Investigation into Hand Impact Force during Forward Falls on Uneven Terrain

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Abstract

Outdoor falls predominantly occur because of environmental factors, such as tripping caused by uneven terrain; as a result, the faller may land on an uneven surface. Forward falls are among the most frequent causes of fractures. Previous investigations concentrated on the evaluation of impact forces acting on the hand/wrist on even terrains; however, further studies are necessary to evaluate the impact force during forward falls on uneven surfaces, which may occur frequently in daily activities. This study investigated the distal/proximal hand impact force during forward falls on even/uneven terrain. A series of fall experiments in which the distal and proximal areas of the hand contacted the ground simultaneously (even surface) or at different times (uneven surface) was conducted. The results showed that the magnitude of the peak impact forces acting on the distal and proximal areas are strongly associated with the terrain shape and the contact timing. Although in all experiments, a significant portion of the impact force was exerted on the proximal area of the hand, the earlier distal-ground contact reduced the peak proximal impact force significantly. The results of this study are beneficial for finding strategies to reduce fall-related injuries and the design of protective gloves and wrist guards to satisfy fracture prevention requirements.

Keywords—Forward fall; Distal and Proximal areas of the hand; Impact force; Uneven ground

1. Introduction

Mechanical perturbation such as an external force may endanger human balance during gait [1]. Elevating, lowering, and skip motions have been identified as the most common recovery strategies to maintain balance and avoid falls [2]. However, losing postural stability and failure to recover invariably results in a fall incident, which is a common cause of unintentional injuries, particularly for the elderly, owing to high risk factors [3]. Forward falls, one the most frequent type of falls [4], can result in upper extremity injuries such as wrist fractures [5].

Various researchers have conducted experiments to reproduce less severe fall motions and investigated the impact force and injuries during forward falls. For example, Chiu and Robinovitch [6] conducted free-fall experiments and developed a mathematical model supported by experimental findings to identify the impact force profile during forward falls. Their results showed that the impact force experienced by the hand is governed by an initial high magnitude peak (f_{max1}) occurring shortly after contact, followed by a lower peak (f_{max2}). Moreover, they observed that reduction in surface stiffness attenuates the magnitude of the primary peak impact force, but does not significantly affect the secondary peak [7]. However, the main limitation of their study and other similar studies [8, 9] was the inability of their models to evaluate the effect of elbow flexion on the impact force applied to the hand. DeGoede et al. [10] proposed a 3-DOF model comprising a lumped mass and two arm segments moving on the sagittal plane, and investigated the effect of initial elbow angle and impact velocity during forward falls.

Several researchers have focused on finding training programs to improve postural control [11-13] and the human reaction after losing control [14]. Although the training programs showed promising results, postural control can be different among people with different body factors [15], and always there is a possibility of fall. A falling person has less than 500 milliseconds to perform an appropriate fall strategy prior to ground contact [16]. Initial elbow flexion and reducing the velocity of the hands relative to the torso are strategies that can decrease the impact force during a forward fall [17, 18]. Further, elbow flexion movement at the time of impact leads to a delayed and reduced impact force [19] and is a more effective strategy than shoulder joint flexion [20]. Experimental results show that longitudinal rollover strategy [21] and internally rotated forearm are appropriate fall arrest strategies that reduce the risk of upper extremity injuries, whereas an externally rotated forearm can increase the risk of injuries [22]. Whereas body rotation in the sagittal plane has negligible effect on the impact force, frontal plane rotation can lead to a reduction in the impact force applied to the trailing hand [23].

Aging also affects human postural fluctuations [24] and the impact force during falls. Fall incidents occur frequently among the elderly [25] and may lead to injuries and fractures. The capacity for upper extremity energy absorption among young women is twice that of older women [26]. The force applied to upper limb joints during forward falls and the associated fractures have attracted the attention of various researchers. To identify the mechanical response of the distal radius under impact loading, human cadaveric radii are widely used and the risk of bone fractures estimated [27].

