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Hip fracture and anthropometric variations: Dominance among trochanteric soft tissue thickness, body height and body weight during sideways fall

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ABSTRACT

Background: Hip fracture depends on various anthropometric parameters such as trochanteric soft tissue thickness, body height and body weight. The objective was to evaluate the responses to the variations in anthropometric parameters during sideways fall, and to identify the most dominant parameter among them.
Method: Seven finite element models were developed having anthropometric variations in trochanteric soft tissue thickness (5–26 mm), body height (1.70–1.88 m), and body weight (63–93.37 kg). These were simulated for sideways fall with ANSYS-LS-DYNA® code.
Findings: Significant effect of trochanteric soft tissue thickness variation was found on 'normalized peak impact force with respect to the body weight' ($p = 0.004$, $r^2 = 0.808$) and strain ratio ($p = 0.083$, $r^2 = 0.829$). But, variation in body height was found to be less significant on normalized peak impact force ($p = 0.478$, $r^2 = 0.105$) and strain ratio ($p = 0.292$, $r^2 = 0.217$). Same was true for the variation in body weight on normalized peak impact force ($p = 0.075$, $r^2 = 0.456$) and strain ratio ($p = 0.857$, $r^2 = 0.007$). The risk factor for fracture was also well correlated to the strain ratio for the inter-trochanteric zone ($p < 0.0007$, $r^2 = 0.917$) where the most fractures are clinically observed to happen.
Interpretations: Trochanteric soft tissue thickness was found likely to be the most dominant parameter over body height and body weight, signifying that a slimmer elderly person, taller or shorter, with less trochanteric soft tissue thickness should be advised to take preventive measures against hip fracture under sideways fall.

1. Introduction

Hip fractures due to sideways fall are a worldwide health problem, especially among the elderly population. Hip fracture from sideways fall is a primary cause of morbidity and mortality. Though there is evidence that hip fracture rate is decreasing in western countries (Kannus et al., 2006), about 250,000 hip fractures still occur annually in the United States, thereby costing over 8 billion dollars for medical and nursing home services (Nurmi and Luthje, 2002).

To design a better hip protective system, static and dynamic responses of proximal femur under sideways fall are required to be known thoroughly. Most hip fractures are due to a direct impact on the trochanteric area of the hip due to sideways fall from standing height (Courtney et al., 1994; Hayes et al., 1996). The impact force increases directly with the body weight and falling height of the body and its effect varies with the degree of padding on the greater trochanter by soft tissue and clothing (Bouxsein et al., 2007; Meyer et al., 1995; Robinovitch et al., 1991, 1995). Again body weight has moderate and positive correlation to trochanteric soft tissue thickness (Bouxsein et al., 2007), and body height is non-linearly correlated to hip impact velocity (van den Kroonenberg et al., 1995). It was also established that the body mass index is a strong determinant of hip fracture risk (Bouxsein et al., 2007; Meyer et al., 1995) apart from bone mineral density (Cauley et al., 2003; Cummings et al., 1985; Grisso et al., 1994; Kreiger et. al., 1982). But it is not fully clear about the most dominant parameter for the hip fracture under sideways fall from standing height.

To obtain sophisticated evaluations of hip fracture load, investigators used finite element models developed from computed tomography scan (Keyak et al., 1998, 2001; Lotz et al., 1991). Posterolateral and lateral forces were applied on femoral head to represent the posterolateral and sideways falls on the ground. In our previous study (Majumder et al., 2008b), for the same body height and body weight, the effects of 'trochanteric soft tissue thickness' (STT) variations on hip fracture were investigated. Also for the same tissue thickness and same 'body weight' (BW), the effects of variations of 'body height' (Ht) vis-à-vis

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hip impact velocity were analyzed. But in real life, when STT varies, BW or Ht may not remain the same due to a wide range of anthropometric variations. Similarly, STT or BW may not be the same due to variations in Ht as well as 'fall height' (Ht_{CG}).

