AUTOMATIC PARAMETERIZATION OF THE DISTAL FEMUR BASED ON 3D SURFACE DATA: A NOVEL APPROACH FOR SYSTEMATIC MORPHOLOGICAL ANALYSIS AND OPTIMIZATION

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INTRODUCTION AND OBJECTIVES

For a proper functional restoration of the knee following knee arthroplasty, a comprehensive understanding of bony and soft tissue structures and their effects on biomechanics of the individual patient is essential. If the joint surface is altered due to arthritis, fracture or alloplastic knee surface replacement, knee biomechanics may be disturbed [Sharma2012, Delport2012]. Otherwise, if the ligamentous situation is not compatible to the bony geometry, the biomechanics of the knee joint will be altered as well, potentially resulting in increased joint forces and related wear [Daniel1994]. A systematic description of morphological knee joint parameters and a study of their effects on knee biomechanics could be beneficial for an optimal patient-specific implant design.

In literature, geometric primitives such as circles, ellipses, helixes and cardioids or more complex mathematical approximations have been used to describe the femoral geometry [Hiss1980, Biscevic2005, Heever2012]. However, most studies were used to examine a single parameter or to reconstruct the actual anatomy [Yamada2007, Varadarajan2011]. We developed a full parametric model for a comprehensive analysis of the distal femoral morphology also enabling a systematic parameter variation in the context of a patient specific multiparameter optimization of the knee implant shape.

MATERIALS AND METHODS

The computational framework was intended to be applicable to 3D surface models of the distal femur independent of the acquisition technique (CT, MRI, …). The framework was tested on 20 CT-models which originated from pathological right knees. The femora were segmented semi-automatically and exported in STL-format. The program and workflow was implemented in MATLAB (Fig 1).

At first, the 3D surface model was imported, visualized and 6 reference landmarks were manually defined by the user. Cutting planes through the distal femur were generated spanning from the most proximal end of the trochlear groove to the most proximal point on the femoral intercondylar notch. The cutting planes were rotated around the transepicondylar axis and ellipses were fitted in three prominent areas (medial/lateral condyle and trochlear groove) of the cutting contours based on the extrema of the contour. Thereby, the semi-major axis of the ellipses was forced to be parallel to the rotational axis. If the prominent areas could not be properly identified by the algorithm, the curvature of the contour was considered additionally. The portions between the ellipses were approximated by using a piecewise cubic hermite interpolation polynom such that a closed contour was obtained following the characteristics of the real bone model.

At this point the user could change the parameters of the ellipses (position and size) in order to manipulate the approximated contour or an automatic parameter optimization could be subject to higher-level biomechanical analyses, e.g. based on multi-body simulations or FEA optimization. However, in the framework of this study, the original parameters were not changed and a 3D surface was generated by using the lofting technique which provides the ability to create a continuous surface over a set of splines. Finally, the parameter model was exported in STL-format and compared against the original 3D surface model to evaluate the accuracy of the framework by using the software [CloudCompare2014].

RESULTS

The presented framework could be successfully applied for automatic parameterization of all 20 distal femur surface data-sets without any model-specific algorithmic or parametric adjustment. The mean global accuracy was 0.09±0.62 mm with optimal program settings which is better than the optimal resolution of the CT based data acquisition (Fig 2). The method was insensitive to the variation of the selected reference points. A variation of ±4 mm of the epicondyles in anterior/posterior and proximal/distal direction resulted in a mean deviation of 0.13±0.20 mm in comparison to the reference parameter model. A systematic variation of the femoral morphology could be proofed based on several examples such as the manipulation of the medial/lateral curvature in the frontal plane, contact width of the condyles, J-Curve and trochlear groove orientation.

DISCUSSION

Several authors have proposed different mathematical approximations to describe the femoral geometry [Yamada2007, Varadarajan2011]. However, most studies focused on single parameters or simply reconstructed the bony anatomy. Our objective was to develop a computational framework for an automatic and comprehensive parameterization of the articulating surface which can be used for systematic surface manipulations. The framework showed high accuracy and was robust against 20 pathological input data.

In our opinion, this novel approach might offer the opportunity to study the effect of femoral morphology on knee biomechanics in combination with validated biomechanical simulation models or experimental setups. New insights could directly be used for patient-specific implant design and optimization.