From a design perspective, the data associated with injuries are useful to develop compliant flooring, airbags and wrist guards, which is applicable in both the daily life of the elderly and sports such as snowboarding [28]. The impact force applied to the hip can be reduced using hip protection airbag [29, 30]. Evidence show that wrist guards can attenuate the impact force during forward falls [31]. The distribution and magnitude of the force/pressure over the palm of the hand also provides several guidelines for making more efficient handguards. Choi et al. [32] determined how pressure distribution over the palm of the hand is associated with padding, the impact angle of the arm, the soft tissue foam over the palm, and body mass index.

Previous studies [33] have shown that outdoor falls are more frequent than indoor falls among healthy and active older people. Of the outdoor falls, 73% occur because of environmental factors [34] such as uneven or slippery terrains. Thus, the faller may land on an uneven surface; where one area of the hand may contact the ground earlier than the other areas because of terrain irregularities. To the best of our knowledge, all previous studies investigated the different aspects of the impact forces applied to the hands under various circumstances *only on even terrain*.

In this study, we investigated the impact force applied to two areas of the hand on even/uneven terrain. We assumed the first null hypothesis that the magnitude of the peak impact forces exerted on the distal and proximal areas of the hand are the same. This hypothesis was defined to compare the peak impact forces on distal and proximal areas separately, which is necessary for studying the impact force applied to the hand on uneven surfaces. Moreover, this investigation provides an understanding about the portion of the impact force applied to the proximal area that is the cause of ulna/radius fracture [35]. Secondly, we hypothesized that the shape of the surface (i.e., even or uneven terrain) does not affect the impact force profile applied to the proximal and distal areas of the hand in all conditions. This hypothesis was designated to investigate to what extent the shape of surface (i.e. three different conditions in this paper) can affect the peak impact forces applied to proximal and distal areas of the hand. Both hypotheses and our results can provide useful information for designing effective fall arresting strategies and protective devices.

2. Methods

2.1. Participants

Twelve healthy young male subjects, ranging in age from 20 to 38 years (25.5±5.5), participated in this study. Their average height and weight were 173.4±5.7 cm and 65.9±11.5 kg, respectively. None of the subjects had previously received training such as martial arts techniques, gymnastics, Jodo, or wrestling. Moreover, they did not have any record of major medical or neurological illnesses such as epilepsy, significant hand trauma, balance disorders, or falls. All participants signed a written informed consent form prior to the experiments, and the experimental protocol was approved by the Institutional Review Board of the University. All the experiments were conducted in accordance with the approved guidelines.

2.2. Experimental Protocol

A supporting harness was fitted and attached to each subject's trunk. The participants were instructed to fix their shanks on a soft surface and extend their knees to lean forward against the harness. The thigh orientation was checked to ensure that it was set at 30º from the horizontal using a soft wedge. By pulling the supporting harness connected to the trunk, the participants were elevated to reach the proper height from the ground (Fig. 1(a)). The subjects were instructed to keep their elbows fully extended (i.e., outstretched arm). The arm angle was set at 15° from the vertical. Thus, at the moment of fall, each participant's body posture matched that used in the experimental setup considered in studies in the literature [6].

As in the previous studies, we asked the subjects to keep their hands parallel to the ground before the harness release. The experiments were designed to determine the impact forces on two parts of the hand on uneven and even terrain. We call the headmost part of the hand the distal area, including the distal palmar and fingers. The lower part starts from the middle of the proximal palmar crease, including the Thenar and Hypothenar eminences (Fig. 1(b)). To test the null hypothesis, we conducted several fall experiments in which the distal and proximal areas of the hand contacted the surface simultaneously (even terrain) or at different times (uneven terrain). The experiments were conducted based on three different scenarios:

Experiment 1: The proximal and distal areas contact the ground simultaneously. This experiment is related to forward falls on even terrain.

Experiment 2: The distal area contacts the ground followed by the proximal area of the hand. This experiment is associated with forward falls on uneven terrain.

Experiment 3: The proximal area of the hand contacts the ground first, followed by the distal area. This experiment is related to forward falls on uneven terrain.

