

## Research article

# SHOCK-ABSORBING EFFECTS OF VARIOUS PADDING CONDITIONS IN IMPROVING EFFICACY OF WRIST GUARDS

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### ABSTRACT

The use of wrist guards has limited efficacy in preventing wrist injuries during falling in many sports activities. The objectives of this study were to measure the ground reaction force of the hand under simulated impact of the forearm and hand complex with different padding conditions of wrist guards and to analyze their impact force attenuation and maximum energy absorption for improved functional efficiency. A total of 15 subjects, wearing a commercial wrist guard, participated in a cable-released hand impact experiment to test four different conditions on the volar aspect of the hand, which include a wrist guard without a volar splint (bare hand), with a volar splint (normal use), with a volar splint and additional viscoelastic polymeric padding, and a volar splint and additional air cell padding. The ground reaction force and acceleration of the hand were measured using a force platform mounted on an anti-vibration table and a miniature accelerometer, respectively. Additional padding on the bare hand could substantially improve the maximum energy absorption by more than 39%, with no differences with each other. However, only the air cell padding could simultaneously improve the impact force attenuation by 32% compared with the bare hand impact without compromising the maximum energy absorption. It is recommended that common wrist guard design should provide more compliant padding in the volar aspect to improve the impact force attenuation through optimal material selection and design.

**KEY WORDS:** Accidental falls direction, wrist injuries, prevention, fractures.

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### INTRODUCTION

The upper extremity is one of the most frequent sites of fall-related injuries due to a common strategy of employing it to break a fall (O'Neill et al., 1994; Oskam et al., 1998). Upper extremity fractures are thus often caused by a wide variety of sports activities, particularly snowboarding, in-line skating, and skateboarding. Injuries from these activities have increased with the rise of their popularity (Idzikowski et al., 2000; Schieber and Branche, 1998). According to the 2002 figures from the National Sporting Goods Association, nearly 34 million people participated in these activities more than once in that year (NSGA, 2002). In the analysis of the 2002 National Electronic Injury Surveillance System Equipment (NEISS) data (USCPSC, 2003), it is estimated that 266,884 injuries due to these

activities require hospital emergency visits nationwide. The majority of the injuries (47%) involved the upper extremity, or mostly the distal radius, and significantly 74% of them were fractures (Machold et al., 2000; Schieber et al., 1996). Therefore, finding a means of reducing these fall-related injuries becomes a high priority.

Wrist guards are one of the most common protective devices used for preventing a faller from a distal radius fracture during skate- and snowboard-related activities. Common wrist guards are composed of two semi-rigid plastic splints on the volar and dorsal sides of the hand, wrapping around the wrist and limiting the wrist extension. The current guard configuration could help to prevent hyperextension of the wrist and soft tissue laceration during fall arrests (Schieber and Branche, 1998; Staebler et al., 1999; Young et al., 1998). However,

more than half of the injured patients wearing wrist guards still sustained a fracture of the wrist (Chong et al., 1995; Rønning et al., 2001; Schieber et al., 1996) or a proximal forearm fracture (splint-top fracture) due to the common guard configuration of two semi-rigid splints (Cheng et al., 1995; Jaax, 2000).

It is expected that wrist guards should also play a role of attenuating the impact force and simultaneously absorbing the impact energy to prevent wrist injuries. Recent biomechanical studies have demonstrated inconclusive results on the efficacy of wrist guards with respect to the impact force attenuation. Giacobetti et al. (1997) found no reduction of the impact force in their cadaver fracture study, while other cadaveric studies, though failing to demonstrate significant reduction in the fracture force, found altered or less severe fracture patterns (Lewis et al., 1997; Moore et al., 1997), altered dynamic loading patterns (Greenwald et al., 1998), and decreased distal radius bone strain (Staebler et al., 1999). No studies have reported the amount of impact energy absorption using common wrist guards and further suggestions were not made in improving wrist guard functions. Therefore, the objective of this study was to conduct human subject impact testing of common wrist guards with additional padding materials and to identify their biomechanical roles with respect to the impact force attenuation and energy absorption as an effective means of protection against fall-related injuries.

