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Original Article Submission

Age differences in upper extremity joint moments and strength during a laboratory-based tether-release forward fall arrest in older women

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Abstract

Age-related declines in upper extremity muscle strength may affect an older adult's ability to land and control a simulated forward fall impact. The role of individual upper extremity joints during a forward fall impact has not been examined. The purpose was to evaluate the age differences in upper extremity joint moment contributions during a simulated forward fall and upper extremity muscle strength in older women. A convenience sample of 68 older women (70 (8) yrs) performed three trials of a simulated forward fall. Percentage joint moments of the upper extremity were recorded. Upper extremity muscle strength was collected via handgrip, hand-held dynamometry of the shoulder and elbow and a custom multi-joint concentric and eccentric strength isokinetic dynamometer protocol. Percentage joint moment contributions differed between women in their sixties and seventies with significantly greater relative shoulder joint involvement ($P = .008$), coupled with lower elbow joint contributions ($P = .004$) in comparison to 80 year olds. An increase in each year of age was associated with a 4% increase in elbow contribution (Beta = -0.421, $r^2 = 17.9$, $P = 0.0001$) and a 3.7% decrease in shoulder contribution (Beta = 0.373, $r^2 = 14.6$, $P = 0.002$). Older women exhibit different landing strategies as they age. Fall injury prevention research should consider interventions focused on these differences taking into account the contributions of upper extremity strength.

Keywords: accidental falls, fall related injury, older adult, upper limb

1. Introduction

Fall-related injuries can have a substantial impact on an individual's independence and generate a financial strain on the health care system (Public Health Agency of Canada, 2014). Nearly 60% of fall injuries occur to the upper limb, head or trunk (Public Health Agency of Canada, 2014), with falls being responsible for 80% of hospital admissions for traumatic brain injury (Harvey and Close, 2012). Women are at a greater risk, falling approximately 1.3-2.2 times more often than men (O'Neill et al., 1994; Public Health Agency of Canada, 2014; Sattin et al., 1990). Women experience fractures at a greater frequency when compared to men (Court-Brown et al., 2018), with the most common site for a fall related fracture being the upper extremity, followed by the hip and trunk (Sattin et al., 1990). With 20-30% of older adults in Canada experiencing one or more falls a year (Public Health Agency of Canada, 2014) an understanding of the contribution the upper extremity has during forward fall arrests is needed.

During a forward fall arrest, the upper extremity must attenuate the forces generated during impact to decelerate one's body mass (Nevitt and Cummings, 1993). A common strategy to break a forward fall is Falling On the Out-Stretched Hand (FOOSH) (Sran et al, 2010). The position of the upper extremity at impact affects body mass deceleration post-impact and could help to reduce risk of head and trunk injuries (DeGoede et al., 2003; Hsiao and Robinovitch, 1998; O'Neill et al., 1994). In 97% of falls occurring in a forward direction in long-term care, there was head impact, despite the majority also impacting with the hand, suggesting that older adults may be using an upper arm protective response that is ineffective in reducing head impact (Schonnop et al., 2013). In addition, women are twice as likely to experience a head impact than men (Yang et al., 2017). The kinetic contributions of the wrist, elbow and shoulder during a fall arrest have received limited attention. Implementing an elbow dominant strategy to control the body's momentum, categorised by higher energy absorption at impact, may reduce pain and the risk of injury in young men (Chou et al., 2012). Research on individual joint contributions during forward falls in older adults is lacking, and there are no similar studies involving women.

Age-related declines in upper extremity muscle strength may reduce an older adult's ability to attenuate forward fall impact forces and consequently expose them to higher risk of injury (DeGoede et al., 2003; DeGoede and Ashton-Miller, 2003). Women with weaker triceps extension strength were more likely to endure a fracture following a fall (Nevitt and Cummings, 1993). Older women have a reduced capacity in the upper extremity, by almost half, compared to younger women, to absorb the energy during a simulated forward fall descent (Lattimer et al., 2017; Sran et al., 2010). Eccentric elbow extensor strength may be a key factor in impact force attenuation during a forward fall (Chiu and Robinovitch, 1998; DeGoede and Ashton-Miller, 2003; Sandler and Robinovitch, 2001).

