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Retrospective Study

Risk modeling of femoral neck fracture based on geometric parameters of the proximal epiphysis

Shitova AD *et al.* Risk modeling of femoral neck fracture

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Abstract

BACKGROUND

Fractures of the proximal femur epiphysis are problematic for state health care because they are associated with severe medical and social problems and high morbidity and mortality rates.

AIM

The aim of this study was to model the potential risk of hip fracture *via* femur geometric parameters.

METHODS

Seventy educational cadaveric femurs from people aged 14 to 80 years, 10 X-ray images from the records of the Human Anatomy Department and 10 X-ray images from the Department of Traumatology, Orthopedics and Disaster Surgery of Sechenov University, were evaluated. The parameters of the fractured bone were measured using images captured with a Canon d60 camera. The projection values of the proximal epiphysis of the cadaveric femurs and geometric parameters of the bones shown in the X-ray images were measured with Autodesk software (AutoCAD 2018). Analysis of the video frames showing bone rotation reveal that the greater trochanter can be inscribed in a parallelepiped, where one of the faces is parallel to the plane of view in the frontal standard projection (FSP) and is rectangular. The angle of bone rotation obtained by turning the cube corresponded to the angle measured with the second technique. This reliable method of calculating the rotation of the bone relative to the anterior projection was employed in subsequent calculations. The geometric parameters of the femur were measured using X-ray images according to the proposed method.

RESULTS

The geometric parameters of 70 femurs were analyzed, and correlation coefficients were calculated. Our measurement results were compared with those reported by other

authors. The potential influence of femur geometry on force distribution in the proximal epiphysis of the femur was described, and a 2-dimensional model of the femur epiphysis associated with minimal neck fracture risk was provided. The assessment of the geometric parameters of the femoral epiphysis indicated the greatest risk of a varus fracture of the neck if the angle of the minimal resistance zone (AMRZ) index > 24° and the neck-shaft angle (NSA) <127.5°. In contrast, the minimum risk was observed at AMRZ <14° and NSA> 128.87°.

CONCLUSION

The proposed method provides the potential femur neck fracture risk based on geometric parameters.

Key Words: Fracture, proximal epiphysis of femur, risk, traumatology, hip neck, risk assessment scale

Core Tip: The neck-shaft angle (NSA) and angle of the minimal resistance zone (the area located in Ward's triangle (AMRZ)) were most associated with femoral neck fracture risk, and a method for calculating the true value of these parameters and risk stratification was developed. Assessment of the geometric parameters of the femoral epiphysis revealed the greatest risk of a varus fracture of the neck if the AMRZ index > 24° and NSA<127.5°. In contrast, the minimum risk was observed at AMRZ <14° and NSA> 128.87°.

INTRODUCTION

Fractures of the proximal epiphysis of the femur are problematic for state health care because they are associated with severe medical and social problems[1], high morbidity rates[2], disability[3,4], and high mortality rates[5]. Bone strength depends on the mineral density, architectonics and remodeling ability of bones[6], which change over time due to various factors. Characteristics such as bone mineral density, bone geometry and the properties of bone materials are factors that constitute bone quality[6]. The process by which bone strength decreases due to chemical composition changes and by which it decreases in trabecular density is referred to as osteoporosis[7].

The results of multiple studies on the causes and risk factors of bone deterioration, such as osteoporosis, have been introduced in clinical practice. The Fracture Risk Assessment Tool (FRAX)[8] scale was developed by individuals at the University of Sheffield to evaluate fracture risk; the scale assesses the influence of factors that cause a decrease in bone strength. The FRAX scale allows us to predict the ten-year probability of fracture, to identify patients who require more detailed examinations, including X-ray densitometry, and to prevent excessive radiation exposure[9].

In recent years, numerous studies have investigated the distribution of strain in bone under an applied load, identified areas that are highly influenced by stress and fracture risk and determined the influence of bone cytoarchitectonics and geometry on stress apportionment. High-resolution computed tomography and magnetic resonance tomography are employed in this field to analyze bone morphometric parameters[10]. Finite element analysis is a technique that is widely employed for bone model construction[11]. MATLAB is frequently utilized to calculate stress distributions in bone models[1]. The authors assessed changes in bone sample flexibility *via* a microhardness tester[12]. Other authors have detected structures in loaded femurs *via* a tension detector fixed to the bone[13]. The results of these investigations have been implemented in osteosynthesis operations[14] and endoprosthesis engineering applications[15].

This study aimed to determine the geometric parameters of the proximal femur that contribute most to femoral neck fracture. A method for measuring bone geometric

parameters *via* X-ray images is provided since X-ray images are widely employed by general practitioners, and thus, may be preferable for use in screening studies. According to this finding, in this study, we will mostly rely on X-ray imaging, as a widely utilized diagnostic method.

