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Pressure distribution over the palm region during forward falls on the outstretched hands

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ABSTRACT

Falls on the outstretched hands are the cause of over 90% of wrist fractures, yet little is known about bone loading during this event. We tested how the magnitude and distribution of pressure over the palm region during a forward fall is affected by foam padding (simulating a glove) and arm configuration, and by the faller's body mass index (BMI) and thickness of soft tissues over the palm region.

Thirteen young women with high ($n=7$) or low ($n=6$) BMI participated in a "torso release experiment" that simulated falling on both outstretched hands with the arm inclined either at 20° or 40° from the vertical. Trials were acquired with and without a 5 mm thick foam pad secured to the palm. Outcome variables were the magnitude and location of peak pressure (d, θ) with respect to the scaphoid, total impact force, and integrated force applied to three concentric areas, including "danger zone" of 2.5 cm radius centered at the scaphoid. Soft tissue thickness over the palm was measured by ultrasound.

The 5 mm foam pad reduced peak pressure, and peak force to the danger zone, by 83% and 13%, respectively. Peak pressure was 77% higher in high BMI when compared with low BMI participants. Soft tissue thickness over the palm correlated positively with distance (d) ($R=0.79$, $p=0.001$) and force applied outside the danger zone ($R=0.76$, $p=0.002$), but did not correlate with BMI ($R=0.43$, $p=0.14$). The location of peak pressure was shunted 4 mm further from the scaphoid at 20° than that of 40° falls ($d=25$ mm (SD 8), $\theta=-9°$ (SD 17) in the 20° falls versus $d=21$ mm (SD 8), $\theta=-5°$ (SD 24) in the 40° falls). Peak force to the entire palm was 11% greater in 20° compared with 40° falls.

These results indicate that even a 5 mm thick foam layer protects against wrist injury, by attenuating peak pressure over the palm during forward falls. Increased soft tissue thickness shunts force away from the scaphoid. However, soft tissue thickness is not predicted by BMI, and peak pressures are greater in high individuals than that of low BMI individuals. These results contribute to our understanding of the mechanics and prevention of wrist and hand injuries during falls.

1. Introduction

More than 97% of upper extremity fractures are the result of falls (Palvanen et al., 2000). Distal radius fractures are the most common type of fractures in young adults, and similar in frequency to hip fracture in older adults (Sahlin, 1990; Singer et al., 1998; O'Neill et al., 2001). The scaphoid is the most common carpal bone to be fractured, accounting for 60% of all carpal fractures (Hove, 1999). Wrist injuries represent 35–45% of all injuries among snowboarders and 37% among in-line skaters, and two thirds of those are fractures (Made and Elmqvist, 2004; Matsumoto et al., 2002; Schieber et al., 1996; Callé, 1994).

Previous studies have measured impact forces during falls on the outstretched hands. Chiu and Robinovitch (1998) reported that the hand impact force trace during this event is governed by a high-frequency peak force (F_{max1}) occurring shortly after the instant of contact, and a subsequent lower-frequency, lower magnitude peak (F_{max2}). These authors (Robinovitch and Chiu, 1998) also reported that F_{max1} was attenuated by 35% on average by a 1.3 cm thick foam rubber pad, nearly the same as the 40% attenuation provided by a 7.6 cm thick pad of the same material. The authors concluded that even a thin layer of padding, while having little effect on F_{max2}, may prevent wrist injuries during falls by substantially attenuating F_{max1}. DeGoede and Ashton-Miler (2002) showed that a fall arrest strategy involving elbow deflection reduced F_{max1} by 40% when compared with stiff-arm arrest. While these studies provide valuable insight on force magnitude, fracture risk depends also on distribution of force to the palm surface and underlying bones. To our knowledge, none of the previous study has reported these data.

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The magnitude and distribution of contact force during a fall on the outstretched hands should also depend on the configuration of the body at impact, and soft tissue thickness over the palm region. While previous studies have examined the protective role of cadaveric soft tissue from the trochanteric hip region (Robinovitch et al., 1995), no study has examined the force-attenuating effect of palmar soft tissues.

In high risk activities (e.g., inline skating), hard-shell "wrist guards" are often used to reduce risk for fall-related distal radius fractures. While these splint-like devices undoubtedly reduce wrist hyperextension during impact (Schieber et al., 1996), epidemiological studies have reported contradictory results on clinical effectiveness (Lewis et al., 1997; Giacobetti et al., 1997; Hwang et al., 2006; Muller et al., 2003), or corresponding increases in the frequency of elbow, upper arm, and shoulder injuries—suggesting the need for improved design. Others have noted that the reduction in wrist flexibility created by hard-shell wrist guards makes them unsuitable for high risk activities such as bicycling, scootering, and use of playground equipment (Hagel et al., 2005; Cassell et al., 2005; Kim et al., 2006). Padded gloves or compliant floors represent alternative prevention strategies requiring investigation.

