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Improving the prediction of sideways fall-induced impact force for women by developing a female-specific equation

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ABSTRACT

Impact force induced in sideways falls is an important determinant of hip fracture risk. While body parameters may differently affect the magnitude of impact force in men and women, the effect of sex is not considered in existing impact force predictors. The objective of this study was to construct a female-specific equation to predict the fall-induced impact force applied to the hip and evaluate whether it could improve hip facture risk assessment.

A previously developed human-body dynamic model was used to simulate falling of 80 women and determine the hip impact force. Results were then used to derive a female-specific equation between impact force and body parameters. The proposed female-specific equation and available non-sex-specific impact force predictors in the literature were integrated with a finite element model to discriminate hip fracture patients among 393 women (99 hip fractures; 294 non-fracture controls). Results of the implemented methods were compared to evaluate whether considering the effect of sex could improve the discrimination of females with and without a hip fracture.

The area under the curve (AUC) and odds ratio (OR) for the assessed hip fracture risk by the proposed female-specific method (AUC = 0.799, OR = 4.22) were significantly ($p < 0.001$) greater than those of non-sex-specific methods (the most accurate: AUC = 0.750, OR = 3.62). This study indicates that the proposed equation may be useful to improve hip fracture risk assessment for women.

1. Introduction

Hip fracture has become a common health problem among the elderly (Kanis et al., 2012; Kannus et al., 2006). Clinical observations showed that more than 90% of hip fractures are caused by falls (Cumming and Klineberg, 1994; Cummings et al., 1985; Cummings and Melton, 2002; Grisso et al., 1991; Teppo et al., 2008; Youm et al., 1999). Sideways falls are the most serious types of falls as they cause more that 60% of all hip fractures (Greenspan et al., 1998; Greenspan et al., 1994; Kannus et al., 2006). The socioeconomic impacts of hip fracture underscore the importance of accurately assessing hip fracture risk to identify high risk patients for starting appropriate prevention and protection measurements (Boonen et al., 2004; Huddleston and Whitford, 2001; Lieberman et al., 1999; Phy et al., 2005; Roche et al., 2005).

Dynamic models are available in the literature to simulate human body falling (Kroonenberg et al., 1995; Lo and Ashton-Miller, 2008; Luo and Nasiri Sarvi, 2015; Nasiri Sarvi and Luo, 2015). However, prediction of the impact force by dynamic models or experimentation is not convenient for clinical applications. Generally, anthropometric parameters of body segments are required for developing dynamic models and it requires a separate analysis on the patient. Clinical experiments are also not practical for all patients. Therefore, a simple equation for predicting fall impact force is easier to implement. Two equations have already been introduced to determine the force applied from the ground to the hip in a fall from standing height by Kroonenberg et al. (1995) and Yoshikawa et al. (1994). A method was also proposed by Robinovitch et al. (1995) to consider the effect of greater trochanter (GT) soft tissues in attenuating the impact force. In 2-dimensional (2D) and 3D femur finite element (FE) analyses that considered the fall impact force, a combination of Kroonenberg/Yoshikawa equation and Robinovitch's method has been used to determine the hip impact force and assess femur fracture risk (Kopperdahl et al., 2014; Naylor et al., 2013; Orwoll, 2000). How-

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ever, there are other parameters that can be investigated more to improve fall impact force prediction. As an instance, body parameters, including body mass (BM), body height (BH), and GT soft tissue thickness (STT), may sex-specifically affect the magnitude of the impact force (Nasiri and Luo, 2016). Specifically, the force attenuation by GT soft tissues is not the same in men and women (Nasiri and Luo, 2016; Robinovitch et al., 1991). Statistical studies showed that after bone mineral density (BMD), STT plays the most important protective role against hip fracture in women (Nasiri and Luo, 2016). Surprisingly, prior studies indicated that GT soft tissue thickness in men was not associated with the risk of hip fracture (Dufour et al., 2012; Nielson et al., 2009). Moreover, body mass index may have a sex-specific effect on the fall-induced impact force to the hip (Bouxsein et al., 2007; Nielson et al., 2009).

Although sex-specificity has been investigated with a falling model on the hand (Kawalilak et al., 2014), fall-induced impact force to the hip has not been investigated sex-specifically. Against this background, we hypothesized that a female-specific method for predicting fall impact force can improve hip fracture risk assessment for women. In order to evaluate this hypothesis, a female-specific equation was derived from the results of a dynamic model and then it was integrated with an FE model of the femur to assess hip fracture risk in a clinical study population, including 393 women. Non-sex-specific methods in predicting the fall impact force (Kroonenberg/Yoshikawa equations and Robinovitch's method) were also integrated with the same FE model to discriminate hip fracture patients among the clinical study population. Results were used to compare the proposed female-specific method and the existing non-sex-specific methods in discriminating individuals with and without a hip fracture.

