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Quick Construction of Femoral Model Using Surface Feature Parameterization

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Abstract: To facilitate the modifying of femoral surface model, by dividing the femoral mesh into surface feature units bearing medical significance based on surface feature technology, a new approach of constructing femoral models using surface feature technology is proposed. Firstly, considering of femoral anatomy, the femoral triangle mesh model generated from the averaged point-clouds is divided into several specific regions, which are called feature regions; Secondly, feature parameters are defined and the constraints among them are set up, and feature surfaces are created by skinning the contours; Finally, the adjacent feature surfaces are connected by transition surfaces, and the parametric CAD surface model of femur is constructed. Experimental results show that, with the proposed method, the surface feature model can be intuitively constructed and edited with high-level parameters. Therefore, the proposed method provides a basic tool for the design of implants and the digital restoration of incomplete femurs.

Keywords: Surface feature, Femoral model, Parametric design, Constraint morphing, CAD.

1 Introduction

Three-dimensional (3D) models presenting precise anatomical morphologies provide the significant and useful information for the computer-assisted surgery planning [18], intervention and the personalized prosthesis design [11]. Traditionally, the volumetric images such as computer tomography (CT) and magnetic resonance imaging (MRI), are used to construct 3D models by using the several commercial software applications for medical image processing, e.g., Mimics (Materialise Inc.,

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Belgium), Amira (Visage Imaging Inc., Australia). However, the methods using volumetric data have two disadvantages as follows: firstly, they process massive volume of data and are highly labor intensive and time consuming [7]; secondly, it is impossible to create a model when the images are not always available for use, for example, partial data are missed, or it is hard to obtain data. [5,20]

To overcome these practical drawbacks mentioned above, many methods [3,5,6,8, 14,34] were proposed to create femoral models from a single or a few images (such as X-ray, fluoroscopy, ultrasound). These methods can be classified into two major categories. In the first category, standard CT models are modified according to the simple morphologic information exacted from individual X-ray images. [3,14] For example, the authors of the paper [3] previously extracted the back-projection of the target contours from the X-ray images, and calculated cross-sections for the surface reconstruction. In another work presented in the study [14], the parameters measured from X-ray images were applied to deform the referential CT model by axial scaling, shearing transformation and radial scaling. The studies in the second category focus on the morphing of the templates, which are combination of statistical shape models (SSM) [8] and more knowledge of the considered anatomical structures, with different algorithms [5,6,34]. Filippi et al. [5] used two orthogonal images to represent the specific patient's anatomy, and developed a script for the commercial software package (3ds Max) to reconfigure the femoral template model by using freeform deformation (FFD) technology. In another work [34], the iterative non-rigid registration (NRR) of the features extracted from a statistically instantiated 3D model to those interactively identified from the radiographs was applied in reconstructing the femoral model. Galibarov et al. [6] proposed an automated method to create 3D surface models from planar radiographs. While a composite model was created through possible bone part adaptation and replacement from the generic database of femoral models [22]. All of the above studies provide outstanding contributions to the research field, and can be used to create femoral geometric mesh models of specific patients.

In the past 50 years, the implants have been widely used to improve the treatment efficiency in orthopedics surgery; however, it is hard for doctors to select a suitable implant from the existing serializations to match the specific anatomic morphology in many cases; and the customized implant emerged, nevertheless, its development needs a long cycle [4,31]. Therefore, the quick construction of 3D model representing specific anatomies is very significant for doctors and also for medical device manufacturers to design and manufacture customized implants; and what is more, the model must be convenient for editing. However, inexperienced users can hardly edit and morph the femoral mesh model constituted by massive points; whereas the surface model is more useful and meaningful than the mesh for further processing in computer-aided design/manufacturing (CAD/CAM) system. It has proven challenging to construct and edit the 3D surface model of femur, especially when part of bone data is lost or hard to obtain. Using feature technology [2] for the representation of femoral surfaces, and then constructing the surface feature model of femur (SFMF) would be an effective approach to achieve the convenient representation and editing of the model.

The aim of this study is to provide a parameterization-based method to construct SFMFs in CAD system, so that feature surface models can be quickly constructed and edited by inputting and adjusting values of a few semantic parameters, to help the design of implants for orthopedic surgeries. To achieve this purpose, some major requirements have to be satisfied:

- The surface features should enable users to construct and edit the model according to anatomic functions, that is, features must be defined based on the knowledge of femoral anatomic structure.

- The semantic parameters representing femoral surface features should be acquired in an intuitive way.

- In order to edit the whole and detailed shapes of a SFMF for different application requirements, the hierarchical parameterization and the constraints between parameters must be addressed.

To meet the above requirements, the surface features of a femoral average model are defined based on the anatomic referential entities, and the two-level structure parameters are used to represent a SFMF, namely: feature parameters and model parameters, then two-level structure parameter constraints (i.e., feature constraint and model constraint) are built to archive the shape representing and editing of each local feature and the whole model; the SFMF is sequentially constructed by connecting the feature surfaces.

The paper is organized as follows. In Section 2, the relevant literatures are presented. Section 3 provides an overview of the proposed method. Section 4 presents an approach of creating the basic surface model. Section 5 elaborates the parameterization and the constraint morphing of each feature. Section 6 expounds the model construction with the constraint among model parameters and feature parameters. In Section 7, the proposed approach is implemented, and an example and the deviation analysis are addressed. Section 8 concludes with a summary of the content of this study and proposes future research directions.

