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# On reducing hand impact force in forward falls: results of a brief intervention in young males

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## Abstract

*Objective.* To test the working hypotheses that after a brief (10 min) intervention, (a) young adults can volitionally reduce fall-related wrist impact forces, and (b) no difference in impact force would exist between intervention and control groups at 3-weeks or 3-months follow-up.

*Background.* The wrist is the most commonly fractured site in the body at any age, most often as a result of impact with the ground while arresting a forward fall.

*Methods.* Twenty-nine healthy young male volunteers participated. A 3-month intervention group ($n = 10$) performed five standardized forward falls before and after a 10-min instructional intervention aimed at reducing wrist impact forces during the baseline visit. They, along with a 3-month control group ($n = 11$) who did not receive the intervention, were remeasured in five trials at 3-weeks and 3-months follow-up, without intervening practice. A baseline control group ($n = 8$) performed the five trials, then repeated them at the baseline visit without receiving the intervention. Unilateral body segment kinematics and bilateral hand-ground impact forces were measured and the hypotheses were tested using repeated measures analysis of variance.

*Results.* At the baseline visit, a significant group-by-trial-block interaction was found ($P = 0.02$): the 3-month intervention group reduced their average maximum impact forces by 18% from initial values ($P = 0.002$); the baseline control group did not do so (0.5% increase, $P = 0.91$). The 3-month intervention (20 falls) and control (15 falls) groups did not differ at the 3-month follow-up ($P = 0.62$); however, when the groups were combined their maximum impact force had decreased significantly (8.9%, $P = 0.04$) over that time.

*Conclusions.* Healthy young males learned in 10 min to significantly reduce wrist impact forces in forward falls, but retention was poor at 3-weeks follow-up. Irrespective of group, however, after the 5 falls at 3-weeks subjects had taught themselves to reduce their impact forces at the 3-months follow-up.

## Relevance

A brief educational intervention can significantly reduce forward fall-related impact forces in the short term. However, with or without the brief intervention, the experience of performing between 5–10 forward falls 3 weeks apart apparently resulted in decreased impact forces over the next 2 months, thereby reducing the risk of injury in these forward falls.

*Keywords:* Falls; Impact; Force; Intervention; Young males; Learning

## 1. Introduction

Falls are a costly problem. For example, in the United States one-fifth (21%) of all injuries resulted from falls between the years 1992–95 (Burt and Fingerhut, 1998). It is projected that, by the year 2020, over 17 million people will be injured each year by falls in the United States, with the associated medical costs reaching $85.4 billion dollars (Englander et al., 1996). Insights are clearly needed to reduce these numbers.

The wrist is the most common fracture site in the body (Donaldson et al., 1990), presumably because the upper extremities are commonly used for protection during falls (O'Neill et al., 1994; Hsiao and Robinovitch, 1998; Vellas et al., 1998). The biomechanics of using both arms to arrest mild falls from heights of a few centimeters have begun to be quantified (Chiu and Robinovitch, 1998; Robinovitch and Chiu, 1998; Chou et al., 2001;

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DeGoede and Ashton-Miller, 2002; DeGoede and Ashton-Miller, 2003; DeGoede et al., 2003; Kim and Ashton-Miller, 2003).

It has recently been demonstrated that, after a 10-min instructional intervention, healthy young subjects can learn to reduce the impact forces on their upper extremities by 27% on landing from standardized forward falls from a shoulder height of 1 m (DeGoede and Ashton-Miller, 2002). However, that study did not include a control group. Therefore, it could not be determined whether the immediate reduction in impact force resulted from the 10-min instruction itself or whether it was simply due to a practice effect engendered by performing five consecutive fall-arrest trials.