2. Methods

2.1. Study populations

Two different study populations were used in this study: derivation and evaluation study population. The derivation study population was used to derive the female-specific equation for predicting hip impact force. The evaluation study population was used for clinical validation of the proposed method.

2.1.1. Derivation study population

The derivation study population included 80 women that were recruited in this study under a research ethics approval. None of the individuals had suffered a hip fracture. Anthropometric details of subjects are presented in Table 1. Of this sample, 20% were classified as osteoporotic and 46% as osteopenic, based upon dual-energy X-ray based measures of hip areal BMD (Table 2).

2.1.2. Evaluation study population

The evaluation study population was composed of 393 women, including 99 hip fractures and 294 without a fracture with similar age, body mass, height, and STT. They were extracted from the Manitoba Bone Mineral Density Database, under an approval of University of Manitoba human research ethics. Anthropometric details of the evaluation study population are presented in Table 1. Of this sample, 39% were classified as osteoporotic and 61% as osteopenic (Table 2).

All DXA (dual energy X-ray absorptiometry) scans were performed with single fan-beam scanner configuration (Lunar Prodigy, GE Healthcare, Madison, WI, USA). Hip scans were processed using enCore version 14 software, GE Healthcare, to determine the BMD. Femoral neck hip T-scores (number of SDs above or below young adult mean BMD) were calculated from NHANES III white female reference values (Looker et al., 1998). The DXA images for the hip fracture patients were acquired pre-fracture.

2.2. Developing the female-specific equation and comparing with non-sex-specific methods

A previously developed dynamic model (Luo and Nasiri Sarvi, 2015; Nasiri and Luo, 2016; Nasiri Sarvi and Luo, 2015) was used in this study to determine the impact force of the derivation study population. Obtained impact forces were then used to derive the female-specific equation (between impact force and body parameters). The derived equation was used to predict the impact force in the evaluation study population, including hip fracture patients and non-fracture controls. Derived impact forces were used in an FE model of the hip to assess hip fracture risk. The same process was repeated using the Kroonenberg/Yoshikawa equations and Robinovitch's method in predicting the impact force (Kroonenberg et al., 1995; Robinovitch et al., 1995; Yoshikawa et al., 1994). Also, BMD estimation from hip DXA was used to evaluate hip fracture risk assessment. The procedure of deriving the equations, validating the results, and comparing with available methods is illustrated in Fig. 1 and described in detail in the following sections.

2.2.1. Dynamic model: Calculation of the sideways fall-induced impact force to the hip

In our previous studies (Luo and Nasiri Sarvi, 2015; Nasiri and Luo, 2016; Nasiri Sarvi and Luo, 2015; Nasiri Sarvi et al., 2014), a

Table 1
Scope (range, mean (SD)) anthropometric measurements of women recruited for constructing the female-specific equation.

Study population		Number of subjects	Age (years)	Body height (cm)	Body mass (kg)	GT soft tissue thickness (mm)
Derivation		80	20.1 – 87.8 53.7 (19.9)	124.2 – 186.2 157.7(10.1)	29.5 – 133.8 67.7 (20.6)	12.5 – 131.4 54.3 (23.3)
Evaluation	Fracture cases	99	65 – 91 75.1 (6.7)	141.2 – 168.7 157.5 (5.9)	40.4 – 99.8 62.9 (10.1)	12.7 – 19.20 14.4 (1.4)
	Non-fracture controls	294	65 – 100 75.5 (6.9)	138.4 – 175.3 158.7 (6.3)	32.2 – 105.2 64.2 (11.8)	12.9 – 19.6 14.5 (1.5)

Table 2
BMD level of the derivation study population.

Femoral neck T-score	Derivation study population Percentage of women in each BMD category	Evaluation study population Percentage of women in each BMD category
T-score > −1.0	34%	0%
−2.5 < T-score ≤ −1.0	46%	61%
T-score ≤ −2.5	20%	39%