An understanding of the individual upper extremity joint contributions during forward falls in older women should help to guide exercise and training research interventions designed to reduce fall-related injuries. The purpose of this study was to compare the individual upper extremity joint kinetics and kinematics, joint involvement and upper extremity strength during a simulated forward fall impact in older women across three decades (60s, 70s and 80s). Secondly, the relationship between upper extremity strength and relative joint contributions was explored. We hypothesised that; 1) upper extremity impact strategy, as characterized by relative joint contributions, will be different between age groups and 2) differences in upper extremity strength will be related to the impact strategy utilized, where individuals with greater shoulder strength will demonstrate a shoulder dominant approach.

2. Methods

Participants were recruited from the local community as part of a larger intervention study. Participants were excluded during a telephone screening process if they had: a) a recent upper body injury or painful joint problem that limited day to day activities or results in pain on a daily basis; b) prior distal radius fracture in the past 2 years, or multiple fractures of the wrist or forearm; c) any history of upper extremity neurological problems (i.e. Stroke, Multiple sclerosis, Parkinson's disease, reflex neuropathy) and d) were unable to safely ambulate independently (with or without a walking aid) in the community. All participants were informed of the experimental risks and provided signed informed consent. The study was approved by the BLINDED Biomedical Ethics Review Board.

2.1 Data collection protocol

Participants visited the laboratory for strength assessments and a simulated forward fall protocol. Height and weight were collected utilizing a standardized protocol. Participants completed the Waterloo Handedness Questionnaire (Bryden, 1977) and the Falls risk for older people in the community assessment (FROP-com) (Russell et al., 2008).

2.1.1 Simulated forward fall protocol

Participants completed a tether-released forward fall protocol (Lattimer et al., 2018, 2017, 2016). The experimental set-up (Figure 1) was designed to simulate the pre-impact, impact and the immediate post-impact phase of a forward fall, replicating Lattimer et al. (2018, 2016). Participants were suspended at a 60-degree angle from the horizontal with their feet maintaining contact with the platform, elbows fully extended, shoulder at 90 degrees flexion and the wrists extended to allow a 1 cm distance of the palms to the force plates. Body position was standardized between participants based on limb proportions. The suspension system was attached to a timed magnet-release mechanism, releasing the participant unpredictably within a one to five second delay following trial initiation. A safety harness and tether ensured no other body parts would contact the force platforms. Participants completed three trials and were instructed to "lower themselves in a push up (descent) motion to 90 degrees of elbow flexion on impact and to avoid contacting the force plates with any other body part". Participants and were fully informed of the protocol and completed assisted practice repetitions against a wall.

Upper limb three-dimensional kinematics were collected utilizing an 8-camera motion capture system (sample frequency =200 Hz, VICON Nexus, VICON, Centennial, CO, USA). Reflective markers (14 mm diameter) were placed over the sternum, bilaterally at the acromion processes, lateral and medial humerus epicondyles and the radial and ulnar styloid processes.

Clusters of four markers each were placed on the lateral distal shaft of the humerus and anterior proximal ulna. Joint centres of the elbow and shoulder were calculated via functional calibrations and published standards (Monnet et al., 2007; O'Brien et al., 2000; Wu et al., 2005). Two force plates (sample frequency =2000 Hz, OR6-7, AMTI, Watertown, VA, USA) were attached to the apparatus and positioned parallel to the body angle. Kinematic, force and magnet-release timing data were synchronously collected on the same system. The simulated forward fall impact was defined as the time when the contact force exceeded 10 N following the release from the magnet support. The data collected during the 200 ms immediately post impact was used for analysis. The raw kinematic data were exported and processed with a 4th order zero-lag Butterworth low-pass filter (cut-off frequency =10Hz) implemented in MATLAB (R2019b, Mathworks, Natick, MA, USA). The elbow joint velocity (EV) and elbow joint range of motion (EROM) were extracted. Average elbow joint stiffness (ES) was calculated as the ratio of the change in joint moment to the change in elbow angle (Nm/[BW*height]). The energy absorption (ENRG) represented the total energy absorbed by the upper extremity, normalized to bodyweight and height, and was calculated using the area under the curve defined by the normal reaction forces at the hands and the displacement vector of the shoulder (average of left and right shoulder) perpendicular to the force platforms (Sran et al., 2010). The peak vertical force (VF) was normalized to bodyweight. Absolute peak joint moments of wrist, elbow and shoulder were calculated utilizing standard inverse dynamics techniques and normalized to bodyweight and height. Percentage joint involvement was calculated using the absolute joint moments as a percentage of the total sum of peak moments for all three joints.

