expected to provide robotics researchers with useful data to design algorithms to reduce robot damage during falls.**

***Index Terms*—Human detection and tracking, humanoid robots, impact force, longitudinal rollover strategy during a forward fall.**

I. Introduction

HUMANOID robots are being increasingly used in environments designed for humans. Thus, motion planning for unknown [1] and nonoptimal environments such as uneven terrains [2] has attracted the attention of researchers. Environmental factors such as tripping over obstacles or collision with objects may endanger the balance of robots, which can lead to a fall. Such incidents can damage the robots severely.

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To reduce the risk of humanoid robot damage, various methods have been introduced, such as multiple contact point algorithms [3], [4], fall direction changes [5], [6], an active shock-reduction motion technique [7], and optimization methods [8]–[11]. Design approaches have proposed mounting some hard components [12] or impact-absorbing spots on colliding body segments [13], [14]. Recently, human-based methods have also been employed to reduce the risk of robot damage. The pattern of human motion during a backward fall has been applied to a humanoid robot model [15]. The results are promising for ensuring a safe backward fall while reducing the impact velocity considerably.

The idea of providing an active compliance mechanism for robots has also been inspired by human motion [16], [17]. This mechanism is based on the concept of unlocking the joints of robots and using the arms to function in a manner similar to those of a human to maximize shock absorption. In this technique, the scenarios both before and after ground collision are considered by the algorithm, and the results show that the proposed method works efficiently. Human-inspired fall algorithms have also been applied to humanoid soccer robots [18] to predict the fall in the shortest time, recover the robot motion, and use joints to dissipate the energy generated at impact. To apply such algorithms to real robots, the human motion should be studied and quantified. Thus, further investigation on human fall arresting strategies is necessary.

A wide range of studies have been conducted to explore the biomechanical factors affecting the impact forces and the strategies to reduce fall-related injuries among humans. During a forward fall, an impact force profile is imposed on the hand, including a primary high magnitude peak (fmax1) occurring shortly after the contact followed by a secondary lower peak (fmax2). Fall experiments may endanger subject safety because of the high risk of injuries. Thus, the impact force during a fall from a standing position is predicted by a mathematical model [19]. The simulation results show that a human fall with a locked elbow structure imposes the highest peak impact force and should be prevented.

Biomechanical studies have focused on finding interventions to reduce the impact force. Compliant flooring and protective devices are considered effective interventions to reduce the impact force and consequently the level of injuries [20], [21]. The body configuration can considerably affect the impact force experienced by the hands [22]. Thus, the natural reaction of the human during a falling motion [23] plays an important role in preventing injuries. A typical fall arresting strategy includes the use of the upper extremities to break the fall using two hands and thereby protect the head [24]. Some interventions have been proposed to reduce the impact force based on a bimanual forward fall.

A falling person has only 500 ms to change the body configuration prior to impact [25]. A reduction in the initial elbow angle prior to the impact has been identified as a practical strategy for decreasing the peak impact force and the risk of injuries. This finding has been supported by both performing experiments and using a biomechanical model [26]. The impact force is also considerably affected by the impact velocity. Thus, decreasing the relative velocity between the upper extremities and impact surface attenuates the peak impact force [27].

In addition, elbow flexion after impact produces a lagged and reduced peak impact force [28]. This strategy is more efficient than shoulder joint flexion [29]. Experimental results indicate that an extra shear force is experienced by the shoulder joint during a forward fall with an externally rotated forearm posture and a locked elbow; however, an internally rotated forearm configuration reduces the risk of injuries [30].

The utilization of martial arts and judo techniques to reduce injuries during falls has been studied. Such techniques are mainly based on sideways and backward falls and have produced a 30% reduction in the hip peak impact force [31]. The squat response can also reduce the hip peak impact energy by up to 43% [32]. Forward fall arresting strategies using martial arts include a body rollover to reduce the risk of hip and shoulder injuries. According to such techniques, to break a forward fall, the body should be rolled over the scapula of the ipsilateral shoulder. This technique is highly risky for the hip and shoulder and additionally endangers the neck and head [33].

