REVIEW ARTICLE

Hip Geometry on Femoral Neck Bone Strength; a Review Article

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Abstract

Introduction: Low bone strength of the hip, which depends on both bone mass and bone geometry, leads to risk for fragility hip fracture. Anatomical adaptations of the proximal femoral structure are important to maintain higher bone strength because they predict the fracture risk independent of bone mass. Therefore, it is crucial to evaluate the bone strength of proximal femur to predict the likelihood of fragility fracture risk based on both bone mass and geometric adaptations, as well as the biomechanical strength of femoral neck (FN).

Aim: To discuss the literature on geometric indices and biomechanical indices of the proximal femur to estimate FN strength

Material and methods: Dual energy x-ray absorptiometry (DXA) based hip structural analysis (HSA) technique derived indices of FN geometric adaptations and biomechanical strength at FN and their impact on FN bone strength were explored using the existing literature.

Bone mineral content (BMC, gram) and areal bone mineral density (aBMD, g/cm²) can be measured using the HSA technique. The simple hip geometric indices such as hip axis length (HAL),

femoral neck length (FNL), neck shaft angle (NSA), FN diameters, FN width and biomechanical indices such as cross-sectional moment of inertia (CSMI, cm⁴), section modulus (Z, cm³) and cross-sectional area (CSA, cm²) can be estimated using the HSA technique to estimate FN bone strength.

Conclusion: Estimation of FN bone strength by HSA based geometric adaptations and biomechanical strength indices provides better understanding of bone strength at FN. HAL and FN bone size with BMD provide better hip fracture predictability.

Key words: femoral neck, bone geometry, bone strength, HSA

Introduction

Fragility hip fractures are associated with increased morbidity, mortality and impaired quality of life, leading to social and healthcare burdens. With the increasing elderly population, the incidence of hip fracture is estimated to be increased - especially in Asian countries (1). The strongest risk factor for sustaining a hip fracture is low bone mass, which can be assessed as, bone mineral content (BMC, g) and areal bone mineral density (BMD, g/cm²). However, unfavorable bone structure,

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independent of bone mass, predicts FN fracture risk (2). Therefore, the ability of a bone to resist fracture, or whole bone strength, depends not only on the amount of bone mass but also bone size, bone shape or spatial distribution of bone mass, bone geometry, cortical and trabecular macro and microarchitecture, as well as the balance between bone formation and bone resorption (3) (Table 1). FN Bone diameter or bone size increases with advancing age. This increase in bone size by periosteal apposition is one important geometric adaptation that affects bone strength. FN diameter increases with aging, to compensate for the age related bone loss in order to

maintain higher strength [9]. The fact that bone structure, independent of bone mass, predicts the fracture risk highlights the importance of considering hip geometry and biomechanical properties bone, when predicting bone strength and fragility fracture risk (2). Therefore, understanding the mechanism and anatomical factors associated with bone geometry and biomechanical indices of proximal femur at the hip is an important fracture preventive strategy. Thus, the purpose of this article is to review the literature on bone geometry and biomechanical properties of hip on predicting FN bone strength.

Table 1: Determinants of bone strength

Structural properties	Material properties
Geometry	Mineral
Size (bone mass)	Mineral-to-matrix ratio
Shape (distribution of bone mass)	Crystal size
Microarchitecture	Collagen
Trabecular architecture	Type
Cortical thickness/ porosity	Cross-links
Microdamage/ microfracture	

Determinants of bone strength:

Approximately 80% of the total skeletal mass is composed of cortical bone, mainly found in the outer surfaces of long bone shafts. The cortical bone provides the mechanical strength and stiffness of bone. The remaining 20% of the skeleton comprises trabecular bone, mainly found in bones of axial skeleton such as the ribs, the vertebrae and in the metaphysis, epiphysis and

central part of the diaphysis of long bones (4). Trabecular regions, in the central part of the bone form a honeycomb-like network of thin rods and plates. These trabeculi contribute to form the trabecular network or trabecular microarchitecture, which provides architectural support to the bone. Compared to the cortical bone, trabecular bone comprises a larger surface area to volume ratio. Because

of it, the trabecular bone plays a more important role in the bone remodeling than the cortical bone. The process of bone remodeling is important to adjust bone strength in response to mechanical stress such as physical exercise, as well as to repair any micro-damages, consequently maintaining higher bone strength (5).