We therefore explored two primary (null) hypotheses in healthy young subjects using a standardized upper extremity fall arrest test paradigm (DeGoede and Ashton-Miller, 2002). The first hypothesis tested was that during a single (baseline) laboratory visit, there would be no difference in the maximum reduction of the hand impact force achieved by subjects assigned to a 10-min educational intervention group (3-month intervention group) and subjects assigned to a baseline control group who received no such intervention. The second hypothesis was tested in a prospective, controlled trial conducted without intervening practice sessions: the maximum hand impact force reduction achieved by the 3-month intervention group would not differ from that achieved by an untrained 3-month control group at 3- or 12-weeks follow-up.

## 2. Methods

Twenty-nine healthy young males volunteered for the study (3-month intervention group: (mean (SD)): age: 23(3) years, body weight: 72(9) kgf, and height: 174(3) cm; baseline control group: age: 24(3) years, body weight: 68(6) kgf, and height: 173(3) cm; 3-month control group: age: 25(3) years, body weight: 68(7) kgf, and height: 172(3) cm). Subject anthropometry lay within 6% of the stature and 19% of the body weight of the 50 percentile male. Exclusion criteria included fall training or martial arts experience, as well as self-report of extremity, shoulder, spine fractures or any acute injuries to those structures within the past year. In this exploratory study, subjects were recruited and assigned to one of three groups: 10 subjects to a prospective "3-month intervention group", 11 subjects to a prospective "3-month control group" who did not receive the instructional intervention during the baseline visit, and 8 subjects to a "baseline control group" who did not receive the instructional intervention during the baseline visit but were retested solely to assess practice effects during that visit. The institutional review board approved all test procedures, and all subjects read and signed a written statement of informed consent.

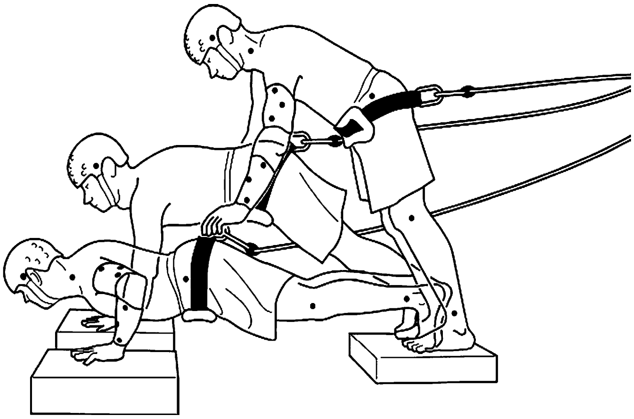

Fig. 1. Experiment setup. Subjects were released from an initial shoulder height of 1 m above the surface of force plates, and then arrested the fall bimanually. The black dots represent kinematic markers.

Subjects were leaned forward and restrained by a waist harness until a cable supported them with a tension of 30% body weight (DeGoede and Ashton-Miller, 2002; and Fig. 1). The shoulders were then lowered to a height of 1 m from the ground by flexing at the hips. The subjects were allowed to position their upper extremities in any configuration in preparation for the fall. They were also informed when the cable would be released to initiate the fall. Upon cable release, the subjects were instructed to arrest the fall with both hands. To establish an average performance, each subject was first asked to perform five trials under each test condition. At the baseline visit, all 29 subjects were asked to perform 5 falls without instruction (termed "natural falls"). The 3-month intervention group was administered a 10-min intervention consisting of instructions (described below) on how to reduce impact by minimizing the hand-ground relative velocity at impact. After intervention, the intervention group subjects performed another five trials (termed "reduced-impact falls"). The baseline control group was not administered the intervention and was retested after a 10-min rest break in order to control for possible practice and self-learning effects in the 3-month intervention group. The baseline control group did not participate in the follow-up tests. Then, at the 3-week and 12-week follow up visits, the 3-month intervention group and the 3-month control group were then asked to perform, without practice or instructions, 5 reduced-impact falls at 3-week and 12-week follow-up visits.