The purpose of the present study was to evaluate the sideways fall responses due to the wide range of anthropometric variations in respect to the parameters STT, Ht and BW when no anthropometric parameter was fixed, using a three-dimensional 'finite element' (FE) model. It was aimed to quantify their effects on subsequent hip fracture in terms of peak impact force, time to peak force and strain ratio. Another objective was also to identify the most dominant parameter for hip fracture under sideways fall.

2. Methods

To consider anthropometric variations, STT, Ht and BW data of seven living male subjects were taken from Robinovitch et al. (1991). Their body segment masses and body segment lengths were calculated based on the data of Nigam and Malik (1987). Our 'computed tomography' (CT) based FE model (Appendix A) was similar to their seventh subject (Table 1; Case G: STT = 14 mm, Ht = 1.78 m, BW = 77.47 kg) but with an age of 58 years. This FE model was used to develop seven FE models (Case A to G) with the anthropometric variations in STT (5–26 mm), Ht (1.70–1.88 m), and BW (63–93.37 kg) when bone geometry and bone properties remained constant. The body mass index ($BMI = \frac{BW}{Ht^2}$) of the seven FE models was also calculated (21.8–26.5 kg/m^2, Table 1).

To quantify the effects of anthropometric variations during sideways fall on rigid floor (Figs. 1, A1), these seven FE models were simulated using ANSYS-LS-DYNA® solver (Hallquist, 1998) under gravitational acceleration of 1g and respective hip impact velocity (2.268–2.385 m/s). These velocities were calculated from Ht vis-à-vis Ht_{CG} (0.874–0.966 m) (Appendix B) to have variable 'impact energy' (KE = 162–265.5 J) (Table 1). All the statistical analyses were done using ORIGIN® (Microcal Software, Inc., Northampton, MA, USA).

3. Results

During sideways fall, for these seven cases (A to G), the 'peak impact force' (F_{max}) varied from 5490 N (case D) to 7513 N (case B) (Fig. B1). Significant effects of STT were found on normalized peak impact force (F_{max} / BW, $p = 0.004$), and 'time to peak force' (t_{max}, $p = 0.012$). But, Ht_{CG} and BW variations were found to be less significant on F_{max} / BW ($p = 0.478$ and 0.075 respectively) and t_{max} ($p = 0.251$ and 0.019 respectively). It was also clear that F_{max} increased and t_{max} decreased gradually for the subjects C, G and B, whose STT as well as Ht_{CG} were in increasing order. Conversely, F_{max} and t_{max} increased for the subjects A and F with increasing STT, in spite of increasing Ht_{CG} as well as Ht (Fig. 2).

Table 1
Variations in anthropometric data.

FE models	BW (Kg)[a]	STT (mm)[a]	Ht (m)[a]	Ht_{CG} (m)	PE (J)	KE (J)	V (m/s)	BMI (kg/m^2)
Case A	86.14	17	1.83	0.941	794.8	238.4	2.353	25.72
Case B	75.64	7 (5)[b]	1.83	0.941	697.9	209.4	2.353	22.59
Case C	81.14	26	1.75	0.900	716.0	214.8	2.301	26.50
Case D	63.00	15 (14)[b]	1.70	0.874	540.0	162.0	2.268	21.80
Case E	64.32	15 (14)[b]	1.70	0.874	551.4	165.4	2.268	22.26
Case F	93.37	23	1.88	0.966	885.1	265.5	2.385	26.42
Case G[c]	77.47	15 (14)[b]	1.78	0.915	695.3	208.6	2.321	24.45

BW: Body weight; STT: Trochanteric soft tissue thickness; Ht: Body height, Ht_{CG}: Height of body CG vis-à-vis fall height; PE: Potential energy; KE: Impact energy or vertical kinetic energy; V: Hip impact velocity; BMI: Body mass index.
[a] Anthropometric data of seven male subjects, taken from Robinovitch et al. (1991).
[b] Values used for 'finite element' (FE) models.
[c] The initial FE model (Figs. 1, A1).

