Comparison of the trabecular architecture and the isostatic stress flow in the human calcaneus

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Received 2 August 2002; received in revised form 24 June 2003; accepted 7 October 2003

Abstract

It is a common theory that the architecture of trabecular bone follows the principal stress trajectories, as suggested by Wolff's pioneering studies of the proximal femur. Since first published in the late 19th-century, this observation (popularized as “Wolff’s law”) has been supported by numerous studies, but nearly all of them have been focused on the femoral head and neck. In this study, the manifestation of Wolff’s law in the human calcaneus has been analyzed. For this purpose, finite element (FE) analysis of the entire complex of the foot during standing was undertaken. Orientation of the principal stress flow through the calcaneus was compared with the trabecular alignment in a single cadaveric calcaneal specimen, by fitting second-order polynomials to real trabecular paths and FE-predicted isostatics and calculating their angle of inclination with the calcaneal cortex at their insertion points. Four dominant trabecular patterns were identified in the cadaveric sagittal section of the specimen of the calcaneus: one directed primarily in the dorsal-plantar direction, one aligned anteriorly–posteriorly, and two that are strongly oblique. Subsequent numerical simulations showed that the dorsal-plantar oriented and posterior oblique trabecular paths are aimed to support compressive stresses, while the antero-posteriorly directed and anterior oblique groups act to bear tension. Insertion angles of real trabecular paths into the calcaneal cortex were similar to those of the isostatics that were computed under musculoskeletal loading conditions of standing (maximum absolute local difference 13°, maximum local error 60%). This suggests that the trabecular patterns of the calcaneus are mainly shaped by isostatics (static principal stress flow) that are characteristic of the standing posture. The present modeling approach can be utilized to explore effects of abnormal alterations in the isostatic flow on the microarchitecture of the calcaneal trabeculae, as well as for better understanding of the mechanisms of calcaneal fractures.

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Keywords: Foot biomechanics; Cancellous bone; Wolff’s law; Finite element analysis

1. Introduction

More than a century ago, it was observed by Wolff (1892) that the architecture of trabecular bone of the femoral neck agrees with the static principal stress trajectories (isostatics) at that location, and this was considered the first evidence that bone remodels in response to the mechanical loads acting upon it [1]. Despite popularization of these findings, commonly referred to as “Wolff’s law”, only a few studies have been focused on the femoral femur. Finite element (FE) analyses were used in these studies to predict the paths of the isostatics and these were compared with the trabecular alignment [2–8]. Other studies have examined the simpler trabecular architecture of the patella in respect to a modeled distribution of principal stresses developed due to the activity of the quadriceps muscle [9,10]. Experiments with different animal models subjected to excision of the Achilles tendon were used to demonstrate changes in mineral content and morphology of trabecular bone at the lower-limbs as a result of abnormal load bearing and disuse [11–13].

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Studies of the effect of altered loading applied to the proximal tibia of canine models following knee arthroplasty further demonstrated realignment of the trabecular trajectories in response to altered directions of the principal stress flow [14]. In humans, changes in trabecular alignment associated with changes in the internal stress distribution were recently observed in osteoarthritic patients with reduced function of the knee joint. For these patients, trabecular orientation at the medial tibial condyle was more perpendicular to the articular surface than that of controls [15,16].

It should be noted, however, that none of the above studies quantitatively analyzed the manifestation of Wolff’s law in the human calcaneus, which is a structure of fundamental importance in bearing loads during body support or locomotion. The goal of the present study was therefore to test correlations between the real trabecular architecture of a human cadaveric calcaneus and the isostatic paths derived from FE analysis.

2. Materials and methods

2.1. Finite element model

The foot model used here to calculate the trajectories of the isostatics in the calcaneus is described in detail elsewhere [17]. For better understanding the application of this model to the investigation of the manifestation of Wolff’s law in the calcaneus, its essential components are described below.

