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Biomechanical and physiological age differences in a simulated forward fall on outstretched hands in women

Lauren J. Lattimer[a,*], Joel L. Lanovaz[a], Jonathan P. Farthing[a], Stéphanie Madill[b], Soo Y. Kim[b], Stephen Robinovitch[c], Catherine M. Arnold[d,*]

[a] College of Kinesiology, University of Saskatchewan, 87 Campus Dr., Saskatoon, SK S7N 5B2, Canada
[b] School of Physical Therapy, University of Saskatchewan, Suite 3400, 104 Clinic Place, Saskatoon, SK S7N 2Z4, Canada
[c] School of Engineering Science, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6, Canada
[d] School of Physical Therapy, College of Medicine, Suite 3400, 104 Clinic Place, University of Saskatchewan, Saskatoon, SK S7N 2Z4, Canada

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ABSTRACT

Background: Falling on the outstretched hands, a protective mechanism to arrest the body and avoid injury, requires upper limb and trunk motor control for effective body descent. Older women are particularly susceptible to injury from a forward fall, but the biomechanical and physiological (e.g., muscle strength) factors related to this increased risk are poorly understood. Determining age differences in the modifiable neuromuscular factors related to a forward fall landing and descent could help to inform injury prevention strategies. The purpose was to investigate age related differences in upper extremity strength and fall arrest strategy differences during a simulated fall and to evaluate the relationships between muscle strength and biomechanical variables.

Methods: Nineteen younger (mean age 23.0 yrs., SD 3.8) and 16 older (mean age 68.2 yrs., SD 5.3) women performed five trials of simulated falls. Biomechanical measures and electromyographic muscle activity were recorded during the descents. Concentric, isometric and eccentric strength of the non-dominant upper limb was measured via a dynamometer using a customized protocol.

Findings: Older women demonstrated lower concentric elbow extension strength compared to younger women ($p = 0.002$). Landing strategies differed where younger women had significantly greater elbow joint angle ($p = 0.006$) and velocity ($p = 0.02$) at impact. Older women demonstrated diminished capacity to absorb energy and control descent on outstretched hands compared to younger women ($p = 0.001$).

Interpretation: The landing strategy used by older women along with decreased energy absorption may increase risk of fall-related injury and increase the likelihood of trunk or head impact with the ground.

1. Introduction

Falls are the leading cause of injury-related hospitalization among seniors and account for 32% of the $8.7 billion annual cost of injury in Canada (Parachute Canada, 2015). In 2011, 15% of the Canadian population was 65 years of age or older, with one third of this age group sustaining a fall annually (Canada, 2011). With the percentage of adults over the age of 65 years expected to double in the next 25 years (Canada, 2011), planning for an aging population and preventing injuries from falls is a global priority (*Ageing well: a global priority*, 2012).

Sixty percent of falls in the community setting occur in a forward direction where reaching with the hands to arrest the body's forward momentum is a protective response to avoid injury to the head, trunk or hip (O'Neill et al., 1994). An unfortunate cost of this protective response is that a fall on the outstretched hand (FOOSH) is the primary cause of fall-related upper extremity trauma (Hill et al., 1998). Hand impact during falls is frequently reported in community-dwelling elderly as well as observed in video surveillance data in long term care (DeGoede et al., 2003; O'Neill et al., 1994; Schonnop et al., 2013; Stevens et al., 2014). Of interest is the observation that head impact still occurred in 79% of the falls with hand impact (Schonnop et al., 2013). An explanation of this finding could be that the protective response of FOOSH may be ineffective for some older adults to prevent head impact. Postmenopausal women tend to experience greater strength declines, decreased functional capacity, increased rates of sarcopenia, and increased risk for falls and fall-related injuries than similarly aged men (Sorensen et al., 2001). Dynapenia, age-related loss of muscle strength, could influence older women's protective responses (Clark and Manini,

* Corresponding authors.
E-mail addresses: lauren.lattimer@usask.ca, lauren.lattimer@acadiau.ca (L.J. Lattimer), Joel.Lanovaz@usask.ca (J.L. Lanovaz), jon.farthing@usask.ca (J.P. Farthing), Stephanie.madill@usask.ca (S. Madill), soo.kim@usask.ca (S.Y. Kim), stever@sfu.ca (S. Robinovitch), cathy.arnold@usask.ca (C.M. Arnold).

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2008) during a FOOSH with the resultant increased risk of upper extremity (UE) fractures and traumatic brain injuries.

A FOOSH can be divided into the following three phases: 1) pre-impact, 2) impact and 3) deceleration. The pre-impact phase is the time period from loss of balance until impact (DeGoede et al., 2003) and involves muscle activity and UE movement strategies in preparation for landing. In the second phase, defined as the impact of the extremity with the landing surface, forces peak within milliseconds and the energy of descent is absorbed through the UE. The deceleration phase is immediately following impact until the final stages of breaking and stabilization of body posture (Santello, 2005).

Muscle strength is an important force-attenuating mechanism, adjusting the amount of shock attenuation through eccentric contractions about the elbow joint and is one of the factors that modify elbow stiffness during the impact and post-impact phases. Elbow joint stiffness has been defined as the resistance offered by muscles and passive structures to deformation (Latash and Zatsiorsky, 1993). Muscle activity and the ability to control dynamic movements are associated with alterations in stiffness (Butler et al., 2003). There is a fine balance between excessive stiffness surrounding a joint which may increase fracture risk and too little stiffness creating functional instability of the joint resulting in increased risk of other body segment or soft tissue injury (Butler et al., 2003). For example, in a FOOSH, hand impact with high stiffness at the elbows may result in higher fracture risk at the wrist (Burkhart and Andrews, 2013; Chou et al., 2001). On the other hand, decreased muscle activation at impact diminishes stiffness and may result in excessive elbow flexion or elbow bucking, thus increasing the risk of injuring the head or torso (DeGoede and Ashton-Miller, 2003). There are higher muscle strength demands to control a forward fall descent with elbow flexion (Chou et al., 2001); it is possible that older adults generate greater elbow joint stiffness at impact as a compensatory mechanism for weaker muscles (Hortobagyi and DeVita, 2000; Nagai et al., 2012).