2 Related works

Surface feature modeling was investigated quite intensively in recent years, features defined as the interfaces between shape models and applications [2] can be divided into regular features and freeform features [9]. The femoral surface model consists of a number of freeform features. To construct and edit the femoral model with surface features, the related works (such as surface model reconstruction of human bones, feature presentation and parameterization, and correlations of femoral parameters) are discussed as following.

2.1 Surface model reconstruction of human bones

With respect to underlying surface representations, the existing approaches on surface reconstruction fall into three categories of polygonal meshes, splines and zero-set surfaces; while spline surfaces suit well for further processing in CAD/CAM. Yoo [33] proposed an effective method for reconstructing a B-spline surface from the point cloud data or a sequence of CT image data by using an efficient implicit surface interpolation scheme. Considering the natural features, Marko and co-workers [21] offered two methods of creating spline curves of tibia from cloud points with reverse engineering technology, and 3D surface models are created with those curves. Moreover, considerable researches have been done in the field of statistical model reconstruction. For example, the predictive model constructions of femur and tibia were generated through the defined spline curves and parametric points [20]. Sholukha et al. [19] presented the multiple regression and quadric surfaces (statistical models) for the femoral geometry prediction; nevertheless, it is impossible to describe the details of anatomy and morphology of femur. The methods mentioned above are useful and meaningful for representing specific anatomical structures of femur or for creating predictive surface models. However, there is no semantic parameters defined in high level, therefore the representing and editing of whole morphology or local shape are still very difficult.

2.2 Feature representation and parameterization

Feature representation and parameterization is a very beneficial way to describe and edit surface model. Nyirenda and Bronsvoort [11] proposed numeric and curve parameters to define freeform features. Pernot et al. [26,27] offered an approach for parameterizing freeform feature templates to represent a surface; this approach requires a highly iterative process between the surface deformation and the feature template. Park and Lee [25] suggested a useful method for freeform mesh models that used control freeform mesh. This method involves constructing a control mesh that surrounds an object model and then imposing constraints on this mesh. Thus, this approach is useful for existing models, allowing users to reduce the time and effort that they spend in converting mesh models to parametric surface models. Langerak and Vergeest [13] demonstrated one possible approach for user-driven feature definition. He et al. [9] proposed a novel method for the creation of user-defined freeform feature (UDFFF) from existing surface models. Feature representation is a parametric description of a freeform surface shape, and complex mappings must be constructed between control points and parameters because parametric influence is defined through the control points. Although a lot of effort has been spent on feature representation of industrial products, the efficient and effective method which can be applied to represent the femoral features is to be developed.

2.3 Correlations of femoral parameters

Many studies [16,19,28,32] were proposed to reveal the correlations among femoral parameters because femoral measurement is an important anatomic landmark in orthopedic research. [32] proposed that the height and width of femur have high correlations with distal parameters, and the femoral height is a significant factor, which determines the selection of prosthesis among the long or short individuals of folks. [28] presented anthropometric measurements to design prostheses for the Indian population. [16, 19] measured the anatomic data of proximal femur and analyzed the relations among the parameters of the Chinese population. The concept that there exist different level correlations among the measured parameters has been supported in above researches. However, such difficult problems as parameter constraints and how to edit the surface feature shapes of femur through parameters have not yet been addressed. The focus of this study is on developing a user-friendly approach for creating surface feature models of femur. It is convenient for user to construct and edit surface model of femur based on the freeform feature technology, the feature definition and parameterization will be discussed in the following sections.

3 An overview of the approach

Considering that anatomical morphology features of femur vary considerably because of the ethnic and regional differences [11], in this study, a collection of 50 samples from the healthy adults residing in Jiangsu, China, whose heights are between 155 and 175(mm), are selected to previously generate an average point cloud model, forming the basis of creating the femoral surface model and defining features. The parameterization representation of the feature model is described in two levels: surface feature and feature model. Feature parameters (FPs) are used to depict local surface feature shapes, while the higher level parameters, model parameters (MPs) are defined to describe the whole shape of femur. The algorithm for constructing a SFMF from the average point could consists of the following major steps:

Step 1. Import the average point cloud model, and segment femur into five units bearing anatomical and functional significance and defined as features, then create feature surfaces to reconstruct the basic surface model from the fitted spline curves.

Step 2. Define the FPs and build the constraints between them, then develop constraint morphing functions to represent and edit each surface feature.

Step 3. Define the MPs to represent whole femoral model and set up the constraints between themselves and the constraints between them and FPs, and connect adjacent feature surfaces with transition feature surfaces to construct a new SFMF.

The complete flow of constructing a SFMF from an average point cloud is shown in Fig.1. Steps 2-3 are the most important of the three steps, which will be expounded in the following sections of this paper.