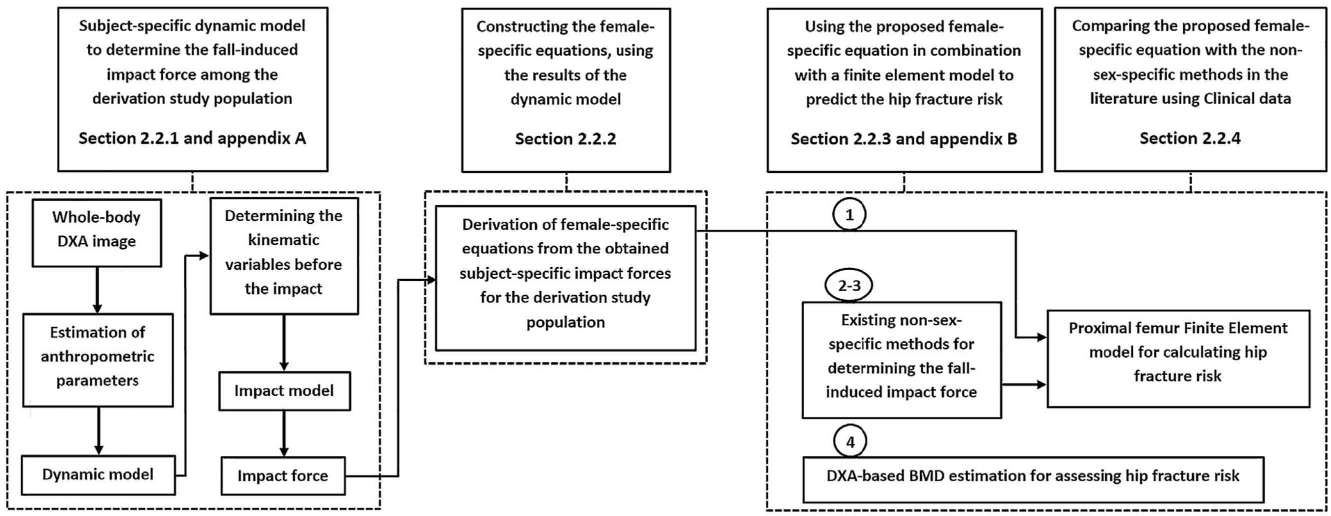

Fig. 1. Procedure of derivation and evaluation of the female-specific equation for predicting the subject-specific fall-induced impact force to the hip and comparing the accuracy with available non-sex-specific methods in the literature.

biomechanical model was introduced to predict the subject-specific impact force and hip fracture risk in sideways falls and its advantages over currently available models were demonstrated. The model considered the effective parameters on the applied force to the hip, including body anthropometric parameters (body segments mass, length, mass center, and mass moment of inertia), body segments kinematics during the fall, and the sex-specific effect of GT soft tissues in attenuating the impact force. Construction of the model is described in detail elsewhere (Luo et al., 2014; Nasiri Sarvi and Luo, 2015; Nasiri Sarvi et al., 2014). In short, body falling was divided to two phases and each phase was simulated by a separate model:

(1) The descent phase, between the instant of instability and impact, was simulated by a human body dynamic model. Each subject's whole-body DXA image (Fig. 2a) was used to extract the required parameters of body segments to construct the dynamic model (Fig. 2b).
(2) The impact phase, when the hip impacted the ground, was simulated by a single DOF mass-spring-dashpot model. This model was used to simulate the vertical motion of the body during the impact stage of the fall (Fig. 2c) and determine the sideways fall-induced impact force, subject-specifically. A complementary explanation about the human body dynamic model is provided in Appendix A.

The described dynamic model was previously validated against experimental falling data to a height of 40 cm ($r^2 = 0.93$) (Nasiri Sarvi, 2015). This falling model is used in this study to determine the impact force for the derivation study population, including 80 women. Obtained impact forces were then used to derive female-specific parameters used in the impact force equation.

2.2.2. Construction of the female-specific equation for predicting the impact force

Before constructing the female-specific equation, correlation coefficients between impact force and body mass/height/STT were studied to find an appropriate mathematical form for the equation. The obtained correlation coefficients are provided in Table 3.

From the correlations presented in Table 3, body mass and body height have a positive correlation with the impact force while this correlation is negative for GT soft tissue thickness. It indicates that greater body mass and body height and smaller GT soft tissue

Table 3
Correlation coefficient, r (p value), between the impact force and body parameters among the 80 women in derivation study population.

	Body mass	Body height	GT soft tissue thickness
Impact force	0.32 (<0.005)	0.43 (<0.001)	−0.27 (<0.05)