2.1.2 Strength assessments

Handgrip (HG) strength was assessed using a calibrated handgrip dynamometer (Model #5030J1, JAMAR, DMM, Canada) via a standardised protocol (Nitschke et al., 1999). Participants held contractions for approximately 5-seconds for each of three maximal efforts with one minute rest. A Hand-Held Dynamometer (HHD, Model #01165, Lafayette Instrument Inc., Lafayette, Indiana, USA) was used to test the strength of the arm muscles using a standard protocol with a 5 second make test (Stratford and Balsor, 1994) for three maximal repetitions. The positions tested consisted of shoulder flexion, shoulder abduction, and elbow extension. The participants were supine on a standard plinth for all HHD tests and a standardised protocol was implemented (Legg et al., 2020).

Maximal voluntary strength measures from concentric (CON) and eccentric (ECC) trials were obtained using an isokinetic dynamometer with a cable-based linear motion attachment (Figure 2, Humac Wheel, Humac NORM Isokinetic Dynamometer, CSMi, Stoughton, MA, USA). The participant was secured in the dynamometer chair with stabilizing lap and vertical shoulder straps. The custom isokinetic dynamometer set-up used within this study aimed to replicate the multi-joint upper extremity movement seen during forward fall arrest by utilizing a similar upper extremity custom isokinetic strength assessment protocol (Lattimer et al., 2018, 2017). Participants performed two submaximal repetitions for each contraction mode. For the CON contractions, the participants started with their shoulder abducted to 45° and elbow flexed at 120°. Participants were instructed to '*punch out*' until the elbow was extended. During the ECC contractions, the participants initiated the movement with a partially extended arm with 60°

elbow flexion and resisted the cable movement to an elbow angle of 120°. For both contraction protocols the linear cable speed was set constant at 17mm/s. The reliability and validity of the custom protocol utilized has been previously demonstrated in older adults (Legg et al., 2020). Data were obtained successively in the CON contraction mode, followed by the ECC mode in the same arm before swapping arms. Participants completed three maximal efforts under each condition; each repetition was separated by a rest period of one minute.

2.2 Statistical analysis

For all strength measures, an average of the three repetitions from the right arm were used for analysis (Legg et al., 2020). The absolute joint moments, percentage joint contributions and biomechanical measures (ES, EV, ENRG, EROM, VF), averaged across all trials and from the right arm were utilized for analysis. All variables were assessed for normality and participants were grouped according to their age decade. Separate mixed design ANOVA (joint x decade groups) tests were used to determine age differences in the percentage joint involvement, absolute joint moments and biomechanical measures utilized. In the event of significant interaction effects, post hoc one-way ANOVAs were utilised to identify differences between age groups. Strength data were analyzed using separate one-way ANOVA to assess differences in each strength assessment with age (decade group). Greenhouse-Geisser corrections were made when violations in Mauchly's Test of Sphericity were present. Finally, three separate multiple regression step-wise backward selection models were conducted to examine the relationships between age (as a continuous variable) and upper extremity strength with percentage joint contributions. Significance was set at $p<0.05$.

3. Results

A convenience sample of 68 older women (70 (8) yrs, 1.61 (.06) m, 71.5 (13.3) kg, 60s: n = 34, 70s: n = 23 and 80s: n =11) completed testing. Mean strength variables and joint moments are reported in Table 1. Two participants (3%) reported being left-handed and 26 women (38%) reported experiencing one or more falls (range 1 - 3 falls) in the previous 12 months.