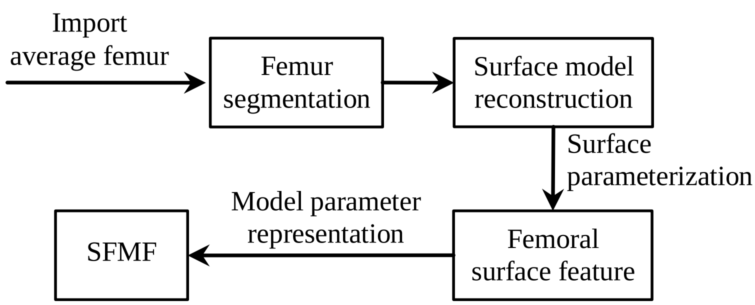

Figure 1: Flow of SFMF construction.

4 Femur segmentation and surface model reconstruction

In this section, the average femoral model is segmented into five feature units by the boundary curves according to the referential entities (REs) [30], and the units are cut by multi-planes to obtain cross-section curves; then, the contour splines fitted for those cross-section curves are used to create feature surfaces; and finally feature surfaces are connected to create the basic surface model of femur.

There are several significant anatomical morphologies on the femoral surface. For example, the smooth upper ball-like part is called femoral head, on which there is a femoral fovea, the head stretches downward to form a thin neck. The neck and body intersect into a neck shaft angle. There are two trochanters at the connection of neck and body, the upper lateral and the lower medial are called greater trochanter and lesser trochanter, respectively. Shaft bowing convex to the front is an approximate cylinder. The swelling lower end is called condyle, and its distal is a "U-shaped" knee-joint surface, the parts protruding to both sides are lateral epicondyle and medial epicondyle, respectively [3,18]. Hence, the features are defined as five freeform surface features (i.e., head, neck, trochanter, shaft and condyle) based on the anatomical characteristics employed in both diagnosis and therapy. The basic surface model is represented from local to the whole by reverse engineering, and the construct process consists of the following four steps:

Step 1. Create REs of the femoral model and define the coordinate system.

REs are the entities which are defined on the model in accordance with femoral anatomical and morphological features, e.g., points and planes, and they are the reference objects in creating curves, surfaces. After importing the point cloud into the reverse engineering module of existing software tools, the REs can be created (Fig. 2a-c); and the coordinate system (Fig. 2d) is defined based on REs as follows: $P_{t,si}$ as the origin, L_{dsax} as Zdirection.

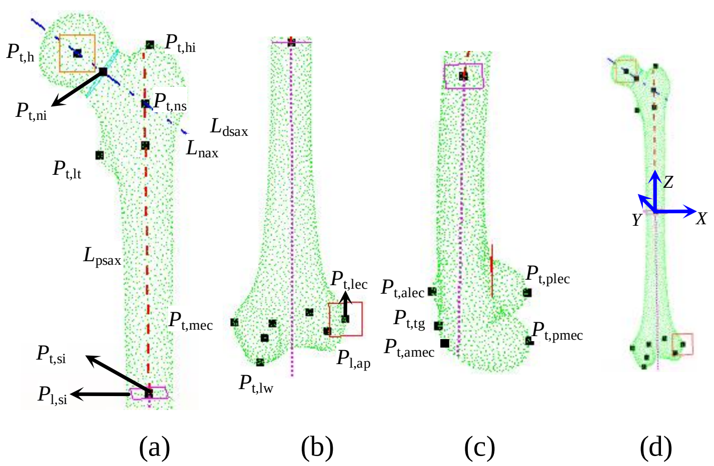

Figure 2: Definition of REs and coordinate system: (a) proximal REs; (b) distal REs(main view); (c) distal REs(left view); (d) definition of coordinate system.

Step 2. Segment femur into feature regions.

The mesh model created from the point cloud is divided into five units by the following boundary curves (Fig. 3a). Firstly, the mesh is cut by the plane perpendicular to L_{hax} and through $P_{t,h}$ to create C_{HN} (the boundary curve between head and neck). Secondly, C_{NT} (the boundary curve between neck and trochanter) is created by the method described in the paper [30]. Thirdly, the mesh is cut by the plane parallel to XY plane and through $P_{t,lt}$ to create C_{TS} (the boundary curve between trochanter and shaft). Finally, the mesh is cut by the plane at 155(mm) below XY plane to create C_{SC} (the boundary curve between shaft and condyle).

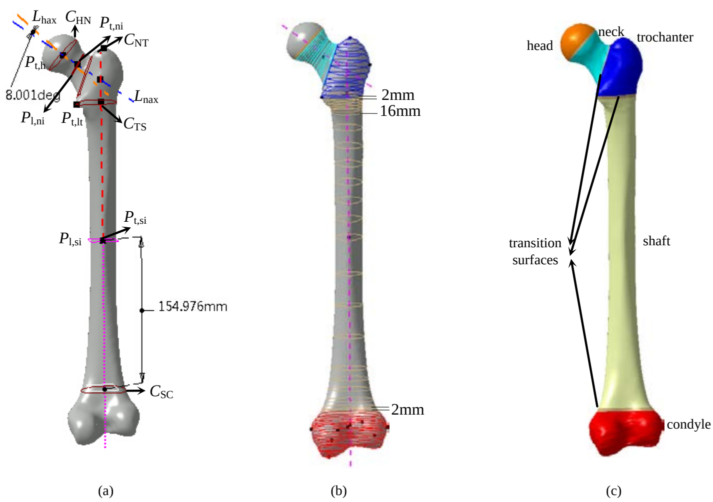

Figure 3: Base surface model construction: (a) femur segmentation with boundaries; (b) create contour splines; (c) create feature surfaces and connect transition surfaces to construct basic surface model.