It was found that the inter-trochanteric zone was having the 'maximum principal compressive strain' (ε_{max}). Trochanteric fractures are observed to occur through this zone clinically (Shultz et al., 1999) and experimentally (Keyak et al., 2001). A normalized parameter 'strain ratio' (StrainR) was described (Lotz et al., 1991) as the ratio of ε_{max} to the 'ultimate compressive strain' (ε_u). StrainR was calculated taking the value of ε_u for the cancellous bone as 0.015 (Kopperdahl and Keaveny, 1998) and the obtained values of ε_{max} from our seven FE models where the basic FE model was experimentally validated with human cadavar and cadaveric pelvic bone (Majumder et al., 2008c). StrainR was found to vary from 1.34 (case D) to 2.955 (case B). Trends of variations of StrainR with STT, Ht_{CG}, BW, KE and BMI were also established (Fig. 3). STT showed a moderate significance level with the StrainR ($p = 0.083$; Fig. 3a) while the variations of Ht_{CG} vis-à-vis Ht ($p = 0.292$), BW ($p = 0.857$), KE ($p = 0.736$), and BMI ($p = 0.593$) were insignificant with the StrainR (Fig. 3b, c, d, e).

In sideways fall experiments with cadeveric femoral bone from 10 elderly donors of mean age 73.8 years (4 females, 6 males), Courtney et al. (1994) found the range of femoral fracture load as 2200–8800 N and described the 'mean femoral fracture load' (F_u) as 4170 N. Another parameter 'risk factor for hip fracture' (ForceR) was described (Bouxsein et al., 2007; Hayes et al., 1991, 1996) as the ratio of the obtained F_{max} to the estimated F_u. We calculated ForceR based on F_u (4170 N) and F_{max} (5490–7513 N) from our seven FE models generated from CT data of 58 year old male (Appendix A). ForceR was found to vary from 1.317 (case D) to 1.802 (case B). One common observation was that all the seven FE models had suffered trochanteric fractures, as StrainR and ForceR were found to be more than 1. The values of the two parameters were close to each other for all the anthropometric cases, except for the case B where STT, Ht and BW were 5 mm, 1.83 m, and 75.64 kg respectively (Fig. 4a). In the absence of any pre-fixed anthropometric condition, StrainR also demonstrated a very high significance level with ForceR ($p < 0.0007$; Fig. 4b).

4. Discussions

In an epidemiologic study, Grisso et al. (1997) reported that though men have lower incidence rates of hip fractures than women, hip fractures are also common in men, affecting more than one percent of elderly men each year. Although there have been few studies on risk factors for hip fracture in men, explanations for gender differences in hip fracture rates include differences in bone mass, absence of perimenopausal-associated bone loss, and possibly decreased rates of falls in men compared with women (Cummings et al., 1985). For women, the protection from fall related hip fracture due to increased BMI has been postulated to be a result of increased adipose-based production of estrogen and greater gravitational forces on bone mass, resulting in increased bone density (Cauley et al., 2003; Grisso et al., 1994; Kreiger et al., 1982). As we wanted to establish the most dominant anthropometric factor among trochanteric soft tissue thickness, body height and body weight during sideways fall, we considered the CT data of 58 year old male having no osteoporosis and kept the bone geometry and bone properties the same for all the FE models.

In real life situation, there might be large variations in STT and energy absorption capacity of the soft tissue covering the hip, along with Ht and BW. Hence, available KE and hip impact velocity may vary considerably from individual to individual, and for one individual from fall to fall. The basic differences between our previous (Majumder et al., 2008b) and present studies are lying within the facts discussed above. In our previous study, for the same BW of 77.47 kg, we considered a fixed hip impact velocity of 1.904 m/s (for a fixed Ht as well as Ht_{CG}) to study the effects of variations of STT, and for a fixed STT of 14 mm to study the effects of variations of hip impact velocity as well as Ht. But in the present study, no anthropometric parameter remained the same and our seven FE models with variable STT (5–26 mm), Ht (1.70–1.88 m), BW (63–93.37 kg), and BMI (21.8–26.5 kg/m^2) were