3.1 Percentage joint involvement

Percentage joint contributions during the simulated forward fall are reported in Figure 3. Compared to individuals in their eighties, those in their sixties and seventies had significantly greater shoulder involvement (mean % contribution (SD): 60s = 54 (7), 70s = 53 (9), 80s = 45 (7), P = .008), and significantly less elbow joint contributions (mean % contribution (SD): 60s = 33 (6) , 70s = 34 (7), 80s = 41 (6), P = .004). There were no differences present between those in their sixties and seventies.

3.2 Biomechanical measures and absolute joint moments

There were no significant differences across the three age decade groups for all biomechanical measures (Table 1): ES; P = .450, VF; P = .286, EV; P = .380, ENRG; P = .279, and EROM; P = .777. For joint moments (Table 1), individuals in their eighties had a reduced absolute elbow joint moment compared to women in their seventies (P = .028) and a lower absolute shoulder joint moment than women in their sixties (P = .005). There were no differences present for absolute wrist joint moments across the three decades.

3.3 Muscle strength

Significant differences were found (Table 1), with women in their eighties displaying lower strength levels in their shoulder flexion and CON compared to women in both their sixties (*P* = .002 and *P* = .019) and seventies (*P* = .002 and *P* = .037). Women in their sixties had stronger shoulder abduction (*P* = .039) and ECC (*P* = .005) than women in their eighties. No differences according to age were shown in HG (*P* = .657) and elbow extension (*P* = .742) strength assessments.

3.4 Percentage joint involvement relationship with muscle strength and age

Significant backwards regression models were found for % elbow (r^2 = 17.7, *P* = 0.0001) and % shoulder contribution (r^2 = 14.6, *P* = 0.002), but not for the % wrist contribution. Both % elbow and % shoulder contribution were associated with age, explaining 17.9% and 14.6% of the variance respectively. For every year increase in age there was an associated 4% increase in elbow contribution (Beta = -0.421) and a 3.7% decrease in shoulder contribution (Beta = 0.373).

4. Discussion

The aim of this study was to evaluate age differences in upper extremity kinetics and kinematics, joint involvement and strength during a simulated forward fall impact. Secondly the relationship between upper extremity strength and impact strategy was explored in older women. In support of the primary hypothesis, women in their 80s exhibited an increase in elbow involvement leading to a more equal (shoulder and elbow) upper extremity strategy, immediately following impact, whereas women in their 60s and 70s utilise a shoulder dominant strategy. For the second hypothesis, upper extremity strength did not predict the joint involvement strategy, however, older age was associated with an increase in % elbow and a decrease in % shoulder contribution.

A FOOSH strategy upon impact is used to avoid injury (head and torso) by absorbing energy with the upper extremity. Currently, a limited number of studies have investigated the individual kinetic contributions of the wrist, elbow and shoulder during a forward fall arrest. The upper extremity strategy utilized during a simulated FOOSH alters energy contributions at the elbow and shoulder joints (Chou et al., 2012). Through a combination of experimental and modelling methods in young adults during stiff-arm landings, with fully extended elbows, the shoulder has been shown to experience low levels of force and absorb the majority of the energy at impact (Chiu and Robinovitch, 1998). In a group of young men, an elbow dominant strategy, categorized by higher energy absorption, was better for pain reduction and generated a dampening effect for the shoulder joint (Chou et al., 2012), but little attention has been given to the role of individual joint contributions in women during forward falls. Lattimer et al., (2017) reported no significant differences in elbow joint moments between older (~68 years) and younger (~25 years) women during controlled FOOSH descent trials. Here we show women in their 60s and 70s utilised a shoulder dominant strategy, characterised by higher % shoulder contribution, during an unexpected simulated FOOSH whereas women in their 80s used a more equal upper extremity strategy (shifting to similar % elbow and shoulder contributions). Women in their 80s also exhibited lower shoulder flexion strength compared to the women in their 60s and 70s. The association between age and elbow and shoulder joint contributions, suggests a link between increasing age and a more elbow focused strategy.

