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# Soft tissue stiffness over the hip increases with age and its implication in hip fracture risk in older adults

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## ARTICLE INFO

## ABSTRACT

Risk of hip fracture depends on the bone strength as well as the impact force delivered to the proximal femur during falls, and femoral soft tissue may help to reduce the hip fracture risk by attenuating the impact force. Femoral soft tissue stiffness was measured from a large sample, and compared how this was affected by age, gender and site.

One hundred fifty healthy individuals (fifty-two young (aged between 19 and 29), forty-eight middle-aged (30–64), and fifty old (over 65)) participated. Each age group included an equal number of males and females. Using an automated hand-held indentation device, soft tissue stiffness was measured over twelve sites with respect to the greater trochanter (GT).

For both left and right hips, the stiffness was associated with age ($p < 0.0005$), gender ($p < 0.0005$), and site ($p < 0.0005$). On average, the stiffness was 26% greater in older than young adults (321.5 versus 254.3 N/m). On average across twelve sites, the regression analysis indicated that the stiffness increases 1.33 N/m every year ("soft tissue stiffness over the hip = 1.33*age + 221.8"; $R = 0.518$, $p < 0.0005$). Furthermore, the stiffness was 18% greater in male than female (308.8 versus 262.6 N/m), and differed across twelve sites over the hip, being greatest (424.2 N/m) at the GT, and least (206.3 N/m) at the superior gluteal region.

The results provide insights into the shock absorbing property of soft tissue over the hip, and inform the improvement of fall-related injury prevention interventions (i.e., hip protector, safe landing strategies) in older adults.

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## 1. Introduction

Osteoporotic hip fractures are common in older adults, and over 90% of cases are due to falls (Grisso et al., 1990). Consequences of the hip fracture are often debilitating and life-threatening, and one of five older adults suffering from hip fractures dies within a year, and one of two ends up with permanent disabilities, requiring assistive devices (i.e., wheel chair) for locomotion for the rest of life (Empana et al., 2004; Wolinsky et al., 1997). This affirms that prevention is important in hip fractures in older adults. While a number of interventions have been suggested to address this issue, it doesn't seem to be solved, yet (Cameron et al., 2018; Gillespie et al., 2012). Instead, unintentional fall death rates in individuals aged over 65 have continuously increased over the past decade (CDC, 2015). This is because the aging population has been growing dramatically, but also because the suggested prevention strategies

had been developed based on incomplete understanding of mechanisms and risk factors of osteoporotic hip fracture. For example, while research has identified more than ten biomechanical factors that determine the risk of osteoporotic hip fracture (Bouxsein et al., 2007; Cheng et al., 1997; Choi et al., 2015a; Choi et al., 2010; Keyak, 2000; Laing and Robinovitch, 2008; Lotz et al., 1995; Manske et al., 2006; Pulkkinen et al., 2006), it has not been well documented how these play together to cause hip fracture during a fall (i.e., what would be primary or secondary factors). Simply speaking, to date, no complete understanding exists on what determines injurious versus non-injurious falls.

Risk of hip fracture during a fall is defined as a ratio of hip impact force to failure strength, and hip fracture occurs when the hip impact force exceeds the strength of the proximal femur. A number of biomechanical factors have been identified that influence the numerator (hip impact force) and denominator (femur strength), and factors affecting the numerator include impact velocity, shock absorbing property (stiffness and damping) of trochanteric soft tissue, muscle forces spanning the hip joint, knee boundary condition, pelvis impact configuration, and body mass

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index (Bouxsein et al., 2007; Choi et al., 2015a; Choi et al., 2010; Choi et al., 2015b; Laing and Robinovitch, 2008; Nankaku et al., 2005). Factors altering the denominator include age, geometry of the femur, bone density, loading angle and rate (Carter and Hayes, 1977; Ebbesen et al., 1999; Eckstein et al., 2004; Haider et al., 2013; Keaveny et al., 1999; Pinilla et al., 1996; Zioupos and Currey, 1998). Most of these factors are modifiable, and governed by fall mechanics (i.e., how they fall and land, fall direction, body rotation during descent, protective responses), which are further affected by different conditions (i.e., medical conditions, physiological changes, environmental factors, life style, and hand and leg dominance) that often co-exist in older adults. This explains the great complexity of risk and mechanisms of osteoporotic hip fracture, requiring more research to understand better.

