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Femur shape prediction by multiple regression based on quadric surface fitting

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ABSTRACT

Quadric surface fitting of joint surface areas is often performed to allow further processing of joint component size, location and orientation (pose), or even to determine soft tissue wrapping by collision detection and muscle moment arm evaluation. This study aimed to determine, for the femoral bone, if the position of its morphological joint centers and the shape morphology could be approximated using regression methods with satisfactory accuracy from a limited amount of palpable anatomical landmarks found on the femoral bone surface. The main aim of this paper is the description of the pipeline allowing on one hand the data collection and database storage of femoral bone characteristics, and on the other hand the determination of regression relationships from the available database. The femoral bone components analyzed in this study included the diaphysis, all joint surfaces (shape, location and orientation of the head, condyles and femoro-patellar surface) and their respective spatial relationships (e.g., cervico-diaphyseal angle, cervico-bicondylar angle, intercondylar angle, etc.). A total of 36 morphological characteristics are presented and can be estimated by regression method in in-vivo applications from the spatial location of 3 anatomical landmarks (lateral epicondyle, medial epicondyle and greater trochanter) located on the individual under investigation. The method does not require any a-priori knowledge on the functional aspect of the joint. In-vivo and in-vitro validations have been performed using data collected from medical imaging by virtual palpation and data collected directly on a volunteer using manual palpation through soft tissue. The prediction accuracy for most of the 36 femoral characteristics determined from virtual palpation was satisfactory, mean (SD) distance and orientation errors were 2.7(2.5) mm and 6.8(2.7)°, respectively. Manual palpation data allowed good accuracy for most femoral features, mean (SD) distance and orientation errors were 4.5(5.2) mm and 7.5(5.3)°, respectively. Only the in-vivo location estimation of the femoral head was worse (position error=23.2 mm). In conclusion, results seem to show that the method allows in-vivo femoral joint shape prediction and could be used for further development (e.g., surface collision, muscle wrapping, muscle moment arm estimation, joint surface dimensions, etc.) in gait analysis-related applications.

1. Introduction

Bone shape is of interest for a variety of biomechanical applications. Soft tissue wrapping and joint contact problems based on bone shape analysis help predict muscle moment arms and forces as well as joint reaction forces (Charlton and Johnson, 2001; Gatti and Hughes, 2009; Vasavada et al., 2008). Quadric surface (QS) fitting methods for human (Matsuura et al., 2010; Xi et al., 2003) and animal (Ogihara et al., 2010) studies allowed parameterization of joint surface morphologies. When three-dimensional (3D) meshed bone surfaces are available, the problem of surface collision can be solved directly with advanced computer graphic techniques (Ericson, 2005). Accurate vertex fitting by QS (Levy, 1995) not only solves the surface collision problem, but also enables the derivation of bone morphological characteristics such as joint center and shape approximation (e.g. diaphysis bending and twisting for longitudinal bones). QS fitting has previously been widely used in biomechanics (Charlton and Johnson, 2001; Gatti and Hughes, 2009; Gu et al., 2008; Heistand et al., 2006; Lee and Guo, 2010; Vasavada et al., 2008), astronomy and metrology. A recent study used a heuristic method that automatically computes the proximal femur morphological parameters by processing the mesh surface (Cerveri et al., 2010).

A validated regression method has previously been presented, which enables the location of various characteristics (joint center location, joint dimensions and joint orientation) of all joint surfaces of the bones involved in the shoulder joint complex (Sholukha et al., 2009). Regression equations used palpable anatomical landmarks (ALs) and a large bone database to approximate joint characteristics,

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while no information about bone and joint shape and shape orientation was processed.

The spatial location of anatomical landmarks (ALs) is required to build and obtain regression equations. ALs are also required to define anatomical frames to represent movement data according to frame definition convention (Cappozzo et al., 2005). Most ALs can be located either by manual palpation through the skin or by virtual palpation on 3D models, or a combination of both (Van Sint Jan, 2007). Key ALs such as joint center (JC) positions are unfortunately not palpable directly but are required to meet standards necessary for data comparison and data exchange (Wu and Cavanagh, 1995; Wu et al., 2002; Wu et al., 2005). Functional methods are recognized to be the most accurate methods to locate JCs (Camomilla et al., 2006; De Momi et al., 2009; Lee and Guo, 2010; Lempereur et al., 2010; Siston and Delp, 2006; Stokdijk et al., 2000; Zhang et al., 2004). However, despite their usefulness they show some practical shortages. Indeed, they use particular motion patterns and seem satisfactory for ball-and-socket joints in normal conditions (Cappozzo, 1984; Leardini et al., 1999), but the same motion patterns are often too complex for patients showing a limited joint range (Di Silvestro et al., 2007). Morphological methods have previously used spatial AL locations to determine JCs by regression analysis (Barbaix et al., 2000; Bell et al., 1989; Bell et al., 1990; Meskers et al., 1997). Morphological methods seem more appropriate because the patient can remain at rest during the palpation. To allow reproducible JC construction, bony ALs must lie close to the skin surface to be relatively accessible to palpation and must also be readily identifiable by less experienced investigators. A strict guideline to ALs definition has been developed to improve ALs palpation reproducibility (Van Sint Jan, 2007). A recent study (Salvia et al., 2009) also reported that ALs manual palpation of the humerus, scapula and other region can be achieved with a satisfactory accuracy.

This study aimed to determine if the position of the morphological JCs and the shape morphology of the femoral bone could be approximated with satisfactory accuracy from a limited amount of palpable ALs found on the bone-of-interest itself. The research aimed to extend the paradigm from (Sholukha et al., 2009) to the femoral bone, augmented by QS fitting for shape and orientation prediction of various femoral bone components such as condyles, femoral shaft twisting and bending, neck orientation, head dimensions, etc. This study used detailed palpation definitions (Van Sint Jan, 2007) of skeletal ALs to increase palpation repeatability.