Accordingly, our goals in the current study were to conduct laboratory-based falling experiments to investigate how pressure distribution over the palm region during forward falls on the outstretched hands is affected by (1) a 5 mm thick foam pad, simulating a compliant surface or protective glove, (2) the impact angle of the arm, (3) the body mass index of the faller, and (4) the thickness of soft tissue over the palm region (as measured by ultrasound). Based on our results, we discuss potential applications to improved fracture prevention.

2. Methods

2.1. Subjects

Thirteen healthy young women between the age of 18 and 35 participated. Participants were selected so that approximately one-half ($n=7$) possessed a body mass index (BMI=weight/(height^2)) greater than 25, and the others ($n=6$) had a body mass index less than 18.5. Average body weight and height were 47 (SD 4) kg and 162 (SD 6) cm in the low BMI group, and 75 (SD 9) kg and 163 (SD 5) cm in the high BMI group. All participants provided written informed consent. The experimental protocol and consent form were approved by the Committee on Research Ethics at Simon Fraser University.

2.2. Equipment

During each trial, we collected total hand impact force from a force plate (Bertec, USA) and pressure distribution from a 2D scanning plate (RSscan International, Belgium) placed on the force plate, at 500 Hz of sampling rate. Reflective markers were placed on the dorsal surface of each hand, directly over the scaphoid, hamate, 2nd metacarpal head, and 5th metacarpal head (identified by palpation). The 3D positions of these markers were recorded at 250 Hz with an eight-camera video-based motion measurement system (Motion Analysis Corp., USA).

2.3. Protocol

Forward falls were simulated through "torso release experiments," which involved releasing the participant (via a tether and electromagnet) from a state of impending impact with the palm raised 5 cm above the ground (see Chiu and Robinovitch (1998) for further details). To assess the effect of impact configuration on contact force and pressure, trials were acquired for initial inclinations of the arm from the vertical of 20° and 40° (Fig. 1). Given the brief interval between tether release and impact, negligible changes occurred during descent in the relative positions of the arm, forearm and hand, as confirmed during the trials through visual monitoring by one of the investigator, and later by review of video footage acquired for each trial. Trials were also conducted without a pad and with a 5 mm thick ethylene vinyl acetate (EVA) foam pad (13 × 21 cm; density of 46.6 kg/m^3; see inset in Fig. 1), which was placed on the palm by means of double sided tape. Three trials were acquired for each condition. The order of presentation of the conditions was randomized.

2.4. Data analysis

Our main outcome variables were the magnitude of peak pressure, location of peak pressure, total peak force, and integrated force applied to each of three defined palm regions. Except for the total peak force, each of these variables were calculated for the right and left hand separately, and then averaged for analysis (Troy and Grabiner, 2007). Data analysis was conducted with customized Matlab routines. The magnitude of peak pressure was determined by the peak value from the pressure versus time trace, where the maximum pressure values from 4096 pressure sensors in the RSscan plate were plotted as a function of time. The

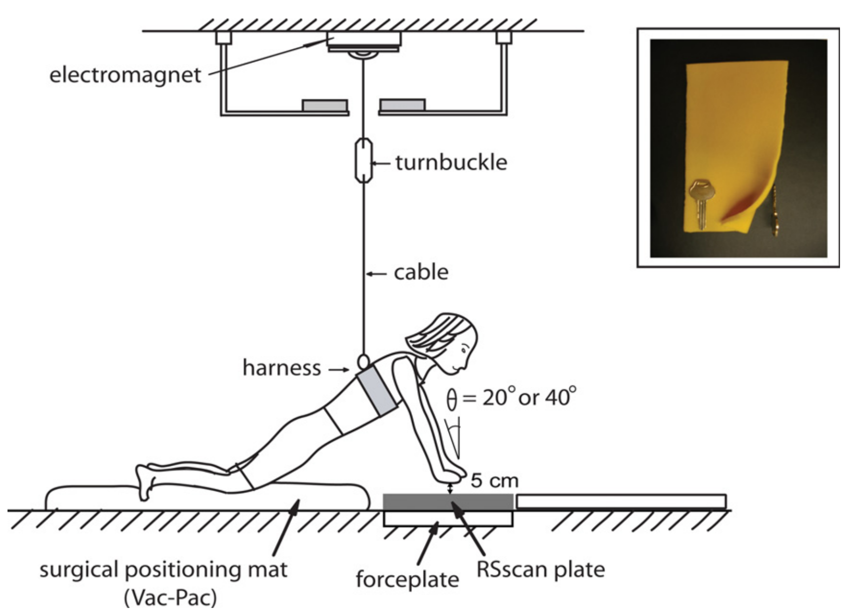

Fig. 1. Schematic of the "torso release experiment". In some trials, we placed a 5 mm thick layer of EVA foam (13 × 21 cm, density of 46.6 kg/m^3) over the palmar surface, as shown in the inset. Surgical positioning mats (Vac-Pac, Olympic Medical, Seattle, WA, USA) were placed under the knee, shin, and foot to ensure consistent positioning of the participant between successive trials in a given impact configuration.