A recent study has broadened knowledge on how shock absorbing properties contribute to determine hip fracture risk in older adults. Choi et al. (2015) have employed a concept of force transmissibility to estimate stiffness and damping of soft tissue over the greater trochanter (GT) (Choi et al., 2015b), and found that stiffness and damping of trochanteric soft tissue are more than three times smaller in older than young adults. However, the implication of their findings should be interpreted in light of several limitations. First, they focused on soft tissues over the GT only, even though a point of application of the hip impact force (i.e., peak pressure) during sideways falls occurs at about 5–6 cm inferior and posterior to the GT (Choi et al., 2010). Furthermore, they included females only, and excluded middle-aged individuals, justifying the need of a following study involving various sites over the hip, both sexes, and a large sample across the adult life span (young, middle, and old) to generalize the findings.

A manual hand-held indentation device allows to estimate tissues' stiffness by measuring force and deformation while a specimen (i.e., soft or hard tissue) is being compressed by hands. Using this device, researchers have found that trochanteric soft tissue stiffness is 34 kN/m (SD = 16) at a compressive force of 60 N in young women (Robinovitch et al., 1995), and 35 kN/m (SD = 14) at a compressive force of 140 N in older women (Laing and Robinovitch, 2008). However, the applied compressive force was provided by hands, and thus the rate of loading might not be accurately and consistently controlled. Furthermore, while the magnitude of compressive force was small to minimize deformation of hard tissue (i.e., femur) or soft tissue inside joints (i.e., cartilage and labrum between the femoral head and acetabulum), its compressive effect on those tissues (i.e., deformation) was not clearly examined. Therefore, the reported stiffness values could be a result of combination of compression of the trochanteric soft tissue and other tissues (i.e., cartilage and labrum).

Against this background, using an automated hand-held indentation device that is designed to characterize soft tissue property (not hard tissue) by analyzing tissue's response (vibration) to the very small and consistent compressive (tapping) force (0.4 N), stiffness of soft tissue over the hip region was measured from one hundred fifty individuals, and examined how the property changed with age, sex, and sites with respect the GT.

## 2. Methods

### 2.1. Subjects

One hundred fifty healthy individuals (fifty-two young (aged between 19 and 29), forty-eight middle-aged (30–64), and fifty older adults (over 65)) participated. Each age group included an equal number of males and females. Participants' demographic information has been shown in Table 1. Exclusion criteria included recent musculoskeletal and neurological injuries, including, but

**Table 1**
Demographics of participants (standard deviation shown in parentheses).

|  | Young | Middle | Old |
|---|---|---|---|
| Age (years) | 22.9 (1.9) | 43.2 (11.6) | 77.1 (4.8) |
| Body weight (kg) | 68.1 (12.9) | 68.5 (15.1) | 63.4 (11.9) |
| Body height (cm) | 170.9 (7.5) | 167.0 (9.1) | 158.3 (9.7) |

not limited to, fractures, sprain, strain, stroke, and hyperalgesia over the hip area. The study protocol was approved by the Institutional Review Board at Yonsei University in Wonju, and all subjects agreed to participate by providing a written informed consent form.

### 2.2. Experimental protocol and data analysis

Participants lay sideways on a bed with hips and knees flexed 30 and 40 degrees, respectively, exposing the lateral surface (skin) of the hip (Fig. 1a). A small panel was used to mark twelve sites with respect to the GT. The panel had size 21 cm × 30 cm, contained a 3 × 4 grid of 1 mm diameter circular holes spaced 6 cm apart. Investigators placed the panel over the hip so the second hole from the top in the middle column was centered at the GT, and the middle column was aligned with the femur diaphysis (Fig. 1b and c), then marked twelve points on the skin through the holes with a water soluble marker. The stiffness of soft tissue over the twelve sites was then measured using an automated hand-held indentation device (MyotonPRO, Myoton AS, Tallinn, Estonia). The indentation device provided a very low compressive (tap) force (0.4 N) to the skin surface for 15 ms (tap time) through a 3 mm diameter polycarbonate probe, and recorded damped natural oscillation of soft tissue in the form of an acceleration signal, simultaneously computing the dynamic stiffness (dynamic stiffness (N/m) = (maximum acceleration*probe mass) / (maximum displacement of the tissue)). Previous studies have shown that MyotonPro produces valid and reliable measure of soft tissue stiffness, highlighting test-retest reliability is moderate to excellent (interclass correlation coefficient (ICC) is ranged from 0.53 to 0.99) (Bizzini and Mannion, 2003; Chuang et al., 2012; Ko et al., 2018; Lo et al., 2017; Pruyn et al., 2016; Zinder and Padua, 2011). Five trials (taps) were acquired for each site, and average value was used for data analysis. Both left and right hips were measured.

