Age Differences in Energy Absorption in the Upper Extremity During a Descent Movement: Implications for Arresting a Fall

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Background. Falls are the number one cause of unintentional injury in older adults. The protective response of “breaking the fall” with the outstretched hand is often essential for avoiding injury to the hip and head. In this study, we compared the ability of young and older women to absorb the impact energy of a fall in the outstretched arms.

Methods. Twenty young (mean age = 21 years) and 20 older (M = 78 years) women were instructed to slowly lower their body weight, similar to the descent phase of a push-up, from body lean angles ranging from 15° to 90°. Measures were acquired of peak upper extremity energy absorption, arm deflection, and hand contact force.

Results. On average, older women were able to absorb 45% less energy in the dominant arm than young women (1.7 ± 0.5% vs 3.1 ± 0.4% of their body weight × body height; p < .001). These results suggest that, even when both arms participate equally, the average energy content of a forward fall exceeds by 5-fold the average energy that our older participants could absorb and exceeds by 2.7-fold the average energy that young participants could absorb.

Conclusions. During a descent movement that simulates fall arrest, the energy-absorbing capacity of the upper extremities in older women is nearly half that of young women. Absorbing the full energy of a fall in the upper extremities is a challenging task even for healthy young women. Strengthening of upper extremity muscles should enhance this ability and presumably reduce the risk for injury to the hip and head during a fall.

Key Words: Hip fracture—Wrist fracture—Falls—Biomechanics—Aging.
body mass from 54.4 to 87.2 kg (M = 68.8 ± 8.6 kg), and in height from 1.45 to 1.74 m (M = 1.61 ± 0.07 m). Potential participants were screened initially for eligibility with a telephone interview. Those who seemed to meet our inclusion criteria were further screened on physical examination by an experienced physiotherapist. Exclusion criteria included (a) regular exercise averaging once a week or more for the past 3 months (because our intent in this study was to examine how normal aging influences ability to arrest a fall, without the confounding effect of varying levels of exercise), (b) impairment of neuromuscular function secondary to neurologic disease (e.g., traumatic brain injury, Parkinson’s disease, cerebral palsy, multiple sclerosis, diabetic neuropathy), (c) amputation or other debilitating orthopedic conditions (e.g., joint replacements, rheumatoid arthritis), (d) inability to raise the arms to shoulder height, and (e) inability to follow simple instructions in English. Each participant provided written informed consent, and the experimental protocol was approved by the Office of Research Ethics at Simon Fraser University.

The experimental protocol simulated the descent phase of a push-up activity, with gradually increasing energy absorption demands, allowing for measurement of the participant’s maximum energy-absorbing capacity. In designing the protocol, we considered that real falls would create too great a risk for injury, especially for older participants, and that the task of breaking a forward fall is similar to the descent phase of a push-up. We also considered that there are several strategies available for arresting a fall with the upper extremities. In particular, DeGoede and Ashton-Miller (9) showed that a “stiff arm” approach can be used to break a fall, which produces a small amount of joint flexion over a short time interval. Our experiments simulated fall arrests involving much larger deflections of the upper extremity and downward movement of the torso during contact (via flexion at the elbow and shoulder). This arrest strategy mimics the “natural” or “minimal impact” condition of DeGoede and Ashton-Miller (9) much more closely than the stiff arm fall. In addition to safety considerations, we opted for this approach based on the expectation that this type of fall results in considerably greater energy absorption in the upper extremity (for a given force level) and thereby provides a more accurate measure of the true energy-absorbing capacity of the upper extremity.

At the beginning of each trial, the participant stood with her body inclined at an angle θ from the vertical, with her elbows fully extended, shoulders flexed at 90°, and palms contacting two flush-mounted 25 × 35-cm force plates (MU2535; Bertec Corp., Columbus, OH) to acquire measures of hand contact force (Figure 1). Her hands were positioned with the middle fingers pointing superiorly and the wrists in the same sagittal plane as the shoulders. The platform was rotated to match the body lean angle θ, and the height was adjusted to allow the required upper extremity position (Figure 1).

