Bone 92 (2016) 9–17

Contents lists available at ScienceDirect

Bone

journal homepage: www.elsevier.com/locate/bone

Full Length Article

Exercise loading history and femoral neck strength in a sideways fall: A three-dimensional finite element modeling study

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ARTICLE INFO

Article history:
Received 7 February 2016
Revised 27 July 2016
Accepted 27 July 2016
Available online 28 July 2016

Keywords:
Bone strength
Finite element modeling
Exercise
Falling
Osteoporosis
Hip fracture

ABSTRACT

Over 90% of hip fractures are caused by falls. Due to a fall-induced impact on the greater trochanter, the posterior part of the thin superolateral cortex of the femoral neck is known to experience the highest stress, making it a fracture-prone region. Cortical geometry of the proximal femur, in turn, reflects a mechanically appropriate form with respect to habitual exercise loading. In this finite element (FE) modeling study, we investigated whether specific exercise loading history is associated with femoral neck structural strength and estimated fall-induced stresses along the femoral neck. One hundred and eleven three-dimensional (3D) proximal femur FE models for a sideways falling situation were constructed from magnetic resonance (MR) images of 91 female athletes (aged 24.7 ± 6.1 years, >8 years competitive career) and 20 non-competitive habitually active women (aged 23.7 ± 3.8 years) that served as a control group. The athletes were divided into five distinct groups based on the typical loading pattern of their sports: high-impact (H-I: triple-jumpers and high-jumpers), odd-impact (O-I: soccer and squash players), high-magnitude (H-M: power-lifters), repetitive-impact (R-I: endurance runners), and repetitive non-impact (R-NI: swimmers). The von Mises stresses obtained from the FE models were used to estimate mean fall-induced stresses in eight anatomical octants of the cortical bone cross-sections at the proximal, middle, and distal sites along the femoral neck axis. Significantly ($p < 0.05$) lower stresses compared to the control group were observed: the H-I group — in the superoposterior (10%) and posterior (19%) octants at the middle site, and in the superoposterior (13%) and posterior (22%) octants at the distal site; the O-I group — in the superior (16%), superoposterior (16%), and posterior (12%) octants at the middle site, and in the superoposterior (14%) octant at the distal site; the H-M group — in the superior (13%) and superoposterior (15%) octants at the middle site, and a trend ($p = 0.07$, 9%) in the superoposterior octant at the distal site; the R-I group — in the superior (14%), superoposterior (23%) and posterior (22%) octants at the middle site, and in the superoposterior (19%) and posterior (20%) octants at the distal site. The R-NI group did not differ significantly from the control group. These results suggest that exercise loading history comprising various impacts in particular is associated with a stronger femoral neck in a falling situation and may have potential to reduce hip fragility.

1. Introduction

Bone structure adapts to habitual mechanical loading [1,2]. Walking, as the predominant form of human locomotion, causes higher compressive stress at the inferior cortex and smaller tensile stress at the superior cortex of the femoral neck. This asymmetric loading results in a thicker inferior and thinner superior cortical bone [3,4]. With aging, cortical thinning becomes evident; the thickness of the posterior part of the superolateral cortex, called the superoposterior cortex, declines from a mean 1.6 mm at the age of 25 to 0.3 mm at the age of 85 years in females [4,5]. Mayhew and colleagues [4] suggested that the thinning of the superoposterior cortex contributes significantly to hip fragility. Cortical thinning increases the elastic instability of the cortical shell and can lead to a fracture because of local buckling under compressive load [4]. When one falls sideways, the superolateral cortex experiences unusually high compressive stress due to a high impact force imposed on the greater trochanter [6,7]. The peak magnitude of such a fall-induced stress can

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http://dx.doi.org/10.1016/j.bone.2016.07.021

be 4 times greater than the stress induced by normal gait [3]. Accordingly, it has been speculated that the fracture initiates from this thin cortical layer of the superolateral region [4,7,8]. Several finite element (FE) modeling and cadaveric experimental studies have consistently shown that a sideways fall exposes the femoral neck to the greatest risk of a fracture [7,9–13]. Indeed, over 90% of hip fractures are directly caused by falls [14,15]. Therefore, if the superolateral cortical thickness could be maintained or even increased with appropriate exercise training, bone strength may be maintained and hip fracture risk reduced in old age.

In our previous studies [16,17], we found that female athletes with a history of high impact and/or impact exercises from unusual directions have higher areal bone mineral density (aBMD), section modulus, and thicker cortical bone of the femoral neck including the superolateral cortex. However, the influence of this exercise-induced structural benefit on femoral neck strength in the sideways fall was not examined. Several FE modeling studies have been conducted to obtain a better understanding of the hip fracture mechanism [3,6,9,11–13,18–22]. To the best of our knowledge, however, no FE modeling study has so far been conducted to investigate the influence of specific exercise loading history on the structural strength of the femoral neck in a falling situation. In particular, it is not known whether specific exercise loading history is associated with lower stresses during a fall.

The purpose of the present study is to investigate whether the femoral necks adapted to distinct exercise loading patterns show different stress profiles in a sideways fall. For this purpose, proximal femur FE models were created from three-dimensional (3D) image data of 111 female participants with distinct exercise loading histories. These results are expected to provide further insight into the potential of specific exercise types in strengthening the proximal femur and alleviating hip fracture risk.