The model comprises five planar cross-sections through the foot, which together yield a convenient representation of its complex half-dome shaped structure (Fig. 1a). The geometric data of the skeletal cross-sections of the foot were detected in vivo from a healthy normal female volunteer (age 27, weight 60 Kg) using magnetic resonance imaging (MRI). Next, geometry was transferred to a commercial FE analysis software package (ANSYS) for construction of planar models for the five rays of the foot (Fig. 1b,c). Cartilage layers and ligaments were introduced in the joints based on anatomic data. Bony elements and cartilage were assigned as having the properties of linear, elastic and isotropic materials, while ligaments, fascia and the soft tissue fat pad were considered as being non-linear materials. The Young modulus and Poisson ratio for cancellous bone were taken as being 7300 MPa and 0.3, respectively, and 10 MPa and 0.4, respectively, for cartilage. The typical experimental non-linear stress–strain relations for the ligaments, the plantar fascia and soft tissue pad were fitted to polynomial expressions of the fifth-order (with the constants as given in Ref. [17]). The Poisson ratios were taken as 0.4 for the ligaments and fascia and as 0.49 for the soft tissue pad.

The total load carried by the foot model was determined to be 300 N, which were distributed as 25%–19%–19%–19%–18% for the first through the fifth rays, respectively [17,18]. In addition to the body-weight surface load, a concentrated force of 30 N was applied at the posterior aspect of the calcaneus in each cross-section to represent the contraction of the triceps surae muscles during standing [17,18]. Supports constraining the model’s vertical displacements were positioned under the calcaneal base, under each of the five metatarsal heads and under the lateral metatarsal and cuboid bodies. The FE analysis resulted in the distributions of principal tension, principal compression, and the von Mises stresses, as well as the deformations of the foot rays in the standing posture. The model’s predictions of percentage of weight carried by the segments of a normal foot were compared with experimentally measured foot-ground contact stress...
data obtained from 20 feet of young healthy subjects, and there were no statistically significant differences [17].

2.2. Calcaneal specimen preparation

Embalmed calcaneal specimen was obtained from a single male elderly donor (at age of about 60, and with no history of bone or joint disease) for a related research protocol concerned with mechanical testing of the trabecular bone of the calcaneus. One centimeter thick sagittal slice (containing the calcaneal volume approximately bounded between planes \( P_2 \) and \( P_4 \) of the above-described numerical model, as depicted in Fig. 1a) was cut from the center of the calcaneus (Fig. 2a). The sagittal slice was then washed and partially dried in preparation for photographic documentation of the trabecular architecture. The photographic images obtained were then scanned at a 600 DPI resolution and contrast was enhanced for further image processing, as described in the following

Fig. 2. Calcaneal specimen preparation: (a) orientation of the sagittal slice; (b) orientation of the oblique specimen cut along the sagittal trabecular lines of the posterior aspect; (c) photographic image of the sagittal slice prepared for removal of an oblique specimen; (d) posterior view of the oblique specimen after removal. The dominant trabecular patterns observed on the anterior and posterior surfaces of the oblique specimen (taken as shown on b, c), are typically “S”-shaped, so that the trabecular paths along these planes are nearly perpendicularly inserted into the cortex at both the dorsal and plantar posterior aspects. A representative path is marked on the oblique image.
section. After the sagittal photos were obtained, the calcaneal slice was further cut along trabecular lines, to produce 1-cm oblique specimens, extending from the talocalcaneal joint dorsally to the posterior heel pad (as marked on Fig. 2b,c). Photographs were then taken of the posterior view of these oblique specimens, as depicted in Fig. 2d.