For statistical analysis, ANOVA was used to test whether the stiffness of soft tissue over the hip area was affected by age, gender and site with respect to the GT. When a main effect was significant, pairwise comparisons were examined using Bonferroni correction with alpha level at 0.05. Independent t test was also used to conduct site-specific comparison between men and women.

## 3. Results

Soft tissue stiffness was associated with age in each side of the hip ($p < 0.0005$) (Fig. 2a, Table 2). On average, the stiffness was 26% greater in older than young adults (321.5 versus 254.3 N/m). Furthermore, on average across 12 sites and gender, our regression analysis indicated that the stiffness increases 1.33 N/m for every year ("soft tissue stiffness over the hip = 1.33*age + 221.8"; R = 0.518, $p < 0.0005$) (Fig. 3).

Soft tissue stiffness was associated with gender for each side of the hip ($p < 0.0005$) (Fig. 2b, Table 2), and the stiffness was, on average, 18% greater in male than female (308.8 versus 262.6 N/m).

For both left and right hips, soft tissue stiffness was associated with site ($p < 0.0005$) (Fig. 4, Table 2). The stiffness differed across 12 sites over the hip, being greatest (424.2 N/m) at the GT, and least (206.3 N/m) at the superior gluteal region (Fig. 4).
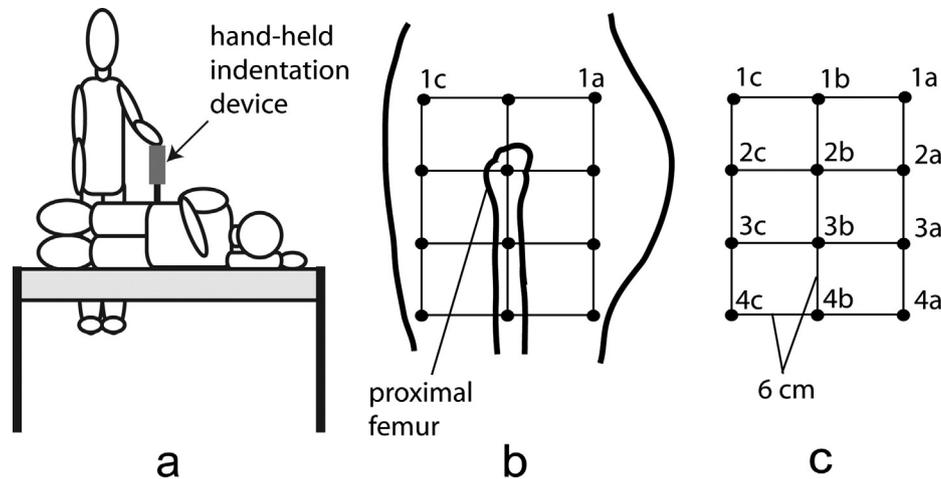
**Fig. 1.** Experimental setup (a), measurement site with respect to the greater trochanter (b), and a 3 × 4 grid of markers spaced 6 cm apart that used to mark on skin surface (c).
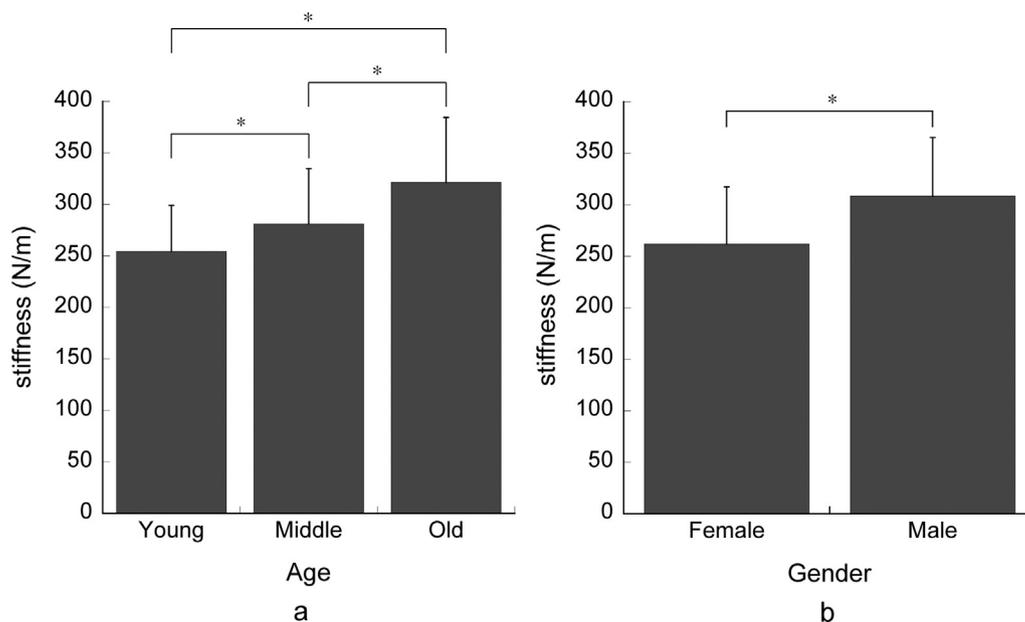