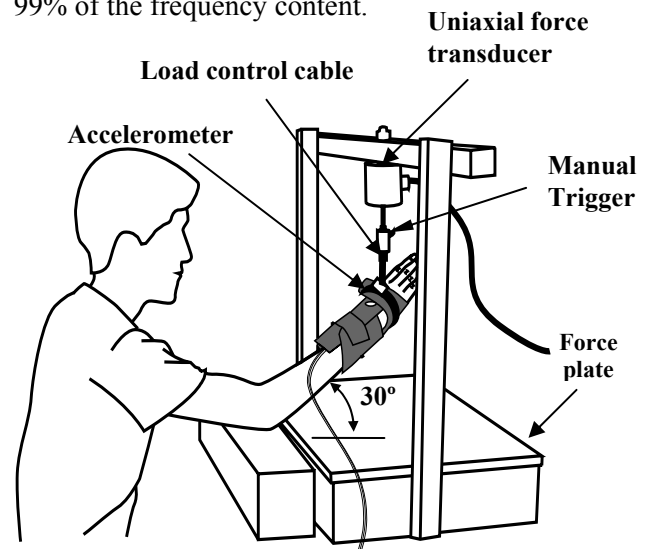
## METHODS

### *Testing Protocol*

A total of 15 young male and female adults (10 M/ 5 F, mean age = 24.3 yrs., mean height = 174.8 cm, mean arm length = 25.9 cm, mean weight = 75.8 kg) participated in this study. All subjects gave informed consent and the testing was approved by the Institutional Review Board.

An impact testing platform (Figure 1) was constructed to recreate the impact force in a fall through a simple pendulum motion of the forearm about the elbow joint. The subject put on a commercial wrist guard (Bone Shieldz, Litchfield, IL) and sat next to a testing table with the upright sitting position. The load control cable was adjusted for the subject to have the forearm position of a 30 degree angle from the horizontal. They were instructed to pull the cable down to have a prescribed force level by visually monitoring an indicator from a uniaxial force transducer (Model: 100-0-CT-BL-FF-2.0-100F, Maywood, CA) and then they were asked to close their eyes. Based on our earlier observations, the force level was set to 50 N for safety consideration so as to obtain the

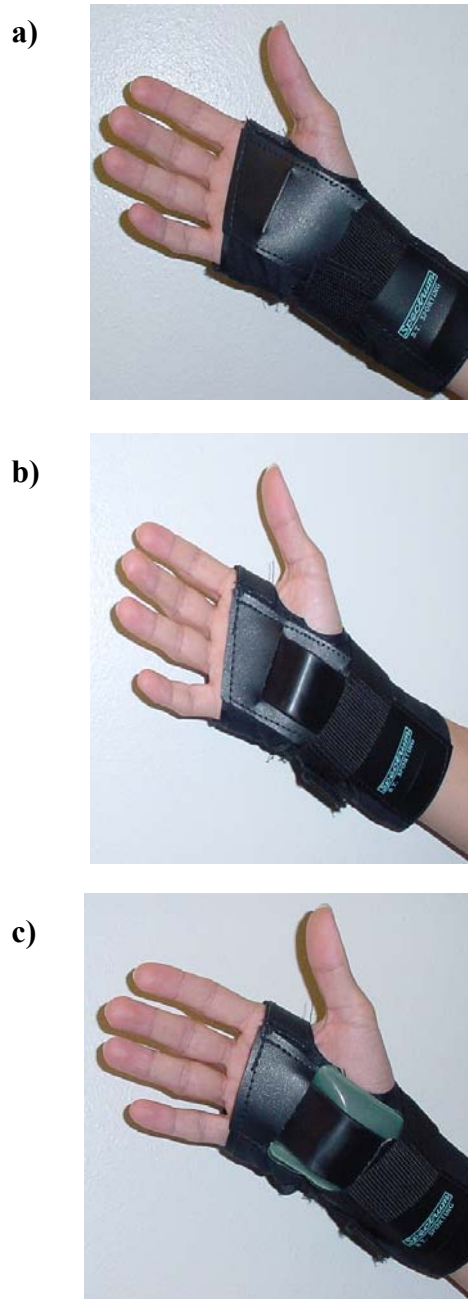
subsequent peak impact force of the hand around 500 N. Without a notice the load control cable was released by a manual trigger and through a swing motion the subject's hand struck a commercial force plate (Type 4060-10, Bertec, Columbus, OH; load capacity 10 kN with 1,000 Hz natural frequency), covered with a 2.5 cm thick wooden plate and, which was mounted on an anti-vibration table. A miniature accelerometer (Model: EGA-F-100, ENTRAN Devices, Inc, Fairfield, NJ) was attached to the dorsal splint of the wrist guard. The impact force and acceleration of the hand were simultaneously collected at a sampling rate of 10,000 samples per second by use of a high-speed data acquisition system (PCI-6024E & SCXI 1121, National Instruments, Inc, Austin, TX) interfaced with an IBM PC. Both data were bi-directionally filtered using a sixth-order Butterworth low pass filter with a cut-off frequency of 500 Hz, containing 99% of the frequency content.



