Referential Geometrical Entities for Reverse Modeling of Geometry of Femur

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ABSTRACT: Reverse modeling and engineering of human bone's geometry is the indispensable part of the process of customized implants and external fixators manufacturing. Because of that, it is very important to remodel geometry of the human bone fastly and accurately. The basic prerequisite for fast and accurate reverse modeling of a human bone's geometry is identification of the referential geometrical entities (RGEs), that is characteristic points, directions, planes and views. All other elements of the bone's geometry (curves, surfaces and solids) should be referenced to RGEs. The paper presents idetification of RGEs in the case of specific reverse modeling approach of the geometry of femur, which starts with radiology image input. In addition, the results presented in the paper, suggest some guidelines for the future MIP and CAD software communication.

Keywords: Reverse modeling, Reverse engineering, Femur

1 INTRODUCTION

Medical image processing (MIP) plays very important role in determination of diagnosis as well as in surgery and therapy. In orthopedic surgery, but also in all other sub-branches of surgery, where the need for creation of customized implants or fixing devices exists, there is a specific requirement for reverse modeling (RM) and reverse engineering (RE) of tissue. In general, there are two main directions in reverse engineering application. The first one is related to reverse engineering of hard tissues like bones, and the second one is related to reverse engineering of soft tissues like skin or vascular tissue (Sun et al. 2004a, b). In both application directions, reverse engineering has to deal with tissue geometry. Manufacturing of customized bone's implant or external fixing device in the case of bone fracture requires reverse modeling of the bone's geometry. Manufacturing of soft tissue implant can require customized scaffold or a woof for tissue growth or restoring. Thus, it is closely related to the tissue geometry also.

Medical image processing is the starting point of geometry tissue capturing. The radiology image of the tissue represents input set of data for reverse modeling and engineering, which is often called *raw data* in CAD (computer-aided design) terminology. It is the reason why RE technologies needs to communicate with MIP closely. The paper reports about a case (geometry of femur) where the results gained from RE can affect MIP and its standards (conventions).

2 REFERENTIAL GEOMETRICAL ENTITIES

The basic prerequisite for successful reverse modeling of a human bone's geometry is identification of *referential geometrical entities* (RGEs). Usually, these RGEs include characteristic points, directions, planes and views. All other elements of the bone's geometry (curves, surfaces and solids) should be referenced to RGEs. In order to create the robust geometrical model of the bone, which is easy to operate with, one should strive to minimize the set of primary RGEs. Thus, all other geometrical constraints and relations should be based on that minimal set of primary referential geometrical entities. In the same time, this is the approach for successful parametrization of human bone's geometry. Moreover, the correct identification of RGEs helps RE to be fast and accurate, which is the basic imperative in urgent cases.

3 MATERIAL

For the geometry analysis of femur, we used raw data of 10 scans of femur samples. The samples were scanned by computer tomography (CT) in resolution of 0.5mm. The *raw data*, that is coordinates of the points of scanned tissue, were imported into appropriate CAD (computer aided design) software for reverse modeling (Fig. 1) The CT scans were obtained fast, but in a low resolution (in terms of RE). That affected on accuracy of some details in the 3D digital model, but not on accuracy of the total bone morphology. In addition, CT scans contained internal bone tissue structures so as other type of tissues. That is the reason why these scans require considerable length of time for model post processing (for cleaning and healing the model). Despite the difficulties of using CT scans, it is very important to practice reverse modeling of bones using CT scans because, in real situations, reverse modeling and engineering can help orthopedic applications just working with CT or MRI (Magnetic Resonance Imaging) scans. Because of its widespread utilization and low radiation exposure of patients, X-ray image processing must be involved in RE, too (Dong & Zheng 2008, Baudoin et al. 2008, Zanetti et al 2005).

4 REVERSE MODELING

Reverse modeling of a human bone's geometry using CAD software means generating digital 3D model of bone's geometry from radiology image (X-Ray, CT, MRI). In this particular case, CATIA V5 R19 CAD software and its reverse engineering modules were used (Goh et al. 1990). Importing the raw data into the CAD system results in generating of one or more clouds of points (discrete points of the tissue, which are scanned by some of radiology methods – Fig. 1). In the next phases of remodeling, the geometrical features of higher order (curves, surfaces and solids) are being designed.