**Fig. 2.** Effect of age (a) and gender (b) on the stiffness of femoral soft tissue. Soft tissue stiffness is 26% greater in older than young adults, and 18% greater in male than female.

## 4. Discussion

The purpose of this study was to acquire clinical measures of the stiffness of soft tissue over the hip area from a large sample across the adult life span, and examine how the femoral soft tissue stiffness changes with age, gender and site. We found that the femoral soft tissue stiffness increases with age, which compares well with previous findings that compressive stiffness of soft tissue over the face, shoulder, neck and plantar surface of the foot increases while aging (Dietsch et al., 2015; Kocur et al., 2017; Teoh et al., 2014). This aging effect might be explained, in part, by biological changes in soft tissue, where structure and content of collagen within soft tissue change with age, causing stiffness of vessels and epimysium to increase (Bruel and Oxlund, 1996; Kjaer, 2004; Rodrigues et al., 1996). However, this finding conflicts with a previous finding that the soft tissue stiffness over the GT decreases with age (Choi et al., 2015b). This discrepancy may be explained by differences in measurement techniques. Choi et al. used a mass-spring-damper model with base excitation to esti-

mate stiffness of soft tissue over the GT. While they minimized contribution of hard tissues and joints (femur, pelvis and spine) in their quantification of trochanteric soft tissue stiffness by modeling the hard tissues and joints as a single moving mass, deformation of each bone and joint during vibration (i.e., deformation of cartilage and joint space) was not carefully examined. Whereas, an automated hand-held indentation device eliminated the contribution of hard tissues and joints, and allowed to measure stiffness values arisen from the soft tissue only, by applying low force (0.4 N) to the soft tissue, which is critical to understand force attenuation behavior of soft tissue as greater force magnitude (>1 N) is transmitted to the underlying bone and joint and may cause deformation (Serina et al., 1997). Another reason for the discrepancy may include that stiffness of soft tissue exhibits nonlinear behavior that is age-dependent, causing greater stiffness in young than older adults in low force regime (0.4 N in our experiment), and opposite result in high force regime (40 N in Choi et al.).