MATERIALS AND METHODS

Seventy femurs from the records of the Human Anatomy Department at Sechenov University from people aged 14 to 80 years were selected to measure geometric parameters of the proximal epiphysis.

A video of femur rotation around the anatomic axis (for the estimation of the bone projection changes during the turning process) and stills from the video and X-ray images of the femur of 10 adult patients (18–24 years) were provided by the Human Anatomy Department at Sechenov University (18–24 years), and 10 images of adult patients (18–63 years) were provided by the Department of Traumatology, Orthopedics and Disaster Surgery of Sechenov University (18–63 years). These X-ray images contained images of both femurs: one femur was fractured, and the other femur was intact and considered equal. The parameters of the fractured bone were measured using images captured with a Canon d60 camera.

The projection values of the proximal epiphysis of the femurs from the Human Anatomy Department and geometric parameters of the bones shown in the X-ray images were measured with Autodesk software (AutoCAD 2018).

Method of measuring bone geometry parameters

To ensure accurate measurements, centimeter rulers were attached to the bones, which helped to correctly scale the images.

The projection that defines the femoral neck base and accuracy of the neck-shaft angle (NSA) measurements, i.e., the frontal standard projection (FSP), was selected to plot the segments signifying the main geometric parameters of the proximal epiphysis of the femur.

In this study, a method for assessing the morphometric parameters of the proximal femur based on the projection values and angle of rotation around the anatomical axis relative to the FSP was developed.

In this study, the rotation angle was determined by the rotation of the cube installed on the tripod turning the bone. The rotation of the cube thus indicated the rotation of the bone at every point in time.

The anatomical axis was drawn through the midpoint of the diaphyseal diameter. The mechanical axis passed through the center of the femoral head and the midpoint of the distal epiphysis of the thigh bone (half of the distance between the condyles). The femoral neck axis was determined by the segment passing through the center of the femoral head and the plane perpendicular to the midpoint of the upper base of the femoral neck.

The triangle ABC designations, which are employed in formulas, comprising NSA (angle CAB); AC, the neck axis; and AB, the diaphyseal axis segment (connecting the diameter of the diaphysis to the neck axis), were plotted (Figure 1, A) as a major component of the epiphysis of the proximal femur.

The angle between the principal compressive trabecular pattern and the secondary compressive group (angle of the minimal resistance zone (AMRZ)) was applied to assess the value of Ward's triangle. The principal compressive trabecular pattern and secondary compressive group are indicated by segments KL and LJ, respectively. Segment KL was defined as the segment from the upper projection point of the distal base of the neck (point K) to the lower projection point of the lesser trochanter (point L). The segment LJ was defined as the segment parallel to the mechanical axis, which connects the center of the femoral head to the point between the femoral condyles and passes through point L (Figure 1, B).

The minimal resistance zone was demonstrated using photos of gross sections of the proximal epiphysis of the femur from the Department of Human Anatomy at Sechenov University. Trabecular patterns, following the course of the main forces acting on the femoral epiphysis under physiological vertical loading, were clearly visualized

on the gross sections. The direction of the chosen segments corresponded to the physiological stress lines and comprised a zone containing fewer trabeculae than were present in adjacent areas (Figure 1, C).

The projection values of the proximal femoral geometry parameters are equal to their actual values if the bone is positioned such that the planes of the CAB and KLJ triangles are parallel to the plane of the screen onto which the bone is projected. If the bone is somehow rotated, its parameter cannot be measured directly. Therefore, the bone elements that can assist in determining the presence of bone rotation relative to the standard projection and in measuring its angle were selected.

When analyzing the video frames that show bone rotation, we determined that the greater trochanter can be inscribed in a parallelepiped, one of the faces of which is a rectangle when the bone is in FSP. Consequently, this geometric parameter was chosen to evaluate the rotation of triangle ABC relative to the anatomical axis, to which segment AB is parallel.

Thus, on an X-ray, the angle of rotation of the bone relative to the FSP can be determined by calculating the angle of rotation of the parallelepiped that contains the greater trochanter using spatial construction (Figure 2).

To assess the reliability of determining the angle of rotation on the basis of the greater trochanter, this angle was calculated by measuring the angle of rotation of the cube fixed to a tripod using the following formula:

QCN =135°- arcos (a1/a), where a is the edge of the cube (whose length is 50 mm) and a1 is the length of the cube verge in a projection other than the FSP.

The angle of bone rotation obtained by turning the cube corresponded to the angle measured with the second technique, which uses the previously described feature of the large spit. Thus, this method of calculating the rotation of the bone relative to the anterior projection was deemed reliable and utilized in subsequent calculations.

During the rotation of the bone around axis AB to a random angle, triangle ABC was projected onto ABC1.