Figure 1. The part of cloud of points (distal femur)

The reverse modeling procedure for the bone geometry is consisted of following phases:

1. Importing and editing (filtering, aligning, etc.) of clouds of points (Fig. 1),
2. Tessellation of polygonal model (mesh) by creating a huge number of small triangular planar surfaces between the points in the cloud, as well as editing of polygonal model (Fig. 2).
3. Identification of RGEs (points, directions, planes and views)
4. Creating and editing the curves on polygonal model of the bone,
5. Creating and editing the surface model of the bone's outer surface sweeping the curves,
6. Optionally, the last phase of the bone remodeling is creating the solid model of the bone. This is the case, e.g. when there is a need for restitution of the part of a bone captured by cancer (Fig. 3).

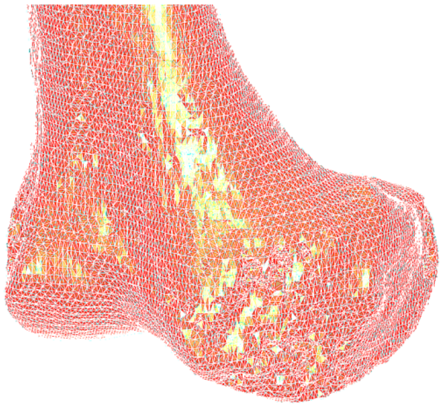


Figure 2. The part of polygonal model (distal femur)

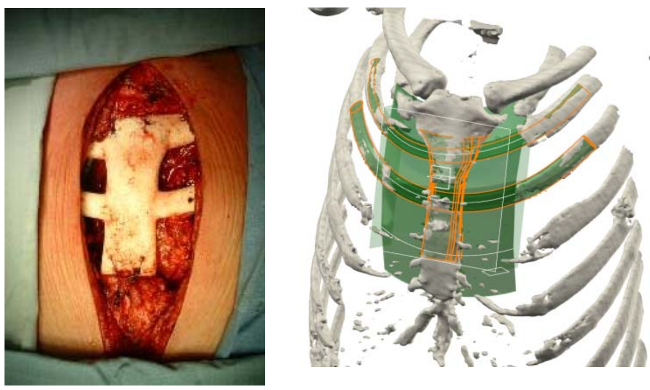


Figure 3. Solid modeling of sternum implant (solid freeform fabricated)

5 RGE FOR REVERSE MODELING OF FEMUR

For the medical purposes and applications, there are two basic views of femur, that is, spatial orientation of femur. The first one is so called anterior-posterior view or orientation (A-P) and the second one is lateral-medial (L-M) view or orientation. For the reverse modeling of femoral geometry, it is necessary to create several (not always orthogonal) directions and the coresponding projections of the bone or a part of the bone. What is specific in reverse modeling, is that it is neccessery to establish the rules for the creation of all directions and views which should be used, including A-P and L-M, very precisely (Kwak et al. 1995, Schmutz et al 2006).

5.1 *A-P plane definition*

The crucial RGE for reverse geometry of femur is A-P plane. All further directions, views and planes are directly related to A-P direction. Because of that, it is necessary to define A-P plane and its direction (line perpendicular to A-P plane) precisely. For the definition of A-P plane, direction and view we used following geometrical referential points of femoral geometry (REGs):

- Point of the center of the femoral head (P_CFH)
- Point of the lateral epicondyle (P_LEc) – the most prominent point on the lateral epicondyle,
- Point of the medial epicondyle (P_MEc) - the most prominent point on the medial epicondyle,

In addition, besides these three points, there are three points more that are located on a very same plane (A-P plane) with a very small deviation:

- Point of the intercondylar fossa (P_IcoF) – point in the center of the intercondylar fossa,
- Point of the lateral condyle (P_LC) – the lowest (inferior) point on the lateral condyle, and
- Point of the medial condyle (P_MC) – the lowest (inferior) point on the medial condyle.

The most important referent point of femoral geometry is the center of the femoral head (P_CFH). This point is made as an intersection of two axes of the circles that represent orthogonal projection of the femoral head (Fig. 4). We can use MPI to identify P_CFH as the center of the arc of femoral head image slice with greatest value of radius.