The aging process is associated with a decline in physical capacity and strength (Brady and Straight, 2014; Smee et al., 2012) which contributes to a reduction in functional competency (Desrosiers et al., 1999). Declines in upper extremity strength have been reported to begin during the 4th decade of life (Metter et al., 1997), with expected annual declines of 1-3.5% past 60 years of age (Skelton et al., 1994). Age-related declines in upper limb muscle strength can reduce an older adult's ability to control the impact of a fall and consequently result in an injury to the upper extremity, head and/or torso (DeGoede et al., 2003; DeGoede and Ashton-Miller, 2003). The lower shoulder strength observed in women in their eighties of life may suggest an important age bracket for targeting shoulder and elbow strengthening exercise. Despite differences in other strength measures (shoulder abduction and flexion, CON and ECC), there were no differences in HG across the age groups. HG provides a measure of overall strength and has been strongly associated with an individual's physical function (Leong et al., 2015; Rijk et al., 2016). These data suggest a discrepancy between HG and other strength measures for 80 year old participants compared to the other age groups.

A previous study measuring multi-joint upper extremity CON and ECC strength found a preservation of ECC strength and a reduction in CON strength in older women compared to younger women (Lattimer et al., 2018, 2017). The same was shown within the current cohort, with 80-year-old women having weaker CON strength compared to 60 and 70-year-old women but weaker ECC compared to 60-year-old women only. During the impact phase of a fall, ECC strength has been identified as a key factor in controlling the impact (Sandler and Robinovitch, 2001), specifically an individual's elbow extensor strength (Chiu and Robinovitch, 1998; DeGoede and Ashton-Miller, 2003). The evidence points toward the importance of preserving an older woman's upper extremity multi-joint ECC strength to aid in reducing their likelihood of a fall injury to the head, torso or upper extremity.

The differences in upper extremity joint moment contributions and muscle strength indicate the women within this study are implementing different upper extremity loading strategies to control the initial impact. To counteract a lack of upper extremity strength, impacting with a more extended elbow position to minimise 'buckling' could consequently reduce the risk of head impact; but possibly at a cost to increase risk of a forearm fracture (DeGoede and Ashton-Miller, 2003). Within this study, there were no differences in ES, EV or EROM, suggesting that similar kinematic upper extremity strategies are utilised and the differences in individual joint contributions within this cohort may be explained by the neuromuscular strategies undertaken. Further investigation into the neuromuscular strategies utilised at impact would be beneficial.

Previous research has demonstrated energy absorption differences between young and old women , where older women were 45% less equipped to absorb energy during controlled and unexpected descents compared to younger women (Lattimer et al., 2018). Here we show no age differences in ENRG were found suggesting older women exhibit similar ENRG despite utilising different joint moment contributions. Lattimer et al. (2018) suggested elbow velocity

(EV) was a contributing factor to the energy absorption differences between the young and old women, with younger women exhibiting greater EV and older women exhibiting a bracing strategy at impact. The EV similarities across the age groups within the current study, coupled with the lack of differences in ES, EROM, PF and elbow extension strength suggest older women, may be adopting similar arm configurations just prior to impact.

This is the first study, to our knowledge, that has investigated the upper extremity simulated forward fall dynamics in a population of older women ranging in age from 60 to 89. There are some limitations in utilizing a laboratory simulation protocol. Firstly, the fall simulation only focussed on the impact of a forward fall and does not fully represent all stages of a real fall. The pre-impact response aspects of a fall, such as; unexpected balance perturbation, reaction time, and pre-impact upper extremity movement strategies were not incorporated. Secondly, for participant safety, the falling range was limited, removing the factors connected with full body excursion from vertical to the floor and the associated increases in the force and velocity parameters. Participants were positioned with an extended wrist and flexed shoulder position with their arms extended prior to the fall release to ensure participants landed safely on their hands at impact. In order to enhance participant safety and reduce the potential risk of upper extremity injury or fracture participants were instructed to “lower themselves in a push up (descent) motion on impact”, this may have removed a natural impact response. As all participants were able to complete the task successfully, it may be the body position requirements were not challenging enough to show further differences between the age groups or the effects of the different strategies utilised by the upper extremity.