The 3-month intervention group subjects were told that the goal of the educational intervention administered at baseline was learning to reduce their hand impact force(s) in the standardized falls. They were instructed to: "Reduce your elbow extension speed prior to hand-ground impact"; "Avoid accelerating your hand into the ground at impact – just hold it steady and wait for the ground to hit it"; "Land with a slightly flexed elbow angle; do not ever land with a straight elbow"; "Attempt to 'catch' the ground". For this latter point, they were given a verbal description of how one catches an object with minimum impact force and then two visual demonstrations: catching a rapidly-approaching medicine (heavy) ball with arms that have already begun to flex (correct) rather than with stiff, extended arms (incorrect); and secondly, a fall against a wall arrested by moving the hands toward the body just prior to impact using flexing elbows (correct) vs. stiff, extended, elbows (incorrect) (Kim and Ashton-Miller, 2003). For this experiment, they were also instructed to "Try to halt the downward motion of your torso before it comes within 15 cm of the ground, but if you cannot, at least slow it to 0.5 m/s and do not let it touch the ground". A 15 cm threshold and a speed of 0.5 m/s were then demonstrated. To enhance learning, the 3-month intervention group subjects were informed of their peak impact forces, percentage impact force reductions from initial (no-instruction) values after each "reduced-impact" trial at baseline and follow-up visits, and the torso speed if it crossed the 15 cm threshold above ground level.

Neither control group received the educational intervention. They were simply instructed to "arrest the fall in any way that feels natural to you".

For all subjects the kinematics of the left-side body segments were measured at 200 Hz using a single Optotrak 3020 system. The 11 infrared-emitting markers were placed 5-cm above the lateral malleolus, at the center of rotation of the knee, at the lateral aspect of the waist and the neck, on a safety helmet around the temporal bone, on the forearm and upper arm (Fig. 1). The resultant impact forces on both hands were measured at 2 kHz using dual AMTI force plates (Advanced Mechanical Technology, Inc., Watertown, USA), covered by 2.4-cm-thick compact rubber foam (American Society of Testing Materials Code No. ASTM-D-1056-85:2B2, West Coshohocken, USA). The left-side kinematic data were low-pass filtered using a fourth-order Butterworth filter (MATLAB) with a cutoff frequency of 30 Hz. The data from each force plate were similarly filtered with a cutoff frequency of 300 Hz. The start of the impact was defined as when the left-side impact force exceeded 20 N, and the kinematics data were considered from that instant. The kinematic data were processed according to the methods described previously (DeGoede and Ashton-Miller, 2002). Thus, the elbow angle between the forearm and upper arm was obtained by projecting the markers defining the long axis of the two segments onto a plane perpendicular to the instantaneous elbow axis of rotation. The instantaneous elbow axis of rotation for a given time step described the arm rotation from 50 ms before to 50 ms after the current time, and was calculated from the direction cosine matrix of the forearm relative to the upper arm (Roberson and Schwertassek, 1988). The elbow angular velocity and the wrist velocity were obtained by differentiation of the elbow angle and wrist position data using a five-point formula. The wrist and elbow impact velocities were then found at the instant of the onset of impact.

The hand impact force response can be characterized as having two peaks. The initial (higher-frequency) peak impact force, resulting from the deceleration of hand and arm, preceded and exceeded in magnitude a lower-frequency peak. Therefore, the first peak force was considered to be a more likely cause of wrist injury and the greater of the left and right initial peak forces on each hand (termed $F_{\max}$) was used as the dependent variable in the statistical analysis.

To test the first null hypothesis, a two-way repeated-measure analysis of variance (rm-ANOVA) was performed to test for a lack of a difference in the averaged $F_{\max}$ of both the 3-month intervention and baseline control groups between pre-intervention and post-intervention trials. To test the second null hypothesis, averaged $F_{\max}$ was compared across visits (the baseline natural falls, 3-week follow-up and 12-week follow-up) and across groups (3-month intervention and 3-month control groups) using a two-way rm-ANOVA. Post-hoc tests were performed using the Tukey–Kramer method. To control for the slight differences in body weight between individuals, $F_{\max}$ was adjusted statistically using body mass as a covariate in all rm-ANOVA analyses. These were all conducted using the General Linear Models method (SAS/STAT User's Guide, 1999).

