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Age-related changes in dynamic compressive properties of trochanteric soft tissues over the hip

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ABSTRACT

Hip fracture risk increases dramatically with age, and 90% of fractures are due to falls. During a fall on the hip, the soft tissues overlying the hip region (skin, fat, and muscle) act as shock absorbers to absorb energy and reduce the peak force applied to the underlying bone. We conducted dynamic indentation experiments with young women (aged 19–30; $n=17$) and older women (aged 65–81; $n=17$) to test the hypothesis that changes occur with age in the stiffness and damping properties of these tissues.

Tissue stiffness and damping were derived from experiments where subjects lay sideways on a bed with the greater trochanter contacting a 3.8 cm diameter indenter, which applied sinusoidal compression between 5 to 30 Hz with a peak-to-peak amplitude of 1 mm. Soft tissue thickness was measured using ultrasound.

On average, stiffness was 2.9-fold smaller in older than young women (5.7 versus 16.8 kN/m, $p=0.0005$) and damping was 3.5-fold smaller in older than young women (81 versus 282 N s/m, $p=0.001$). Neither parameter associated with soft tissue thickness.

Our results indicate substantial age-related reductions in the stiffness and damping of soft tissues over the hip region, which likely reduce their capacity to absorb and dissipate energy (before "bottoming out") during a fall. Strategies such as wearable hip protectors or compliant flooringmay compensate for age-related reductions in the shock-absorbing properties of soft tissues and decrease the injury potential of falls.

1. Introduction

Hip fractures are a major cause of death and disability in older adults, and over 90% of cases are caused by falls (Empana et al., 2004; Grisso et al., 1990; Wolinsky et al., 1997). Risk for hip fracture increases exponentially with age (Johansson et al., 2011), due in part to age-related declines in bone density and strength, and an increased incidences of falls. An additional contributor to this trend may be age-related changes in the mechanical properties and thickness of soft tissues (skin, fat, and muscle) over the hip region, which act as a natural "shock absorbers" for attenuating and distributing impact forces applied to the bone (Choi et al., 2010; Choi and Robinovitch, 2011). Supporting this notion, clinical studies have reported that older adults with high body mass index (who tend to possess greater tissue thickness over the hip (Choi and Robinovitch, 2011; Maitland et al., 1993)) have lower risk for hip fracture risk in the event of a fall (Greenspan et al., 1994; la Vecchia et al., 1991; Wolinsky and Fitzgerald, 1994).

Researchers have measured the force-attenuating behavior of soft tissues during simulated falls. Lauritzen and Askegaard (1992) reported that a 9 mm difference in porcine cadaveric soft tissue thickness produced 60% greater tissue energy absorption during impact. Robinovitch et al. (1995b) conducted impact experiments on human cadaveric trochanteric tissues (of mean thickness 24 mm), and found that, on average, these tissues attenuated peak femoral impact force by 13% and absorbed 34 J of the total impact energy of 140 J. Furthermore, for each 1 mm increase in tissue thickness, peak force decreased by approximately 71 N and tissue energy absorption increased by 1.7 J. In experiments with young women undergoing low-height falls on the hip, the effective stiffness of the body decreased by about 50% for a 3-fold increase in soft tissue thickness, as measured by ultrasound (Robinovitch et al., 1991). Other researchers have utilized these data in mathematical models of sideways falls to predict how fracture risk depends on soft tissue stiffness, along with impact velocity, body

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height and weight, and bone strength (Bouxsein et al., 2007; Majumder et al., 2009, 2013).

Studies have also reported measures of the isolated stiffness of trochanteric soft tissues from living humans (which may differ substantially from cadavers, due to post-mortem changes in cell and tissue integrity (Majno and Joris, 1995)). Robinovitch et al. (1995a) used a hand-held indentation device to measure the quasi-static stiffness of soft tissue over the hip region in young women of mean age 24 yrs (Robinovitch et al., 1995a). Laing and Robinovitch (2008) used a similar technique with older women of mean age 77 yrs (Laing and Robinovitch, 2008). Both studies found that tissue stiffness varied across different pelvis locations, and was highest directly over the greater trochanter (GT). Unfortunately, comparison of results across these studies (to estimate age-related differences) is challenging, due to the use of different force magnitudes, and the fact that the load was applied by hand, and thus the rate of loading was not accurately controlled.