We then instructed the participant to slowly lower her body weight while maintaining her knees and hips extended, similar to the descent phase of a push-up, until she reached 90° of elbow flexion. To prevent further descent, the participant wore a fall restraint harness, which was attached via a tether to an overhead support, and did not apply a restraining force until the elbow angle exceeded approximately 120°. Each participant started at a lean angle of 15°. If they were able to complete the lowering task three repeated times and achieve elbow flexions of approximately 90° in each trial with no assistance from the tether, the body lean angle was increased 15° (up to a maximum of 90°) and the experiment was repeated. For participants who were able to complete trials at 90°, a further set of trials were conducted at 90° with the addition of a 7 kg weight secured with a strap between the scapulae. We provided rest periods of 20 seconds between individual trials (in the inclined position) and 5 minutes between sets.

During each trial, we used a seven-camera, 60-Hz motion measurement system (Qualisys Inc., East Windsor, CT) to acquire the three-dimensional (3D) positions of 27 skin surface markers located at the top of the head, seventh cervical vertebra, sacrum and bilaterally at the acromion processes, lateral radial epicondyles, medial ulnar epicondyles, radial styloids, ulnar styloids, third metacarpal heads, anterior superior iliac spines, greater trochanters, lateral femoral epicondyles, lateral malleoli, and fifth metatarsal heads. We acquired simultaneous measures of hand contact force and center of pressure at 960 Hz from the force plates underly- ing the hands.

For each trial, we used custom MATLAB routines to calculate time-varying values of arm deflection, hand contact force, and energy absorbed by both upper extremities. Marker position data and force data were first filtered using...
Figure 2. Traces recorded during descent of hand contact force and arm deflection for one typical young participant and one typical older participant.

Table 1. Mean Parameter Values and Results From t Tests

| Parameter                                      | Young, n = 20, mean ± 1 SD (range) | Older, n = 20, mean ± 1 SD (range) | Mean Difference (95% confidence interval) | p Value |
|------------------------------------------------|------------------------------------|------------------------------------|-------------------------------------------|----------|
| Peak energy absorption, normalized (% body weight × body height) | 3.1 ± 0.4 (2.4–3.9) | 1.7 ± 0.5 (0.7–3.2) | 1.3 (1.0–1.6) | <.001 |
| Peak hand contact force, normalized (% body weight) | 36.5 ± 3.2 (30.0–44.0) | 23.8 ± 6.7 (13.9–36.5) | 12.6 (9.3–16.0) | <.001 |
| Peak arm deflection, normalized (% body height) | 13.7 ± 1.8 (11.0–17.0) | 13.6 ± 2.7 (9.7–22.1) | 0.1 (–1.3 to 1.6) | .822 |
| Maximum angle performed (°) | 87 ± 8 (60–90) | 67 ± 10 (45–90) | 20 (14–26) | <.001 |
| Angle of peak energy absorption (°) | 79 ± 11 (60–90) | 56 ± 12 (30–75) | 23 (16–30) | <.001 |
10 participants completed 60°, and 1 participant completed 45°. The angle of peak energy absorption for the older women was 75° for 3 participants, 60° for 12 participants, and 45° for 5 participants.

**Discussion**

Our results suggest that older women are substantially less able than young women to absorb energy in their upper extremities during a push-up task that simulates arresting a fall. This may contribute to the increase with age in the prevalence of fall-related hip fracture (10,11) and head and neck injury (12–15). To place these results in the context of the ability to safely arrest a fall, it is useful to compare our observed energy absorptions with measures of the average energy content of a forward fall (16). In a previous study, where forward falls from standing were initiated by means of a tether and electromagnet in an experimental study of forward falls from standing, the average energy content of the body at contact was $0.17 \pm 0.09$ J/(body weight \times body height) (16), which exceeds the average energy that our older women could absorb in their upper extremities by 5-fold ($0.017$ J/(body weight \times body height)) and exceeds by 2.7-fold the average energy that young women could absorb ($0.031$ J/(body weight \times body height)). Thus, the task of absorbing all the energy of a forward fall in the upper extremities, and thereby completely avoiding contact to the trunk and head, presents a major challenge even for healthy young women. Of course, rather than being able to absorb all the energy of the fall in the upper extremities, a more reasonable goal is to absorb just enough energy to prevent impact to the head and reduce to safe levels the residual energy that must be absorbed through contact to the trunk and pelvis. Quantifying this value is a challenging but important goal for future research.