Fall studies have received considerable attention from sport injury researchers. A few studies have investigated the risk of fall injuries in sports such as inline skating and introduced strategies [34] such as the use of wrist guards to reduce fall-related injuries [35], [36]. Rollover about the longitudinal axis is an effective strategy to reduce injuries during a forward fall in inline skating [37]; however, to the best of the authors' knowledge, previous studies have not investigated this strategy.

In this study, we aimed to compare the longitudinal rollover and bimanual strategies. To determine whether fall arresting strategies affect the impact force, the following null hypothesis was tested: the application of the bimanual and longitudinal rollover strategies would not considerably change the peak impact force experienced by the hand (i.e., the bare hand and the hand equipped with a wrist guard). To test the hypothesis, some forward fall experiments were performed and the subjects were instructed to arrest the forward fall using the bimanual and longitudinal rollover strategies. A comparison of the impact forces revealed that the application of the rollover strategy considerably reduced the impact force and the risk of injuries. Moreover, electromyography (EMG) data associated with the peak impact force showed the reduced muscle activities using the rollover technique. Kinematic data were obtained for the longitudinal rollover strategy. This study not only explores an efficient fall arresting strategy to reduce fall-related injuries but also provides useful kinematic data that can be used to manage the fall motion of robots.

II. Materials and Methods

A. Participants

Six healthy young male subjects participated in this study. Their ages ranged between 20 and 38 years (mean $\pm$ standard deviation [SD] $= 25.5 \pm 5.5$). Their average heights and weights were 173.1 ± 5.9 cm and 68.3 ± 11.5 kg, respectively. None of the subjects had any records of major medical or neurological illnesses or movement disorders. All of them were right handed, and one of the subjects was a professional inline skater. The subjects were trained to arrest a forward fall using the bimanual and longitudinal rollover strategies. All the subjects provided written consent before the experiments. This study was conducted with the approval of the Institutional Review Board of Nagoya University, Japan. All the experiments were performed in accordance with the approved guidelines.

B. Experimental Protocol

The subjects were instructed to kneel on a soft surface while maintaining an upright posture. They were instructed to extend their hands forward while keeping the back straight. The subjects were free to choose their preferred elbow angle. They were asked not to bend the upper torso backward or forward. Two force plates (M3D Force Plate, Tec Gihan Corp., Japan) were mounted in front of the subjects to measure the impact force experienced by each hand. The force plates were covered with soft foam paddings to prevent injuries. The stiffness of the paddings was 62.5 kN/m, which was measured using the Discovery Hybrid Rheometer (DHR-2-NA, TA Instruments, US). The muscular activity was measured by attaching three wireless surface EMG devices (Noraxon USA Inc., Scottsdale, AZ) on each set of biceps and triceps muscles. To obtain the elbow angles during the fall motion, a goniometer (Noraxon USA Inc., Scottsdale, AZ) was attached to each elbow. A motion capture system (MAC3D System, Motion Analysis Corp.) with 10 cameras and 25 reflective markers was used to measure the torso rotation and impact velocity during the fall motion. All the devices were synchronized, and the data were recorded at a frequency of 1 kHz. The full-wave EMG data were rectified and filtered using a low-pass filter with a cut-off frequency of 50 Hz. The EMG data were normalized relative to the average reference EMG values obtained from the maximum contractions of each muscle.

Two types of experiments were performed:

Experiment 1 – Bimanual strategy: The subjects were asked to rotate their bodies in the sagittal plane about the flexion-extension axis of the knees. They were instructed to arrest their fall by making the two hands land on the force plates with a motion similar to a pendulum free-fall motion. The subjects were trained to land on both their hands simultaneously. The