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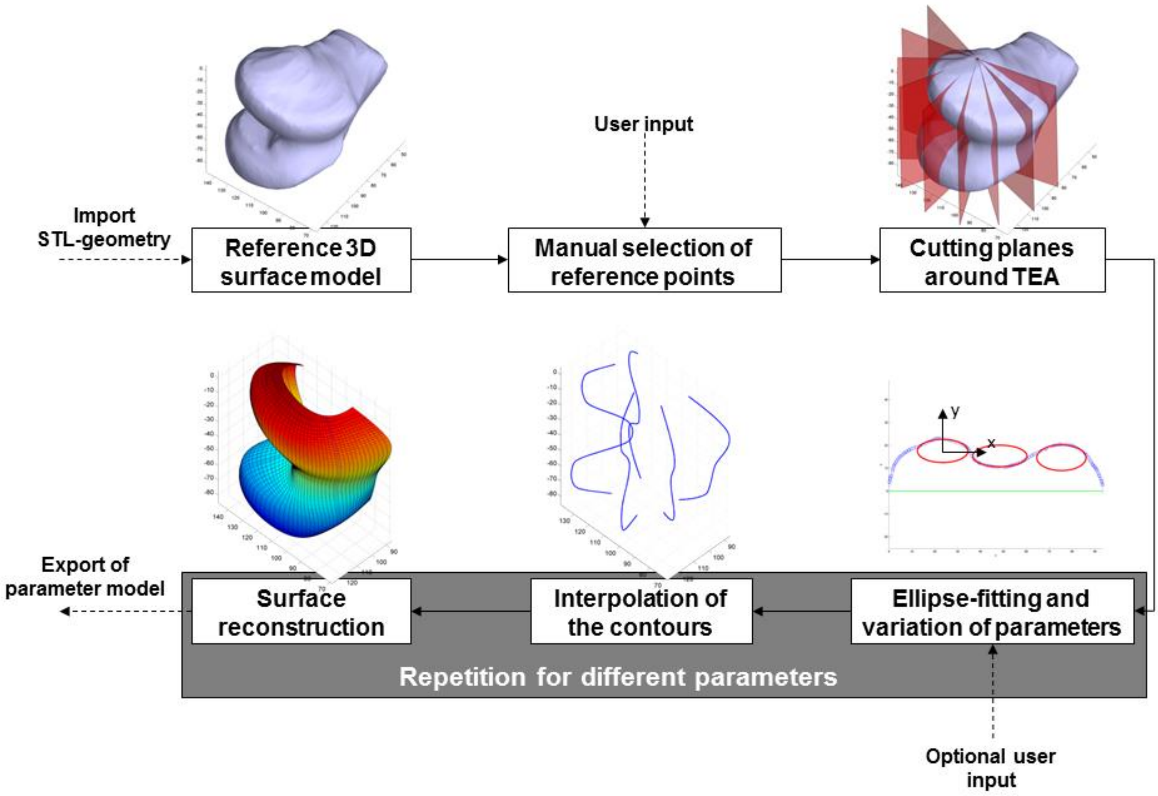

Fig 1: Concept overview of the proposed framework

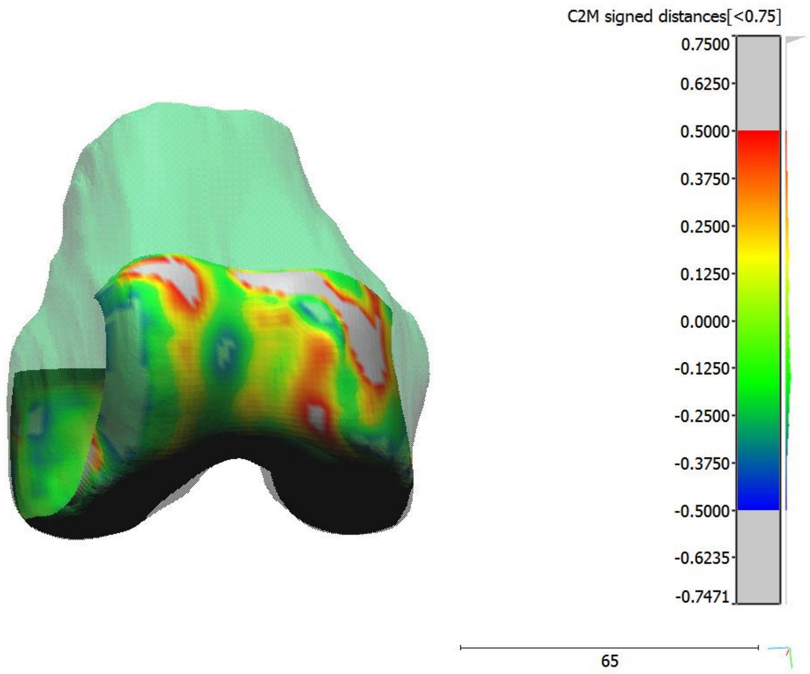

Fig 2: Exemplarily visualization of the deviation between the bony geometry (transparent) and parameter model