Step 3. Create contour splines.

For the complexity of femoral anatomy, the contours must be created in an appropriate way which will be convenient for the further feature representation and morphing of surface model. The mesh is sliced by multi-planes to obtain cross-section curves as follows:

Step 3.1. Create cross-section curves of the neck. Create four isometric points between $P_{t,ni}$ and $P_{t,h}$, and slice the mesh by clock-wisely rotating subsequently at the four points respectively for 0°, 2°, 4° and 6° based on $P_{l,ni}$, then four cross-section curves are obtained. Create three isometric points between $P_{t,ni}$ and the intersection between $P_{l,nl}$ and L_{nax}; then similarly, slice the mesh by anti-clockwise rotating subsequently and successively at the three points respectively for N_a /4, N_a /2, N_a 3/4 based on $P_{l,nl}$, and all cross-section curves of the neck are created. Where the curve C_{nl} (Fig. 4a) is the lateral boundary contour; N_a (neck angle, shown in Fig. 4a) is the angle between L_{nax} and the plane $P_{l,nl}$ (C_{nl} locates).

Step 3.2. Create cross-section curves of the trochanter. From $P_{t,hi}$ to the plane where C_{TS} locates, the mesh is isometrically sliced to create ten cross-section

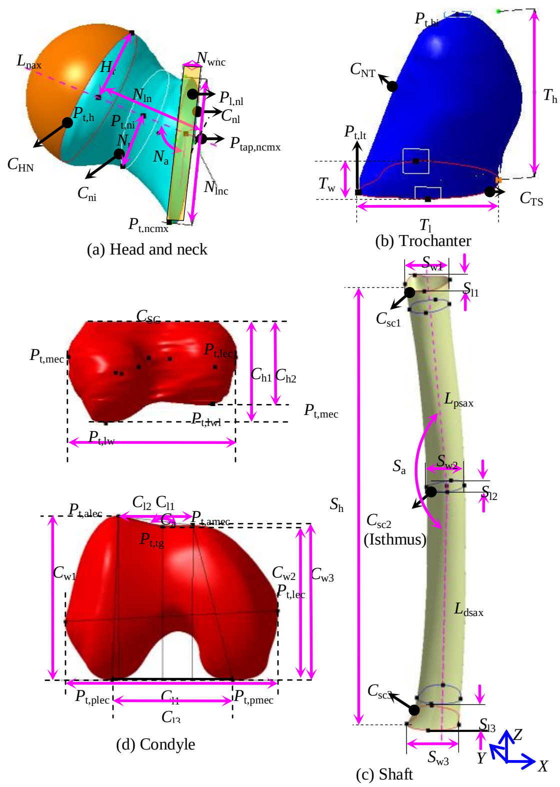

Figure 4: Definition of feature parameter.

curves.

Step 3.3. Create cross-section curves of the shaft. From 2 to 18(mm) below the plane where C_{TS} locates, the mesh is isometrically sliced to obtain six cross-section curves; from 18(mm) below the plane where C_{TS} locates to 2(mm) above the plane where C_{SC} locates, the mesh is isometrically sliced at intervals of 30(mm) to create cross-section curves.

Step 3.4. Create cross-section curves of the condyle. The condyle unit of the mesh is isometrically sliced at intervals of 2(mm) from the plane where C_{SC} locates parallel to *XY* plane, and the cross-section curves are obtained.

At last, the splines (Fig. 3b) fitted for those cross-section curves are created to represent contour curves.

Step 4. Create the whole surface model.

As shown in Fig. 3c, a hemisphere is created with L_{hax}, $P_{t,h}$ and the fitted head radius [24] to represent the head feature surface, and specific freeform surfaces are created by skinning, lofting and/or filling the corresponding contour splines to depict other four feature surfaces. At last, the feature surfaces are connected with transition freeform surfaces [10] created by lofting the two contour splines of adjacent features, to create the basic surface model of femur. The parameterizations of each feature and the model are expounded in Sections 5, 6.

5 Surface feature parameterization

The primary motivation for feature parameterization lies in that ordinary users (such as doctors) can consider the femoral model in terms of functions and parameters to be fulfilled. The concept that feature morphologies have specific influences on femoral biomechanical functions was supported in many studies [1,24], for example, the head determines the center of rotation and the stability of joint [17]; the femoral neck length mainly affects hip contact forces such as anterior-posterior, vertical, and medial-lateral components during gait [10]; and the axis of condyle as an important anatomical mark relates to the knee joint rotation [1]. Therefore, for the further practical applications, the special anatomical and biological functions of femur must be taken into consideration in the parameterization of surface features. In this section, the surface feature parameterization is used to represent and edit various feature surfaces with the semantic FPs; the parameter definition and constraint morphing of each surface feature are described in detail as follows.

5.1 Definition of surface feature parameters

The feature parameterization is represented with a series of FPs which have anatomical semantic and are convenient to measure; according to the special shapes, the FPs of each feature (Fig. 5) are defined as follows:

If not considering the femoral head fovea, the head feature can be depicted with a semi-sphere (Fig. 5a, orange), only one FP is defined: H_r (head radius) which is fitted from the point cloud of head.