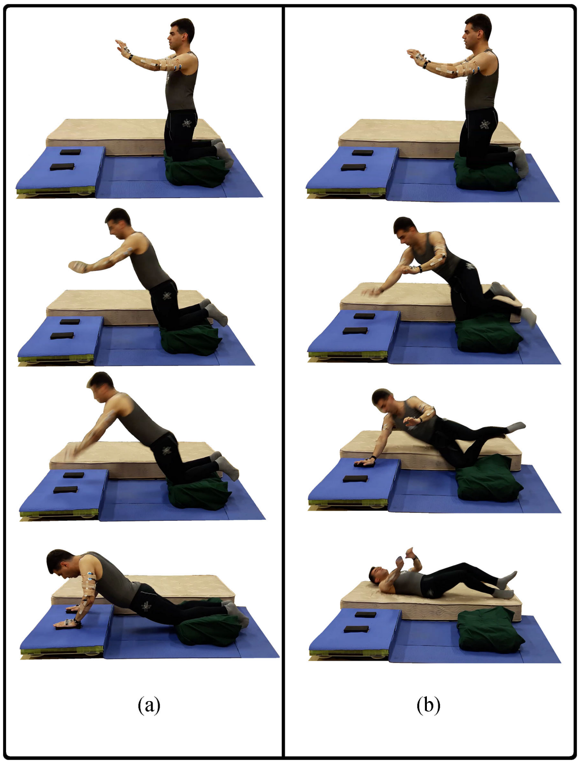

Fig. 1. Forward fall arresting motion using (a) bimanual and (b) rollover strategies. The bimanual fall arresting strategy involves body rotation in the sagittal plane and landing with both hands; however, in the longitudinal rollover strategy, the body rotates not only in the sagittal plane, but also about the longitudinal axis. The landing occurs only on the right hand.

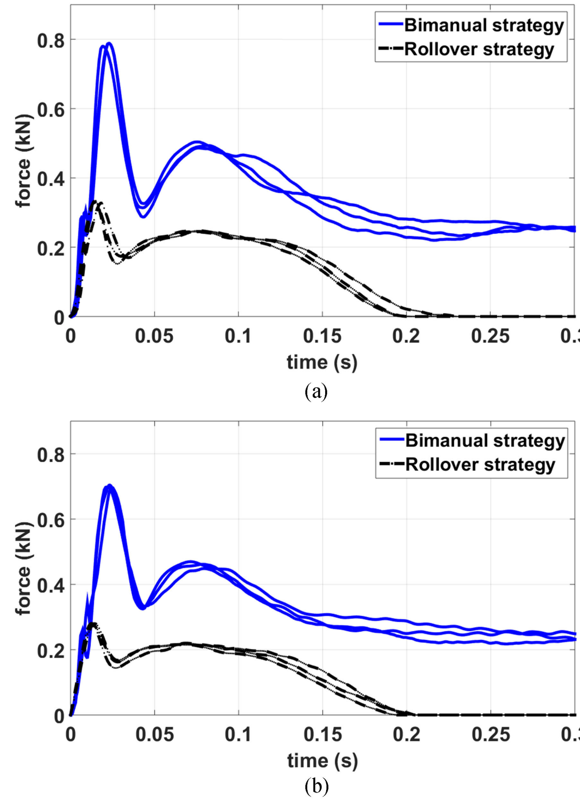

Fig. 2. Impact force experienced by hands during forward fall motion using bimanual and longitudinal rollover strategies with (a) bare hand and (b) hand equipped with wrist guard. All the impact force profiles are associated with two peaks. The primary peak has a higher magnitude and frequency, which is followed by the secondary one.

participants were free to choose the position of their upper extremity. This experiment was performed with bare hands and hands equipped with wrist guards (Fig. 1(a)).

Experiment 2 – Longitudinal rollover strategy: The subjects were instructed to rotate their bodies in the sagittal plane about the flexion-extension axis of the knees while gradually rotating their bodies about the longitudinal axis so that only the right hand made contact with the ground. The fall was broken by the right hand while the body continued to rotate and landed on the right side. To avoid any kind of injuries, a mattress was placed on the right side of the experimental setup. This experiment was performed with both bare hands and hands equipped with wrist guards (Fig. 1(b)). In this experiment, ground contact occurred first with the hands and then with the lower extremity.

The wrist guards were provided by Denso Sports Inc., Japan. Each subject performed twelve trials—six trials with wrist guards and the rest with bare hands. Initially, they were instructed to use the bimanual fall breaking technique, which is a very common reaction among people during a fall. The rollover training and the associated trials were carried out after the bimanual experiments. If the rollover training were carried out at the beginning, the training might have affected the bimanual fall arresting trials. For each fall arresting strategy, training was continued until the subjects could perform the strategy correctly. It is noteworthy that the number of training trials was different depending on the subjects and strategies. For example, performing the bimanual arresting strategy is normally easier than performing the other strategy. Moreover, all the experiments were recorded and checked by experts to verify the accuracy of motion.