In order to measure the proximal and distal hand impact forces, two force plates were installed under each hand (i.e. in total, four separated force plates (US06-H5, Tech Gihan Co., Ltd., Japan)). After the release of the harness, the participants fell on these force plates, which were fixed on the ground. To conduct the experiments related to uneven terrains (Experiments 2 and 3), two force plates (i.e., one under each hand) were mounted 1 cm higher or lower. For example, to perform the second experiment, the force plates under the distal areas of the hands were installed 1 cm higher than the force plates under the proximal areas. The first experiment enabled us to measure the impact force on even terrain, separately for proximal and distal areas. It is obvious that the force plates were installed at the same height for the first experiment. Three fall heights were considered at h = 2, 5, and 8 cm. The height was measured and set as the distance between the hand and the highest force plate. Each participant completed 18 trials in which there were three experiments, repeated twice for each of the three fall heights.

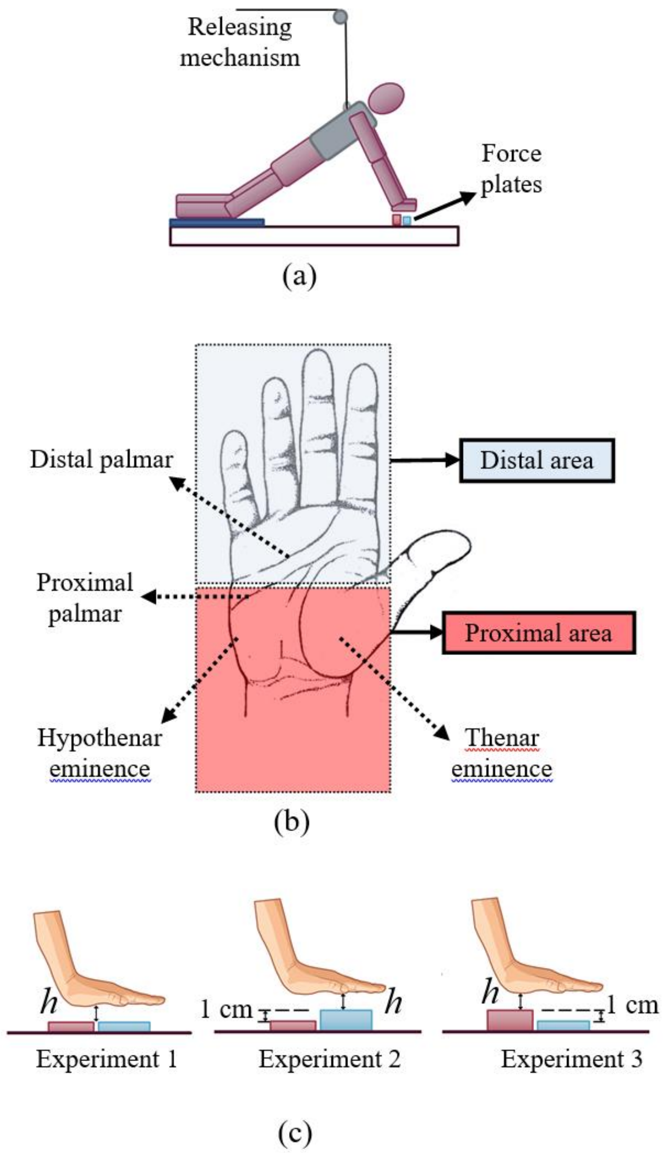

Fig. 1 (a) The experimental setup used to evaluate impact forces during forward falls on outstretched arms at heights of 2, 5, and 8 cm. (b) Two parts of the hand; distal and proximal areas. (c) Different types of experiments: Experiment 1 is associated with falls on even terrain, where both distal and proximal areas of the hand contact the

ground simultaneously. Experiment 2 is related to falls on an uneven terrain, where the distal area of the hand contacts the ground followed by the proximal area. Experiment 3 is associated with falls on uneven terrain, where the proximal area of the hand contacts the ground first, followed by the distal area.

To examine the first null hypothesis, an independent sample t-test was conducted to compare the mean values of the peak impact forces applied to the proximal and distal areas for various fall heights. Subsequently, we performed one-way analysis of variance (ANOVA) to evaluate the effect of different surface shapes (i.e., even and uneven terrain) on the peak impact forces at the distal and proximal areas (Table 1). Statistical analysis was conducted using SPSS Software (version 23; IBM Corporation, Armonk, NY, US). A statistically significant value was considered at $p < 0.05$. Moreover, a Pearson product-moment correlation was used to determine if there is a significant relation between two parameters: 1. Body mass and BMI, 2. The peak impact force.