2.3. Correlation of trabecular alignment with isostatic trajectories

In order to allow quantitative comparison between the trabecular patterns observed along the cadaveric calcaneal specimen and the FE-resulted isostatics (Fig. 3a,d), a computational procedure was elaborated as follows. The real trabecular patterns in the sagittal section of the calcaneus were classified into four major groups (Fig. 4a), according to their geometrical orientation (as further detailed in the Results section). The boundaries of the sagittal cross-sections of the calcaneus were then segmented into seven partitions, marked $S_1$-$S_7$, to conform to the typical surfaces of connectivity of these four major trabecular patterns to the bone cortex, as depicted in Fig. 5a. The calcaneal cross-section was placed within an orthogonal planar axis system, so that its lower plantar point lies on the horizontal ($x$) axis and the posterior surface is bounded by the vertical ($y$) axis. In respect to this axis system, the dimensions of the sagittal cross-section were scaled so that the $y$ coordinate of the apex of the calcaneal cross-section and the $x$ coordinate of the most anterior point on its perimeter were both assigned a value of 1, thus allowing a dimensionless representation for any coordinate $\{0 \leq x \leq 1, 0 \leq y \leq 1\}$ on or within the calcaneal boundaries (Fig. 5b). Using this axis system, at least 10 polynomial functions of the second-order were fitted by means of a software package (DataFit 8.0, Oakdale Engineering) to cover (as homogeneously as possible) each of the four dominant trabecular patterns. It was found that polynomials of the form $y = a_2x^2 + a_1x + a_0$ (with constants $a_i$) could be fitted to the trabecular paths of all four dominant groups using the least square method, with a correlation coefficient $R^2$ of no less than 0.98 and an error smaller than 3% between measured and fitted coordinates. Subsequently, the derivative of these polynomials, $dy/dx = 2a_2x + a_1$, was calculated for each trabecular path at its two edges (where connections with the

Fig. 3. Stress analysis of the calcaneus as related to the trabecular architecture: (a) the isostatic stress flow (vector representation of the static principal stresses) in a longitudinal cross-section through the entire foot in the direction of the second ray, $P_2$. The arrows marking the alignment of the isostatics represent the transfer of tension (bright) and compression (dark) stresses; (b) distribution of von Mises stresses in the calcaneus during standing; (c) the trabecular architecture in a sagittal slice of a cadaveric calcaneus; (d) the isostatics in the calcaneus.
cortex are made) as shown in Fig. 5b. This provided numerical measures of the inclination of the trabecular paths at their insertion points into the cortex (the derivative $dy/dx$ at the connection of the trabecular path to the cortex equals the tangent of the inclination angle in respect to the horizontal axis, as depicted in Fig. 5b). This process of fitting polynomial curves and calculating their derivation along the calcaneal perimeter was performed on both the real trabecular patterns and the numerically obtained isostatic paths, so that real versus numerically-predicted trabecular alignments could be compared over each of the partitions $S_1$–$S_7$.

The variations in geometry between the FE model and the cross-sectional specimen of the individual cadaver (Fig. 3c,d) require some normalization of the shapes of partitions $S_i$ at both the model and specimens, to allow comparison of the results. This was accomplished by deploying these partitions over a linear course, ranging from 0 to 1, where an increase in the relative position on such normalized course reflects tracking the contour of a corresponding partition in the “clockwise” direction (Fig. 5a). This allowed comparative plotting of inclinations of the trabecular paths measured on the cadaveric specimen and of the isostatic paths that were numerically-predicted, over the entire perimeter of the calcaneal cross-section.

3. Results

Analysis of the cadaveric cross-sectional specimen of the calcaneus showed that the highest concentration of trabeculae is located in the superior region (Figs. 3c and 4b). The least dense area was located in the antero-inferior part of the calcaneus, corresponding to region previously termed by Harty as the “neutral triangle” [19–21] (Figs. 3c and 4b). The major trabecular patterns at the anterior and posterior surfaces of the oblique cross-sections were shown to be “S”-shaped (Fig. 2b,d), so that trabecular paths are nearly
The principal and secondary tensile patterns are at an angle of 55–82°, respectively. Quantitative comparisons of real versus model-predicted insertion angles of the trabeculae into the cortex are given in Figs. 6 and 7 for all four dominant trabecular patterns. Overall, the agreement between experimental and numerical results of trabecular insertion angles is good for the principal groups (maximum local error 60%; Fig. 7b left diagram). The maximal discrepancies in absolute angles of inclination were detected for the secondary compressive (maximum local error 25%) and tensile (maximum local error 34%) groups, for which insertion angles of the trabecular paths into the anterior and posterior aspects of the cortex, respectively, were lower by 12–13° degrees in the model, compared with the real ones. For the principal groups, difference between measured and predicted trabecular alignment around the cortex did not exceed 9°, and was 4° in average. However, we found local discrepancies (maximum local error 60%) for principal tensile patterns concentrated on a narrow region of the upper anterior cortex, corresponding to the range 0.8–1 of outline S₁ (Fig. 7b, left diagram). One reason for the discrepancies between real trabecular patterns and the ground reaction. The trabecular paths of the secondary tensile group are noticeably aligned to counterbalance tension in the deep and superficial plantar ligaments.