This paper presents a method to create a database of femoral morphological information, including, for each bone, surface data and spatial coordinates of manually palpable ALs. This database should allow the evaluation of multiple regression coefficients between the available ALs and various anatomical features characterized by particular dimensions, shape, location and orientation. The main goal of this paper is the description of the pipeline allowing storage of bone characteristics and the determination of regression relationships applicable for in-vivo femoral bone shape prediction. The adopted multiple regression approach is similar to that of Sholukha et al. (2009). In-vitro and in-vivo accuracy analysis was performed.

2. Material and methods

2.1. Data collection

Data were collected from medical imaging of 75 femoral (39 right and 36 left) bones available from the ULB bone repository (10 pairs of bones were from fresh-frozen donators, 2 pairs of bones from two volunteers who must undertake medical imaging for clinical purposes not related to bone disorders and the remaining were from dry bones). All bones were normal and did not show any signs of degenerative bone or joint disorders; volunteers did not complain of any joint problems. Three-dimensional reconstruction was performed by a senior anatomist to obtain accurate bone models of each bone (Van Sint Jan et al., 2002, 2006). Available models were then processed by virtual palpation to determine the spatial location of three particular ALs: lateral epicondyle (LE), medial epicondyle (ME) and greater trochanter (TC) (FLE, FME and FTC, respectively according to Van Sint Jan (2007)). Note that the above-palpated ALs are also readily palpable manually; this to ensure that the method can be used in an in-vivo setting. Virtual palpation was further used to set landmark clouds on each femoral joint surface. These landmark clouds were then used to identify the vertices of the surfaces-of-interest of the bone model and to estimate joint surface morphology using primitive geometrical shapes. Virtually palpated femoral joint surfaces include the head (H), the lateral and medial condyles, the lateral (PL) and medial (PM) aspects of the femoro-patellar joint and femoro-patellar sulcus (S) (Fig. 1).

Surface vertices related to specific anatomical areas were also selected on all models to divide each available bone model into 9 areas-of-interest (Fig. 1). Bone area splitting was performed using a semi-automated method based on a template to pre-process each bone available from the database. The template was a femoral bone, which had been manually divided by a senior anatomist into the 9 areas-of-interest and included the 3 above-mentioned ALs. The bone template was then transformed (Golub and Reinsch,1970) to each database bone by heterogeneous weighted scaling using the available ALs (see Appendix A, Annex A). Visual control allowed the above anatomist to validate the results and to perform manual corrections if required. The available data were then processed for data approximation as explained below.

2.2. Data approximation

QS data fitting was previously widely used, but mainly for specific bone areas (e.g., isolated condyles, femoral head shape and neck orientation; Cerveri et al., 2010; Lee et al., 2006; Saikia et al., 2008; Xi et al., 2003; Toogood et al., 2009). All bone surface related data (Fig. 1) before data fitting were converted in bone Local Coordinate System (LCS) according to Appendix A, Annex B.

2.2.1. Data convexity control

Landmarks set on the areas-of-interest were used to approximate joint surface by primitive shapes (e.g. planes and spheres). Each approximated primitive object should uniquely define a closed area corresponding to the 3D shape vertices and enclosing the available palpated landmarks. Surface vertices related to each specific area were also selected using the landmarks previously virtually palpated.

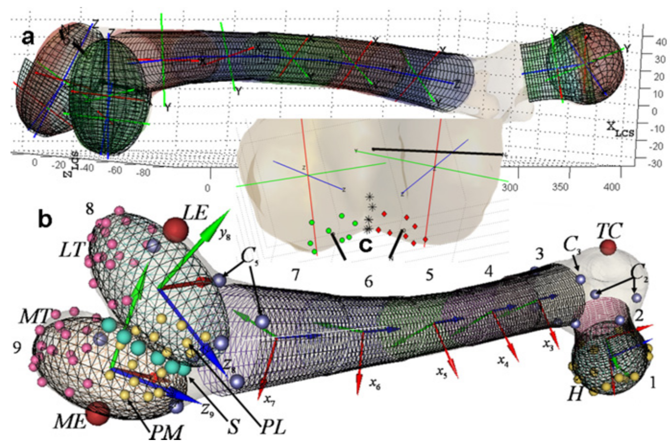

Fig. 1. Anatomical features digitized in this study (illustrated on the 3D models obtained from the femoral bone model used for the in-vivo validation study) and quadric surfaces from vertex fitting: (a) medio-inferior view, (b) latero-inferior view and (c) anterio-superior view on the femoro-patellar area. On (a) and (b), two condyles approximated by semi-ellipsoids are visible. On (c), two short black lines indicated the normals to the femoro-pattelar surfaces; circles and diamonds are markers palpated on the lateral and medial aspect of the joint; the femoro-patellar sulcus are indicated with star markers. Areas-of-interest fitted by QS are indexed: (1) femoral head, (2) femoral neck, (3–7) the five diaphysis segments, (8) lateral condyle and (9) the medial condyle. Each QS was oriented using an orthogonal frame (*XYZ*). The *Z*-axis for each of the 5 diaphysis segments was oriented along the femoral shaft; the origin of the corresponding frame was located at the middle *Z* point of the fitted primitive object. Large spheres indicated palpated AL location (TC, LE and ME). Spheres indicated by C are reference points used to determine cutting planes used for anatomical segment extraction (see text for explanations): H, PL and PM spheres—virtually palpated points of head and lateral; medial patellar aspects; LT and MT spheres—tibio-femoral joint area; S spheres—sulcus line.