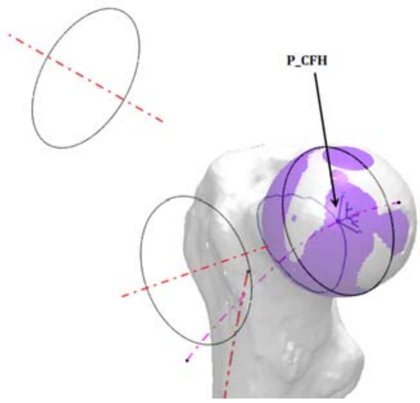
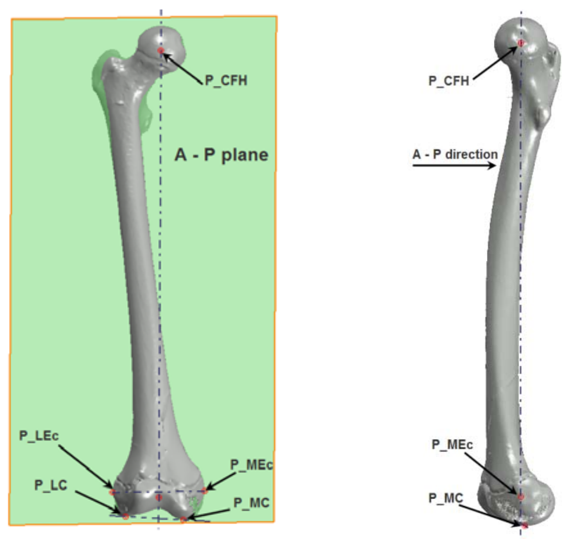


Figure 4. Construction of center of femoral head: P_CF

The center of the femoral head (P_CFH) and (P_LEc, P_MEc) were used as the referential points for creation of A-P plane and so-called A-P view (Fig. 5). Other three points (P_IcoF, P_LC and P_MC) were used for the inspection of A-P plane accuracy. The next very important RGE of femoral geometry is so-called *mechanical axis* of femur, which passes through the P_CFH and P_IcoF. It defines vertical orientation of the femur in this specific reverse modeling approach (This is not the true vertical axis of body because mechanical axis is in about 3 degrees of valgus from the true vertical axis of body, Wheeless 2009, Cooke et al. 2007). P_LEc and P_MEc can be identified in radiology image easily as the most distant points from mechanical axis. The L-M plane (another RGE of geometry of femur) is the plane that is perpendicular to A-P and includes mechanical axis.



a) A-P view b) L-M view (medial aspect)

Figure 5. Identification of referential geometrical entities of femur

5.2 *RGE for proximal femur*

Besides the A-P plane and its orthogonal match L-M plane there are more planes and directions for different parts of femoral geometry that are specific. For example, reverse modeling of proximal femur (head, neck and trochanters) defines new set of characteristic planes. One of the most important morphologic details related to the proximal femur that should be identified in A-P view is the *inferior margin* of trochanter's wedge. It is a line, in A-P plane, that extends from the lowest point of the major trochanter lateral side to the lowest point of the minor trochanter (Fig. 6).

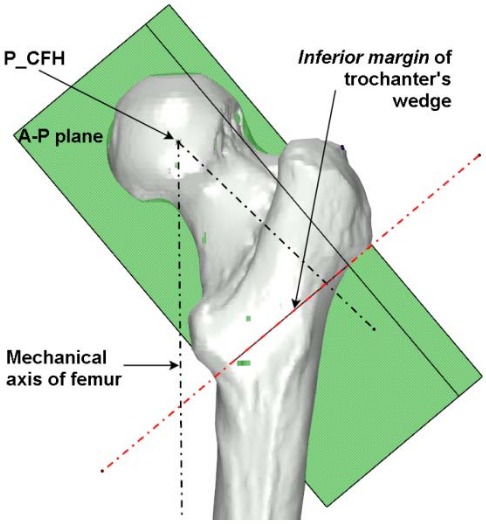


Figure 6. RGE of proximal femur - Inferior margin of trochanter's wedge

The plane that is perpendicular to the A-P plane and passes through this line defines a specific kind of *top* view on proximal femur. This plane and view is then used for definition of other axis, directions planes, and views (Fig. 7), which help effective reverse modeling of proximal femur and trochanteric region (Fig. 8).