Kinematic adjustments in arm configuration during a forward fall can result in decreased impact forces (DeGoede and Ashton-Miller, 2002, 2003). A Pearson correlation analysis was, therefore, used to examine the relationship between each left-side kinematic measure and left-side impact force. All statistical analyses were performed using SAS, and a $p$-value <0.05 was considered statistically significant.

## 3. Results

Due to a technical problem which caused data from the fifth trial to not be saved in half the 3-month intervention group, we did not use any fifth trial data in the data analyses. $F_{\max}$ was then averaged over the first four trials of each trial block prior to statistical analyses.

During the baseline visit, the educational intervention resulted in an 18% decrease in the impact force in the 3-month intervention group (one-way rm-ANOVA, $P = 0.002$, Fig. 2), while there was no such evidence in the baseline control group, who received no instruction (0.5% increase, one-way rm-ANOVA, $P = 0.91$). The first

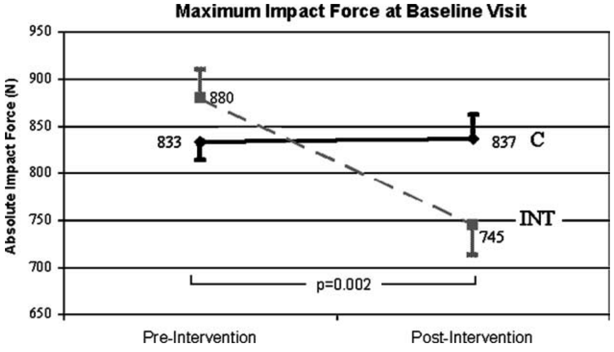

Fig. 2. Results from the baseline visit showing the effect of the intervention on $F_{\max}$ by group (square symbols: 3-month intervention group "INT", $n = 10$; diamond symbols: baseline control group "C", $n = 8$). Bars denote standard error. Note the significant difference between pre- and post-intervention within-visit values of $F_{\max}$ in the 3-month intervention group, $P = 0.002$. Note that in this and the following figure, the ordinal scale does not begin at zero.

hypothesis was, therefore, rejected (significant group-by-trial-block interaction; two-way rm-ANOVA, $P = 0.02$). Similar trends were found whether the first four trials of each trial block were averaged or only the first trial of each block was considered in the analyses.

The second hypothesis could not be rejected in that, at 3-months follow-up, the impact force reduction achieved by the 3-month intervention group ($n = 10$) did not differ from that in the 3-month control group ($n = 11$) at 3 months (two-way rm-ANOVA, $P = 0.62$). However, although the longer term behavior of the two groups was indistinguishable, subjects in both groups exhibited a similar trend: there were significant decreases in the impact force across visits ($P = 0.03$) and between baseline and 3 months (8.9% decrease, $P = 0.04$, Fig. 3). It is noteworthy that, across all subjects, $F_{\max}$ for the very first fall at 3-month follow-up was also significantly less than the average baseline values (two-way ANOVA, $P = 0.01$).

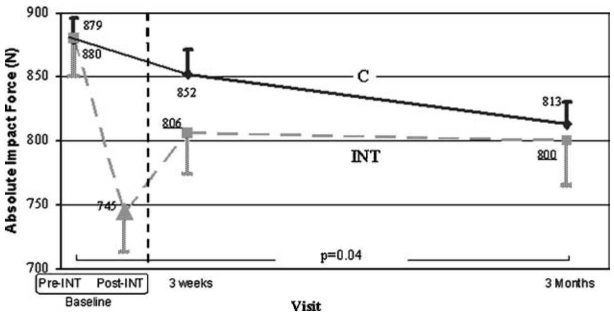

Fig. 3. Lack of retention of educational intervention effect on $F_{\max}$ and evidence of self-education in $F_{\max}$ reduction over the 3-month trial. Data are presented by group (square symbols: 3-month intervention group "INT", $n = 10$); diamond symbols: 3-month control group "C", $n = 11$. Bars denote standard error. Note the significant difference in $F_{\max}$ between baseline and 3-month follow-up visits across all subjects, $P = 0.04$.