To examine the null hypothesis, an independent sample t-test was performed. Here, the mean values of the peak impact forces experienced by the hand during the fall motion were compared between the bimanual and longitudinal rollover strategies. Statistical analysis was carried out using SPSS software (version 23; IBM Corporation, Armonk, NY). A statistically significant value was considered to be $p < 0.05$. The mean of the peak impact forces was summarized based on the mean value $\pm$ SD. The average left and right hand impact forces were reported.

III. Results

Fig. 2 shows a few samples of average hand impact forces associated with the bimanual strategy and the right hand impact force associated with the rollover strategy. The experiments were performed with (a) bare hands and (b) hands equipped with wrist guards. For all the impact force profiles, two peaks can be identified; the primary one has a higher magnitude and frequency, which is followed by a secondary peak. In addition to the two peaks, a trivial peak can be detected shortly after the contact (9 ± 3 ms) in the bimanual fall arresting strategy.

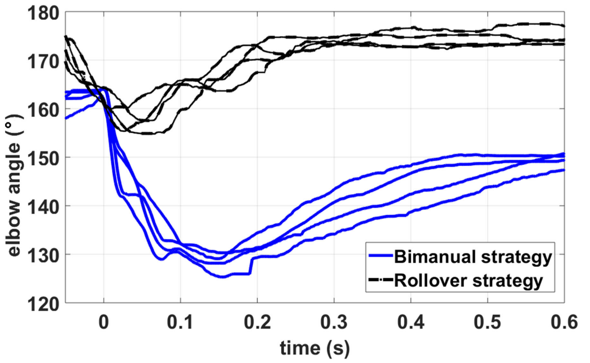

Fig. 3. Elbow angle during forward fall arresting using bimanual and rollover strategies. The graph shows the data from 0.05 s prior to the hand–ground contact.

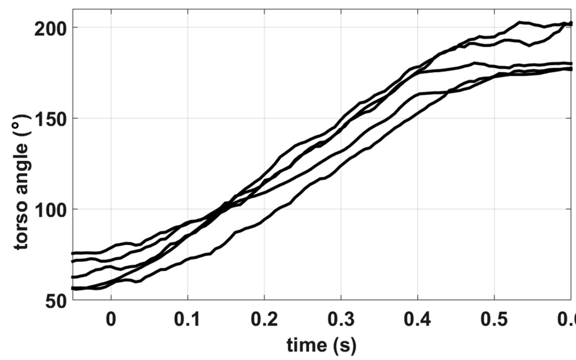

Fig. 4. Torso rotation about longitudinal axis during forward fall using rollover fall arresting strategy.

All the subjects exhibited a considerably higher magnitude of peak impact forces using the bimanual strategy: 788 $\pm$ 141 and 699 $\pm$ 135 N for the peak bimanual impact force with a bare hand and a hand equipped with a wrist guard, respectively. The application of the rollover strategy decreased the peak impact force by an average of 59% ($p < 0.002$) (331 $\pm$ 85 and 278 $\pm$ 81 N for the peak impact force using the rollover arresting strategy with a bare hand and a hand equipped with a wrist guard, respectively). It can be inferred that the impact force experienced by the hand for the bimanual strategy was approximately 117.6% (bare hand) and 104.3% (hand equipped with a wrist guard) of the body weight; however, the impact force reduced to 49.4% (bare hand) and 41.5% (hand equipped with a wrist guard) of the body mass for the rollover strategy.

The application of the rollover strategy affected the second peak by an average of 51% ($p < 0.0005$) (246 $\pm$ 52 and 217 $\pm$ 45 N for the peak rollover impact force with a bare hand and a hand equipped with a wrist guard, respectively). The peak impact force was achieved faster in the rollover technique (15 $\pm$ 4 ms) than in the bimanual fall technique (23 $\pm$ 5 ms), and the total contact time reduced to approximately 200 ms in the rollover technique.

Our experimental results replicated the previous findings that the wrist guards and compliant floorings attenuated the peak impact force experienced by the hand. The effect of the wrist guards on the first peak was higher than that on the second one, which was measured as 497 $\pm$ 89 and 455 $\pm$ 87 N for the bare hand and the hand equipped with the wrist guard, respectively, for the bimanual arresting strategy. The second peak appeared at 76 $\pm$ 6 ms. The time variation between the two hands contacting the ground was 6 $\pm$ 3 ms. This delay was negligible and less than that in previous studies [22].