The neck feature is represented with an approximate tubular freeform surface which both ends are thick and the middle is narrow (Fig. 4a, green), and the following six FPs are defined: N_r (neck radius) which is the radius fitted from C_{ni}; N_{lnc} and N_{wnc} are the height and width of C_{nl}(approximate ellipse), respectively; N_{ln} (neck axis length) is the distance between $P_{t,h}$ and $P_{t,ncmx}$; N_a is the angle between L_{nax} and $P_{l,nl}$; H_r is also the radius of C_{HN} (medial boundary contour).

The trochanter feature is represented by a freeform surface skinned and filled its contour curves (Fig. 4b), three FPs are defined to describe the shape, namely: T_h (trochanter height) which is the distance between $P_{t,hi}$ and the plane C_{TS} in; T_l

(trochanter length) and T_w (trochanter width) which are the length and width of C_{TS} (approximate ellipse).

The shaft feature is a long approximate tubular freeform surface which two end contours (C_{sc1} and C_{sc3}) and one isthmus contour (C_{sc2}) are all approximate ellipses (Fig. 4c); C_{sc1} locates at 2(mm) below the plane where C_{TS} locates, C_{sc3} is located at 2(mm) above the plane where C_{SC} locates. The FPs of the shaft are defined: S_{l1} to S_{l3} (lengths of corresponding contours, respectively); S_{w1} to S_{w3} (widths of corresponding contours, respectively); S_h (distance between the two planes through C_{sc1} and C_{sc3}); S_a (angle between L_{psax} and L_{dsax}).

The condyle feature is located below the boundary C_{SC}, as shown in Fig. 4d, its FPs are defined: C_{h1} (lateral condylar height) which is the distance between $P_{t,lw}$ and the plane through C_{SC}; C_{h2} (medial condylar height) which is the distance between $P_{t,lwl}$ and the plane through C_{sc}; C_{l1} (medical-lateral length) which is the distance between $P_{t,mec}$ and $P_{t,lec}$; C_{l2} (anterior condylar length) which is distance between $P_{t,amec}$ and $P_{t,alec}$; C_{l3} (posterior condylar length) which is the distance between $P_{t,pmec}$ and $P_{t,plec}$; C_{w1} (lateral condylar height) which is the distance between $P_{t,amec}$ and L_{ecs} (the line through $P_{t,pmec}$ and $P_{t,plec}$) ; C_{w2} (trochlear groove height) which is the distance between $P_{t,tg}$ and L_{ecs}; C_{w3} (medical condylar height) which is the distance between $P_{t,alec}$ and L_{ecs}; C_a (trochlear groove angle) which is the angle of $P_{t,amec}$, $P_{t,tg}$ and $P_{t,alec}$.

5.2 *Constraint morphing of surface feature parameters*

The core issue of surface feature parameterization is the parameter constraint which is built to represent and morph the surface shape, it consists of the numberic value constraint and the topology constraint. These constraint relations are always maintained during the parameterization; in other word, the constraints are satisfied in the initial stage, when new values are assigned to parameters, the constraints are still maintained to generate a new freeform surface. In this study, the constraint among FPs and feature morphing are discussed in the following subsections.

5.2.1 *Constraints among feature parameters*

Table 1: FP constraint of neck.

	H_r*	N_r	N_{al}
H_r*	1		
N_r	1.444	1	
N_{al}	1.082	0.749	1

Table 2: FP constraint of trochanter.

	T_h*	T_l	T_w
T_h*	1		
T_l	0.759	1	
T_w	0.517	0.681	1

Table 3: FP constraint of shaft.

	S_h*	S_{l1}	S_{w1}	S_{l2}	S_{w2}	S_{l3}	S_{w3}
S_h*	1						
S_{l1}	0.202	1					
S_{w1}	0.138	0.679	1				
S_{l2}	0.131	0.649	0.956	1			
S_{w2}	0.127	0.628	0.968	0.906	1		
S_{l3}	0.256	1.276	1.885	1.954	2.016	1	
S_{w3}	0.174	0.681	1.261	1.328	1.370	0.680	1

Table 4: FP constraint of condyle.

	C_{h1}*	C_{l1}	C_{w1}
C_{h1}*	1		
C_{l1}	0.606	1	
C_{w1}	0.493	1.230	1

In this subsection, the FP constraints of each feature are set up through the linear regression analysis of the mean parameters proposed in the existing medical studies [17,19,27,28,30,32]; and each constraint consists of three components: feature parameters, primary and minor coefficients. The primary coefficient represents the main linear relations between feature parameters, and the minor one describes the error range for individuals. In this study, the formal definition *FC* is provided as follows:

$$FC = (FP, \Lambda, E).$$

In the above definition, *FP* includes the feature parameters of each feature, i.e., *FP* = (FP_1, FP_2, ..., FP_i, FP_m), m is the parameter number of each feature; Λ and E are both symmetric matrices; Λ consists of the primary coefficients which indicate linear relations between FP_i and FP_j, while E includes the minor coefficients which represent individual errors between each two FPs.

$$\Lambda = \begin{pmatrix} \lambda_{11} & \dots & \lambda_{1m} \\ \vdots & \ddots & \vdots \\ \lambda_{m1} & \cdots & \lambda_{mm} \end{pmatrix}, \qquad \lambda_{ii} = 1; E = \begin{pmatrix} e_{11} & \dots & e_{1m} \\ \vdots & \ddots & \vdots \\ e_{m1} & \cdots & e_{mm} \end{pmatrix}, e_{ii} = 1;$$

The linear equation between FP_i and FP_j is defined as follows:

$$FP_j = (\lambda_{ij} \pm e_{ij}) * FP_i + FP_{j0}.$$

The constraint relations of the neck, trochanter, shaft and condyle are shown in Table 1-4, respectively; where the *FP**s (i.e., H_r, T_h, S_h, C_{h1}) are defined as the key parameters of each feature, through which the higher level constraints among FPs and the MPs can be built (to be discussed in Section 6.2).