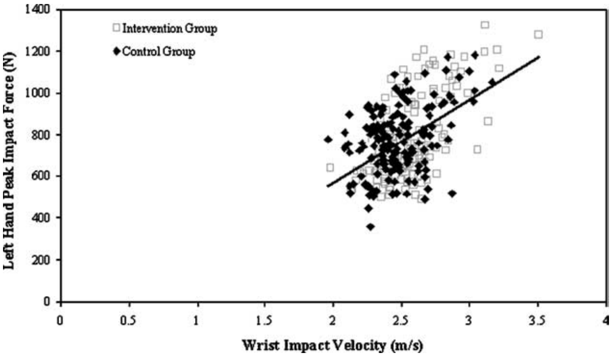

Fig. 4. Scatter plot of left-side peak impact force ($N$) vs. wrist impact velocity (m/s) across all subjects and trials for all visits (slope = 402 $Ns/m$; Pearson correlation coefficient $r = 0.52$, $P < 0.0001$).

Across all subjects, left-side impact forces correlated significantly with the left wrist velocity just prior to impact ($r = 0.52$, $P < 0.0001$; see Fig. 4). Additionally, neck velocity, elbow angle and elbow extension speed just prior to impact also played a significant role in determining the impact forces ($P < 0.02$). However, it was only the wrist impact velocity and the elbow impact extension speed of the 3-month intervention group that decreased significantly after the 10-min instruction at the baseline visit (Table 1). Both the wrist velocity and the elbow extension speed at impact tended to decrease over the 3-month period, but not significantly so (Table 2).

## 4. Discussion

After the 10-min intervention, young males demonstrated an 18% reduction in the magnitude of hand impact force while arresting a forward fall from a shoulder height of 1 m. This reduction was achieved without any other body part, such as the torso, impacting the ground. By contrasting these results with those of the 8-subject baseline control group, we conclude that this short-term gain was due to the educational intervention itself.

The ability of subjects to volitionally reduce their impact forces by 18% corroborates the results of DeGoede and Ashton-Miller (2002), although their subjects achieved a 27% reduction in impact force. The difference in the two results may be explained by the DeGoede and Ashton-Miller subjects having been permitted to arrest residual downward momentum with their torso in their minimum-impact trials, whereas the present subjects were not permitted to do so. The present results may generalize better to subjects of either gender because it is instinctual to want to reduce the risk of the head striking the ground, and this goal is furthered by increasing the minimum clearance between the torso and the ground.

We assume that a Colles' fracture is associated with $F_{\max}$, the first peak in the wrist impact force, reaching the

Table 1
Mean (SD) absolute impact forces, reported for each hand, and left-side kinematic data averaged across the first four trials at the baseline visit by group

| Group | Visit | $F_{\mathrm{left}}$ | $F_{\mathrm{right}}$ | $V_{\mathrm{wrist}}$ (m/s) | $V_{\mathrm{neck}}$ (m/s) | $\theta$ (deg) | $\theta_{\mathrm{dot}}$ (deg/s) |
|---|---|---|---|---|---|---|---|
| 3-Month intervention ($n = 10$) | Pre-test | 840 (182)[a] | 832 (181)[b] | 2.66 (0.21)[c] | 2.69 (0.25) | 159 (6) | 141 (94)[d] |
| | Post-test | 721 (198)[a] | 716 (177)[b] | 2.52 (0.18)[c] | 2.68 (0.24) | 155 (12) | 42 (48)[d] |
| Baseline control ($n = 8$) | Pre-test | 758 (144) | 813 (94) | 2.49 (0.21) | 2.71 (0.15) | 156 (7) | 114 (86)[e] |
| | Post-test | 744 (212) | 819 (132) | 2.45 (0.24) | 2.73 (0.12) | 155 (9) | 46 (101)[e] |

$F_{\mathrm{left}}$ and $F_{\mathrm{right}}$ are the left and right hand impact forces ($N$), respectively; $V_{\mathrm{wrist}}$ and $V_{\mathrm{neck}}$ (m/s) represent the wrist and neck velocity right prior to impact; $\theta$ (deg) and $\theta_{\mathrm{dot}}$ (deg/s) are the elbow angle and the elbow extension speed upon impact.