Fig. 3 illustrates the variation in the elbow angle for a few exemplary trials. The impact occurred when the time was 0 s. During the bimanual forward fall, the subjects arrested the fall with an initial elbow angle of 163° $\pm$ 6°. The force experienced by the hand caused the elbow to flex up to 131° $\pm$ 17° and after breaking the fall, the elbow extended. The elbow extension started after the second peak, and the elbow angle ended up at approximately 152° $\pm$ 11°. For the rollover arresting strategy, an initial slight flexion occurred, and then, the elbow returned to the nearly fully extended position. The flexion during rollover arresting was an average of only 8° followed by an extension. The extension expedited the torso rotation about the longitudinal axis.

A few samples of the torso rotation in global coordinate system is shown in Fig. 4. The graph was obtained using the results obtained from the markers on the pelvis, shoulder, STRN, C7, and clavicle. From the initial body posture, the subjects rotated their torsos by an angle of 71° $\pm$ 12° about the longitudinal axis at the moment of contact. The torso rotation was quickened using their right hand, and the subject fell on the mattress on the right side.

The hand impact velocity was strongly associated with the impact force experienced by the hand. In our experiments, the absolute vertical hand impact velocity was estimated using the markers on the hand. The hand impact velocity associated with the bimanual strategy was 3.2 $\pm$ 0.4 m/s; however, the application of the rollover strategy reduced the impact velocity to 1.8 $\pm$ 0.3 m/s. Such results show the superiority of the rollover strategy over the bimanual arresting strategy to reduce the risk of injuries.

The EMG data were calculated as an average normalized value over a period of 50 ms, which covered the peak impact force. The triceps and biceps EMG values were 0.65 $\pm$ 0.25 and 0.62 $\pm$ 0.21, respectively, for the bimanual arresting strategy; however, the muscle activities reduced during the application of the rollover arresting strategy, with EMG values of 0.42 $\pm$ 0.18 and 0.40 $\pm$ 0.22 for the triceps and biceps muscles, respectively.

IV. Discussion

In this study, we sought to assess whether a longitudinal rollover fall arresting strategy could reduce the impact force experienced by the hand and the risk of injuries. Although wrist fracture strongly depends on bone strength, the magnitude of the induced impact force considerably affects the possibility of a fracture occurrence. Thus, we assumed that the force experienced by the hand was strongly associated with the risk of wrist injuries.

Our results provided evidence that altering the fall arresting strategy to longitudinal rollover reduced the magnitude of the impact force experienced by the hand. Thus, the null hypothesis was rejected. The most efficient strategy reported so far to reduce the hand peak impact force claimed only a 27% reduction [22]; however, our proposed arresting strategy reduced the impact force by 59%. Although our discussion of fracture risk was based on the peak impact force, one may assume that the energy absorbed by the hand was strongly proportional to the risk of injuries. From our study results, it can be inferred that the corresponding wrist energy absorption during the rollover strategy diminished because of an earlier peak with a smaller magnitude.

One advantage of our study was the use of human subjects, whose motion data were obtained through a series of safe experiments in which the depicted motion was similar to real human fall motion. In the bimanual arresting strategy, we found the body configuration to be unnatural and difficult to control and instruct at impact. Thus, the subjects were allowed to choose their preferred landing posture in the bimanual technique.

The subjects were instructed to try to make contact with the ground with both the hands simultaneously. We did not observe a major difference between the impact forces experienced by the left and right hands during the bimanual forward fall. This finding reflected the fact that the bimanual fall arresting strategy was performed properly. In the rollover strategy, all the subjects were instructed to arrest the fall with their right hand. The reason for this instruction was the fact that right-handed subjects have a better capability to arrest a fall using their dominant hand.

Based on the data obtained from the motion capture system, no major difference was found between the initial postures of the subjects in the rollover and bimanual strategies. Thus, it can be inferred that although the subjects were aware of the strategy they had to apply to arrest the fall, the initial posture and consequently the results were not affected by their awareness.