The change in the projection value of the NSA as a function of the angle of the rotation is represented by the following equation:

CAB = 180°-arctg (SA/(SC1/cosHSC)), where HSC is the angle of rotation, SA is the segment of the diaphyseal axis, and SC1 is the perpendicular segment, which passes through the center of the head of the femur to the diaphyseal axis (Figure 3, A).

Based on the abovementioned findings, the formula for calculating the true value of the AMRZ takes into account the rotation of the bone:

$K_1L_1J_1$ = acrtg (KO/(cos (KOH) * OL)) + arctg (OJ/(cos (JOH) * OL)), where KLJ is the projection AMRZ, $K_1L_1J_1$ is the true AMRZ, KO and OJ are segments of the perpendicular line toward the diaphyseal axis passing through point J (Figure 3, A), and KOH and JO indicate the angle of rotation.

Determination of the true parameters of the proximal epiphysis of the femur from an X-ray

A technique is proposed for determining the angle of rotation of the bone relative to the plane of the X-ray image based on the estimated rotation of the greater trochanter. In this technique, a box is created around the greater trochanter. Geometric constructions (Figure 2) are performed to estimate the angle of rotation similar to the technique previously mentioned for native bones and their videos.

Subsequently, this value is used to determine the true AMRZ.

The change in the projection magnitude of the NSA as a function of the angle of rotation can be represented by the following equation:

CAB = 180o-arctg (SA/(SC1/cosHSC)), where HSC is the angle of rotation, SA is the segment of the axis of the diaphysis, and SC1 is the segment of the perpendicular line connecting the center of the femoral head to the axis of the diaphysis (Figure 3, B).

The true value of the AMRZ was calculated as follows:

$K_1L_1J_1$ = acrtg (KO/(cos (KOH) * OL)) + arctg (OJ/(cos (JOH) * OL)), where KLJ is the AMRZ projection, $K_1L_1J_1$ is the true AMRZ, KO and OJ are segments of the

perpendicular line toward the axis of the diaphysis drawn through point J (Figure 2), and KOH and JOH are the angles of rotation (Figure 3, B).

When the plane including the axes of the neck and diaphysis is parallel to the plane of the X-ray, it is possible to directly measure the AMRZ (Figure 4).

This study does not take into account any parameters other than geometric parameters. Sex, age, concomitant diseases and other conditions can affect these parameters, but this study evaluates the results of these effects.

RESULTS

Interrelations among proximal femoral morphometric parameters

The results of a statistical analysis of the geometric parameters of the proximal epiphysis of the femur are presented in Table 1.

The correlation coefficient for the correlation between the NSA and the AMRZ, for the correlation between segment BC and the zone of minimum resistance, and for the correlation between the length of segment BC and the upper-to-lower neck length ratio was -0.155, 0.0617, and -0.119, respectively, which indicates weak negative correlations among these parameters. These findings suggest that the NSA and AMRZ vary independently of each other, and regarding the influence of these changes on the risk of fracture of the femoral neck, they must be evaluated as independent values. The correlation coefficient between the NSA and the upper-to-lower neck length ratio was -0.396, that is, there was a moderate negative correlation between these parameters.

The strongest correlation was found between the AMRZ and the upper-to-lower neck length ratio, with a correlation coefficient of 0.872 (Figure 5).

Based on this finding, we use the upper-to-lower neck length ratio to determine the size of the AMRZ.

Model of the proximal epiphysis that provides a minimal risk of femoral neck base fracture

The model of the proximal epiphysis, which provides a minimal risk of femoral neck base fracture, consists of an NSA of 134° (which is 1° smaller than the mean of the maximal and mean values of this parameter shown in our study (144°+125,9°)/2=134,99°)) and an AMRZ of 14° (minimal value of the parameter in our study) (Figure 6).

The femoral proximal epiphysis, which has parameters included in this model, is the most resistant to femoral neck base fracture when a patient falls on his or her side, according to our study.

Evaluation of the risk of femoral neck fracture using X-ray images

The scale was developed to evaluate the risk of femoral neck base fracture (Table 2). Scores were assigned to bone parameters within certain intervals, as specified in the table. According to the sum of the points, the degree of fracture risk for a given bone was determined: 2 points indicated low risk, 3–4 points indicated average risk, and 5–6 points indicated high risk.

The analysis of 10 X-ray images stored in the Department of Human Anatomy and 10 X-ray images of patients from the Department of Traumatology, Orthopedics and Disaster Surgery of Sechenov University showed that the value of the NSA and AMRZ differed from the optimal value for all bones.

DISCUSSION

We aimed to determine the bone parameters that are risk factors for a fracture of the base of the femoral neck when the patient falls on his or her side and did not take into account other types and mechanisms of fracture. However, the selected optimal values still remain within the reference values, even if they increase the risk of other mechanisms of femoral fracture.