5.2.2 The constraint morphing of surface features

The constraint morphings for each feature are developed based on above parameter constraints, to smoothly edit the surface shape by moving the fitted points of corresponding feature contour splines along special directions.

As described in Fig. 5, each feature morphing consists of five elements: the original and the edited fitted points group P and P' to create feature contour curves; the original or default value and the new value of a given parameter P_m and P'_m, e.g. H_r and H'_r; the constraint morphing is achieved through moving the points from PtoP', according to the parameter value changing from P_m to P'_m. When the minor coefficient E of the constraint relations is assigned a null value, the feature morphing is defined as follows:

- For the head, the feature (semi-sphere surface) is simply scaled based on L_{hax} and $P_{t,h}$ through the radius value changing from H_r to H'_r (Fig. 5a).

- For the neck, the feature is modified by length scaling in neck axial direction, and thickness scaling in radial direction based on L_{nax} and $P_{tap.ncmx}$, for example, the feature surface is morphed (Fig. 5b) .
- In the same manner, the trochanter is morphed (Fig. 5c) based on L_{tax} (trochanter axis).
- The shaft is morphed (Fig. 5d) by S_h based on the shaft axes.
- The condyle is morphed (Fig 5e) by C_{h1}.

6 Construction of femoral surface feature model

This section expounds how to construct a new SFMF with the MP representation and constraints among the MPs and FPs. Firstly, MP representation are defined and the constraints among MPs and FPs are built. And then, the referential points (RP) are oriented and repositioned through the value changing of MPs and constraints among the two-structure parameters. Next, features are repositioned based on RPs and morphed by FP constraints. Finally the adjacent feature surfaces morphed are connected with transition feature surfaces to construct a new SFMF.

6.1 Model parameter representation of feature model

Table 5: The definition of MPs.

MP	Name	Defintion
F_{h1}	Femoral length	Distance between $P_{t,hi}$ and $P_{t,lw}$ in Z direction
F_{h2}	Proximal length	Distance between $P_{t,hi}$and $P_{t,si}$in Z direction
F_{h3}	Distal length	Distance between $P_{t,si}$ and $P_{t,lw}$in Z direction
H_{off}	Head offset	Distance between $P_{t,h}$and L_{psax}
H_j	Head height	Distance between $P_{t,h}$and $P_{t,lt}$ in Z direction
N_l	Neck length	Distance between $P_{t,h}$and $P_{t,ns}$
A_{ns}	Neck shaft angle	Angle of L_{pfax} and L_{nax}

To represent the whole femoral model, the higher level parameter, MPs are defined among features (Fig. 6), namely: F_{h1}, F_{h2}, F_{h3}, H_{off}, H_h, N_l and A_{ns}, and their definition are shown in Table 5.

Similar to the parameter constraints among FPs discussed in Subsection 5.2.1, linear algebraic parameter constraints are set up between MPs and between MP and FPs, the formal definitions may be presented as follows:

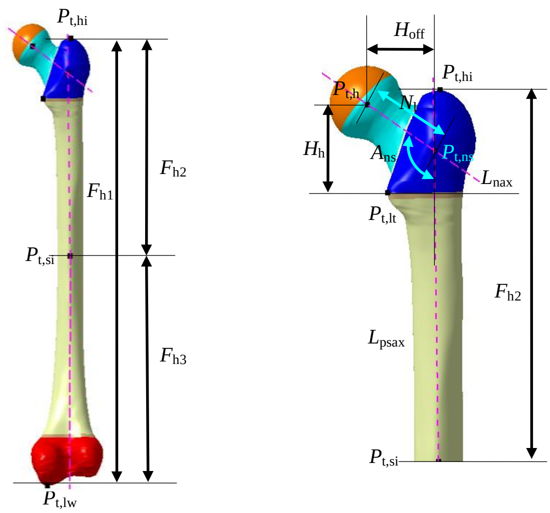

Figure 6: Definition of MPs.

$MC = (MP, \Lambda, E)$,

$MFC = (MP, FP, \Lambda, E)$,

where MC is the constraint between MPs, while MFC is the constraint between MP and FPs.

The constrain MC is represented as shown in Table 6, in which F_{h1} is defined as the key model parameter; while MFC which provides the constraint between the key MP and the key FPs are shown in Table 7.

Table 6: Constraint between MPs.

	F_{h1}*	F_{h2}	F_{h3}	H_h	H_{off}	N_l
F_{h1}*	1					
F_{h2}	0.642	1				
F_{h3}	0.358	0.558	1			
H_h	0.172	0.268	0.471	1		
H_{off}	0.179	0.279	0.480	1.041	1	
N_l	0.203	0.3164	0.567	1.180	1.134	1

According to the different levels of parameters, the two-level structure constraints mentioned in Section 5-6 are assigned to different solving priorities (Table 8); the

Table 7: Constraint between MP and key FPs.