[a] $P = 0.004$.

[b] $P = 0.03$.

[c] $P = 0.008$.

[d] $P = 0.003$.

[e] $P = 0.06$ for pre-post-intervention differences (rm-ANOVA).

Table 2
Mean (SD) absolute impact forces for each hand and left-side kinematic data averaged across the first four trials by group and visit

| Group | Visit | $F_{\mathrm{left}}$ | $F_{\mathrm{right}}$ | $V_{\mathrm{wrist}}$ (m/s) | $V_{\mathrm{neck}}$ (m/s) | $\theta$ (deg) | $\theta_{\mathrm{dot}}$ (deg/s) |
|---|---|---|---|---|---|---|---|
| 3-Month intervention ($n = 10$) | Baseline | 840 (182) | 832 (181) | 2.66 (0.21) | 2.69 (0.25) | 159 (6) | 141 (93) |
| | 3 weeks | 790 (197) | 735 (205) | 2.58 (0.22) | 2.73 (0.25) | 156 (6) | 86 (50) |
| | 12 weeks | 777 (205) | 756 (211) | 2.53 (0.29) | 2.70 (0.26) | 149 (12) | 99 (56) |
| 3-Month control ($n = 11$) | Baseline | 810 (123)[a] | 859 (98) | 2.50 (0.23) | 2.59 (0.18) | 155 (7) | 143 (90) |
| | 3 weeks | 788 (150)[a] | 804 (101) | 2.46 (0.18) | 2.58 (0.25) | 155 (10) | 83 (76) |
| | 12 weeks | 738 (138)[a] | 771 (133) | 2.45 (0.19) | 2.56 (0.16) | 159 (7) | 105 (83) |

$F_{\mathrm{left}}$ and $F_{\mathrm{right}}$ refer to forces ($N$) on the left hand and right hand, respectively; $V_{\mathrm{wrist}}$ and $V_{\mathrm{neck}}$ (m/s) denote wrist and neck velocity immediately prior to impact; $\theta$ (deg) and $\theta_{\mathrm{dot}}$ (deg/s) are the elbow angle and the elbow extension speed upon impact.

[a] $P = 0.04$ (rm-ANOVA between visits).

ultimate strength of the bone. If true, then even a 9% decrease in $F_{\mathrm{max}}$, such as that found in this study, can make the difference between fracture and no fracture when $F_{\mathrm{max}}$ nears the injury threshold.

In testing the second hypothesis, we sought to determine whether the 3-month intervention group could retain, without practice, the skill they learned at baseline over the 3-week, and then over the 3-month follow-up period. The results showed that, in the absence of practice, they could not retain this short-term learning over 3 weeks. However, when the 3-month intervention and 3-month control group subjects were pooled, a significant reduction in maximum wrist impact was found at 3-months follow-up. An important practical point in terms of reducing injury is that the first fall at 3 months was significantly less than baseline values. This suggests that learning had occurred after the experience of having performed the task on previous visits.