Table 1 specifies the convexity of the polynomials that provided the best fit with trabecular patterns of the four dominant groups (in terms of their constants \( a_2, a_1 \)), for the cadaveric cross-section and the FE simulation of the isostatic stress flow. It is shown that the proportion of trabecular paths, the variation in curves obtained using the FE method is smaller compared with that of corresponding experimental curves, and this can be attributed to the inherent biological variation and factors other than the principal stresses which influence the directional preference of the actual trabecular microarchitecture. Numerical differentiation yielded that in the vicinity of the cortex, the principal and secondary compressive groups of trabecular paths are tilted from the horizontal axis by 55–82°, and by 26–55°, respectively (as schematically shown in Fig. 4a).

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lar paths and isostatics is that isostatics intersect, by definition, at right angles, while trabecular paths do not necessarily cross at right angles. Overall, the above results suggest that the stress flow in the standing position (as manifested by the isostatics) is a governing factor affecting the arrangement of the trabecular microarchitecture in the calcaneus.

4. Discussion

In the present paper, FE calculations of the isostatics in the calcaneus during standing were determined for correlating their paths with the trabecular paths in a human calcaneus. While a large volume of literature was focused on classification of trabecular patterns in the proximal femur according to their functional role in supporting principal stresses [22,23] and resistance to fractures [24,25], to the best of our knowledge, the present study is the first one to characterize such stress-morphology interactions in the human calcaneus.

Dominant trabecular patterns were classified into four groups, of which one is directed primarily in the dorsal-plantar direction, one is mostly aligned anteriorly–posteriorly, and two are strongly oblique, in agreement with the anatomical report of Sabry et al. [21]. Subsequent numerical simulations allowed attribution of the above categories as being associated with either principal compression or tension, and it was found that the dorsal-plantar oriented and posterior oblique trabecular paths support compressive stresses, while the antero-posteriorly directed and anterior oblique groups bear tension.

Quantitative comparison of the insertion angles of the four dominant trabecular paths into the cortex of the calcaneus, as measured in a cadaver or predicted by the foot model, yielded that trabecular architecture of the human calcaneus conforms quite well to the isostatic stress flow (with a maximal difference of 12 to 13° for the secondary groups). This indicates that the stress flow during standing is a predominant factor shaping the sagittal trabecular microarchitecture in the calcaneus.

During the heel-strike stage of gait, the calcaneus is subjected to repetitive stress waves [26,27]. At the time of ground-contact, about 80 kPa of compression stress are transmitted to the fat layer padding the calcaneus [27], resulting in focal stresses of ~1 MPa on its plantar-posterior cortex [26], which are higher by an order of magnitude than corresponding stresses during standing. Achilles tendon loads are also substantially higher during walking or running (4–7 times body-weight, [28]) compared with standing (~0.25 body-weight, [17]). In spite of these differences, we found that the isostatics of the standing posture can predict the true trabecular architecture with a reasonable accuracy. This can be attributed to studies of the calcaneus indicating that the profound difference between static and dynamic loading states in the fully supported foot is the intensity of calcaneal stresses, rather than major changes in the pattern of spatial distribution and directions of flow of stresses. Hence, cancellous regions of the calcaneus subjected to elevated stresses while standing are subjected to even greater stresses during the midstance and early push-off stages of gait, but the overall pattern of highly loaded versus less loaded bone
sites is similar (see Refs. [17] and [26] for static and dynamic stress analyses of the foot, respectively).

The major differences in real versus model-predicted trabecular alignments were found at the secondary patterns, which are associated with stresses in linked soft connective tissues. Accordingly, it is expected that individual mechanical characteristics of these connective tissues (e.g. their material behavior, the size of their insertion surfaces and the quality of attachments into the calcaneus) will have considerable effects on the corresponding trabecular shapes. Our representative model of the foot, built to simulate stress transfer in the normal, healthy skeleton, could not account for changes in trabecular paths that are associated with age-related degenerative changes in the interlinking soft tissues, as could have occurred in the calcaneal specimens taken from the elderly donor. Accordingly, we conducted a sensitivity analysis to study the extent of change in model predictions in response to variation in soft tissue material properties. This analysis showed that predictions of trabecular path alignments, at their insertion to the cortex, may vary by up to 5° while stiffness of each soft tissue component is decreased from 1.5 to 0.5 times its neutral stiffness (defined in the Materials and methods section). Alterations in cartilage stiffness were shown to have the most profound effect.