	F_{h1}*(MP)	H_r*	T_h*	S_h*	C_{h1}*
F_{h1}*	1				
H_r*	0.076	1			
T_h*	0.177	2.329	1		
S_h*	0.674	8.868	3.808	1	
C_{h1}*	0.144	2.329	0.814	0.214	1

Table 8: Priorities of each constraint.

Constraint	Parameter	Solving priority
MC	MP	3
MFC	MP, FP	2
FC	FP	1

MC which provides the constraint of MPs is first solved, while *FC* is solved at last. In other word, the MP constraint is prior to the constraint between MPs and FPs which is prior to the FP constraints.

6.2 Feature model construction

In this component, the new feature surfaces are oriented and repositioned by *MC*, *MFC* and *FC*, then they are connected by the transition surfaces to construct a new SFMF, the main steps are as follows:

Step 1. Orient and reposition reference points (RPs). The RPs are the points selected from the REs to construct the feature axes, and they have important significance in representing and morphing the features. As shown in Fig. 7a, the RPs are initially created in the basic femoral surface model mentioned in Section 4, and they are oriented by the following steps: First, the MPs can be caculated from *MC* (Table 6); Second, the key FPs are evaluated from *MFC* (Table 7); Next, all FPs could be obtained from *FC* (Table 1-4); Finally, the RPs are oriented and repositioned according to the new value of FPs (Fig. 7b, red).

Step 2. Orient and reposition the features. Along the corresponding directions determined by the RPs, the features are oriented, repositioned and morphed (Fig. 8a-f) with the new values of MPs and FPs evaluated from all the constraints.

Step 3. Connect feature surfaces for the whole model. The transition surfaces are morphed by the adjacent feature contour curves which are constraint morphed, and

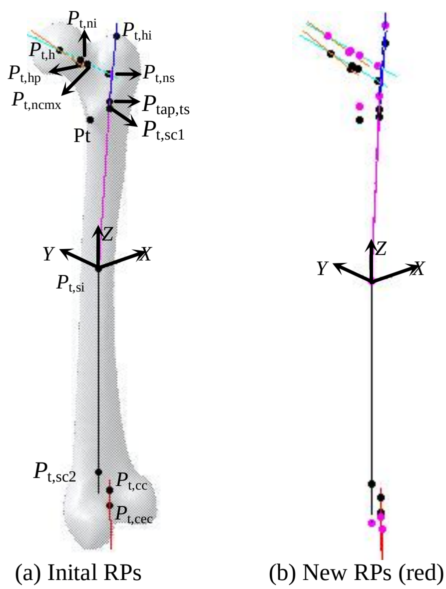

Figure 7: Constraint reposition of RPs.

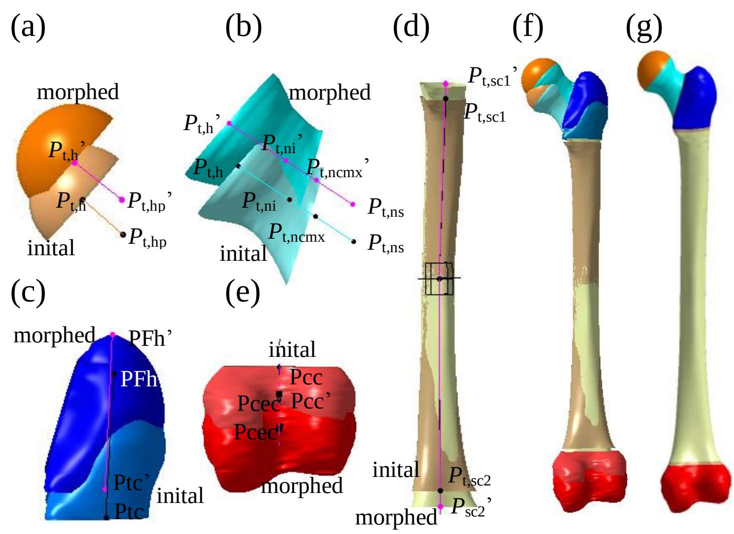

Figure 8: Construction of a new SFMF: (a) Head; (b) Neck; (c) Trochante; (d) Condyle; (e) Shaft; (f) Feature reposition; (g) construction of a SFMF.

with them the new feature surfaces are connected to construct a SFMF (Fig. 8g).

7 An application example and deviation analysis

The methodology and algorithms that are presented above were implemented in Microsoft Visual C++, and Dassault System CATIA V5R21 was used as the development platform. In this section, a study case of constructing SFMF and the deviation analysis of the constructed model are illustrated.

7.1 Feature model construction

The study example is to construct a SFMF with a given MP value. To expound the creation process of the feature model, the parameters of the basic surface model (Fig. 9a-b) created in Section 4 is regarded as the default values. When a given value (F_{h1} = 431.331mm) is assigned to the MP, according to the solving priorities of constraints, the other related parameters can be evaluated by solving the constraints successively. First, the other MP values, e.g., F_{h2}, F_{h3}, H_{off}, H_h and N_l, can be evaluated from the MC; Next, the related FP values, i.e., H_r, T_h, S_h, C_{h1}, C_{l1} and C_{w1}, could be evaluated from the MFC; Finally, all other FP values may be evaluated from the FC. Basing on those values of constraint parameters, the feature surfaces are repositioned and morphed to construct a new SFMF (Fig. 9c-d).