**Figure 1.** A cable-released impact testing setup.

The subject repeated each of the trials with the following four different conditions of the volar aspect of the hand. It was postulated that the dorsal splint in the wrist guard would contribute only to prevent hyperextension of the wrist but play a limited role in absorbing impact energy since it is not physically involved in the impact. Therefore, the dorsal splint remained in the wrist guard in all of the testing conditions. The four conditions of the volar aspect of the hand are 1) without a volar splint to simulate bare hand impact (Figure 2a, WG-condition), 2) with a volar splint to simulate regular wrist guard use (Figure 2b, WG+ condition), 3) with a volar splint and a 13 mm thick viscoelastic polymeric padding (Sorbothane, Sorbothane, Inc, Kent, OH) (WGS condition), and 4) with a volar splint and an air cell from a pneumatic armband (Aircast, Inc, Summit, NJ) (Figure 2c, WGA

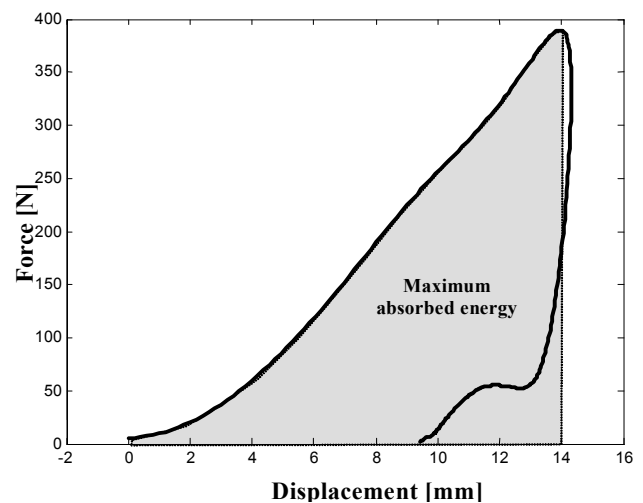
condition). The Sorbothane padding was achieved by wearing a Sorbothane palm protector (ER-502, Ergotech Canada, Inc, Ontario, CA) inside the wrist guard. The air cell is a thin rectangular bag made of PVC film with the dimension of 57 mm × 70 mm × 13 mm and inserted between the volar splint and the hand to play a role of an air spring. Each trial was repeated three times to take an average measure.



**Figure 2.** Four testing conditions of the hand for a subject wearing a commercial wrist guard with a) no volar splint (WG- condition), b) a volar splint (WG+ condition) and a volar splint + a 13 mm thick Sorbothane palm protector inside the wrist guard (WGS condition, not shown), and c) a volar splint splints and an air cell between the volar splint and the hand (WGA condition).