Researchers have examined age-related differences in soft tissue compression at sites other than the hip. Boyer et al. (2009) used a dynamic indentation device to estimate the stiffness and damping of the skin over the anterior forearm (6 cm proximal to the elbow) of young and older adults. They found that, when compared to older adults, the forearm skin of young adults had 50% greater stiffness (42.5 versus 28.4 N/m) and 17% greater damping constant (0.074 versus 0.062 N s/m). However, this study involved very small baseline forces (0.007 N) and tissue deformation (200 μm). In contrast, both Hsu et al. (2005) and Kwan et al. (2010) reported that the elastic modulus of plantar soft tissue over the big toe and heel was up to 287% greater (122.9 versus 31.7 kPa) in older than young adults. This may reflect location-dependent changes with age in the dynamic compressive behavior of soft tissues.

Against this background, we conducted experiments involving dynamic compression to quantify the stiffness and damping of soft tissue over the hip in young and older women (in a sideways landing configuration). We also examined how these parameters associated with soft tissue thickness, as measured with ultrasound. We hypothesized that tissue stiffness and damping over the hip would be lower in older than in younger women (as observed for the forearm by Boyer et al. (2009)), and would decrease with increasing tissue thickness.

2. Methods

2.1. Subjects

Participants included 17 young women between the ages of 19 and 30 (mean age = 21.2 (SD = 2.7), mean height = 1.65 m (SD = 0.07), mean body mass = 57.1 kg (SD = 8.8), and mean body mass index (BMI) = 21.1 (SD = 2.8)) and 17 older women between the ages of 65 and 81 (mean age = 69.9 (SD = 4.7), mean height = 1.56 m (SD = 0.07), mean body mass = 62.4 kg (SD = 12.0) and mean BMI = 25.9 (SD = 5.7)). The experimental protocol was approved by the Committee on Research Ethics at Simon Fraser University, and all participants provided written informed consent.

2.2. Protocol

In the first session, participants lay sideways on a bed having a cut-out at the hip region (Fig. 1a). A mechanical indenter, having a 3.8 cm diameter circular end plate, contacted the skin over the greater trochanter (GT). The indenter was vibrated sinusoidally by a mechanical shaker (LDS shaker V408, Bruel&Kjaer, Royston, UK), with a peak-to-peak amplitude of 1 mm and frequency sweeping from 5 to 30 Hz at a rate of 1 Hz/s. 5 Hz was the lowest attainable frequency and the 30 Hz was well above the documented resonant frequency of the body (6 Hz) during falls on the hip (Robinovitch et al., 1997). The small indenter head induced pain during trials, and the baseline level of tissue compressive force was 40 N in all trials due to a safety reason. Time-varying force was measured from a load cell (MLP100, Transducer Techniques, Temecula, CA, USA) and displacement was measured from a linear position transducer (MLT 38000102, Honeywell, Freeport, IL, USA) mounted within the indenter, with sampling rate of 1 kHz. The experimental setup measured the stiffness of a steel spring, to within 4 (SD = 17.8) % error (of the known value of 5.6 kN/m) over a range of frequencies between 2–15 Hz.

In the second session, we used B mode ultrasound imaging (SonixRP, Ultrasonix, Richmond, BC, Canada) with a 60 mm linear array probe (model L14–5W/60, Ultrasonix) to measure the thickness of skin, fat, and muscle layers over the GT. Using a technique trained by an experienced sonographer (Choi et al., 2010; Choi and Robinovitch, 2011), the midpoint of the GT was marked with water soluble ink, where (following initial exploratory measures of the bone surface) the mid-point of ultrasound probe was placed. Care was taken to apply the minimal pressure that allowed full contact between the skin and the ultrasound probe. Using a calibrated cursor, measures were then acquired from screen captures (Fig. 2) of the thickness of skin (which appeared as a low-intensity white layer), fat (which appeared as a black layer), muscle and fascia (which appeared as a low-intensity white layer), and bone (which appeared as a high-intensity white layer).