Our findings should inform the design of exercise programs aimed at enhancing fall protective responses, in particular resistance training, a treatment mode that is commonly used in the management of individuals who are at high risk of falls or those with osteoporosis (17). The reduced energy absorption capacity of our older participants was associated with reduced ability to generate force in the upper extremities, which is likely secondary to age-related loss of eccentric muscle strength (7,18) in the chest, scapular, shoulder, and arm muscles (19) that are required to decelerate the body mass as the shoulder horizontally abducts and the elbow flexes as in the descent phase of a push-up. Thus, training for this task should include eccentric pectoralis major and triceps brachii exercise, with adequate stabilization of the scapulae and thorax. These muscles and movements should be key targets in future studies of exercise therapy for the improvement of upper extremity energy absorption in falls.

Our results extend the findings of previous studies investigating age- and gender-related differences in the ability to break a fall with the hands. Nevitt and Cummings (2) reported that 49% of fallers aged 64–74 years and 33% of those aged 75 years or older reported landing on a hand during a fall. In contrast, Feldman and Robinovitch (4) found that 98% of young adults impacted one or both hands...
during unexpected falls in a laboratory setting. O’Neill and colleagues (21) found that older women were half as likely as young women to first impact the hand when falling. Finally, Vellas and colleagues (20) observed that 50% of older men but only 33% of older women reported absorbing the main impact of their fall with the hands.

To safely include older women in our study, we substituted an actual fall with the descent phase of a push-up task. On the one hand, the relevant muscle dynamics may be surprisingly similar because impact forces during falls on the outstretched hand are characterized by a higher frequency peak force (with little associated elbow and shoulder rotations) followed by a lower frequency oscillation. It is during this latter period, where force levels are considerably lower, and near the range used in the current study (7–9), where the great majority of elbow and shoulder rotations occur, allowing for energy absorption. On the other hand, the task we studied differs considerably from a fall in the rate of stretch of eccentrically contracting muscles. Although we did not record the time of descent in our trials, it was considerably longer than the ~350 ms observed in DeGoede and Ashton-Miller’s (9) natural fall arrests, and thus, the rate of muscle stretch was considerably slower. It is well known that muscle force (and thus energy-absorbing capacity) increases with increasing rate of stretch and that there is a relative preservation of eccentric muscle strength with aging. In reviewing the literature, Thelen (22) concluded that, when compared with an isometric contraction, maximum muscle force during a rapidly lengthening contraction can be as much as 1.8-fold greater for older women and 1.4-fold greater for younger women. Although such differences would not affect our primary conclusions, they would reduce slightly the differences between young and older women and lessen the gap between the energy that can be absorbed in the upper extremities versus that available in a fall.

There are additional limitations of this study worth noting. The resolution of our reported peak energy absorptions may have been limited by performing trials at discreet increments of 15° in body lean angle. Although this was important to minimize participant fatigue, a participant’s maximum energy absorption may have been observed at a body lean angle between two performed levels or at a lean angle slightly larger than the maximum performed angle. However, the latter scenario is unlikely as 13 of 20 older participants absorbed greater energy at a lean angle smaller than their maximum performed angle. It is also possible that a participant may not have performed at her true maximum ability due to fatigue, lack of motivation, or fear of inability to halt downward movement of the body with her arms. We attempted to reduce these effects by providing a safety harness, frequent rest periods, and “coaching” to emphasize and encourage each participant to descend as far as possible. Although we did not calculate individual energy absorptions in the wrist, elbow, and shoulder, previous studies indicate the dominant role in energy absorption of the shoulder over the elbow (8,23). Furthermore, we calculated arm deflection based on the distance between the wrist and acromion markers and did not specifically measure and include shoulder retraction in our estimates of arm deflection. This may have contributed to an underestimation of energy absorption for both our young and older participants.

Finally, it is important to note that, although upper extremity impact is protective for reducing the risk for head injury and hip fracture, it obviously increases one’s risk for fracture or dislocation at the wrist, hand, or elbow during a fall. Thus, we recommend that exercise programs train individuals to “break the fall” in a way that also minimizes their risk for upper extremity injury. For example, DeGoede and Ashton-Miller (9) have shown that impact forces are reduced substantially by flexing the elbow just before descent, and Groen et al. (24) recently showed that older adults can be trained over a few sessions in using a martial arts falling technique.

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