5. Conclusions

This study sought to examine age differences in upper extremity joint contributions and the relationship of upper extremity muscle strength to upper extremity joint contributions during a forward fall impact. Older women exhibited different landing strategies; 60 and 70-year-old women had more shoulder involvement during forward fall impact; whereas, women in their 80s displayed a more equal joint involvement strategy at impact. These differences are partly explained by differences in upper extremity muscle strength, primarily at the shoulder. Fall injury prevention research should consider focused interventions to account for differences in upper extremity landing contributions.

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References:

Brady, A.O., Straight, C.R., 2014. Muscle capacity and physical function in older women: What are the impacts of resistance training? J. Sport Heal. Sci. https://doi.org/10.1016/j.jshs.2014.04.002

Bryden, M.P., 1977. Measuring handedness with questionnaires. Neuropsychologia 15, 617–624. https://doi.org/10.1016/0028-3932(77)90067-7

Chiu, J., Robinovitch, S.N., 1998. Prediction of upper extremity impact forces during falls on the outstretched hand. J. Biomech. 31, 1169–1176. https://doi.org/10.1016/S0021-9290(98)00137-7

Chou, P.P.H., Chen, H.C., Hsu, H.H., Huang, Y.P., Wu, T.C., Chou, Y.L., 2012. Effect of upper extremity impact strategy on energy distribution between elbow joint and shoulder joint in forward falls. J. Med. Biol. Eng. 32, 175–180. https://doi.org/10.5405/jmbe.952

Court-Brown, C.M., Duckworth, A.D., Clement, N.D., McQueen, M.M., 2018. Fractures in older adults. A view of the future? Injury 49, 2161–2166. https://doi.org/10.1016/j.injury.2018.11.009

DeGoede, K.M., Ashton-Miller, J.A., 2003. Biomechanical simulations of forward fall arrests: Effects of upper extremity arrest strategy, gender and aging-related declines in muscle strength. J. Biomech. 36, 413–420. https://doi.org/10.1016/S0021-9290(02)00396-2

DeGoede, K.M., Ashton-Miller, J.A., Schultz, A.B., 2003. Fall-related upper body injuries in the older adult: A review of the biomechanical issues. J. Biomech. 36, 1043–1053. https://doi.org/10.1016/S0021-9290(03)00034-4

Desrosiers, J., Hébert, R., Bravo, G., Rochette, A., 1999. Age-related changes in upper extremity performance of elderly people: a longitudinal study. Exp. Gerontol. 34, 393–405. https://doi.org/10.1016/S0531-5565(99)00018-2

Harvey, L.A., Close, J.C.T., 2012. Traumatic brain injury in older adults: Characteristics, causes and consequences. Injury 43, 1821–1826. https://doi.org/10.1016/j.injury.2012.07.188

Hsiao, E.T., Robinovitch, S.N., 1998. Common protective movements govern unexpected falls from standing height. J. Biomech. 31 31, 1–9. https://doi.org/https://doi.org/10.1016/S0021-9290(97)00114-0

Lattimer, L.J., Lanovaz, J.L., Farthing, J.P., Madill, S., Kim, S., Arnold, C., 2016. Upper limb and trunk muscle activation during an unexpected descent on the outstretched hands in young and older women. J. Electromyogr. Kinesiol. 30, 231–237. https://doi.org/10.1016/j.jelekin.2016.08.001

Lattimer, L.J., Lanovaz, J.L., Farthing, J.P., Madill, S., Kim, S., Robinovitch, S., Arnold, C., 2017. Female Age-Related Differences in Biomechanics and Muscle Activity During Descents on the Outstretched Arms. J. Aging Phys. Act. 25, 474–481. https://doi.org/10.1123/japa.2016-0102

Lattimer, L.J., Lanovaz, J.L., Farthing, J.P., Madill, S., Kim, S.Y., Robinovitch, S., Arnold, C.M., 2018. Biomechanical and physiological age differences in a simulated forward fall on outstretched hands in women. Clin. Biomech. 52, 102–108. https://doi.org/10.1016/j.clinbiomech.2018.01.018

Legg, H.S., Spindor, J., Dziendzielowski, R., Sharkey, S., Lanovaz, J.L., Farthing, J.P., Arnold, C.M., 2020. The reliability and validity of novel clinical strength measures of the upper body in older adults. Hand Ther. 175899832095737. https://doi.org/10.1177/1758998320957373