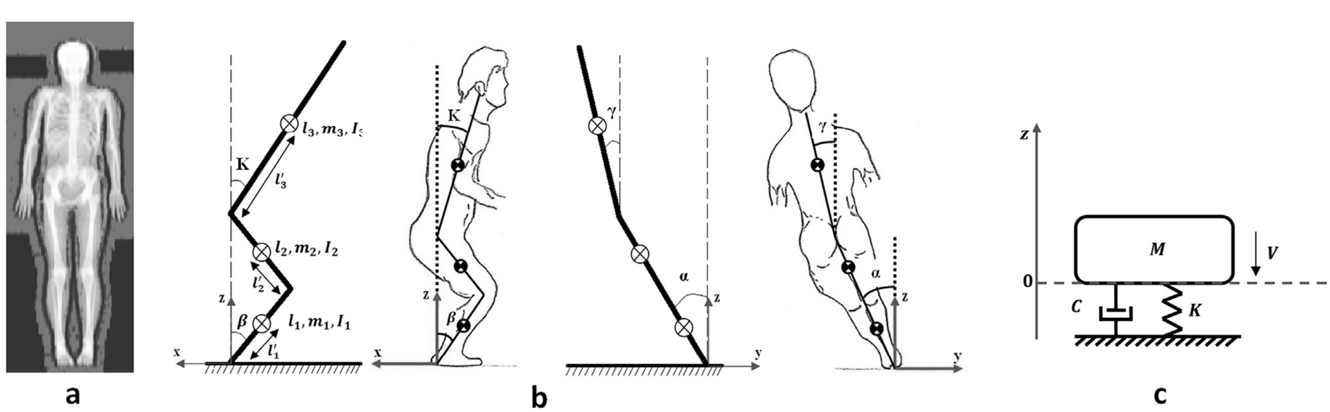

Fig. 2. (a) The whole-body DXA image to extract body segments anthropometric parameters. (b) The dynamic model to simulate body falling and determine the impact velocity at the impact moment. (c) The impact model to determine the fall-induced impact force. (reproduced from (Nasiri Sarvi and Luo, 2015) with permission).

thickness increases the fall impact force. However, the correlations between the impact force and body parameters can be nonlinear. Therefore, the following format of equation was constructed to reflect the explicit effect of each parameter on the impact force:

$$F = C \times \frac{BH^{\alpha} \times BM^{\beta}}{STT^{\gamma}} \tag{1}$$

Nonlinear regression between the impact force, predicted by the presented dynamic model, and BM, BH, and STT was performed among the 80 women in derivation study population in order to determine the female-specific coefficients for C, α, β, and γ in Eq. (1). Resulted equation is as follows,

$$F = 0.811 \times \frac{BH^{0.261} \times BM^{0.769}}{STT^{0.504}}, \quad r^2 = 0.95, \quad RMSE = 3.5\% \tag{2}$$

where F, BH, BM, and STT are respectively in kN, m, kg, and mm.

2.2.3. Comparing the female-specific impact force predictor with existing non-sex-specific impact force predictors

This study incorporated the proposed female-specific equation for predicting hip impact force with a DXA-based FE model of the hip. The method of constructing the FE model is described in appendix B. As a brief explanation, proximal femur was segmented from hip DXA image of the patient and inhomogeneous material properties were assigned. Then, fracture risk index (FRI) that compares the mean ratio between the actual and allowable stress at the femoral neck was calculated (Luo et al., 2013). The proposed equation for predicting fall impact force was integrated with the FE model to estimate the hip fracture risk of evaluation study population, including 393 women, and discriminate the hip fracture patients. Results were then compared with clinical observations.

The reasons for using hip fracture risk assessment as an evaluation method, instead of directly validating the predicted impact forces, are two-fold. First, it was not practical to experimentally measure the real-life fall-induced impact force to the hip in an individual and directly validate the proposed model for predicting the impact force. Second, the purpose of developing a fall-induced impact force predictor is to integrate it with hip fracture risk assessment tools. Therefore, this study evaluated how the proposed method for predicting hip impact force could be integrated with an FE model to assess hip fracture risk.

Non-sex-specific impact force predictors offered by Kroonenberg, Yoshikawa, and Robinovitch were also integrated with the aforementioned FE model to discriminate hip fracture patients and relative results were compared with the proposed sex-specific method. The two non-sex-specific impact force predictors that have been used in hip fracture risk assessment tools are described as follows:

(1) Kroonenberg's equation in combination with Robinovitch's method (Robinovitch et al., 1995):

$$F = m_e \times g \times (n \sin(\omega) - \cos(\omega) + 1) - 71 \times STT \tag{3}$$

where effective mass was determined from body mass in kg, i.e., $m_e = 0.35 \times \text{BM}$, impact velocity was correlated to the body height in m, i.e., $V = 2.72\sqrt{h}$, $n = V(\sqrt{\frac{71.000}{m_e}})/g$, $\omega = \pi - \tan^{-1}(n)$, and STT is GT soft tissue thickness in mm.

(2) Yoshikawa's equation in combination with Robinovitch's method:

$$F = 8.25 \times W \times \sqrt{\left(\frac{h}{170}\right)} - 71 \times STT \tag{4}$$

where h is body height in cm and W is body weight in Newtons.

In order to evaluate the effectiveness of the combination of the impact force predictors and the FE model, findings of hip fracture risk assessments were also compared with results of bone densitometry based on hip DXA. This method evaluates areal BMD at critical locations and compares the measured BMD with that of healthy young persons (Binkovitz and Henwood, 2007). DXA-based densitometry is still considered as the clinical gold standard in assessing hip fracture risk. Nevertheless, this method lacks sensitivity and specificity (Stone et al., 2003).