During the second impact phase of a FOOSH, forces of 1–4 kN are enough to cause a wrist fracture in an older adult based on cadaveric studies (Augat et al., 1998). Straight arm or “stiff landings” produce greater peak impact force, impulses, load rates and shorter impulse durations than self-selected or bent elbow landings (Burkhart and Andrews, 2013; Lo and Ashton-Miller, 2008). Altering UE positioning (i.e. moderate elbow flexion) just prior to impact can reduce impact forces by 32% to 58% (DeGoede et al., 2001; DeGoede and Ashton-Miller, 2002; Latash and Zatsiorsky, 1993). Chou et al. (Chou et al., 2001) found that if the elbow flexed slightly (i.e. approximately 11°) upon impact, the time to peak force was delayed, which resulted in greater impulse absorption. This landing strategy may be optimal to both diminish the risk of impact to the head, hip or torso by increasing the dampening effect and improving energy absorption to decrease the risk of wrist fracture. Past studies have indicated that older women absorb 35%–45% less energy during a controlled descent on the outstretched arms, but the energy absorption capabilities have yet to be investigated during a simulated forward fall impact and descent in women (Lattimer et al., 2016a; Sran et al., 2010).

Controlling the third, deceleration phase on the outstretched hands requires several co-ordinated muscle actions at the shoulder and elbow in order to control the descent to avoid injurious impact to other body parts such as the head or torso. Although there is some evidence where older women are less able to flex their elbows to descend as far as younger women can in a controlled reverse push-up motion (Lattimer et al., 2016a; Lattimer et al., 2016b) it is unclear what differences exist in this phase of a simulated FOOSH.

It is necessary to quantify the mechanisms that affect injury risk before introducing measures to reduce the risk and severity of injury. Studies that quantify landing strategies in women are limited. Past in vivo studies of forward falls have investigated fall strategies from varying heights in older and younger male participants or younger adults including younger women where descents were controlled, or participants anticipated the fall (Burkhart and Andrews, 2013; Chiu and Robinovitch, 1998; Chou et al., 2001; Kim and Ashton-Miller, 2003; Lattimer et al., 2016a; Lo and Ashton-Miller, 2008). The objectives of this study were to: 1) compare age differences among women in biomechanical and physiological variables during the impact and descent phases of a simulated forward impact and descent on outstretched arms and 2) determine the association of UE muscle strength to these variables. It was hypothesized that older women would: 1) demonstrate a fall arrest and descent strategy characterized by decreased elbow flexion angles at impact and during descent, decreased energy absorption and greater elbow stiffness and 2) exhibit decreased muscle strength in the UE compared to younger women It was also hypothesized that UE strength would be positively associated with energy absorption. Other biomechanical variables likely to contribute to injury risk such as impulse and velocity at impact were also explored, but no hypotheses were formed as potential age differences were not clear from previous literature.

2. Methods

Participants were recruited by community poster and newspaper advertisements. Potential participants were screened for eligibility with a telephone interview. Exclusion criteria for this study were: a) fracture to the wrist or forearm less than two years ago; b) any previous surgery to the UE; c) recent (within the past 6 months) injury to the shoulder, wrist or hands; d) any current medical or neurological conditions involving weakness or pain in the UE; e) any other recent significant medical or neurological concern (e.g. stroke, heart attack, chest pain). Written informed consent was obtained, and the experimental protocol was approved by the institution's Biomedical Research Ethics board.

2.1. Data collection protocol

Participants first completed the Waterloo Handedness Questionnaire (WH) and the International Physical Activity Questionnaire-Short Form (IPAQ) (Craig et al., 2003). Height and weight were measured using a standardized protocol with a portable stadiometer and a weigh scale. Additionally, limb length measurements were used to standardize the participant's position during testing.

2.1.1. Strength assessment

Strength was assessed by measuring peak torque using an Isokinetic Dynamometer (Humac NORM, CSMi, Stoughton, MA). Peak torque (Nm) was recorded during maximal effort isometric, concentric and eccentric contractions of the non-dominant upper limb using a custom protocol developed to better simulate the plane of movement and muscle activation patterns required for a controlled body descent (Lattimer et al., 2016a). Each participant was given one or two practice repetitions before each contraction type with standardized encouragement provided by the same tester for all tests. Test order was randomized, and participants performed three maximum voluntary contractions separated by one minute rest periods. For the isometric contractions, the shoulder was abducted 30° and horizontally adducted 45° and the elbow was flexed to 90°. During concentric contractions, the participants moved the handle away from the body from a position of 60° of elbow flexion to full elbow extension. During eccentric contractions, the participants initiated the contraction at a position of 120° elbow flexion and completed the contraction at 60° elbow flexion (i.e. an abbreviated range of motion) concentric and eccentric were standardized to $45°\cdot s^{-1}$ [$0.78\ rad\cdot s^{-1}$]. The custom protocol was pilot tested, and reliability was confirmed for 10 older and 10 younger women tested on repeat occasions. Test re-test reliability intra-class coefficients (ICC) over 3–5 days for isometric, concentric and eccentric contractions were $r = 0.932$, $r = 0.907$, and $r = 0.956$ respectively.