Adaptive Bone Remodeling to Capture the Trabecular Bone Morphology of the Proximal Femur
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Abstract
Bone is a living tissue which changes continuously. Wolff (1982-1986) proposed a law which asserts that every change in the internal structure of bone is in response to external loads. Many researchers have investigated Wolff's law. However, most of them either have considered the trabecular bone as a continuous material while it actually consists of a porous structure made of rods and plates, or cost a huge amount of time for computational calculations.

In this study we have developed a model of femur which resembles bone natural structure. The model initially consists of a solid shell representing cortical bone and a network of cubic interconnected rods with circular cross-sections as trabecular bone. A code has been developed which iteratively changes the structure of trabecular bone by keeping the local stress in the structure in a defined boundary. The stress is controlled by adding and removing structural elements. Two load cases have been used, walking and stair climbing.

Converged results are comparable with natural morphology of femur and also volume fraction of critical regions of converged results have a good agreement with natural properties of bone.

Background
Since Wolff (1982-1986) proposed his well-known law of bone remodeling, many researchers have investigated Wolff's law and have tried to refine it. During the past years computational methods and finite element models have been used widely. The first use of FE models in bone remodeling goes back to 1972 [1]. Since then many investigations have been done by others on two-dimensional (2D) models of femur [2]. Bone adaptation has also been investigated in three-dimensional (3D) models [3]. In all of the adaptation models there is a stimulus which triggers the start of the bone adaptation process which changes the structure of the bone. Mechanical stimuli such as strain, strain energy density and stress have been proposed. The effect of mechanical forces on maintenance and adaptation of trabecular bone has been investigated [4].

Methodology
Model: The cortical bone is considered solid and the trabecular bone is made up of a network of interconnected rods. As the majority of the loads exerted on femur are in the vertical direction (hip joint load) and as a result, trabecular plates are mainly directed vertically, in this study a cubic structure has been used as trabecular bone to be able to capture natural orientation of trabecular plates. Rods have a mean circular cross-section of 0.1 mm radius initially. Modulus of elasticity and Poisson's ratio for both cortical and trabecular bone are considered 6.17 GPa and ν = 0.3.

Loads: We have used the previously developed load profiles for walking and stair climbing [5].

Remodeling Method: For the remodeling process we have developed a code using ANSYS Parametric Design Language (APDL). Our remodeling program works as illustrated in the following graph. The main goal of the program is to keep the stress in rods (e) of the trabecular bone structure in a defined boundary. It should be noted that created surface will have the thickness of mean diameter of its edges.

Results
In the following figure the initial distribution of stresses in the trabecular bone architecture which initially contains rods only is shown under (a) walking and (b) stair climbing load.

Homminger, J., et al. (2002) [6] used a combination of compression testing and microfinite element analysis to calculate mechanical properties of the cancellous bone of the femur at the order of 10³ mm. They reported a yield stress of 6.7±2.7 MPa. In the following figure the upper bound (σ_u) is set to 10 MPa which is based on the reported yield stress. Lower bound is set to 1.5 MPa which is arbitrarily selected based on the acceptability of the converged structure. Note that in these figures only trabecular bone structure which has been under the adaptation process is shown.

There are four groups of loads namely, principal compressive, principal tensile, secondary compressive and secondary compressive in the internal structure of femur which shape the architecture of femur’s trabecular bone. Also there is a triangular region known as Ward's triangle which has the least density. These patterns are also displayed in the following figure for comparison purpose.

Conclusion
In this study two load cases were compared and it is displayed that how higher magnitude of loads imposed by abductors attached to greater trochanter in stair climbing can result in higher densities in center and even in the neck of femur where femur is prone to fractures. This method can also conveniently be used with different load cases. With available data of muscle loads for different exercises, it can be investigated that what kind of exercises can increase bone's strength in a specific region.

References

Figure: From left to right: Initial Model, Model under walking load, Model under stair climbing load

Figure: Stress boundary conditions from left to right: [15, 80], [15, 120], [20, 100], [30, 100] MPa

Table: Values of stress boundary conditions in MPa

<table>
<thead>
<tr>
<th>Region</th>
<th>Stress Boundary Conditions (MPa)</th>
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<tbody>
<tr>
<td>Head</td>
<td>0.465 ± 0.04 0.293 ± 0.06 0.325 ± 0.02</td>
</tr>
<tr>
<td>Trochanter</td>
<td>0.172 ± 0.006 0.20 ± 0.03 0.253 ± 0.015</td>
</tr>
<tr>
<td>Neck</td>
<td>0.128 ± 0.006 0.15 ± 0.02 0.225 ± 0.015</td>
</tr>
<tr>
<td>Trochanter Ratio</td>
<td>3.12 2.9 3.0</td>
</tr>
<tr>
<td>Neck/Trochanter Ratio</td>
<td>0.71 0.68 0.60 0.75</td>
</tr>
</tbody>
</table>

In the following figure results for different boundary conditions is displayed. All of the cases are under walking loading condition.