The recorded fall motion of the professional skater and the other subjects were observed carefully, and no special differences were found between them. Although, it can be concluded that the training and the arresting strategies were conducted appropriately, more investigation is necessary to assure the accuracy of subjects' fall breaking motion and the initial posture.

In addition to the two peaks, we observed a trivial early peak in bimanual fall arresting. This peak can be interpreted to be caused by the effect of elbow flexion after the contact and is not considered to be an independent peak in previous studies [28]. Moreover, in our bimanual experiments, the first peak appeared later than that in similar studies [19]. The most likely explanation for this delay is the effect of using compliant flooring and the elbow flexion at impact.

The use of human subjects restricted the experiments to a safe range of impact forces. The use of a padded force plate is a common strategy to prevent injuries during fall experiments [22]. Although the impact force was considerably lower than that during an actual fall, this does not impair the outcome of this study. In our experiment, the maximum force experienced by the hands occurred during bimanual fall arresting with the bare hands (788 ± 141 N), which was below the reported measures of the wrist fracture threshold.

Previous studies showed that in forward falls, knee impact might occur considerably earlier than hand impact [38]. Thus, similar to previous studies [19], we assumed that during the forward fall, the knees contact the ground before the hands. This order of contact makes the velocity of the feet and shins to be zero and does not affect the upper extremity velocity. Moreover, previous research studies performed fall experiments from the kneeling position, claiming that the working mechanism of a fall arresting technique is similar to the mechanism of falls from kneeling and standing positions [31]. Therefore, we asked the subjects to keep their shins fixed on the ground.

To check the muscle activation, the EMG data associated with the peak impact force were calculated. Although the muscle activation rate may not change as quickly among the elderly as that among young people [39], muscle weakness is one of the most important reasons for falls. This weakness may restrain the proper arresting strategy for a forward fall. The rollover strategy, which requires lower muscle activity, can help the elderly in more easily arresting a fall.

Although our study considered only one type of wrist guard, our assessment showed that the application of the guard lowered the magnitude of the peak impact force for both the bimanual and rollover fall arresting strategies. This reduction effect was lower on the second peak than on the first peak. Wrist guards can play a major role by not only reducing the impact force but also constraining the wrist motion. Further experiments using various wrist guards are needed to confirm the effect of such preventive guards on the impact force during the rollover arresting strategy.

V. Conclusion

Only few studies have previously explored the effect of fall arresting strategies on the impact force experienced by the hand during a forward fall. The present study is the first one to quantify the effect of a longitudinal rollover fall arresting strategy on the impact force experienced by the hand and to compare the results with those of the bimanual strategy. To achieve the study objective, human subjects were hired to perform the experiments. The subjects were trained to arrest a fall motion using the bimanual and longitudinal rollover strategies through a set of forward fall experiments. The bimanual strategy is the most common technique used by humans to arrest forward falls [23].

Our results revealed the advantages of the longitudinal rollover strategy. This strategy reduces the peak impact force experienced by the hands by 59%. To the best of the authors' knowledge, this is one of the most efficient fall arresting strategies reported so far to reduce the peak impact force experienced by the hand. Although changes in the experimental conditions may vary the results to some extent, our findings are obtained using a standard and reasonable experimental condition that is very similar to an actual fall motion.

We also sought to determine the upper extremity posture during the forward fall and presented the results for the elbow angle and torso rotation to realize the longitudinal rollover arresting strategy. From a biomechanical point of view, such data can be used in fall prevention programs to reduce the risk of injuries.

The use of assistive devices has widely increased in the last few years [40]. Such devices can be equipped with special algorithms to reduce fall injuries. Our study results can provide useful data for these devices. In addition, the findings of this study are noteworthy because the obtained information can be used to enable humanoid robots to demonstrate human-like fall motion and hence reduce damage.

It is unclear as to what extent the elderly and robots can make use of the longitudinal rollover strategy successfully. Previous studies [18] have illustrated that robots can successfully cope with human-inspired techniques, and hence, our study results can be used to design longitudinal rollover algorithms for humanoid robots.

In conclusion, we have shown that altering the fall arresting strategy can considerably affect the risk of injuries. We limited our study to the bimanual and rollover strategies. Further investigations are necessary to identify other fall arresting strategies and compare their results with those of the bimanual and rollover strategies.

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