Fig. 7. Comparison of insertion angles of the real trabecular pattern and the computed isostatics: (a) principal compressive group; (b) principal tensile group; (c) secondary compressive group; (d) secondary tensile group. The approximate locations of relevant surfaces of insertion of the trabecular paths into the cortex are marked on the top left image. In order to allow comparative plotting, the curved geometries of these surfaces in the cadaveric and model cross-sections were deployed over a straight line, scaled to range from normalized coordinates “0” to “1”. An increase in the relative position on such normalized linear course reflects tracking the contour of a corresponding partition Si in the “clockwise” direction (as shown on the top left diagram).
on the isostatic stress flow, and this can be explained by the direct influence of these changes on the overall joint stiffness, and thus, on the load bearing performances.

Limitations of the present approach for testing Wolff's law are due to a few simplifying assumptions that were required for constructing the foot model. First, the set of plane stress solutions that was used to simplify the problem cannot fully represent the three-dimensional complexity of the real calcaneus. Second, there may also be some difference along the medio-lateral direction in the planes of analysis determined for the cadaveric calcaneus and FE model, because the cadaveric specimen was cut along a true sagittal plane, while the MRI-based FE analysis was obtained for a plane in the direction of the second ray of the foot (P₂) which is close to the sagittal plane but does not necessarily overlap with it. Third, predictions of alignment of the isostatics in the calcaneus are derived for a single musculoskeletal loading case, i.e. quiet standing, but comparison is made to real trabecular paths. Several studies have shown that for the proximal femur, a single loading case cannot predict the trabecular structure accurately, and models incorporating multiple-load dynamic conditions (e.g. representing averaged daily activity) provide better prediction of the trabecular orientation [6,29,30]. Although this may explain, in part, the small discrepancies between the present numerical predictions and the actual trabecular paths (Figs. 6 and 7), it is shown that the loading conditions during standing are still representative for calculating the trabecular orientation in the calcaneus.

Fig. 7 (continued)
Wolff believed that trabecular paths should cross at right angles because the principal stresses must cross at right angles [1]. In fact, Wolff was so deeply convinced of this effect that he severely criticized the anatomical drawings of the trabecular architecture published at his time by von Meyer (1867) [31] for not applying the “observation” that trabecular paths must be perpendicular in order to correspond to the principal stresses. Accumulation of experimental evidence indicates that trabeculae do not necessarily align at right angles [32] and this can be attributed to the complex dynamic loading of bone (as opposed to static loading applied in models) as well as to factors other than the mechanical loads, which may affect trabecular orientation. Since recognizable differences were found herein between the isostatic stress flow (which must cross at right angles) and the real trabecular paths of the calcaneus, this study concur the von Meyer’s observations rather than Wolff’s assumption.

In closure, the present characterization of the trabecular architecture is a key for understanding fracture mechanisms of the calcaneus and for identifying fracture-sensitive internal surfaces [21]. The proposed method of study of the trabecular architecture can be applied in other situations, to explore the manifestation of Wolff’s law in different load-bearing structures of the skeleton. It can also be used to test hypotheses regarding abnormal alterations in the alignment of trabeculae and composition of trabecular bone, as a result of disorders or pathologies affecting the stress flow in the skeleton. This can make the present computational approach an effective biomechanical tool for characterizing the critical factors in normal and abnormal functional adaptation of trabecular bone.

Acknowledgements

This study was supported by the “Ela Kodesz Institute for Medical Engineering and Physical Sciences”, by the “Dan David Foundation” and by the Internal Fund of Tel Aviv University, Israel.

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[29] Acknowledgements

This study was supported by the “Ela Kodesz Institute for Medical Engineering and Physical Sciences”, by the “Dan David Foundation” and by the Internal Fund of Tel Aviv University, Israel.

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