Table 1. Experimental orders for ANOVA analysis

Experiment number	Shape of surface (Different terrains)	Hand areas which were considered in impact force measurement
1	Experiment 1 (Even terrain, h = 2, 5, 8 cm)	Proximal
		Distal
2	Experiment 2 (Uneven, distal area contacts the ground followed by the proximal area, h = 2, 5, 8 cm)	Proximal
		Distal
3	Experiment 3 (Uneven, proximal area contacts the ground followed by the distal area, h = 2, 5, 8 cm)	Proximal
		Distal

3. Results

Fig. 2 shows the average of the left and right hands' impact forces for the fall heights of 2, 5, and 8 cm on even terrain. The impact force profiles have similar trends for both areas of the hand, involving an initial high magnitude peak (f_{max1}) occurring shortly after contact, followed by a lower peak (f_{max2}). For both the proximal and distal areas, the first peak force has a significant growth rate affected by the fall height; however, the second peak rise is low. All participants displayed increasing peak impact force magnitude with increasing fall height: 194±33 N and 49±14 N for the proximal and distal areas at the 2 cm height, 313±49 N and 72±20 N for the proximal and distal areas at the 5 cm height, and 392±58 N and 90±25 N for the proximal and distal areas at an 8 cm height (Table 2).

Table 2 The peak impact forces for different experimental conditions

Fall Height	Area	Peak Impact Force Magnitude (N)		
		Experiment 1 (Even Terrain)	Experiment 2 (Uneven, distal area contacts followed by the proximal area)	Experiment 2 (Uneven, proximal area contacts followed by the distal area)
2 cm	Proximal	194±33	127±29	218±47
	Distal	49±14	75±23	43±19
5 cm	Proximal	313±49	205±42	334±56
	Distal	72±20	109±43	59±28
8 cm	Proximal	392±58	264±74	415±63
	Distal	90±25	136±54	73±30

The results of Experiment 1 show that the distal area of the hand possesses a low proportion of the total impact force during forward falls on even terrain where the distal and proximal areas of the hand contact the ground simultaneously. There is a significant difference in the peak impact forces between the distal and proximal areas; thus, the first null hypothesis was rejected. On average, about 19% ($p < 0.002$) of the total peak impact force is applied to the distal area; the remainder is exerted against the proximal area of the hand.

Fig. 3 shows the average left and right-hand impact forces for the fall heights of 2, 5, and 8 cm on the uneven terrain where the distal area contacts the force plates prior to the proximal area. Whereas the proximal area impact force includes two peaks, the distal area impact force profile is governed by three peaks. The first peak occurs approximately 6 ms after contact and the other two peaks occur at timings close to the proximal area peaks. Both the proximal and distal area impact forces were significantly affected by the fall height.