Leong, D.P., Teo, K.K., Rangarajan, S., Lopez-Jaramillo, P., Avezum, A., Orlandini, A., Seron, P., Ahmed, S.H., Rosengren, A., Kelishadi, R., Rahman, O., Swaminathan, S., Iqbal, R., Gupta, R., Lear, S.A., Oguz, A., Yusoff, K., Zatonska, K., Chifamba, J., Igumbor, E., Mohan, V., Anjana, R.M., Gu, H., Li, W., Yusuf, S., 2015. Prognostic value of grip strength: Findings from the Prospective Urban Rural Epidemiology (PURE) study. Lancet 386, 266–273. https://doi.org/10.1016/S0140-6736(14)62000-6

Metter, E.J., Conwit, R., Tobin, J., Fozard, J.L., 1997. Age-associated loss of power and strength in the upper extremities in women and men. Journals Gerontol. - Ser. A Biol. Sci. Med. Sci. 52, 267–276. https://doi.org/10.1093/gerona/52A.5.B267

Monnet, T., Desailly, E., Begon, M., Vallée, C., Lacouture, P., 2007. Comparison of the SCoRE and HA methods for locating in vivo the glenohumeral joint centre. J. Biomech. 40, 3487–92. https://doi.org/10.1016/j.jbiomech.2007.05.030

Nevitt, M.C., Cummings, S.R., 1993. Type of fall and risk of hip and wrist fractures: The study of osteoporotic fractures. J. Am. Geriatr. Soc. 41, 1226–1234. https://doi.org/10.1111/j.1532-5415.1993.tb07307.x

Nitschke, J.E., McMeeken, J.M., Burry, H.C., Matyas, T.A., 1999. When is a change a genuine change?: A clinically meaningful interpretation of grip strength measurements in healthy and disabled women. J. Hand Ther. 12, 25–30. https://doi.org/10.1016/S0894-1130(99)80030-1

O’Brien, J.F., Bodenheimer, R.E., Brostow, G.J., Hodgins, J.K., 2000. Automatic Joint Parameter Estimation from Magnetic Motion Capture Data. Proc. Graph. Interface 2000 53–60.

O’Neill, T.W., Varlow, J., Silman, A.J., Reeve, J., Reid, D.M., Todd, C., Woolf, A.D., 1994. Age and sex influences on fall characteristics. Ann. Rheum. Dis. 53, 773–775. https://doi.org/10.1136/ard.53.11.773

Public Health Agency of Canada, 2014. Seniors’ Falls in Canada: Second Report - Public Health Agency of Canada. Ottawa, ON.

Rijk, J.M., Roos, P.R., Deckx, L., van den Akker, M., Buntinx, F., 2016. Prognostic value of handgrip strength in people aged 60 years and older: A systematic review and meta-analysis. Geriatr. Gerontol. Int. 16, 5–20. https://doi.org/10.1111/ggi.12508

Russell, M.A., Hill, K.D., Blackberry, I., Day, L.M., Dharmage, S.C., 2008. The reliability and predictive accuracy of the falls risk for older people in the community assessment (FROP-Com) tool. Age Ageing 37, 634–639. https://doi.org/10.1093/ageing/afn129

Sandler, R., Robinovitch, S., 2001. An analysis of the effect of lower extremity strength on impact severity during a backward fall. J. Biomech. Eng. 123, 590–8.

Sattin, R.W., Lambert Huber, D.A., DeVito, C.A., Rodriguez, J.G., Ros, A., Bacchelli, S., Stevens, J. a, Waxweiler, R.J., 1990. The incidence of fall injury events among the elderly in a defined population. Am. J. Epidemiol. 131, 1028–37.