### Data Analysis

The measured ground reaction force data was normalized according to the subject's body weight (BW). Subsequently, the peak impact force ( $F_{\max}$ ), corresponding peak time ( $T_{\max}$ ; time to reach  $F_{\max}$  from touchdown), and loading rate (time rate of the impact force to reach its peak =  $F_{\max}/T_{\max}$ ) were estimated. The peak acceleration was estimated from the measured acceleration data. The impact velocity was calculated by numerically integrating the acceleration profile along the time period between the trigger release and the impact. The estimated velocity profile was integrated once again to calculate the peak displacement. It accounted for the combined displacements of the hand soft tissue and the splint from touchdown. The maximum energy absorption was estimated by integrating the area under the impact force vs. estimated displacement curve between the impact incident and the peak impact force,  $F_{\max}$  (Figure 3).



**Figure 3.** The measured ground reaction force of the hand vs. the acceleration of the hand. The shaded area is the maximum energy absorbed during impact.

### Statistics

The ground reaction force and acceleration parameters with various hand conditions were compared with the Student-Newman-Keuls test for paired sample data by use of SYSTAT statistical analysis software (SYSTAT, Inc, Evanston, IL). Differences were considered significant at  $p < .05$  level.

## RESULTS

The measured force and acceleration parameters are summarized in Table 1. Typical measured force and corresponding acceleration profiles for a single subject under the four different hand conditions are

**Table 1.** Impact response parameters for different hand conditions. Values are mean (standard deviations).

Hand condition	$F_{\max}$ (BW)	$T_{\max}$ (msec)	$G_{zi}$ (BW $\cdot$ sec $^{-1}$ )	$a_{\max}$ (G)	$x_{\max}$ (mm)	E ( $\times 10^{-3}$ ) (J $\cdot$ BW $^{-1}$ )
WG-	.68 (.16)*	11.9 (5.0)*	82.2 (75.3)*	43.1 (11.9)*	18.9 (9.6)*	2.39 (.89)*,†,‡
WG+	.71 (.14)*	10.5 (2.4)*	74.0 (23.4)*	48.0 (15.2)*	17.7 (6.4)*	3.31 (1.00)
WGS	.75 (.16)*	10.7 (3.6)*	84.8 (51.6)*	45.4 (13.0)*	18.2 (7.9)*	3.45 (1.32)
WGA	.48 (.08)*	18.9 (9.6)	29.2 (5.9)	27.3 (4.2)	28.4 (5.9)	3.57 (.65)

Abbreviations: ( $F_{\max}$ = Peak impact force,  $T_{\max}$ = Peak impact time,  $G_{zi}$ = Impact loading rate,  $a_{\max}$ = Peak acceleration,  $x_{\max}$ = Peak displacement, E: Maximum absorbed energy).

\* Statistical difference with WGA from the paired t-test ( $p < .05$ ).

† Statistical difference with WGS from the paired t-test ( $p < .05$ ).

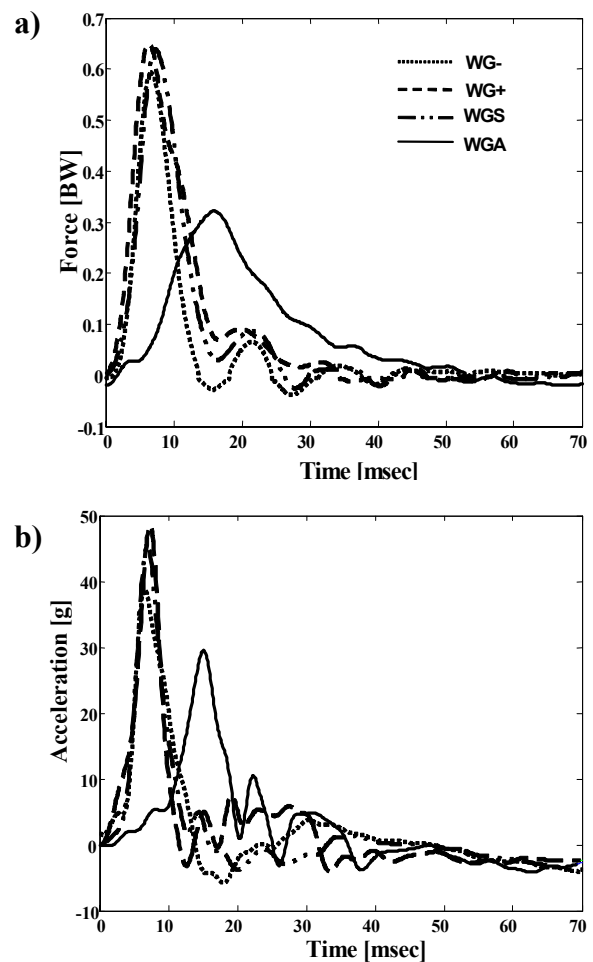
‡ Statistical difference with WG+ from the paired t-test ( $p < .05$ ).