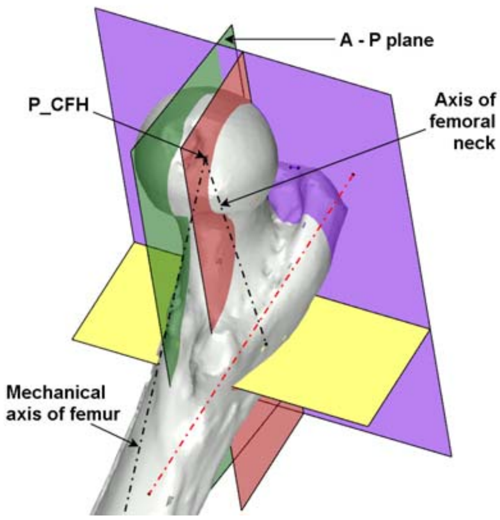


Figure 7. RGEs of proximal femur – characteristic plane based on inferior margin of trochanter's wedge

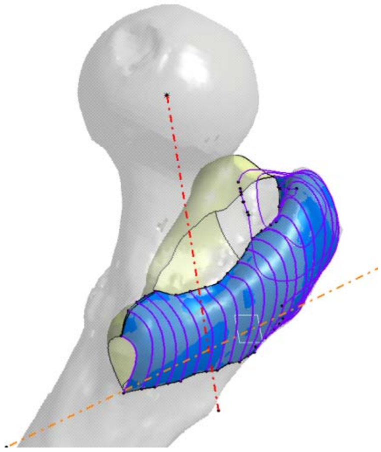


Figure 8. Reverse modeling of trochanteric wedge

5.3 *RGEs for femoral shaft*

Considering the shaft-like shape of *corpus femoris*, it is obvious that the most prominent geometrical entity is so-called ***f****emoral* ***s****haft* ***a****xis* (FSA). It is supposed to be a straight line, which approximately represents the spreading direction of femoral shaft volume. However, the precise geometry analysis indentifies a spatial curve that follows the spreading curve of femoral shaft volume very closely. This curve is determined by the series of gravity centers (points) of minimal area cross-sections of femoral shaft. Mahaisavariya et al. (2002) elaborated the similar, but less accurate approach. The ***f****emoral* ***s****haft* volume-spreading ***c****urve* (FSC) appears as almost straight line in the A-P view, but in L-M view it appears much like two-radius arc (Fig. 9a, b). This means that FSC lies in a plane, which is orthogonal to A-P plane, but is slightly inclined in respect to L-M plane.

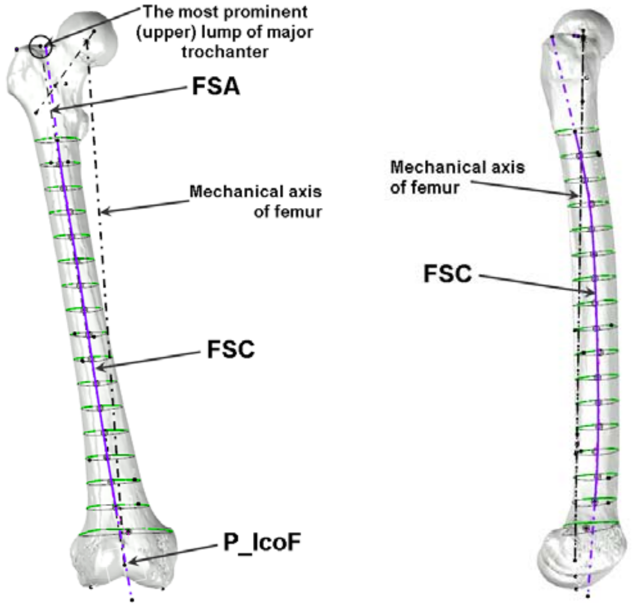


Figure 9. RGE of femoral shaft – Femoral shaft axis

Two points can do identification of A-P projection of this plane approximately: P_IcoF at distal end of femur and the most prominent (upper) lump of major trochanter (Fig. 9 a). The plane that is orthogonal to the A-P projection of FSC determines reference direction for creation of series of femoral shaft cross-sections, and consequently for easy redesign of femoral shaft volume.

5.4 *RGE for distal femur*

Besides the points that are mentioned already (P_LEc, P_MEc, P_LC, P_MEc and P_IcoF), for reverse modeling of distal femur geometry, the most important referential entity is axis of condyles (CAx). The axis of condyles (CAx) passing through two points: P_LEc and P_MEc (Fig. 10).