2.3. Data analysis

To derive tissue stiffness and damping, we fit the force data in the frequency domain (Fig. 3c) with a single degree of freedom mass-spring-damper model with base excitation (Inman, 2008) (Fig. 1b). We focused our analysis in the low-frequency regime between 5 Hz (the lowest frequency captured) and 7 Hz beyond the first observed local maximum in force (resonant frequency). In selecting this model, we considered that previous research has shown that the dynamic response of the body during impact to the hip (in a simulated sideways fall) is well described by a single degree of freedom, mass-spring-damper model (Robinovitch et al., 1991, 1997). We also considered (from inspection) that our force traces consistently displayed a local peak between 6 and 9 Hz (Fig. 3b). This agrees with measures reported by Robinovitch et al. (1997), of the natural frequency of the body during a sideways fall on the hip.

Model parameters were derived from a customized Matlab routine (Version 7.5, MathWorks Inc., Natick, MA, USA) incorporating the least-squares nonlinear curve-fitting routine *lsqcurvefit* to identify, for each trial, values of effective mass (m), damping ratio (ζ) and natural frequency (ω_n) that provided a best fit between model and experimental variations in force as a function of the driving frequency (ω) given by

$$F = m\omega_n^2 Y r^2 \sqrt{\frac{1+(2\zeta r)^2}{(1-r^2)^2+(2\zeta r)^2}} \tag{1}$$

where Y = amplitude of base oscillation, and $r = \omega/\omega_n$ (see Figs. 1b and 3). To acquire accurate parameter values, we set initial values (m = 10 kg; ζ = 0.1; ω_n = 20 rad/s) and upper and lower limits ($0 \le m \le 100$ kg; $0 \le \zeta \le 1$; $0 \le \omega_n \le 180$ rad/s) based on estimates provided in the previous studies (Robinovitch et al., 1991, 1997). We also set "90,000" for the maximum number of iterations and function evaluations, and "1e−20" and "1e−9" for the termination tolerance on the function value and the size of a step, respectively. We confirmed that parameter values from the curve fit optimization were repeatable even when making changes to initial guess within our lower and upper bounds. Acquired parameter values were used to calculate corresponding values of soft tissue stiffness ($k = m\omega_n^2$) and damping ($b = 2\zeta\sqrt{km}$).

For statistical analysis, we used ANOVA to test whether stiffness and damping values associated with age (as a fixed factor) and tissue thickness (as a covariate). We also used t-tests to compare values from young and older women of tissue thickness, and parameters from dynamic compression. All analyses were conducted with a significance level of α = 0.05 with SPSS 18.0.

3. Results

Based on our ultrasound measures, total soft tissue thickness did not differ between young and older women (t = 0.4, p = 0.7; 32.1 (SD = 7.2) mm in young versus 30.4 (SD = 14.9) mm in old; Fig. 2b). Similarly, there were no differences between young and older women in skin thickness (t = 1.0, p = 0.3; 1.2 (SD = 0.3) mm in young versus 1.4 (SD = 0.5) mm in old), fat thickness (t = 1.84, p = 0.08; 3.5 (SD = 2.1) mm in young versus 2.1 (SD = 2.0) mm in old) or muscle thickness (t = 0.13, p = 0.9; 27.2 (SD = 6.0) mm in young versus 26.7 (SD = 14.0) mm in old).

All force traces from our dynamic compression experiments displayed clear peaks (at resonant frequencies) beyond the 5 Hz minimum of the device. Our t-test indicated that the peak force associated with age, averaging 17% greater in young than older women (t = 2.8, p = 0.009; 49.6 (SD = 8.8) versus 42.9 (SD = 4.5) N). Furthermore, age associated with natural frequency (t = −2.1, p = 0.036) and effective mass (t = 3.3, p = 0.002), but not with the damping ratio (t = 1.5, p = 0.12). The natural frequency averaged 11% lower in young than older women (6.37 (SD = 0.71) versus 7.14