shown in Figure 4. With the current impact testing setup the impact velocity remained at about 2.0 m $\cdot$ sec $^{-1}$  with no significant differences among the four hand conditions. This consistence may be attributed to the very brief duration of the arm motion, less than 100msec from the cable release to impact, preventing any voluntary motion. The subsequent ground reaction force lasted less than 20msec, followed by spurious post impact vibrations (Figure 4a). Overall the measured force profiles well resembled those from other experimental studies of falling (Chiu and Robinovitch, 1998; Kim and Ashton-Miller, 2003).

It was found that only the WGA condition significantly modulated the impact responses (Figure 4, Table 1). The WGA condition had significantly smaller peak forces than the other three conditions ( $p < .0002$ ). The smaller peak forces of the WGA condition occurred significantly later at about 19msec than those of the other conditions that occurred about 10-12msec after the impact ( $p < .03$ ). Consequently, the force profiles of the WGA condition became more flattened (Figure 4) and yielded substantially slower loading rates ( $p < .02$ ). Likewise, the WGA condition had significantly smaller peak accelerations but larger peak displacements ( $p < .00012$  and  $p < .005$ , respectively). The three conditions other than the WGA condition demonstrated similar force and acceleration profiles (Figure 4) but didn't show any statistical differences with each other in the above force and acceleration parameters (Table 1).

It was demonstrated that padding on the bare hand could substantially improve the maximum energy absorption (Table 1). The three padded conditions (WG+, WGS, and WGA conditions) demonstrated substantially increased maximum energy absorption than the bare hand condition (WG- condition) by more than 39% ( $p < .02$ ). The three padded conditions, however, didn't show any statistical differences with each other in maximum energy absorption (Table 1), though the WGA condition had the largest maximum energy

absorption without reaching the level of significance.



**Figure 4.** Time history profiles from the touchdown of (a) the measured ground reaction force of the hand for a single subject under four different padding conditions and (b) the subsequent acceleration profiles of the hand during impact.

## DISCUSSION

For effective prevention of impact injuries during falling any protective should attenuate the peak impact force and simultaneously maximize the

impact energy absorption. It was found that a volar splint in common wrist guards plays a role of not only limiting the wrist extension in conjunction with a dorsal splint, but also of improving the impact energy absorption by more than 38% compared with the bare hand. However, it does not help to reduce the peak impact force due to its relatively larger stiffness than the soft tissues of the hand, since in general the stiffness of impacting bodies modulates the impact force during impact of the human body (Gardner et al., 1998; Shiba et al., 1995). Thus, this study confirmed the classic paradigm that compliant padding is one of the simplest ways to improve protective functions of wrist guards by reducing the peak impact force without compromising the maximum energy absorption (Table 1).

The current study also demonstrated that proper selection of the padding material ensures the improvement in protective functions of wrist guards, as demonstrated in the piecemeal improvement using the Sorbothane padding (WGS condition). Parkkari and associates (1994) directed a few considerations for padding materials - good energy absorption capacity, good durability, low weight, good recovery after compression, easy availability, and reasonable price. Typical padding materials used for sports gears include gels, air cells, and polymeric foams such as polyurethane, polyethylene, and Sorbothane. These materials showed a significant effect in attenuating impact forces up to 80% in some studies (Kannus et al., 2000; Sabick et al., 1999; Wiener et al., 2002). Especially, Sorbothane is a well-known viscoelastic polyurethane material used for industrial vibration isolation and sports injury protection under repetitive loading conditions. However, it was demonstrated from our study that its shock-absorbing capability under rapid impact conditions such as falling might not be sufficient due to its relatively larger stiffness than the soft tissues of the hand. From studies of testing various shoe insert materials it was also demonstrated that Sorbothane, despite its high damping properties, transmitted the highest impact force (Brodsky et al., 1988; Shiba et al., 1995), which is consistent with our results.