From a mechanical perspective, one can expect greater force attenuation or energy absorption from a natural padding (i.e., skin,

**Table 2**
Femoral soft tissue stiffness values (N/m) in each condition (standard deviation shown in parentheses).

| Site | Left hip | | | | | | Right hip | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Young | | Middle | | Old | | Young | | Middle | | Old | |
| | Female | Male | Female | Male | Female | Male | Female | Male | Female | Male | Female | Male |
| 1a | 173.1 (39.3) | 194.2* (33.6) | 209.5 (56.3) | 237.9 (57.8) | 218.5 (55.2) | 221.0 (51.6) | 176.0 (33.6) | 193.7 (37.2) | 206.3 (54.3) | 227.5 (39.4) | 196.9 (29.4) | 220.5* (37.1) |
| 1b | 228.4 (43.4) | 267.1* (53.7) | 297.6 (102.2) | 364.4* (91.7) | 270.5 (74.8) | 310.9 (94.3) | 237.5 (39.4) | 280.8* (61.6) | 283.9 (92.1) | 346.4* (91.2) | 247.4 (65.2) | 303.8* (116.2) |
| 1c | 268.1 (54.5) | 297.0 (60.8) | 303.1 (68.2) | 348.6* (69.4) | 315.2 (96.0) | 356.4 (120.7) | 274.8 (39.4) | 314.2* (77.3) | 297.7 (60.2) | 348.8* (76.2) | 325.6 (144.9) | 366.2 (130.0) |
| 2a | 183.7 (33.5) | 213.4* (43.5) | 212.3 (46.3) | 241.0* (44.2) | 231.4 (47.9) | 253.6 (42.7) | 187.4 (38.1) | 207.4 (39.4) | 205.8 (57.5) | 216.5 (38.5) | 212.1 (28.6) | 255.5* (38.4) |
| 2b | 304.5 (61.9) | 438.8* (150.7) | 354.6 (123.1) | 450.9* (169.5) | 469.2 (221.4) | 565.0 (193.1) | 298.1 (57.0) | 438.1* (151.6) | 367.4 (105.8) | 451.2* (170.2) | 437.0 (199.4) | 516.1 (173.4) |
| 2c | 263.1 (60.3) | 329.2* (95.9) | 291.6 (67.2) | 322.0 (72.3) | 309.8 (80.2) | 395.3* (95.0) | 261.8 (51.6) | 332.3* (84.0) | 294.9 (53.4) | 317.5 (88.2) | 327.1 (85.1) | 465.6* (116.9) |
| 3a | 184.7 (38.2) | 205.5* (28.3) | 214.3 (38.3) | 224.1 (51.4) | 244.7 (48.3) | 261.5 (39.0) | 182.0 (37.3) | 193.5 (32.0) | 201.8 (43.7) | 221.2 (57.6) | 231.9 (34.8) | 269.1* (44.3) |
| 3b | 260.1 (62.1) | 301.7* (67.1) | 264.1 (66.2) | 292.8 (85.2) | 357.7 (119.3) | 392.0 (118.7) | 257.7 (50.9) | 301.2* (69.5) | 272.0 (74.9) | 280.1 (86.4) | 349.4 (101.1) | 381.4 (115.9) |
| 3c | 248.7 (37.5) | 272.4* (42.2) | 266.6 (50.2) | 277.5 (36.1) | 293.7 (54.0) | 351.8* (77.3) | 239.4 (46.0) | 263.8* (35.1) | 261.4 (53.7) | 280.2 (41.6) | 296.3 (79.3) | 369.4* (73.0) |
| 4a | 188.2 (24.4) | 214.0* (34.7) | 217.5 (44.5) | 230.7 (40.3) | 254.1 (45.8) | 286.3* (39.8) | 189.9 (30.1) | 206.7* (21.6) | 208.1 (42.6) | 230.1 (46.5) | 237.6 (44.0) | 289.2* (50.0) |
| 4b | 213.1 (35.3) | 314.6* (79.5) | 258.3 (96.5) | 327.4* (88.2) | 341.4 (121.7) | 366.0 (121.5) | 210.3 (28.4) | 305.5* (80.2) | 253.8 (93.6) | 320.1* (81.1) | 316.1 (112.1) | 339.6 (83.2) |
| 4c | 230.8 (24.8) | 314.2* (49.1) | 274.3 (46.7) | 334.3* (40.7) | 325.8 (69.8) | 370.3* (71.5) | 233.8 (23.6) | 313.4* (48.0) | 270.0 (49.4) | 322.3* (42.5) | 313.0 (60.0) | 401.0* (114.0) |