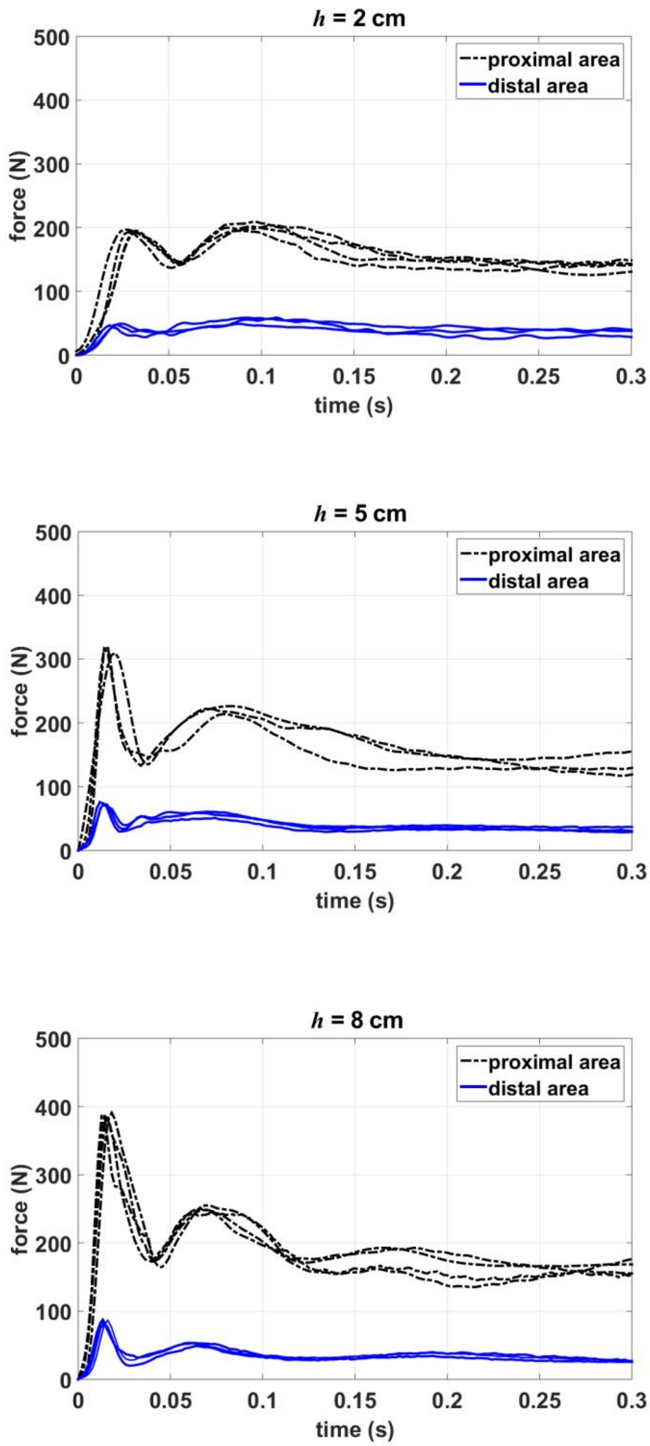

Fig. 2 Impact force profile applied to the proximal and distal areas of the hand during a fall on an even surface (i.e., both the proximal and distal areas of the hand contact the surface simultaneously) from heights of 2 cm, 5 cm, and 8 cm.