7.2 Deviation analysis

To evaluate the effectiveness of the proposed approach, the constructed SFMF is compared with a normal femoral sample the length of which is 325.214mm, and the shape errors between them are measured for each feature; the Hausdorff distance, which has been proven to perform well for the assessment of surface reconstruction [15], is used to represent errors.

The SFMF constructed by the proposed method can accurately represent the vast majority of the femoral anatomical morphology (Fig. 10a). For the difference of individual human bones, there are still some errors between the sample (Fig 10, green) and the feature model (Fig. 10, other colors). The greatest Hausdorff distance of head locates at the lateral (Fig. 10b), there is a fovea for the tendon connection in head anatomical structure, while the head feature is represented with a hemisphere because that the head fovea is neglected in the artificial hip joint. The neck and condyle surface shapes are very significant for the design of artificial hip and knee joint; The neck error (Fig. 10c) and condyle error (Fig. 10e) are all less than 1mm, hence, they are acceptable for the selection and development of joint prosthesis [12]. The trochanter error (Fig. 10d) is 0.882mm. The maximum error of shaft locates in the lesser trochanter part (Fig. 10f) because there exist

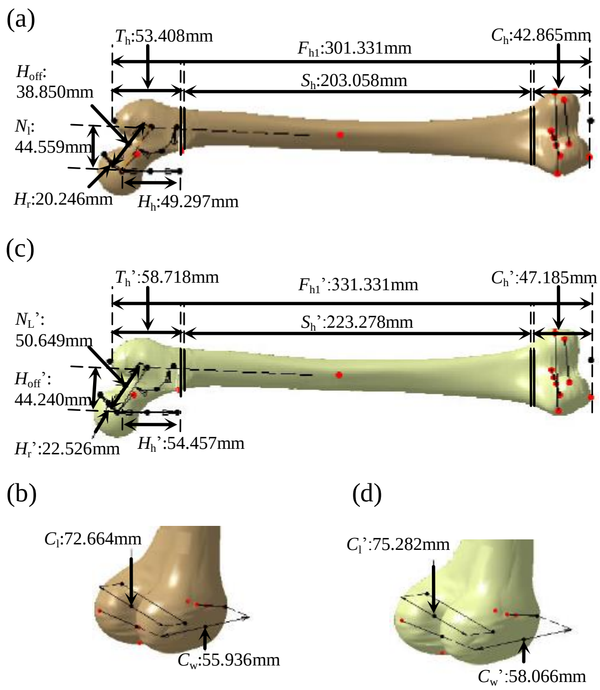

Figure 9: Parameterization of new SFMF: (a) Parameters of basic model; (b) Condyle parameters of basic model;(c) Parameters of new SFMF; (d) Condyle parameters of new SFMF.

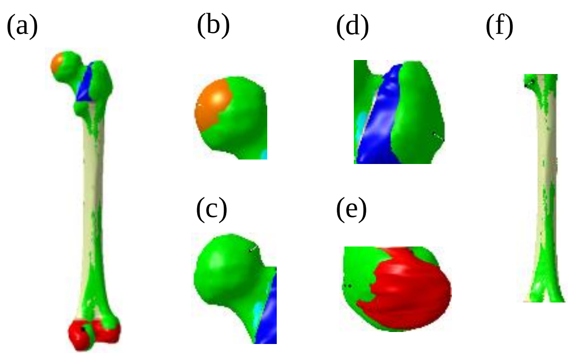

Figure 10: Errors between a sample and constructed model (green is sample, others are feature surfaces): (a) Sample and model; (b) Head error:1.042mm; (c) Neck error:0.631mm; (d) Trochanter error:0.882mm; (e) Condyle error:0.707mm; (f) Shaft error:1.458mm.

three kinds of morphologies in this part [16,19], yet the constructed component is meaningful for the locked plate design of the proximal femur; Therefore, how to improve the accuracy of this part would be researched in future work.

The above results show that the constructed SFMF is effective for doctors to design the implants quickly and conveniently in assisting orthopedic surgery.

8 Conclusion

This paper proposes a method for creating the SFMF based on surface feature technology. Users can input one or a few MP values to obtain the values of other MPs and FPs by constraints, and a special feature surface model can be constructed automatically. The method simplifies the process of creating femoral models and thereby allows untrained personnel to rapidly create femoral surface models. The main characteristics of this approach are as follows.

- The femoral feature surface can be quickly constructed by feature parameterization rather than from scratch.
- It supports the parameter constraints and feature morphing; the SFMF can be created with a few given parameters by constraint morphing even in the case that the femoral data is not complete.

The proposed method of constructing the SFMF constitutes a very promising and useful extension of freeform feature representations for the surface modeling of human bone. However, some directions must be researched in future work, including the following avenues of investigation:

- More powerful constraint relationships must be built to improve the accuracy of a SFMF.
- More features must be defined to represent the detailed surface shape of femur, e.g., less trochanter and condyle.

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