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Sensitivity study of the morphometric fitting on the pressure field inside ankle joints

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ABSTRACT

The increasing importance of human joints study as complex mechanical systems involves medical data processing, system fluid dynamic modelling and the establishing of reliable boundary conditions. Understanding the dynamical behaviour of joints is crucial to face prosthesis design and the associated research. This process is presented in a case study of the human ankle joint. From a proper medical image segmentation, bone surfaces are 2D-modelled as constant curvature surfaces (circles) under different criteria. The fluid dynamic problem is solved under different boundary conditions. Finally, the pressure field is obtained inside the joint and the sensitivity of the system with respect to the fitting methodology is consequently analyzed. Concluding remarks outline the findings for practical use in system study.

1. Introduction

Both the prevalence of osteoarthritis and the reconstruction of Articular Cartilage Layers (ACLs) have lead to early Total Ankle Arthroplasty (TAA), so the challenge to develop realistic natural ankle model is receiving a lot of attention. The success of all kinds of human joint arthroplasty depends not only on the knowledge of the dynamic behaviour but also on available information of the relevant bones morphology. Although several studies of other human joints are reported in the literature, studies centred on the morphology of the bones building the ankle or talo-crural joint are scarce. Only a few works deal with ankle joint geometrical measurements [1–3]. The ankle joint may be modelled as bearing from an engineering point of view [4] where the tibia and fibula form the mortise (socket) into which the talus fits thus forming the hinge joint. Both surfaces are covered with cartilage layers. This is a white connective tissue and its thickness varies from 1 to 6 mm in lower extremity joints, including the hip, knee, and ankle joints. Normal healthy synovial fluid (SF) is highly non-Newtonian but in osteoarthritis its viscosity becomes reduced particularly at the low shear rates [5,6]. In the last years a large number of concepts and theories of natural synovial joint lubrication have been proposed. These have included a wide range of lubrication concepts, for example hydrodynamic, boundary and mixed-regime. Therefore, the understanding of the influence of the geometric configuration in the joint behaviour is important to study the ankle joint behaviour as a mechanical system which stands the external load (human body weight) under a hydrodynamic regime of lubrication in the synovial capsule during the first moments of the gait cycle [7–9]. We present the data processing chain under different methodology and system simulation results.

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2. Materials and methods

The human ankle joint can be considered a cylindrical surface [10] at a first level approach. The coupling model is defined by two infinite rigid circular cylinders (subchondral bone) in a cylindrical cavity covered with a thin layer (articular cartilage) of uniform thickness. In the sagittal plane the upper articular surface S_l (talar) is supposed to be stationary while the lower surface S_u (tibial) is assumed to have pure squeeze motion $\dot{e}(t)$, where e is the eccentricity or offset of the curvature centres. Between the upper and the lower articular surface there is a SF film [7,8] (Fig. 1).

In order to obtain a model for the biomechanical behaviour of lubricated contact in the ankle joint, in this study we describe the morphometry of the contact between the tibial mortise S_u and trochlea tali S_l (Fig. 2) through the digitalization of the articular surfaces.

The measurement of the radii of curvature of the surfaces R_m and R_t (Figs. 1 and 2), and the relative position of the centres (Table 1), will be carried out based on the image of the ankle sagittal anatomic section of a corpse taken with a high resolution technique colour cryosection [11] (Fig. 3).

A proper use of image processing segmentation and edge detection [12] allows identifying the coordinates of the pixels which define the edge of the upper (tibia) and lower (tali trochlea) surfaces of the joint. In order to calculate the circles (Fig. 2) that best fit the pixels that define the edge of each surface two algorithms are used: least square and minimum zone. The least-squares algorithm is retrieved from [13], and our own minimum zone tolerance algorithm has been developed based on the polarity transformation of the circle [14]. Once the centre and radii of the circles are established, the eccentricity and radial clearance can be calculated. These boundary conditions are imposed onto the system of equations that govern the fluid dynamic problem [7]. The study's pursuit is quantitative evaluation of the sensitivity in the pressure field and in the fluid film thickness with respect to the geometric boundaries of the joint determined by different methods.

2.1. Image processing and edge detection

The algorithm has been implemented in MatLab R2007b along with the efficient library for image analysis, Image Processing Toolbox. The original RGB image (Fig. 3) is treated as a matrix of points (pixels), where each matrix element is identified by its position (coordinates i, j) and it contains the colour intensity RGB of the pixel. For segmentation purposes the image was converted to a greyscale image, and a median filter to remove impulse noise was used [15]. The image was then

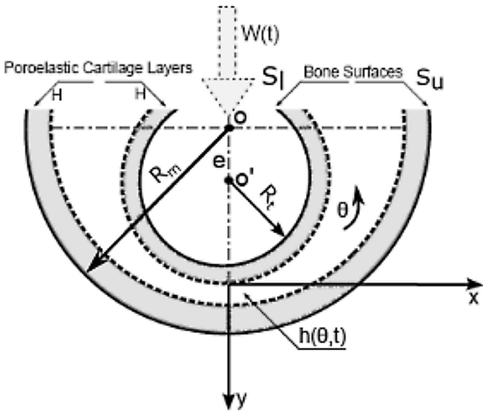

Fig. 1. Human ankle joint equivalent bearing.

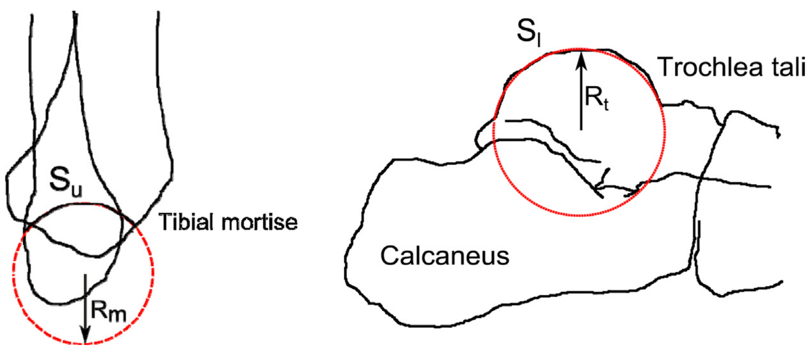

Fig. 2. Schematic view of the morphometry of the contact between the tibial mortise and trochlea tali.