Schonnop, R., Yang, Y., Feldman, F., Robinson, E., Loughin, M., Robinovitch, S.N., 2013. Prevalence of and factors associated with head impact during falls in older adults in long-term care. Can. Med. Assoc. J. 185, E803–E810. https://doi.org/10.1503/cmaj.130498

Skelton, D.A., Greig, C.A., Davies, J.M., Young, A., 1994. Strength, power and related functional ability of healthy people aged 65-89 years. Age Ageing 23, 371–377. https://doi.org/10.1093/ageing/23.5.371

Smee, D.J., Anson, J.M., Waddington, G.S., Berry, H.L., 2012. Association between physical functionality and falls risk in community-living older adults. Curr. Gerontol. Geriatr. Res.

2012, 864516. https://doi.org/10.1155/2012/864516

Sran, M.M., Stotz, P.J., Normandin, S.C., Robinovitch, S.N., 2010. Age differences in energy absorption in the upper extremity during a descent movement: Implications for arresting a fall. Journals Gerontol. - Ser. A Biol. Sci. Med. Sci. 65 A, 312–317. https://doi.org/10.1093/gerona/glp153

Stratford, P.W., Balsor, B.E., 1994. A comparison of make and break tests using a hand-held dynamometer and the Kin-Com. J. Orthop. Sport. Phys. Ther. 19, 28–32. https://doi.org/10.2519/jospt.1994.19.1.28

Wu, G., Van Der Helm, F.C.T., Veeger, H.E.J., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. J. Biomech. 38, 981–992. https://doi.org/10.1016/j.jbiomech.2004.05.042

Yang, Y., MacKey, D.C., Liu-Ambrose, T., Leung, P.M., Feldman, F., Robinovitch, S.N., 2017. Clinical Risk Factors for Head Impact during Falls in Older Adults: A Prospective Cohort Study in Long-Term Care. J. Head Trauma Rehabil. 32, 168–177. https://doi.org/10.1097/HTR.0000000000000257

Figures:

Figure 1: A) Participant suspended at 60-degrees from the horizontal by a safety harness over dual force plates with their arms and wrists extended prior to the magnet-cable release B) Participant impacting the force plates following the magnet-cable release.

Figure 2: The isokinetic dynamometer cable-based linear motion attachment utilised in concentric and eccentric upper extremity strength assessments (Humac Wheel, Humac NORM Isokinetic Dynamometer, CSMi, Stoughton, MA, USA).

Figure 3: Joint % contributions of the wrist, elbow and shoulder joints during the initial impact (200 ms) of a simulated forward fall in older women in their sixth, seventh and eighth decade. Differences were shown primarily for comparisons with the oldest age group (80s). *Significant difference between groups, $p<0.01$.

Tables

Table 1: Means and standard deviation (SD) for all strength variables and upper extremity biomechanical variables in older women in their sixties, seventies and eighties.

	60s	70s	80s
Strength variables (Kg)			
HG	22.3 (6.1)	23.0 (6.2)	21.0 (4.6)
Shoulder abduction	5.6 (1.3) *	5.1 (1.1)	4.6 (1.1)
Shoulder flexion	7.1 (1.4) *	6.8 (2.0) *	5.1 (1.1)
Elbow extension	6.6 (1.5)	6.4 (1.2)	6.2 (1.7)
CON	15.4 (4.3) *	14.2 (3.1) *	10.4 (4.5)
ECC	20.8 (4.7) *	18.8 (2.9)	16.3 (2.9)
Joint moment (Nm/ [BW*height])			
Wrist	.006 (001)	.006 (.002)	.006 (.002)
Elbow	.017 (.004	.015 (.003) *	.019 (.004)
Shoulder	.027 (.005) *	.024 (.006)	.021 (.005)
Energy Absorption (Joules /[BW* height])	.007 (.003)	.006 (.003)	.007 (.003)
Peak vertical force (% BW)	29.63 (5.26)	27.81 (3.87)	27.42 (6.62)
Elbow joint stiffness (Nm/deg)	.028 (.026)	.035 (.030)	.039 (.022)
Elbow velocity (deg/sec)	73.02 (77.56)	90.49 (87.86)	113.00 (100.74)
Elbow ROM (deg)	15.55 (8.88)	13.76 (10.78)	14.52 (7.64)

Abbreviations: HG; handgrip, CON; concentric strength, ECC; eccentric strength, ROM; range of motion, BW; body weight in N. *Significant difference compared to women in their 80s, $p<0.05$.