2.2.4. Clinical evaluation and statistical analysis

Hip fracture risk assessment by all implemented methods was performed blinded to the fracture status of the subject. In the other words, the information of the validation study population, including BM, BH, STT, and hip DXA scan, was received from Manitoba Bone Mineral Density Database without any cognition of the hip fracture cases. Hip fracture risk of all subjects was then calculated and the results were transferred to our collaborators at the University of Manitoba Medical School for statistical analysis. To quantitatively compare the models in predicting the hip fracture risk, odds ratios and 95% confidence intervals (CI) were calculated from logistic regression models using the maximum likelihood approach. Prediction capacity of different models was assessed by the area under the curve for receiver operator characteristic analysis. A p-value < 0.05 was considered to be statistically significant.

3. Results

Fig. 3 compares the impact force predicted by the proposed equation and the dynamic model for 80 women in derivation study population. Regression analysis showed that $r^2 = 0.95$ and normalized root-mean-square-error $(RMSE) = 3.5\%$. The predicted impact forces by the dynamic model was in the range between 1883 N and 4782 N with the $mean(SD) = 3200.6$ $N(517$ $N)$. The predicted impact forces by the proposed equation was in the range between 1716 N and 4573 N with the $mean(SD) = 3200.3$ $N(495$ $N)$.

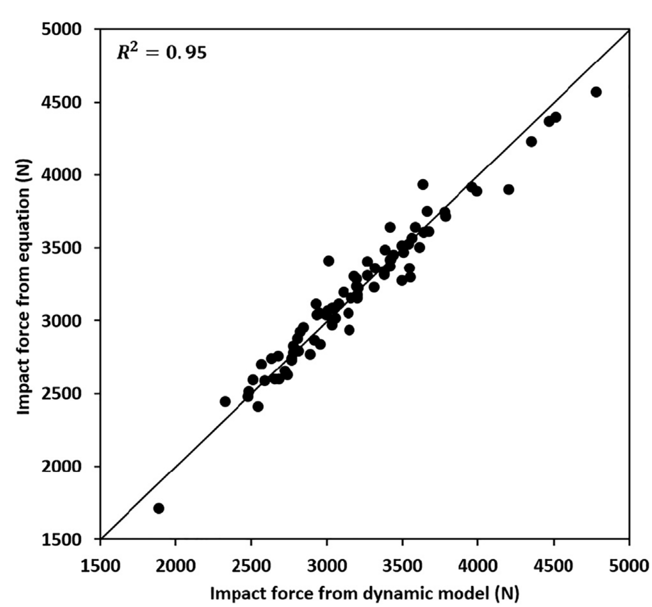

Fig. 3. Comparison between the predicted hip impact forces by the proposed equation and the dynamic model for 80 women in the derivation study population $(r-square = 0.95, \; root\text{-}mean\text{-}square\text{-}error \; (RMSE) = 112 \; N)$.

Table 4
Area under the ROC curve and odds ratio in discriminating clinical fracture cases by different methods.

Method of hip fracture risk assessment		AUC, (95% CI)	OR, (95% CI)
1	Proposed female-specific method	$0.799,\ (0.723-0.835)$	$4.22,\ (2.60-6.86)$
2	Kroonenberg+Robinovitch method	$0.750,\ (0.689-0.811)$	$3.62,\ (2.32-5.66)$
3	Yoshikawa+Robinovitch method	$0.749,\ (0.690-0.808)$	$3.47,\ (2.21-5.44)$
4	DXA-based BMD estimation	$0.713,\ (0.646-0.779)$	$2.27,\ (1.72-3.00)$

Table 4 summarizes the AUC and OR for different methods in assessing the hip fracture risk. The AUC for the proposed method, AUC $=0.799, (95\%$ CI $0.723-0.835)$, was significantly $(p<0.001)$ greater than all other implemented methods. The AUC for Kroonenberg + Robinovitch method, AUC $=0.750, (95\%$ CI $0.689-0.811)$, was not significantly different from Yoshikawa + Robinovitch, AUC $=0.749, (95\%$ CI $0.690-0.808)$. However, the AUC for both Kroonenberg + Robinovitch and Yoshikawa + Robinovitch was significantly $(p<0.001)$ greater than BMD estimation from DXA, AUC $=0.713, (95\%$ CI $0.646-0.779)$. The OR for the proposed method was also numerically the highest compared to other implemented methods. However, the OR for all methods was remarkably greater than 1.

4. Discussion

This study proposed a female-specific equation to predict the sideways fall impact force to the hip. The proposed equation was integrated with an FE model to discriminate hip fracture patients among 393 women and results were compared with non-sex-specific methods for determining fall impact force. Concordant with our hypothesis, the proposed female-specific equation improved the hip fracture risk assessment compared to the currently existing non-sex-specific methods.