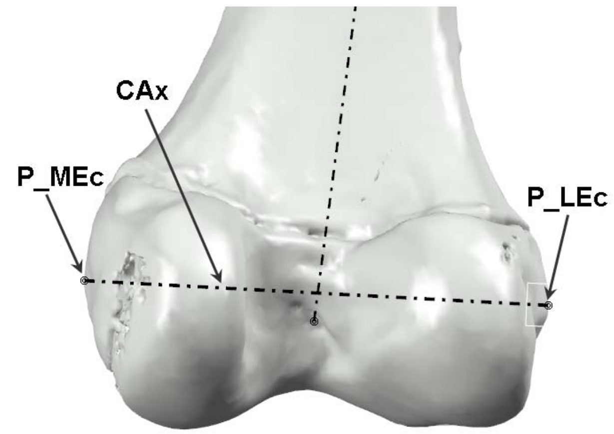


Figure 10. RGE of distal femur – Axis of condyles

CAx is used for creation of rotational pattern of cross-sections of distal end of femur (Fig. 11). The pattern of cross-section curves that looks like a cage in which the distal end of femur is located, is used as a base reference for design feature, which precisely and in one-step remodels very complex shape of condyles (Trajanovic et al. 2009).

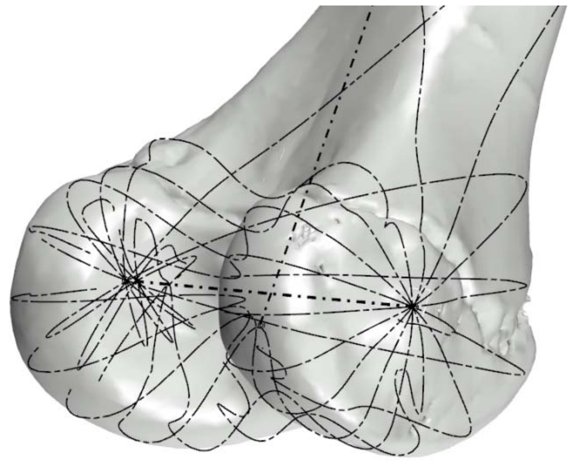


Figure 11. The rotational pattern of cross-section curves of distal end of femur

6 DISCUSSION

The RGEs of the femur, as well as any other human bone (or any other free form), makes so-called *skeleton* or *base* of the 3D digital model. The skeleton is then used as a referential frame for efficient remodeling of the femoral or other bone geometry. All other elements of the bone's geometry (curves, surfaces and solids) are referenced to RGEs.

In addition, the proposed choices for RGEs of femur, allows introducing a small set of parameters that can accurately represents geometrical proportions (lengths, distances and angles) between all the femoral morphology entities. Furthermore, this set of parameters can be put into relatively simple set of relations and design rules to manage approximate geometrical model of femur robustly (Kurazume et al, 2009). Thus, parameterization of the femoral (bone) geometry is a way to provide ourselves with a tool to respond in the urgent cases when fast and relatively accurate redesign (and reverse engineering process) of the bone or implant is necessary.

From the viewpoint of CAD/CAE/CAM software development and its application in bioengineering, the bottleneck is the communication with MIP software. In the same time, this is the field for remarkable research efforts in future. These efforts involve creating new standards in data transfer from MIP to CAD as well as creating new class of design features of CAD software that should be used for efficient design of different types of tissue or bio-shapes. Another joint challenge that can be seen is developing new CAD modules – equipped with special-purpose geometrical features related to bioengineering, which could be integrated into MIP software. These CAD modules, which would be able to remodel bone easily through the intuitive interface, could help orthopedic surgeons to prepare their operations better and faster.

In a particular case of reverse engineering of femoral geometry and its implants, it would be very useful for engineers involved in the process, to equip MIP with some kind of features for precise finding and marking the proposed RGEs of femoral images (especially the X-ray ones, because of its availability and low radiation exposure of patients). This could help engineers to be more efficient in the process of remodeling and reverse engineering of femur, its parts and immanent implants.

7 CONCLUSION

Explicit definition of RGEs of femur provides significant improvement in reverse modeling and engineering of geometry of femur. In addition, using CAD and reverse modeling techniques brings new quality into the human bone morphology perceiving. Besides the morphometric analysis, which can be performed with MIP software quite precisely also, reverse modeling and engineering provide all necessary tools for design and rapid prototyping of customized implants. Reverse modeling features help development of operational methods and operation preparation by identification more accurate entrance and more accurate placement for different fixing devices. Moreover, reverse modeling of the human bone's geometry is the indispensable part of the bone's structure and kinematic analyses.

Following the results gained from reverse modeling of geometry of femur, future CAD and MIP software could communicate much closer including automated marking of RGEs for the specific bone.

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