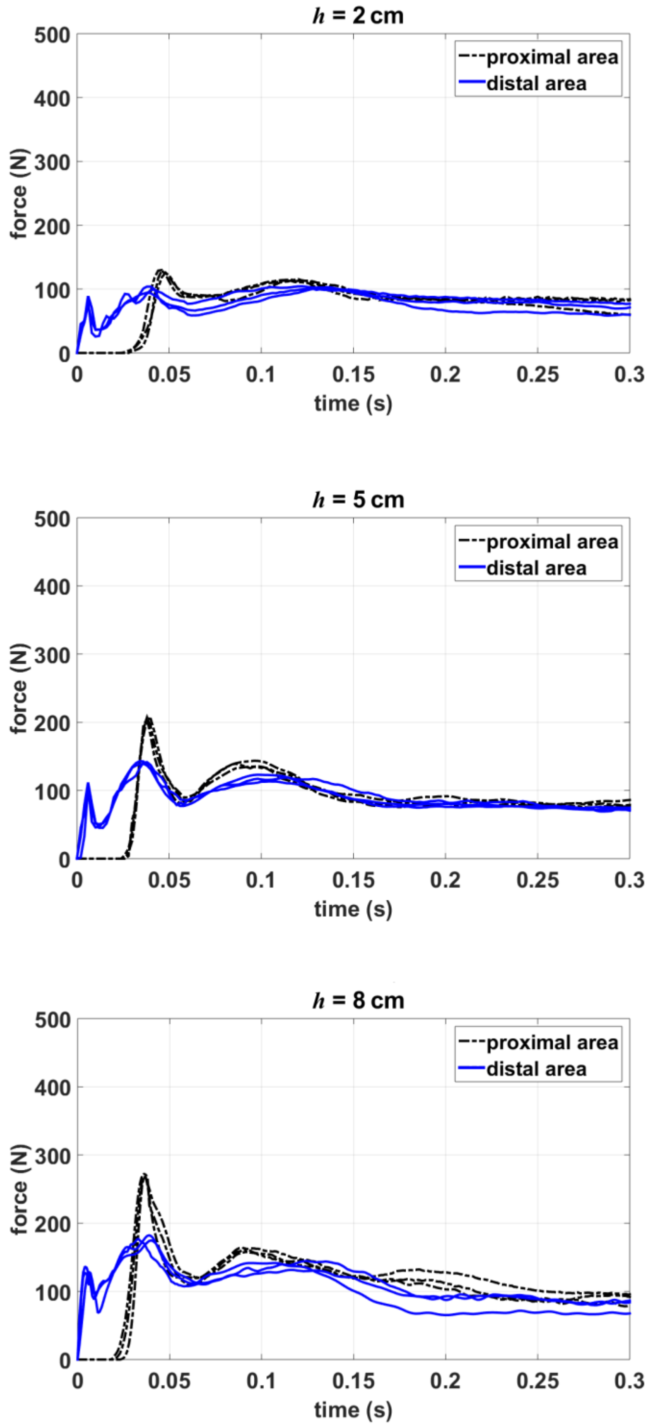

Fig. 3 Profile of the impact forces applied to the proximal and distal areas of the hand during a fall on an uneven surface, where the distal area of the hand contacts the surface followed by the proximal area from heights of 2 cm, 5 cm, and 8 cm.

All subjects exhibited a significantly higher magnitude of peak impact forces by increasing the fall height: 127±29 N and 75±23 N for the proximal and distal (i.e., second peak) areas at the 2 cm height, 205±42 N and 109±43 N for the proximal and distal (i.e., second peak) areas at the 5 cm height, and 264±74 N and 136±54 N for the proximal and distal (i.e., second peak) areas at the 8 cm height (Table 2). The average peak impact force applied to the distal area was approximately 35% ($p < 0.005$) of the total peak impact force. The magnitude of the first peak (i.e., extra peak compared to the proximal area force profile) impact force applied to the distal area displayed an increasing trend associated with the fall height: 97±31 N at the 2 cm height, 122±29 N at the 5 cm height, and 138±35 N at the 8 cm height.

The average left and right-hand impact forces for the fall heights of 2, 5, and 8 cm on the uneven terrain where the proximal area contacts the force plates prior to the distal area is shown in Fig. 4. The magnitude of the peak impact forces applied to the distal area of the hand is the highest and the magnitude of the peak proximal area is the lowest among the three types of experiments: 218±47 N and 43±19 N for the proximal and distal areas at the 2 cm height, 334±56 N and 59±28 N for the proximal and distal areas at the 5 cm height, and 415±63 N and 73±30 N for the proximal and distal areas at the 8 cm height (Table 2). The impact force of the proximal area can be characterized by two peaks; however, the distal area second peak can be difficult to recognize. On average, only 15% ($p < 0.001$) of the total peak impact force was applied to the distal area. As in other experiments, the larger fall heights induce higher peak impact forces on both the distal and proximal areas of the hand.

The secondary null hypothesis was also rejected following comparison of the distal and proximal impact forces on different terrain shapes. The ANOVA analysis revealed that there was a significant effect of surface shape on the mean value of the peak impact force at the proximal ($F(2,186) = 83.1$, $p < 0.0005$) and the distal ($F(2,186) = 34.7$, $p < 0.0005$) areas. Post hoc pairwise comparisons conducted using the Tukey HSD test indicated that the mean of the peak impact force for Experiment 2 differed significantly from that of Experiment 1 and Experiment 3. However, the average peak impact force in Experiment 1 did not significantly differ from Experiment 3 at the proximal ($p = 0.218$) and the distal ($p = 0.161$) areas.

The peak impact force applied to the proximal area for the earlier distal-ground contact is about 39% ($p < 0.001$) and 34% ($p < 0.002$) less than earlier proximal-contact and distal/proximal-ground contact, respectively.

4. Discussion

This study examined the role of surface shape on the impact force applied to the distal/proximal areas of the hand. The results obtained show that the proximal area peak impact force is significantly higher than that of the distal area for all conditions. Although a large portion of the impact force acts on the proximal area of the hand, the magnitude of the exerted forces against the distal and proximal areas are strongly dependent on the shape of the surface and the contact. In these experiments, we did not observe a significant difference between the impact forces applied to the left and right hands during the bimanual forward fall. Thus, the average left and right-hand impact forces were reported.