The results of this study indicate that all impact force predictors integrated with the FE model improved $(p<0.001)$ assessment of hip fracture risk compared to areal BMD alone. This improvement is still evident after adjusting for areal BMD; proposed method AUC $=0.786, (95\%$ CI $0.71-0.81)$, Kroonenberg + Robinovitch method AUC $=0.737, (95\%$ CI $0.65-0.78)$, Yoshikawa + Robinovitch AUC $=0.732, (95\%$ CI $0.66-0.76)$. It indicates that predicting impact force integrated with FE analysis provides additional information beyond areal BMD for the prediction of hip fractures. This improvement in accuracy is in part due to the use of an FE model to calculate hip fracture risk. With FE, bone strength can be more accurately estimated compared to BMD estimation since the bone geometry and material inhomogeneity are taken into account (Naylor et al., 2013; Yang et al., 2014). The other potential reason for this improvement is that, in addition to femur strength, impact force is also taken into account in the implemented FE model. For example, if the femur strength is the same in two subjects, the impact force, which is related to the anthropometric parameters, is the factor that will discriminate which subject is more prone to hip fracture. Related to this, the effect of loading is not directly considered in fracture risk estimation using BMD from DXA.

Among the evaluation study population, the fracture and control groups were not significantly different with respect to age (Table 1). This may be a potential reason why results do not show a remarkable difference before and after adjusting for age (proposed method AUC $=0.791, (95\%$ CI $0.72-0.81)$, Kroonenberg + Robinovitch method AUC $=0.744, (95\%$ CI $0.68-0.80)$, Yoshikawa + Robinovitch method AUC $=0.741, (95\%$ CI $0.68-0.79)$, DXA-based BMD estimation method AUC $=0.718, (95\%$ CI $0.65-0.78))$.

Our results indicated that the AUC for the proposed female-specific method was greater $(p<0.001)$ than the non-sex-specific methods. This implies that the proposed method for predicting hip impact force may improve hip fracture risk assessment for women. Potential reasons for higher accuracy are two-fold. First, the proposed impact force predictor was specifically developed for women. It has been demonstrated in our previous study (Nasiri and Luo, 2016) and in follow-up studies on hip fracture patients (Dufour et al., 2012; Nielson et al., 2009) that the impact force is differently affected by body parameters in men and women. Experimental side impacts (Etheridge et al., 2005) and statistical studies (Bouxsein et al., 2007; Johansson et al., 2013) showed that thicker GT soft tissues can reduce the risk of hip fracture in women due to the attenuation of hip impact force. However, Nielson et al. (2009) found in a follow-up study on 5995 men that tissue thickness in men is not associated with the risk of hip fracture. Dufour and colleagues (Dufour et al., 2012) also found that lower GT soft tissue thickness was not associated with higher hip fracture risk in men, but there was an association in women. Therefore, the attenuated force by GT soft tissues in a fall is different between men and women; subsequently, the force applied to the femur is different (Dufour et al., 2012; Nielson et al., 2009). Since the proposed method is specifically derived for women, it can more properly predict impact force for female subjects in the evaluation study population compared to non-sex-specific methods. The second potential reason is the number of subjects in the population used to construct our equation. Since the subjects used to derive Eqs. (3) and (4) are within a limited range of body habitus, they are suggested to be used for subjects with STT in the range of 8–45 mm (Robinovitch et al., 1995). However, the proposed equation in this study (Eq. (2)) can be used for subjects with a wide range of body habitus, including STT (up to 132 mm). The wider spectrum of anthropometric parameters that was incorporated by our equation could affect the accuracy of the function constructed by statistical regressions. However, it has to be pointed out that this study is using indirect validation method for the proposed equation. It is good to be mentioned that an equation is also recently proposed (Enns-Bray et al., 2019) to determine the force at the contact between femoral head and acetabular cup in women based on femoral head radius, pelvis width, and soft tissue thickness.

Although our study has several strengths, including independence of the method to the whole-body DXA image, it also has some limitations. First, for the implemented single degree of freedom impact model used for determining the impact force, the mass of the spring and damper are ignored, which is a simplification (Derler et al., 2005). More realistic impact models are still needed to precisely estimate impact force. Second, there is no clinical information to verify whether the falls that caused hip fractures in our evaluation study population were sideways, forward, or backward. However, the literature indicates that more than 60% of hip fractures are caused by sideways falls (DeGoede et al., 2003; Greenspan et al., 1998; Kannus et al., 2006; O'Neill et al., 1994). Therefore, we expect most of the hip fractures among the evaluation study population were caused by sideways falls. Nevertheless, it does not affect the comparison between the proposed female-specific equation and the non-sex-specific methods because Kroonenberg and Yoshikawa equations also predict the impact force in sideways falls. However, more information about the cause of hip fracture in evaluation study population can generally improve the precision of interpreting the results. Third, the proposed equation for predicting the impact force was not directly validated against experimental falling data. Instead, it is evaluated by a dynamic model that itself was validated by dropping individuals. The volunteers used in dropping experiments were young adults with minimal GT soft tissue thickness and did not include subjects with a wide spectrum of anthropometric parameters. Therefore, deriving an equation from dropping experiments subjects will limit its application to subjects with a specific range of anthropometric parameters. We thus selected the derivation study population of various body habitus with a wide range of age to derive the proposed equation. Since the derived equation was not validated directly against dropping experiments, we clinically evaluated the equation in assessing hip fracture risk when it was integrated with an FE model. Fourth, our evaluation study population did not include any subject with $T\text{-}score > -1$. A big number of hip fractures was observed among women with T-score higher than -1.5 (Stone et al., 2003), where hip fracture prediction with aBMD alone might not be accurate. Therefore, including impact force information by the proposed method might improve hip fracture risk assessment among women with normal bone score. But it remains to be evaluated in future studies. Fifth, the follow-up period, i.e., the time from taking the DXA scan until a fracture occurs, was not recorded among the evaluation study population. Including the follow-up period could improve interpretation of the results.

