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Computational evaluation of different numerical tools for the prediction of proximal femur loads from bone morphology

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ABSTRACT

Patient-specific modeling is becoming increasingly important. One of the most challenging difficulties in creating patient-specific models is the determination of the specific load that the bone is really supporting. Real information relating to specific patients, such as bone geometry and bone density distribution, can be used to determine these loads. The main goal of this study is to theoretically estimate patient-specific loads from bone geometry and density measurements, comparing different mathematical techniques: linear regression, artificial neural networks with individual or multiple outputs and support vector machines. This methodology has been applied to 2D/3D finite element models of a proximal femur with different results. Linear regression and artificial neural networks demonstrated a good load prediction with relative error less than 2%. However, the support vector machine technique predicted higher relative errors. Using artificial neural networks with multiple outputs we obtained a high degree of accuracy in the prediction of the load conditions that produce a known bone density distribution. Therefore, it is shown that the proposed method is capable of predicting the loading that induces a specific bone density distribution.

1. Introduction

Bone tissue undergoes permanent changes in response to different signals such as external loads, hormonal influence, nutrition, etc. This process of microstructural change is normally known in the literature as bone remodeling, where the change in the distribution of the material properties is considered. Wolff [1] was a pioneer in studying the relationship between bone structure and applied loads. Many theories and mathematical models have been developed to analyze the evolution of bone microstructure and its mechanical properties depending on a certain loading pattern [2–6]. Previous bone remodeling models have normally been implemented in finite element (FE) models, and these have proved to be very useful tools for predicting the response of bone after prosthesis implantation [4,7–12]. However, these models have been developed for general purposes. Nowadays, the development of patient-specific models is becoming increasingly important [13]. This importance lies in determining the specific loads that have caused the patient's bone density distribution in order to use these loads in the design of a patient-specific treatment. This problem, formulated in such a way, represents an inverse approach to the common bone remodeling analysis as is usually described in the literature, in which the apparent density distribution is estimated by fixing the loads.

This inverse problem has been previously solved by various authors using different numerical approaches. In fact, Fischer et al. [14] developed an optimization procedure that adjusted the magnitude of each basic load to achieve the desired

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bone density. This approach was applied to the proximal femur in 2D for determining the loads using QCT data [15,16]. Later, the approach was applied to the forearm [17] and to the femur for different animals [18]. Bona et al. [19] proposed a contact algorithm for density-based load estimation and used the method to distinguish between different modes of locomotion of animals. More recently, Christen et al. [10] also developed a bone loading estimation algorithm to predict loading conditions by means of calculating the loading history that produces the most uniform strain energy density on the bone tissue. These previous approaches were based on iterative load prediction techniques which involved significant computational cost. However, there are other numerical strategies that require less computational time. Indeed, many researchers have been trying to solve different inverse problems in biomechanics by developing controllers which employ intelligent computing methods such as artificial neural networks (ANN), neural-fuzzy (NF) networks, support vector regression (SVR), genetic algorithms or wavelet networks [20–24]. Hambli's studies [25–27] used a multiscale methodology for bone remodeling simulation using coupled finite element and ANN analysis. Nevertheless, Campoli et al. [28] were the first to use the ANN approach for femur load prediction from the bone density distribution. They combined a wavelet decomposition technique with an artificial neuronal network for estimating the loading parameters of the femur. Although their results are very promising, they can be improved by analyzing the effect of each variable on the ANN performance. Zadpoor et al. [29] also used ANN for prediction of tissue adaptation loads from a given density distribution of trabecular bone in a 2D example.

Therefore, the main goal of this work is to present a general methodology in order to accurately solve the inverse bone remodeling problem. For this purpose, we propose two precise objectives: to develop, evaluate and compare three existing numerical approaches to estimate the musculoskeletal loads in the femur and to optimize the procedure of the ANN performance. The methodology has been initially applied to a theoretical 2D model. The musculoskeletal loads have resulted from a certain measured density distribution using a bone remodeling theory. Thus, this work focuses on two different machine learning techniques (MLT): multilayer percepton (MLP) as a representation of the artificial neural networks (ANN) [30] and support vector machines (SVM) [31], comparing their results with a classical technique: linear regression (LR). Linear regression is a statistical technique. MultiLayer Perceptron (MLP), or ANN, is a feed-forward network characterized by its layered structure where each layer consists of a set of perceptron neurons and its training algorithm. Finally, support vector machines (SVM) are a set of supervised learning algorithms. These techniques have been previously used by researchers to solve different classification and regression engineering problems [32–35] and they are beneficial even if the numerical analysis is time consuming or unfeasible. In the proposed methodology, the machine learning techniques and linear regression have been applied to predict the likely loading supported by a proximal femur. From the optimization procedure developed for the ANN, the most adequate ANN methodology has been finally extrapolated to a 3D FE model of a real proximal femur.

2. Materials and methods

We propose a hybrid methodology based on solving two problems and comparing their solutions: the bone remodeling problem (Section 2.1) and the inverse bone remodeling problem (Section 2.2) (Fig. 1).

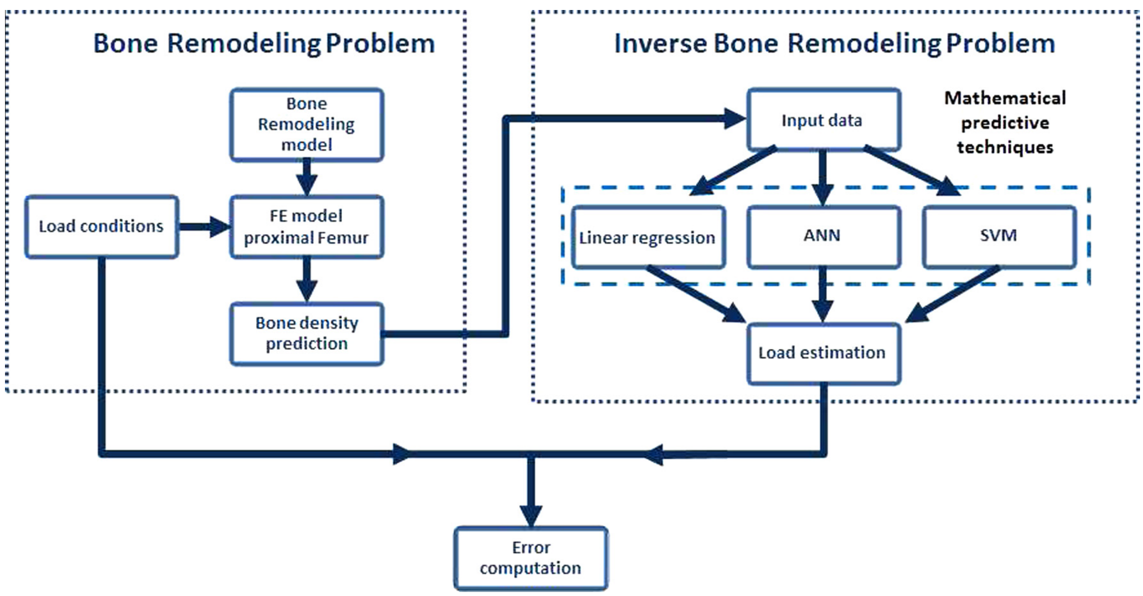

Fig. 1. Schematic diagram of the computational approach.