By 3 weeks, the $F_{\mathrm{max}}$ reduction in the 3-month intervention group had diminished from 18% to 9%, where it remained for 3 months (Fig. 3). The surprising result was the reduction in impact force with time in the combined 3-month groups. This result is noteworthy because it is the first time that healthy subjects have been shown to be capable of self-learning in reducing their wrist impact forces over a series of falls: indeed, the stimulus was as few as five (uninstructed) falls at baseline, followed by five (uninstructed) falls after a hiatus of three weeks. We attribute this to the phenomenon of 'consolidation', in other words 'learning without practice' (Brashers-Krug et al., 1996; Schmidt and Lee, 1998). The reason for this is that the baseline control group, who were simply instructed to arrest their falls naturally, did not improve during the baseline visit, yet the 3-month control group, who received identical instructions, did exhibit learning over the 3-week and 3-month follow-up. This is a striking result because the learning effect was the same in both groups (Fig. 3) in spite of the fact that the 3-month control group had only experienced 10 falls, while the 3-month intervention group experienced 15 falls. This suggests that the instruction had a short-term effect, but the long-term effect was achieved only through self-learning. This self-learning might have occurred because of the challenging nature of this task: the impact force was sufficiently large (approximately one body-weight) that it bordered on being uncomfortable. Therefore, subjects in both 3-month groups may have felt compelled to find ways to reduce it if possible, and many did so. The clinical significance of this result is that repeated falls may lead to individuals teaching themselves how to improve their fall-arrest techniques, thereby reducing their risk for fall-related injury.

The scope of the present investigation was limited to a forward fall arrested with both arms. Because a fall forward is the most common fall direction (see Section 1), the direction of these test falls is representative of many falls. The results cannot necessarily be extrapolated to asymmetrical forward falls.

Subjects in the current study were instructed to make all adaptations prior to impact with the force plates (DeGoede and Ashton-Miller, 2002), because post-impact kinematic modifications are known to have a negligible effect (Chou et al., 2001). Since the initial fall height was less than standing height, the average descent time (i.e., from release to hand-ground contact) was 0.53 s, which leaves more than enough time for young or older subjects to position their arms ready for impact (DeGoede et al., 2001). Indeed, a fall from standing height takes an average of 0.7 s (Hsiao and Robinovitch, 1998). Although it further increases the available response time, the advantage of the extra time to prepare for the fall arrest is likely more than outweighed by the additional kinetic energy that must be dissipated. For safety reasons, our subjects were always informed prior to their fall being initiated.

The difference between the downward neck and wrist impact velocities may correlate with the ability to reduce the impact force (DeGoede and Ashton-Miller, 2002). If a subject can perform a fall arrest with a relatively low wrist impact velocity (with respect to the neck impact velocity), then this indicates he/she knows how to land without protracting the arms. Indeed, the baseline control group at the baseline had a smaller mean wrist impact velocity and a larger mean neck impact velocity in the natural trials than the 3-month intervention group did at a similar time point. This limited the potential reduction in impact force that the baseline control group could achieve.

Limitations of this exploratory study include the fact that the subjects were not randomized into each group. We first studied the 3-month intervention group to determine if there was longer-term retention of learning. Then, on finding a learning effect, the 3-month control group was added to test the second hypothesis. Finally, to test the first hypothesis, the eight baseline controls were added. The study needs to be repeated with contemporaneous subject randomization into each group. An additional design limitation is the fact that the 3-month control group performed five, as opposed to the 10 trials performed by the 3-month intervention group, at baseline. However, since the first hypothesis was rejected, the 3-month control group would not have learned how to reduce their impact forces at the baseline visit had they performed those five additional trials. A further limitation is that neither of the control groups were administered a sham intervention. However, since they had the same contact time with the test team as the 3-month intervention group did, we regard this lack of a sham intervention a slight limitation. Next, it could be argued that the fall we asked subjects to perform does not resemble a "real" fall, which is usually unanticipated. Although the fall initiation is not realistic, we argue that the final part of the flight phase is realistic. The one-body-weight magnitude of the impact force on each hand also lends much realism to the arrest. It remains to be demonstrated whether our results can be extrapolated to healthy young women or to healthy older adults. Lastly, there may be ways to improve the efficacy of the intervention received by the 3-month intervention group including, for example, regular fall practice sessions.

## 5. Conclusions

Healthy young males can learn to reduce impact forces during forward falls after 10-min instruction. Without such instruction, no such improvement was attained at baseline. Retention of the skill at 3 weeks was poor. However, over a 3-month period, there is evidence that subjects taught themselves how to reduce $F_{\max}$ after as few as 5 falls spaced 3 weeks apart.

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