It also has to be pointed out that there are other parameters that can affect the magnitude of the fall-induced impact force, such as joint torques (Choi et al., 2015a) and age (Choi et al., 2015b). As an example, experimental studies showed age-related reduction in impact force attenuation by GT soft tissues (Choi et al., 2015b). Also, contraction of the hip abductor muscles at the moment of impact during a fall, and landing with the knee free of constraints, reduce the peak impact force to the femur in a sideways fall (Choi et al., 2015a). Moreover, not only may the effective parameters vary from subject to subject, but they may also differ for one subject from fall to fall (Nasiri Sarvi and Luo, 2017). Therefore, further research is needed to consider these parameters subject-specifically.

5. Conclusions

In summary, this study proposed a female-specific equation for predicting the fall impact force to the hip and it improved the hip fracture risk assessment for women compared to the available non-sex-specific methods in the literature. Considering the context of the available literature that has now accumulated on the FE analysis of proximal femur, the proposed method can be used for meeting better accuracy in hip fracture risk assessment and identifying patients at high-risk of fracture who may benefit from in-time treatment.

Acknowledgments

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Conflicts of Interest

Masoud Nasiri Sarvi and Yunhua Luo declare that they have no conflict of interest.

Appendix A. . Human body dynamic model for determining the fall-induced impact force to the hip

In order to construct the subject-specific human body dynamic model, a body tissue mass estimation method (Durkin et al., 2002; Nasiri Sarvi and Luo, 2015) was utilized to extract body segments properties, including length, mass, mass centre, and mass moment of inertia, from the subject's whole-body DXA image (Fig. 2a). Obtained anthropometric parameters were then used in a three-link model representing the shank, the thigh, and the trunk (Fig. 2b), proposed by authors (Nasiri Sarvi and Luo, 2015, 2017; Nasiri Sarvi et al., 2014), to simulate the kinematics of body segments during a sideways fall from standing height. Lagrange's method was used to obtain the equations of motion (Luo and Nasiri Sarvi, 2015; Nasiri Sarvi et al., 2014). The model is able to predict the position and the velocity of body segments at impact.

After simulating the body falling from standing height to impact by a human body dynamic model, the interaction between the body and the ground was simulated by an impact model. It has been demonstrated that body motion during impact can be described by a damped vibrational system (Fig. 2c) (Robinovitch et al., 1991; Robinovitch et al., 1997; Robinovitch et al., 2003). Damping was considered in this model to simulate the force attenuation by the GT soft tissues. To make the impact model subject-specific, the required parameters were taken from the concerned subject. The effective mass (M), i.e., the portion of the body that moves in the vertical direction with the impact velocity V prior to impact, was determined by the subject-specific human body dynamic model. Body stiffness (K) and damping (C) properties during the impact were also determined based on the gender of the subject and the GT soft tissue thickness. Experimental data (Robinovitch et al., 1991) was implemented to sex-specifically determine the body stiffness and damping properties from GT soft tissue thickness. The procedure for determining subject-specific body stiffness/damping properties is described elsewhere (Nasiri Sarvi and Luo, 2017). In short, experimentally measured K and C for seven women were extracted from (Robinovitch et al., 1991). Then, nonlinear least-square fits of power functions were used to female-specifically evaluate the correlation between the body stiffness/damping properties and the thickness of GT soft tissues, which resulted in the following equation,

$$For\ \ females : \begin{cases} K = 1.19STT^{-0.91} \\ C = 0.51STT^{0.13} \end{cases} \tag{A.1}$$

where K, C, and STT are respectively in kN/m, $kN.s/m$, and m. Measurement of GT soft tissue thickness was made from the subject's hip DXA scan. The outer limit of the subcutaneous GT soft tissues overlying the hip and outermost point of the greater trochanter were used to determine the thickness of GT soft tissues in mm. GT soft tissue thickness was measured in the left and right side of the subjects recruited in this study and the average value was considered for subsequent analysis. The constructed impact model was able to predict the fall-induced impact force to the hip.