2. Materials and methods

2.1. Participants

Magnetic resonance (MR) image data of proximal femurs from 91 adult female athletes (aged 24.7 ± 6.1 years) competing actively at national or international level and 20 habitually active, but non-competitive female control participants (aged 23.7 ± 3.8 years) were obtained from our previous study [17]. The study protocol was approved by the Ethics Committee of the Pirkanmaa Hospital District, and written informed consent was obtained from each participant before the study.

The athletes were recruited from national sports associations and local athletic clubs, and the control participants were mostly students from local medical and nursing schools. The control participants did recreational exercise 2–3 times a week, but had previously never taken part in any competitive sports. The athletes comprised nine triple-jumpers, ten high-jumpers, nine soccer players, ten squash players, 17 power-lifters, 18 endurance runners, and 18 swimmers. According to our previous exercise classification scheme [16,23], the athletes were divided into five different groups based on the typical loading patterns of their sports: high-impact (H-I) (triple- and high-jumpers); odd-impact (O-I) (soccer and squash players); high-magnitude (H-M) (power-lifters); repetitive-impact (R-I) (endurance runners); and the repetitive, non-impact group (R-NI) (swimmers).

Wearing only light indoor clothing without shoes, the body height and weight of the participants were measured using standard methods. Questionnaires were completed by all participants in order to obtain their training history including weekly sport-specific training hours and the number of training sessions during at least the five preceding years. Other information such as medications, diseases, menstrual status, use of hormonal contraceptives, calcium intake, alcohol, smoking, coffee consumption, and previous injuries and fractures was also collected [17].

2.2. MR image scanning procedure

The hip regions of all participants were scanned using a 1.5-T MR imaging system (Avanto Syngo MR B15, Siemens, Erlangen, Germany). The scanned region covered the proximal femur from the top of the femoral head to the subtrochanteric level of the femoral diaphysis. Using two half-Fourier acquisition single-shot turbo spin-echo localization series, sagittal, axial, and coronal images of the hip region of the dominant side were scanned. The reconstructed imaging plane was adjusted so that the cross-sectional plane of the femoral neck was perpendicular to the femoral neck axis. The MR imaging sequence used was a standardized axial T1-weighted gradient echo volumetric interpolated breath-hold (VIBE)-examination with the following parameters: FOV 35 × 26 cm, TR 15.3 ms, TE 3.32 ms, slice thickness 1 mm without gaps, echo train length = 1, flip angle = 10°, matrix 384 × 288, the in-plane resolution (pixel size) 0.9 mm × 0.9 mm [17].

2.3. FE model construction

The MR images of all participants were first manually segmented by delineating the periosteal and endocortical boundaries of the cortical bone using a touch panel (Wacom Tablet Cintiq 12WX, Wacom Technology Corp., Vancouver, WA, USA) with ITK-SNAP (www.itksnap.org) image processing software [24]. The in vivo precision of periosteal and endocortical delineations of the femoral neck cortex is about 1% [17,25]. The segmented bone geometries were then converted into a volume mesh using the free mesh generation MATLAB (MathWorks, Inc., Natick, MA, USA) tool called iso2mesh [26]. The surface was then smoothed in MeshLab (Visual Computing Lab – ISTI – CNR, http://meshlab.sourceforge.net/) using a method described by Taubin [27]. This method was chosen for its known performance in minimizing the shrinkage of the geometry during the smoothing process. The smoothed proximal femur geometries were subsequently imported into SolidWorks (SolidWorks Corp., Waltham, MA, USA) for the generation

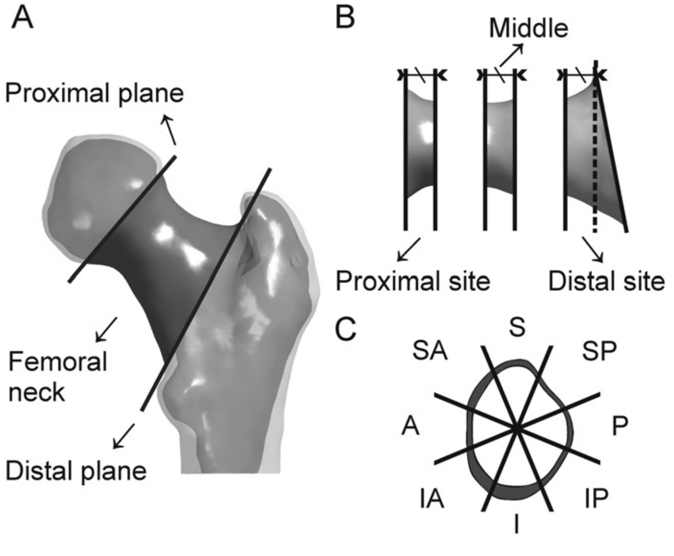

Fig. 1. Division of the femoral neck volume into anatomical sites and octants for the estimation of octant cortical stresses. (A) Posterior view of proximal femur. Dark grey-colored geometry defines the femoral neck geometry of interest. The proximal cross-sectional plane of the defined neck geometry was located at the femoral head-neck junction dividing the femoral head and the femoral neck. The distal plane was adjusted so that the distal plane met following conditions: its superior side is close to trochanteric fossa-greater trochanter junction, its anterior side is close to intertrochanteric line, and its inferior side is close to the lesser trochanter. This distal plane divides the trochanteric region and the femoral neck. (B) The division of the defined femoral neck regions into proximal, middle, and distal sites. The length of the superior surface was kept same for all sites. (C) The equal 45° anatomical octant division in the cross-section of the femoral neck. The femoral neck axis was used as the center of octant division.