Anatomy of the hip:

The proximal femur is a complex structure. Femoral head and neck are predominantly composed of trabecular bone and the outer shell is formed by the cortical bone. The head of the femur articulates with acetabulum forming hip joint, a synovial ball and socket joint, allowing a wide range of movements in the hip. Such a range of mobility is pertained by having a neck that is much narrower than the diameter of the head. The FN, which connects the femoral head into the shaft of the

proximal femur, is important to transmit body weight into lower limbs. Greater and lesser trochanters, which are the bony prominences closely related to FN, are important for attachment of muscles. In addition, the greater trochanter, as being the outermost projected bony part, is subjected to the first strikes on the ground when falling. In a cross-section, FN is roughly cylindrical in shape. It has a structure with varying cortical thicknesses (CT) and periosteal diameter (PD) due to the uneven spatial distribution of bone mass throughout its length (6). Because of that, FN shows varying diameters throughout its length. The narrowest neck represents the smallest PD and is identified as the weakest point. The narrowest neck, being the most vulnerable section for FN fracture, is used as the region of interest to determine the geometric indices and biomechanical measures of the FN, to calculate the FN bone strength (7, 8) (Fig 1)

Figure 1: HSA output image showing the measurements of FN geometry and biomechanical properties

Figure 2: Measurements of Hip geometric indices; Hip axis length (HAL), femoral neck width (FNW), periosteal diameter (PD), femoral neck length (FNL), neck shaft angle (NSA), region of interest (ROI), cross-sectional moment of inertia (CSMI) and cross-sectional area (CSA).

Measurements of Hip geometry:

Hip axis length (HAL) is the distance from the base of the greater trochanter to the inner pelvic brim. Femoral neck axis length (FNAL) is the distance from the base of the greater trochanter to the apex of the femoral head. Femoral neck length (FNL/d2) is the distance from the user-defined center of femoral head to the intersection of neck and shaft axes. HAL increases with advancing age and longer HAL increases the risk of FN fracture (9, 10). Thus, HAL has been identified as an independent predictor of hip fracture (10, 11). Femoral neck shaft angle (NSA/θ) is the angle between the FN axis and the femoral shaft axis. The normal range of FNSA is approximately 120-135 degrees in adults. It is wider in young children and gradually becomes narrower with walking and mobility. Larger FNSA is associated with reduced bone strength and increased

FN fracture risk in both men and women. An active lifestyle, by enhancing the level of PA is advisable to reduce NSA and therefore to increase bone strength at FN (12). Femoral neck width (FNW), which is the narrowest diameter across the FN, is also known as PD at the narrowest FN. Endosteal diameter (ED) at the narrowest FN can be estimated using the algorithm described by Thomas J. Beck (13). The mean CT is calculated as the difference between the periosteal and the ED, divided by two.

Biomechanical properties of bone:

Bone is structurally designed for resisting bending and torsional stresses. The resistance to bending and torsional loading is important to maintain bone strength against fracture. When a load is applied to a bone, it causes

deformation. The biomechanical properties of bone describe the impact of both bone mass and the distribution of bone mass based on the relationship between force/load applied to the bone and its deformation. Under normal conditions, long bones are predominantly loaded by bending and axial compressions (14).

The resistance to compressive loading depends on the cross sectional area (CSA, cm^2) of the bone. The resistance to bending strength of a bone is determined by cross-section moment of inertia (CSMI, cm^4) and section modulus (Z , cm^3), which depends on the spatial distribution of bone mass in relation to its neutral axis. The mechanisms of bending and axial strength have been explained using three circular bars, all composed of the same bone mass (Figure 3) (3, 15). For the same BMD, bone C has reported greater bending strength and axial strength than bone B and bone A as reported in the literature (3, 15). When the cortical shell moves further away from the bone's neutral axis, by periosteal apposition or endosteal resorption, resistance to bending can be improved (14). By using the HSA software the contribution of biomechanical parameters on hipbone strength independent of BMD can be estimated (Fig 1).

CSMI, the key biomechanical parameter, describes the ability of the bone to withstand bending forces or torsional forces independent of the material properties of the bone. The HSA software identifies the plane with

the least CSMI across the narrowest FN, together with its center of mass. Z is another biomechanical index that also describes the resistance to bending forces of a bone. It can be estimated when CSMI is divided by “ y ”; the maximum distance from the neutral axis of the bone to perisosteum, or half of the PD (13) (Fig 2).

CSA is an index of the resistance of bone axial or compressive forces and as a result, the bone becomes shorter. CSA represents the minimum CSMI section of the narrowest FN and is equivalent to the BMC of that cross-section when all soft tissues are eliminated (13).

How to Measure hip geometry and biomechanical indices:

Dual energy x-ray absorptiometry (DXA) is used worldwide to measure BMC and BMD. DXA based advanced hip structural analysis (HSA) software is used to extract cross-sectional geometric indices and biomechanical parameters of the narrowest FN to calculate bone strength of the proximal femur (7). Bone geometric indices that determine the FN bone strength include the HAL, FNL, NSA, PD, ED and CT. These hip geometric parameters in combination with the biomechanical indices; i.e. CSMI, CSA and Z of the hip provide a better understanding of FN bone strength and fracture risk (2, 7) (Fig 1). Furthermore, these DXA based geometric indices at proximal femur have shown strong correlations with the biomechanical indices of hip strength of cadaveric proximal femur.