Sideways fall experiments were performed to validate the dynamic and impact model in predicting the impact velocity and the impact force, respectively. The results of fall experiments were published elsewhere (Luo and Nasiri Sarvi, 2015; Nasiri Sarvi et al., 2014). In short, the experiments involved falls from different heights, i.e., 5 cm, 10cm, 15cm, 20cm, 30cm, and 40cm. The volunteers were asked not to use their hands or knees to break the fall in

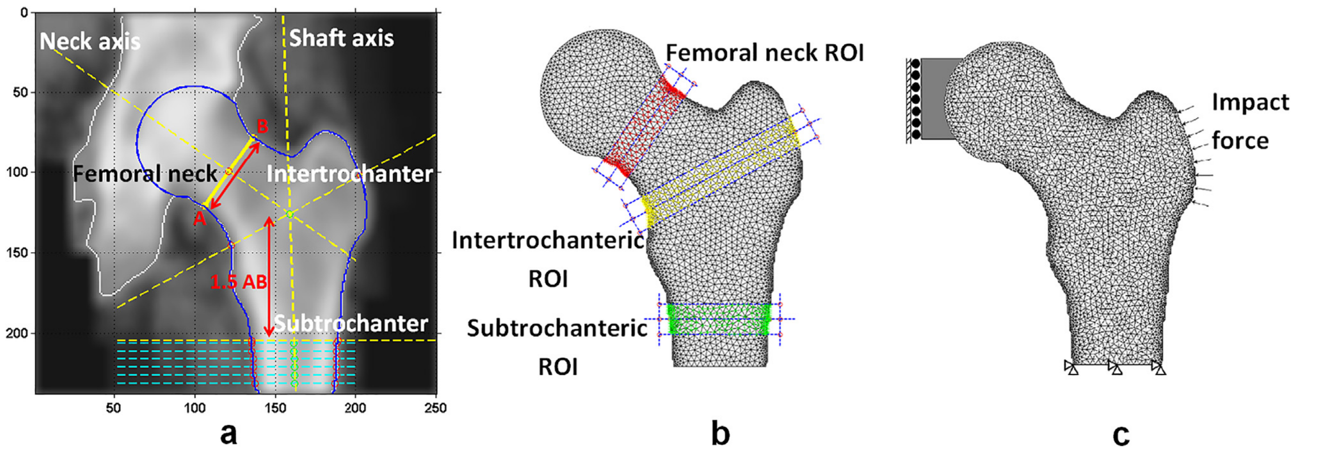

Fig. B1. Procedure of constructing the DXA-based FE model: (a) extracting the contour of the proximal femur from hip DXA image and (b) determining the critical ROIs. (c) Load/constraint conditions of the proximal femur in simulating sideways fall (reproduced from (Nasiri Sarvi and Luo, 2015) with permission).

order to mimic falls that were simulated by the dynamic model. The recorded forces varied from low to high level, i.e., 1400–5200 N (Nasiri Sarvi and Luo, 2017). Experimental validations showed that the subject-specific dynamic and impact model could properly predict the impact velocity (with an average relative error of 7.2%) and the peak impact force (with an average relative error of 9.3% and $r^2 = 0.93$) (Nasiri Sarvi and Luo, 2017).

Appendix B. . Finite element model for assessing hip fracture risk

A finite element (FE) model was used to calculate the hip fracture risk. The method of constructing the FE model has been described elsewhere (Nasiri and Luo, 2016; Nasiri Sarvi and Luo, 2015). As a brief explanation, the proximal femur was segmented from a hip DXA image of the patient using an image-processing algorithm that combined edge detection and thresholding. An in-house MATLAB code was written to extract the pixel-by-pixel BMD map of the hip DXA scan and inhomogeneous material properties were then assigned using the following equation (Kopperdahl and Keaveny, 1998; Kopperdahl et al., 2002). Details of deriving the following equation is described in (Luo et al., 2011, 2013).

$$E = 2,838 \times \rho^{1.05} \quad \text{(B.1)}$$

A fracture risk index (FRI) that compares the mean ratio between the actual and allowable stress was calculated as follows (Luo et al., 2013):

$$FRI = \frac{\sum_{i=1}^{N} \int \frac{\sigma_{applied}}{\sigma_Y} dA}{\sum_{i=1}^{N} A_i} \quad \text{(B.2)}$$

where $A_i(\mathrm{i} = 1, 2, \cdots, \mathrm{N})$ are the areas of the N finite elements enclosed in a region of interest. σ_Y and $\sigma_{applied}$ are respectively the yield and the von Mises stress at the Gaussian points.

$$\sigma_Y = 26.9 \times \rho^{1.39} \quad \text{(B.3)}$$

FRI= 1 was considered as the cut-off value in such a way that FRI greater than one indicates that the patient is in a high risk of hip fracture. The procedure of constructing the FE model is illustrated in Fig. B1.

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