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Research Paper

Subject-specific musculoskeletal loading of the tibia: Computational load estimation

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ABSTRACT

The systematic development of subject-specific computer models for the analysis of personalized treatments is currently a reality. In fact, many advances have recently been developed for creating virtual finite element-based models. These models accurately recreate subject-specific geometries and material properties from recent techniques based on quantitative image analysis. However, to determine the subject-specific forces, we need a full gait analysis, typically in combination with an inverse dynamics simulation study. In this work, we aim to determine the subject-specific forces from the computer tomography images used to evaluate bone density. In fact, we propose a methodology that combines these images with bone remodelling simulations and artificial neural networks. To test the capability of this novel technique, we quantify the personalized forces for five subject-specific tibias using our technique and a gait analysis. We compare both results, finding that similar vertical loads are estimated by both methods and that the dominant part of the load can be reliably computed. Therefore, we can conclude that the numerical-based technique proposed in this work has great potential for estimating the main forces that define the mechanical behaviour of subject-specific bone.

1. Introduction

Subject-specific models are becoming increasingly important because of the clinical demands of patient-centred treatments. Advancements in different current technologies including computed tomography (CT), magnetic resonance imaging (MRI), and gait analysis have enabled the creation of more realistic subject-specific computational-based bone models (Lekadir

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et al., 2015). Subject-specific modelling often starts with previously acquired images that can provide information regarding the geometry and density distribution of the individual bone properties. However, direct subject-specific estimation of bone loads through in vivo imaging remains challenging (Zadpoor and Weinans, 2015).

The combination of subject-specific joint and muscle force-based models with consistent bone geometry into finite element-based (FE) models could be a very important advancement for creating subject-specific models that allow for predictive analyses of personalized treatments. Vahdati et al. (2014) combined gait analysis and a subject-specific musculoskeletal model with subject-specific bone geometry in a computational bone remodelling methodology for predicting bone density distribution. The results confirmed that the predicted bone density distribution in the proximal femur was drastically influenced by the inclusion of subject-specific loading conditions. González-Carbonell et al. (2015) used the subject-specific geometry and material properties to study the tibial torsion using CT. Additionally, Carey et al. (2014) created subject-specific FE models of the tibiofemoral joint using dynamic stereo-radiography data and kinematic analysis. Although these aforementioned models provided full information on bone mechanical properties, several difficulties could arise before their methods can be applied clinically due to the amount of initial information required.

Moreover, musculoskeletal models have been useful tools for virtual orthopedic surgery. Inverse dynamics techniques were used in gait analysis to calculate the net joint torques that the musculoskeletal system produces during human locomotion (Liu et al., 2009; Favre et al., 2012). In recent decades, multiple methods have been developed to improve the performance of subject-specific models (Fluit et al., 2012, 2014). Carbone et al. (2012) showed errors in the estimated position of muscle attachment sites that affected muscle force predictions. Subsequently, Carbone et al. (2015) combined morphing of bone surfaces with muscle volumes and functional optimization of muscle-tendon architecture to create a musculoskeletal geometry dataset. This part was linked with muscle-tendon attachment sites and lines-of-action (Pellikaan et al., 2014), or muscle volumes (Carbone et al., 2012), showing that subject-specific models resulted in more reliable outcomes, whereas conventional anthropometric scaling laws were inadequate and provided less realistic muscle activity predictions. These complex models were, however, troublesome with regard to their immediate application to patients.

For most of these methodologies, it is not easy to prove the clinical benefits due to the complex process involved and their large computational cost. In addition, estimating musculoskeletal loads requires information about the movements of the individual patient. Note that it is very difficult to measure loads in vivo using non-invasive procedures.

Several studies have attempted to estimate loads by solving the inverse bone remodelling problem using different numerical approaches. In fact, Fischer et al. (1995) developed an optimization procedure that adjusted the magnitude of each basic load in 2D to achieve the desired bone density. Bona et al. (2006) proposed a contact algorithm for density-based load estimation and used a method to distinguish between different modes of locomotion of animals. More recently, Christen et al. (2012) developed a bone loading estimation algorithm to predict loading conditions through calculating the loading history that produces the most uniform strain energy density on the bone tissue. Campoli et al. (2012) were the first to use the artificial neural network (ANN) approach to predict femur loads from the bone density distribution. These authors combined a wavelet decomposition technique with an ANN to estimate the loading parameters of the femur. Zadpoor et al. (2013) also used ANN to predict tissue adaptation loads from a given density distribution of trabecular bone in a 2D example of the femur. Garijo et al. (2014b) presented a numerical methodology in which the specific load that the bone was actually supporting was predicted through different mathematical techniques by utilizing the bone density distribution obtained from bone remodelling simulations. They used a single femur, and they theoretically predicted the loading conditions that induced a virtual bone density distribution with good accuracy using ANN.

However, in this work we present a general computational-based methodology to determine the forces that a subject-specific tibia is supporting from the CT images of this specific patient. For this purpose, we used five subject-specific tibias, from which knowing their bone geometry and density distribution, we will predict their specific loading conditions. Finally, to quantitatively validate the predictive capacity of this novel methodology, we will compare these forces with those obtained for each subject from an individual-based gait analysis and subsequent musculoskeletal force prediction.

2. Materials and methods

To determine subject-specific loads acting on the tibia, a computational-based approach was developed, which combined different numerical tools widely used in bone image analysis and bone mechanics. Thus, we first describe this computational approach to determine the subject-specific forces. Next, we present the method used to validate this novel methodology. Finally, we present the final subject-specific cases that were studied.

2.1. *Computational-based methodology for estimating subject-specific loads*

To apply this methodology (see Fig. 1), we required the subject-specific bone geometry and its bone apparent density, which can be obtained from individual CT data (Hounsfield Units – HU) (Section 2.3.2) through current standard image analysis (Bitsakos et al., 2005). Therefore, from this analysis, we were able to construct a subject-specific FE model that replicated the main characteristics of the bone: its geometry and heterogeneous material properties (Fig. 1 – left). This FE model was used for intensive bone remodelling simulations (Doblaré and García, 2001) (see Appendix A) with multiple different load cases that come from inter- and intra-subject variability (Motion data – Fig. 1 – right). The knee joint force was assumed to define the bone density distribution (Fx, Fy and Fz). From the multiple bone remodelling simulations, we obtained different apparent density patterns for each load condition. Then, we selected the apparent density and volume at different regions of interest (ROIs) (Appendix B)