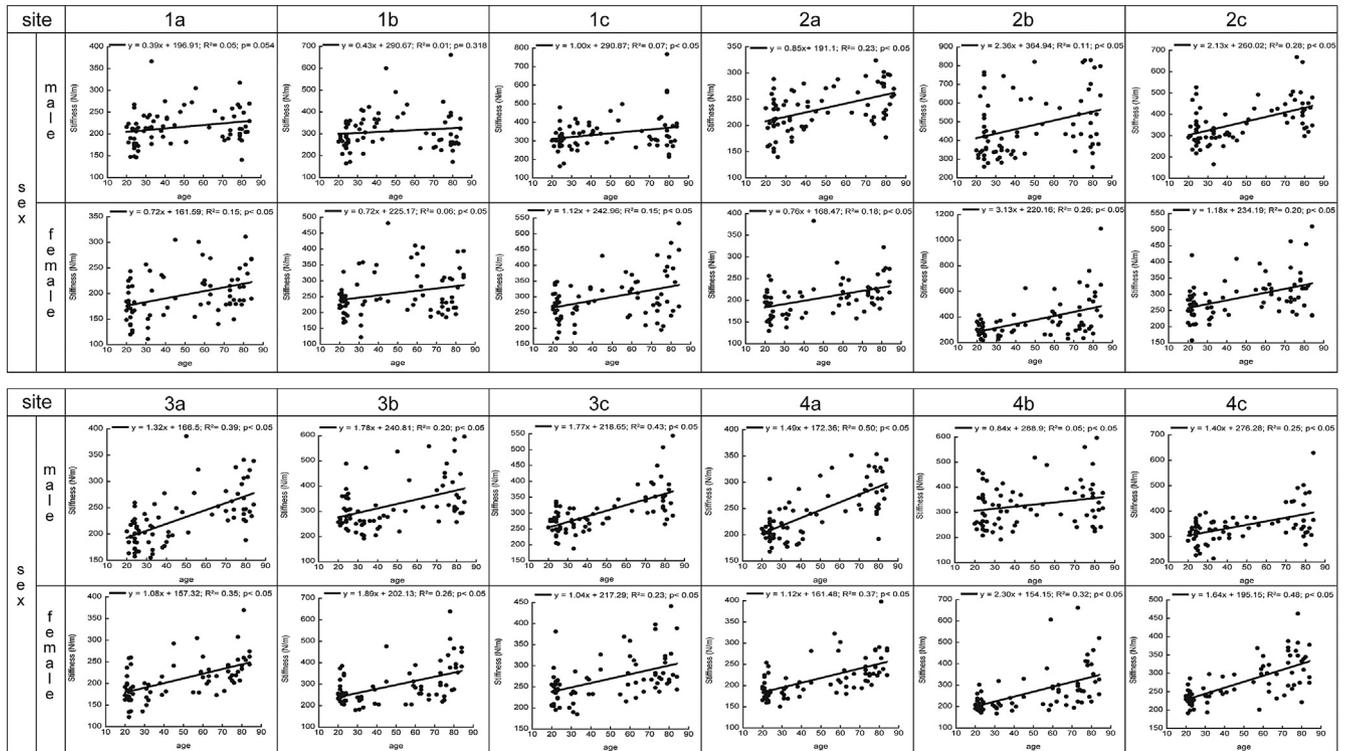\* Significant difference between female and male ($p < 0.05$).



**Fig. 3.** Effect of age on the soft tissue stiffness for twelve sites over the hip region. On average, soft tissue stiffness increases 1.33 N/m for every year (soft tissue stiffness over the hip = 1.33\*age + 221.8). Furthermore, similar results were found for all sites in male and female, except two sites in male (1a and 1b).