HSA is a cost effective approach, with minimum radiation exposure, to evaluate FN geometry and biomechanical behavior of hipbone strength. DXA technology is not designed to assess bone structure. Therefore, hip geometric indices obtained from two-dimensional HSA technology, have their inheriting deficiencies. The CT and the ED are estimated after making assumptions of a homogenous porosity in the cortical shell; a homogenous cross-sectional shape that assumes the FN to be cylindrical, not elliptical (16). However, DXA based HSA remains as a valuable tool to assess bone loss and fragility hip fracture risk. Inconsistent and inaccurate positioning of the femur, mainly due to the ante version of FN has been identified as the important

limitation of the HSA technology. Therefore, careful attention should be paid, in repeated scans of the same person, to ensure the consistency among scans as much as possible, to minimize positional errors by the technician. Studies conducted using the peripheral quantitative computed tomography (pQCT) technique, provide novel insights into better anatomical bone structural changes when predicting fracture risk. However, because of high cost and risk of exposure to radiation, these more advanced technologies to assess FN bone geometry have not yet been well established. Further, in validations studies, HSA and QCT correlate favorably, which supports the validity of HSA derived geometrical properties of proximal hip (17).

Figure 3: The effect of bone geometry on bone strength explained by changes of bone diameters with the spatial distribution of bone mass away from neutral axis. ED= endosteal diameter and PD= periosteal diameter (3).

Applications of hip geometry and biomechanical properties when predicting hipbone strength in adults:

Age related loss of bone mass is a common manifestation in the aging skeleton. In the bone mass life curve, even after reaching the plateau stage of bone mineral accrual where the bone formation equals the bone resorption in young adults, the bone size continuously increases into adulthood providing an important bone structural adaptation for fracture resistance (13,18). Larger bones are stronger than smaller bones, which support the importance of bone size when predicting fracture risk (Fig 2). Men and women reported different patterns of FN geometric adaptations and biomechanical strength at FN. This sexual dimorphism of bone structural changes through geometric adaptations in adult men and women has shown differences in hip fracture prevalence (13). Surface specific apposition of bone tissues on DP and ED is known as periosteal apposition and endosteal apposition respectively. Out of these two processes, increased PD due to periosteal apposition is more important to fracture resistance than the endosteal apposition. Periosteal apposition causes increased bone diameter or width, which is an advantage to have higher bone strength. This theory is implied when mechanical load such as physical exercise is applied on bone tissue to increase bone diameter by the process of periosteal apposition in boys and endosteal apposition in girls (12). In that, small increases in PD of a long

bone, markedly improve its resistance to bending and torsional loading, by the fourth power of the radius (3, 15) and (Fig 3). In general, both BMD and CT decreased gradually but significantly with advancing ages whereas both PD and ED increased with advancing ages (13, 18). When the increase of ED is more than increase of PD, bone mass distributes further away from its neutral axis, which is an advantage because it positively influences bone resistance against bending and torsional loads (19). FN bone strength is more obvious in men than in women as periosteal expansion is more marked in men than in women. Furthermore, the age and sex discrepancies of bone size and spatial distribution of bone mass on bone strength between men and women highlight the importance of bone structural adaptations from childhood into older adults in order to predict FN bone strength and likelihood of fracture risk in elderly men and women (13, 18). In addition, the effects of changing skeletal load on hip BMD and geometry based on body weight have been studied in elderly women. It showed that the hip appears to adapt the body weight between weight gainers and losers by adjusting the Z, an index of bending strength, to new loading conditions (12). Recent studies have further shown that decreased CT, CSMI, and Z were predictive of hip fracture by changing FN diameters. It further showed that the significance was disappeared when the findings were adjusted with BMD. The study further suggests that both geometric properties and BMD are important to predict hip fracture risk (13).

Conclusion:

In conclusion, estimation of FN bone strength by HSA based geometric adaptations and biomechanical strength indices, provides better understanding of bone strength at FN. Simple geometric properties of the hip such as HAL and FN diameters may play a significant role in prediction of hip bone strength and FN fracture prediction ability. However, HAL and FN bone size in combination with BMD provide better hip fracture predictability. These observations have been shown using retrospective and cross-sectional studies. Nevertheless, future prospective and controlled studies are needed to confirm the potential of fracture predictive ability of both HAL and FN diameters. In addition, their applications in primary health care settings to evaluate FN bone strength and fracture risk need to be evaluated in future intervention studies.

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