In our study, we agree with the finding of several authors[16, 17, 18, 19, 20] that some bone parameters, such as NSA, have optimal values, and their deviations can cause a higher risk of fracture. In another study, the NSA value had a weak correlation with the

size of the minimum resistance zone of the proximal femur (AMRZ), indicating that these parameters can independently influence fracture risk.

According to previous studies, neither a decrease in the NSA nor an increase in the NSA can be considered a reliable risk factor for femoral neck fracture since there are data that both confirm and disprove the influence of these factors on the probability of fracture[21, 22, 23].

Nevertheless, it has been confirmed that the strength of the proximal epiphysis decreases when the NSA decreases, and the stress that occurs in the proximal epiphysis under stress conditions shifts to its distal part. The femoral neck can be considered a lever, to the ends of which forces are applied. In this case, the value of the moment of forces that characterize the rotational action of forces acting on the proximal and distal part of the neck relative to the middle of the lever will increase as the NSA decreases. Based on measurements and a fracture risk assessment in another study, we assume that reducing the NSA causes an increase in the risk of femoral neck base fracture.

In the field of orthopedics, proximal femur modeling is utilized to plan interventions and assess their results[24]. When planning corrective osteotomy, to calculate the true value of the NSA using X-ray images, the researchers employed X-ray images of the hip joints projected directly in the middle position, with internal rotation of the thigh, and in a position proposed by Lauenstein, with the mathematical tables proposed by Strzyzewski or Shartlain[19]. However, these measurements allow only approximate planning of the surgical intervention, so the results of the treatment depend heavily on the personal skills of the surgeon. 3-D modeling is considered a more accurate method; therefore, algorithms for calculating surgical interventions on 3D models have been introduced and are highly distributed[24, 25, 26, 27].

Furthermore, modeling of the proximal femoral epiphysis is conducted to create mathematical models to assess the risk of fractures under the influence of external factors. In recent years, special attention has been given to the variability of the shape of the proximal femur and the influence of its geometry on its strength[28]. For this purpose, statistical shape models are employed to simultaneously assess the impact of

risk factors and pathological changes in a variety of bone geometric phenotypes[29]. The analysis of the geometric and strength characteristics of cadaveric proximal femurs continues to be applied for more accurate construction of mathematical models[30, 31].

However, in most cases, statistical shape models require three-dimensional images using tomographic methods. Since the 3D model is associated with a high computational burden, Jazinizaden F. *et al* compared the ability of 2D and 3D femur models to predict hip fracture risk and showed that their productiveness does not differ significantly[32].

We propose a method for calculating the true parameters of the proximal epiphysis based on one projection obtained using an X-ray image. Our technique is assumed to prevent the occurrence of femoral fracture in primary health care practice, unlike other techniques designed to correct the consequences of a fracture. We assume that our method can be used in combination with existing methods for assessing the risk of fractures, since it does not contradict but can complement other methods.

Our study has a retrospective design, which is its first limitation. In the course of this work, a small number of X-ray images were selected; other types and mechanisms of fracture were not taken into account; and any parameters of bone tissue, other than geometric characteristics, were not taken into account. With regard to the selection of cadaveric bones, the age, gender and other parameters of the owners of the bones were not taken into account. In addition, the impact of other risk factors for hip fractures has not been evaluated, and densitometry studies have not been performed.

The scale needs to be evaluated further in future studies and is not ready for use in clinical practice. However, the measurement of these parameters during screening studies can reduce the risk of severe injuries.

The suggested method for measuring the true parameters of the proximal femur does not require special equipment but is quite difficult to implement. This method can be used when special software is not available and in combination with other screening tools that use X-ray scans of the femur. Further improvements to this method are needed. Nevertheless, performing such measurements with modern X-ray

diagnostic systems is not difficult. This method is assumed to be combined with other screening techniques and to be employed when other less complicated measurement methods are not available.

CONCLUSION

Disease prophylaxis *via* the assessment of risk factors and prevention is essential in modern medicine. Therefore, methods for assessing and diminishing risk should be developed.

The method described in this article is assumed to be a tool for first-level health care to predict severe disabling damage. Early detection of the anatomic predisposition to fracture as well as the identification of osteoporosis shall allow general practitioners to identify patients who are in the femur fracture risk group because of proximal femur geometry pathological changes and to take opportune actions for bone strengthening. This screening approach will decrease morbidity, mortality and the costs required for treatment and rehabilitation. Simultaneously, with a decline in incidence, mortality is also expected to decrease. The plotting methods proposed in this study could also be applied to design mathematical models for preoperative preparations. However, in this way, these methods should be further developed.

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