The air cell padding, on the other hand, has demonstrated significant improvements in wrist guard functions by reducing the peak impact force by about 30% but without compromising the maximum energy absorption. Air cells have been widely used in packaging and space industry due to its superior energy-storage capacity per unit weight and greater shock-absorbing efficiency to shock loading (Cavanaugh, 1976). Parkkari and associates (1994) demonstrated that the compliance property of an air spring such as an air cell in this study is derived from its nonlinear compressibility. At the

beginning of deflection it reacts softly but as it is compressed it becomes increasingly stiffer, resulting in more flattened impact force profiles. As seen in our results, the air padding modified the impact mode from a sharp to a blunt impact mode with a smaller peak impact force and longer time duration (Figure 4). It should be noted that the air cell used in this study was not designed for optimal performance. The stiffness of the pneumatic spring (air cell) directly varies with the initial pressure of the air and inversely with its volume, resulting in the flexibility to change its stiffness and shock-absorbing characteristics (Erin et al., 1988; Hundal 1985). Therefore, future study on the optimum design of an air cell warrants further improved shock-absorbing functions of wrist guards.

The major limitation of the current study is the partial simulation of the falling impact. The ground reaction force of the hand during fall arrests demonstrates a characteristic bimodal pattern similar to other ground reaction force profiles of other sport activities such as running and drop landing (Dufek and Bates, 1991; Nigg, 1986). This pattern is composed of two force components - the impact force and the braking force components (Gardner et al., 1998; Kim and Aston-Miller, 2003). The former is due to rapid collision of the body with the ground, whereas the latter is attributed to more gradual build-up of force applied to the hand by the body mass. Though it has not been concluded whether a fracture occurs in response to the energy provided by the impact force component or to the greater energy arising from the braking force component or to both, the two force components have strong positive causal interactions (Kim et al., 2003) so that reduction of the peak impact force will significantly help to reduce the latter peak braking force.

The present study simulated and measured only the former instantaneous impact force component and made relative comparisons of the impact responses between the different hand conditions. It is still inconclusive from the results whether and how, if any, such additional padding would improve or deteriorate modulation of braking function of the body to arrest the latter gradual but excessive force during actual fall arrests. Nevertheless, since both impact energy as well as impact force itself has injurious effects on the body, the ability of a material to reduce the magnitude of an applied force is still an important factor to reduce injuries (Clarke et al., 1983; Jørgensen and Bojsen-Møller, 1989). Furthermore, the results should be interpreted with caution since only a limited number of common padding materials were tested under sub-critical loading and other materials may provide better impact responses. The human subject testing is advantageous over cadaveric testing since the joint

stiffness and the level of muscle contraction can significantly modulate the impact response of a human body (DeGoede et al. 2002; Crisco et al. 1996). For comprehensive assessment, human subject testing with full simulation of both impact and active braking would help further improvement of wrist guard functions.

## CONCLUSIONS

In conclusion, it is recommended that common wrist guard design should provide more compliant padding in the volar side for improved impact force attenuation through optimal selection of the material and biomechanical design for better protective functions.

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## KEY POINTS

- The controversial efficacy of wrist guards in preventing wrist injuries during falling was tested through investigation of their impact force attenuation and maximum energy absorption from the measured ground reaction force of the hand under simulated impact of the forearm and hand complex with four different padding conditions of wrist guards: a wrist guard without a volar splint (bare hand), with a volar splint (normal use), with a volar splint and additional viscoelastic polymeric padding, and a volar splint and additional air cell padding.
- In general, padding on the bare hand could improve the maximum energy absorption by more than 39%, while only the air cell padding could simultaneously attenuate the peak impact force by 32% without compromising the maximum energy absorption.
- Common wrist guard design requires more compliant padding in the volar aspect to improve the impact force attenuation, which should be done through optimal material selection and design.

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