The experimental results show that in a fall on even terrain, only about one-fifth of the peak impact force is applied to the distal area of the hand, the rest is exerted on the proximal area. For falls on an uneven surface, the ratio between the distal and proximal forces is significantly affected by the shape of the surface. In cases of earlier distal-ground contact, the applied force on the proximal area can be substantially reduced. Conversely, if the proximal area contacts the ground prior to the distal area, the peak impact force against the proximal area may increase slightly, which is not significant.

The proximal impact forces had similar trends in all the experiments, both on even and uneven terrain, including two peaks. The magnitude of the peak impact forces in Experiments 1 and 3 are close. In contrast, the peak impact force in Experiment 2 occurs with a longer delay and is significantly lower than that of the two other experiments.

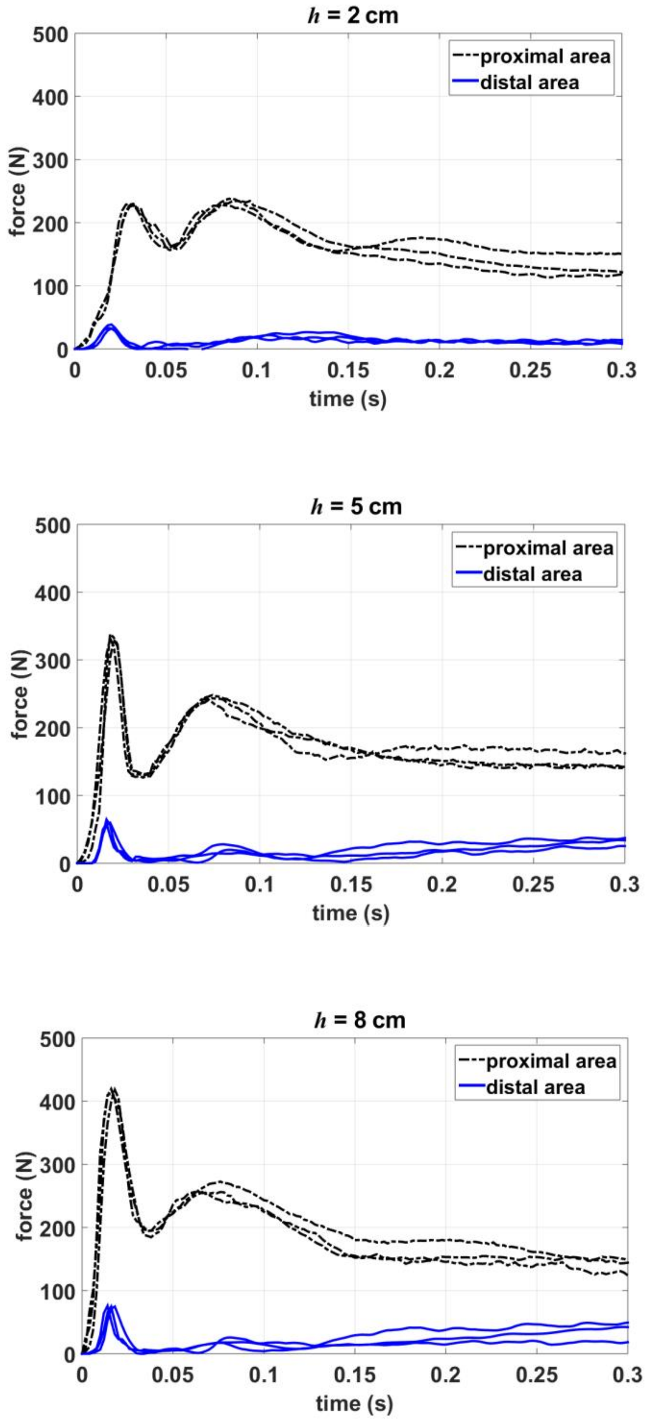

Fig. 4 Profile of the impact forces applied to the proximal and distal areas of the hand during a fall on an uneven surface, where the proximal area of the hand contacts the surface followed by the distal area from heights of 2 cm, 5 cm, and 8 cm.

