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Subject-specific modeling of the scapula bone tissue adaptation

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ABSTRACT

Adaptation of the scapula bone tissue to mechanical loading is simulated in the current study using a subject-specific three-dimensional finite element model of an intact cadaveric scapula. The loads experienced by the scapula during different types of movements are determined using a subject-specific large-scale musculoskeletal model of the shoulder joint. The obtained density distributions are compared with the CT-measured density distribution of the same scapula. Furthermore, it is assumed that the CT-measured density distribution can be estimated as a weighted linear combination of the density distributions calculated for different loads experienced during daily life. An optimization algorithm is used to determine the weighting factors of fourteen different loads such that the difference between the weighted linear combination of the calculated density distributions and the CT-measured density is minimal. It is shown that the weighted linear combination of the calculated densities matches the CT-measured density distribution better than every one of the density distributions calculated for individual movements. The weighting factors of nine out of fourteen loads were estimated to be zero or very close to zero. The five loads that had larger weighting factors were associated with either one of the following categories: (1) small-load small-angle abduction or flexion movements that occur frequently during our daily lives or (2) large-load large-angle abduction or flexion movements that occur infrequently during our daily lives.

1. Introduction

The morphology of bone tissue is partially determined by the mechanical loads it experiences during daily activities (Frost, 1988; Ruff et al., 2006; Turner, 1998). Using adaptation theories (Carter et al., 1987; Cowin and Hegedus, 1976; Huiskes et al., 1987), one could theoretically connect the musculoskeletal loads caused by daily activities to the measured morphology of bone tissue. However, there are two major difficulties in establishing this connection. First, there is no easy way for non-invasive measurement of musculoskeletal loads. Second, bones are loaded differently in the various movements that we carry out in our daily living, and it is not clear how every movement contributes to the measured morphology of bone. These two difficulties exist in the study of both lower- and upper-extremity bones. For example, many researchers have studied bone tissue adaptation of lower extremity bones in both physiological (Campoli et al., 2012; Turner et al., 2005; Weinans et al., 1992; Weinans and Prendergast, 1996) and post-operative conditions (Bernd-Arno et al., 2009; Huiskes et al., 1987; Lengsfeld et al., 2002). The adaptation of the trabecular bone is also extensively studied (Biewener et al., 1996; Jang and Kim, 2008; Shefelbine et al., 2005; Tanck et al., 2006; Tsubota et al., 2009). However, the two above-mentioned difficulties have not been addressed before. In most cases, researchers have simply assumed generic and highly simplified loading conditions. As for upper-extremity bones, even studies that use generic and simplified loading conditions are rare. Indeed, no numerical model of glenoid bone remodeling was available until recently (Sharma et al., 2009, 2010; Sharma and Robertson, 2013).

In this study, we present a methodology for establishing the connection between the movements of daily living and the morphology of the scapula and overcoming both above-mentioned difficulties. Once the above-mentioned difficulties are overcome, we could study the effects of individual movements on bone tissue adaptation and separate the effects of different movements from each other. Scapula was used for this study, because distinguishing between different movements is easier in the scapula. That is due to the fact that upper-extremity loading is more varied as compared to the lower-extremity loading that is dominated by gait. Even though currently available models (Sharma and Robertson, 2013) could predict the density distribution of the scapula quite accurately, they do not differentiate between the effects of different types of movements on bone tissue adaptation.

We use a validated (Nikooyan et al., 2008, 2010) large-scale musculoskeletal model of the shoulder and elbow, namely the Delft

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Shoulder and Elbow Model (DSEM) (van der Helm, 1994a,b; van der Helm and Pronk, 1995; van der Helm and Veenbaas, 1991). For every movement, this model can provide accurate prediction of detailed musculoskeletal loads including joint reaction and muscle forces and their point of application.

In order to overcome the second obstacle, we propose to use an optimization procedure for linking the loads estimated by the musculoskeletal model and their resulting density distributions to the density distribution measured using computed tomography (CT). In this scheme, the CT-measured density distribution is assumed to be explained by a weighted linear combination of the density distributions caused by a number of movements. The optimization process finds the weighting factors of different movements such that the difference between weighted linear summation of the predicted density distributions and the CT-measured density distribution is minimal. The proposed methodology is used for relating the measured density distribution of a scapula to the musculoskeletal loads estimated for the different movements of the same individual using the musculoskeletal model.