fat, muscle, fascia) at impact during a fall, and our data suggest that the protective benefit of soft tissue increases with age. In theory, the femoral soft tissue bottoms out so quickly during impact, where its stiffness approaches infinity and behaves like a hard tissue, thereby small amount of energy is absorbed by the soft tissue covering during compression. Furthermore, research evidence suggests that only about 5 J of energy is required to fracture the femur of individuals aged over 65 (Courtney et al., 1995), and total energy available during descent is about 600–800 J (i.e., potential energy while standing = m\*g\*h, where m = body mass, g = gravitational acceleration, h = height of center of gravity). Collectively, in order to avoid hip fracture during a fall, the majority of the available
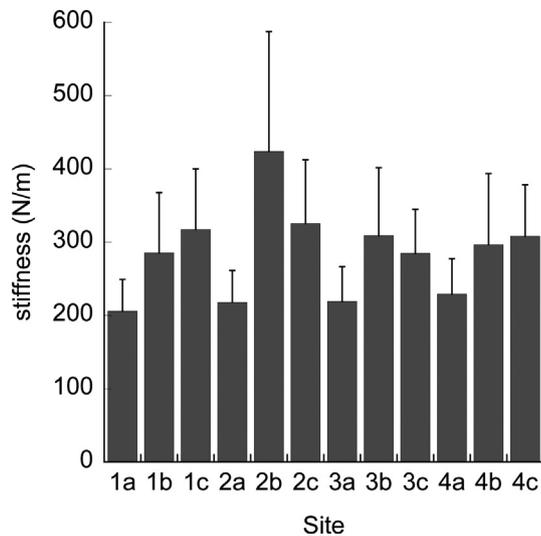
**Fig. 4.** Effect of site on the stiffness of femoral soft tissue. On average, soft tissue stiffness is greater over the shaft of the femur, being greatest over the greater trochanter (2b), and smaller at the posterior hip region (1a, 2a, 3a and 4a).

energy must be absorbed by other mechanisms (i.e., muscle contraction, joint rotation, soft tissue compression), leaving less than 5 J of energy to be absorbed by the femur. Potential protective benefits of soft tissue should be understood in this context as it might, even if small, play as a decisive factor (i.e., casting vote) that determines injurious and non-injurious falls in older adults.

We also found that soft tissue stiffness over the hip region was 18% greater in male than female subjects. This may be due, in part, to a lot greater size (i.e., cross sectional area and length) of muscle, tendon and fascia in men than women (Biuk et al., 2015; Chow et al., 2000; Tas, 2018), and supports a traditional notion that fall-related hip fracture is more common in women. However, previous research has shown that there is no gender difference in the compressive stiffness of soft tissue in other body parts (i.e., face and plantar surface of the foot) (Dietsch et al., 2015; Teoh et al., 2016). Collectively, these suggest that gender difference in compressive stiffness of the soft tissue is site-specific.

We also found that soft tissue stiffness over the hip area differs across different sites with respect to the GT, being greater along the femur diaphysis. This variability may be explained by difference in distribution of skin, fat, muscle, tendon and fascia layers over the hip region. For the lateral surface of the thigh, for example, there exist a lot less muscle and fat tissue, but more fascia and tendon (i.e., iliotibial band). Furthermore, the stiffness was small in the posterior gluteal region compared to the lateral and anterior hip region, supporting that hip fracture risk increases as impact site changes from the anterior to the posterior due to the increased impact force and stresses to the proximal femur (Choi et al., 2010; Choi and Robinovitch, 2018; Nankaku et al., 2005). This should inform the improvement of the design of a hip protector that has variations in stiffness, more stiff posteriorly, and less stiff anteriorly.

The implications of our results should be interpreted in light of several limitations. First, a potential relationship between stiffness and thickness of soft tissue has been documented, and soft tissue stiffness of lower extremity increases with muscle thickness, but decreases with subcutaneous (skin and fat) thickness (Frohlich-Zwahlen et al., 2014). However, our measures did not include tissue thickness and it is difficult to expand discussion. Second, while dynamic stiffness is a relevant parameter to discuss shock (force and/or energy) absorbing capacity of soft tissue during impact, actual amount of force attenuation and/or energy absorption pro-

vided by soft tissue would be the most relevant variables. However, since neither force-deflection behavior nor damping coefficient of soft tissue were measured in this study, it is limited to discuss.

In summary, soft tissue stiffness over the hip increases with age, and changes with gender and sites with respect to the GT. The results should help to improve and develop the hip fracture prevention strategies in older adults.

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## Conflict of interest statement

None of the authors above have any financial or personal relationships with other people or organizations that could inappropriately influence this work, including employment, consultancies, stock ownership, honoraria, paid expert testimony, patent applications/registrations, and grants or other funding.

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