Consequently, a significant portion of the impact force is exerted on the proximal area when it contacts the ground prior to/with the distal area. This factor can increase the radius/ulna fracture risk [35]. Conversely, in cases where the distal area contacts the ground followed by the proximal area, the proximal peak impact force and the fracture risk are reduced. Early proximal-ground contact can be similar to the condition in which a person falls while clenching an object in their hand. The object may be placed between the ground and the proximal area of the hand. This condition may lead to a hamate fracture [36].

Experiments 1 and 3 showed similar patterns for the distal area impact forces comprising two peaks. However, the distal force profile in Experiment 2 has a different arrangement, in which three peaks can be recognized. The difference is due to early contact between the distal area and the surface. This causes an early peak in distal area impact force profile, and then similar to experiments 1 and 3, two other peaks occur afterwards; however, in this case they are delayed (i.e., in total three peaks can be observed). Moreover, the distal early contact causes a reduction in hand acceleration, and consequently the impact force applied to the proximal area reduces. The peak distal impact force of Experiment 2 is significantly higher than that of the other two experiments. This fact shows that the early distal-ground contact leads to a higher portion of the peak impact force on the distal area of the hand and, consequently, reduction in the impact force applied to the proximal area.

Although it may seem beneficial to for the distal part to make contact prior to the proximal area in order to decrease the impact force acting on the proximal area, more studies are necessary to investigate possible injuries that may result from a large impact force on the distal area. The common design of padded gloves is predominantly targeted at covering the proximal area to reduce fracture risk. Such devices should be designed based on the impact force profiles for terrains with different shapes. The outcomes of this study can be useful for researchers investigating the design of such protective equipment to ensure their efficacy.

A Pearson product-moment correlation was performed for forward falls to assess the relationship between the participants' body mass, BMI and the peak impact force in experiments 1, 2 and 3. The correlation analysis showed that there were very strong, positive correlations between the body mass and the peak impact force for both proximal and distal areas, which were statistically significant ($p \leq 0.01$); however, BMI did not have any significant effect on the magnitude of the peak impact force ($p > 0.05$). Our findings are consistent with the previous studies [6].

The populations with the highest risk for a distal radius fracture are children and older adults, particularly older women. This limited many researchers to conduct fall experiments only with healthy young males [17, 18]. This is also a limitation of our study to use only young male adults for our experiments. As a future plan, we are going to design experiments, which are safe enough to involve elderly people, and compare the outcome with the current study.

5. Conclusion

During a forward fall on an uneven surface, one area of the hand may contact the ground earlier/later than the other because of ground irregularities. We designed an experiment to investigate the impact force in such fall conditions, which may occur frequently in daily activities. We sought to determine the impact force on two areas of the hand, which we called the distal (distal palmer and fingers) and proximal (Thenar and Hypothenar eminence). Two conditions were considered for falls on uneven terrain—the proximal area of the hand contacting the ground before or after the distal area. However, falls on even terrain were defined as a condition where both the distal and proximal areas contacted the ground simultaneously.

The results obtained show the proximal impact force as having two peaks for all conditions. However, the surface shape and the falling height may affect the magnitude of the peak impact forces. More specifically, the earlier distal-ground contact reduces the impact force exerted on the proximal area of the hand. The difference between the proximal peak impact forces in the case of earlier proximal-ground contact compared with simultaneous proximal- and distal-ground contact can be ignored. The lower proximal peak impact force is beneficial to reduce the risk of distal radius/ulna and scaphoid fractures.

The distal impact force in the case of earlier distal-ground contact has an extra peak before contact by the proximal area, in contrast to two other conditions. This peak occurs in a very short time after the contact. In this condition, the main distal peak impact force is also higher than the other conditions which leads to reduced proximal impact force. These results are advantageous in finding new strategies to reduce the risk of injuries and provides useful information about the distribution of the impact force that is beneficial for designing of protective gloves and wrist guards to satisfy fracture prevention requirements. Wrist fractures may occur in both forward and backward falls. Thus, future studies will examine how the fall direction influences the impact force on uneven terrain.

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