2. Materials and methods

2.1. Computed tomography

One cadaveric scapula of a male donor (57 years) was CT-scanned using a clinical scanner (Siemens, SOMATOM® Definition Flash, construction diameter: 230 mm)

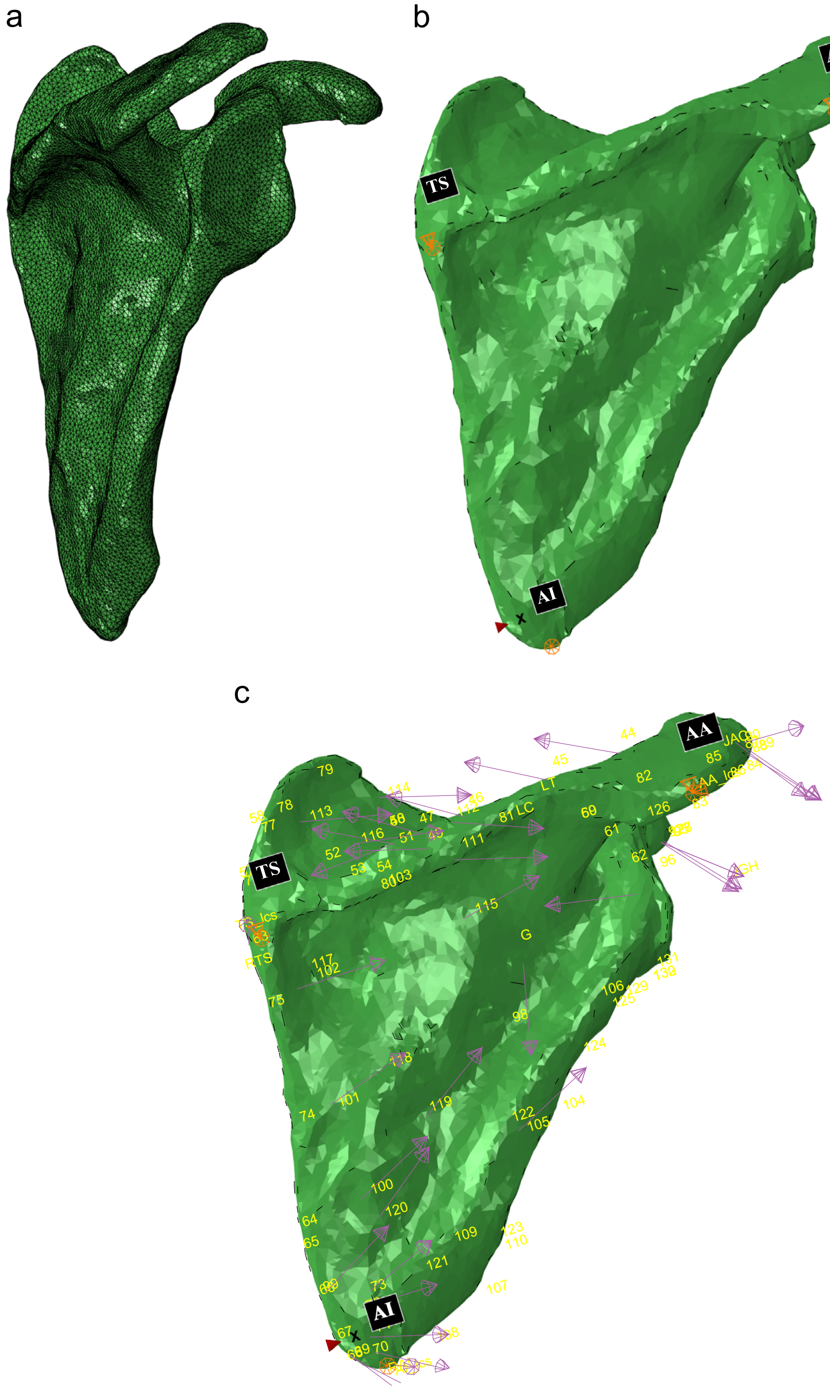

Fig. 1. The FE mesh used in simulations (a), bony landmarks and boundary conditions (b) as well as an example of applied joint and muscle loads (c). The inferior–superior and anterior–superior distances of the glenoid fossa, see von Schroeder et al. (2001), were respectively 34 and 27 mm.