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Different Approaches for the Creation of Femur Anatomical Axis and Femur Shaft Geometrical Models

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In today's medicine, especially in the field of orthopedic surgery, it is very important to use geometrically accurate and anatomically correct geometrical models of human bones for the pre-operative planning and implants creation. In order to create such models, two new methods for geometrical modeling were developed and presented in this paper. These methods enable creation of femur anatomical axis and femur shaft geometrical models, and they are: GCM (Gravity Center Method), and CPM (Curve Projection Method). Both methods enable creation of geometrical models which are based on data acquired from the medical imaging devices (CT, MRI, X-Ray). The basic difference between these two methods and all the others is in the manner of generating the points through which anatomical axis model (3D curve) passes or goes near. The applied methods are developed considering the natural shape and anatomical landmarks of the femur bone, as well as standard CAD techniques for geometrical modeling which are common in engineering.

Različiti pristupi za kreiranje geometrijskih modela anatomske osi femura i tijela femura

Izvorniznanstveni članak

U današnjoj medicini, osobito u području ortopedske kirurgije vrlo je važno koristiti geometrijski točne i anatomski ispravne geometrijske modele ljudskih kostiju za pred-operativno planiranje i kreiranje implantata. Radi kreiranja takvih modela dvije nove metode geometrijskog modeliranja su razvijene i prezentirane u ovom radu. Ove metode omogućuju kreiranje geometrijskih modela anatomske osi femura i tijela femura i one su: GCM (eng. Gravity Center Method), i CPM (eng. Curve Projection Method). Obje metode omogućavaju kreiranje geometrijskih modela koji se temelje na podacima dobivenih od medicinskih uređaja (CT, MRI, X-Ray). Osnovna razlika između ove dvije metode u odnosu na sve ostale je u načinu generiranja točaka kroz koje anatomska os modela (3D krivulja) prolazi ili je u blizini. Primijenjene su tehnike koje su razvijene uzimajući u obzir prirodni oblik i anatomske značajke femura. kao i standardne CAD tehnike za geometrijsko modeliranje koje su uobičajene u inženjerstvu.

1. Introduction

In orthopedic surgery, as well as in all other sub-branches of surgery where there is need for preoperative planning or creation of customized implants and fixators, there is a specific requirement to know the exact geometrical model of the human bone. Therefore, it is very important to create geometry of the bone rapidly and accurately. Having such models, it is possible to build customized bone implants and fixators using rapid prototyping technologies or performing preoperative planning procedures in adequate applications. A lot of different techniques are used for the creation of the human bones geometrical models (especially for long bones). The general classification and analysis of 3D modeling methods for the creation of the human bones geometrical models based on various medical images (CT, MRI, X-ray, etc.) are presented in [1].

The aim of this research is to propose a new CAD modeling method which enables creation of accurate geometrical model of the anatomical axis of femur (3D curve) and femur shaft surface model based on it.

The other important goal is to cultivate a method which is easy and quick to perform. Previous studies ([1], [2],[3] and [4]) and authors' experience show that it is difficult to achieve these goals simultaneously, as the realization of one may obstruct the realization of other. This paper presents two different methods which attempt to accomplish the appointed goals to the greatest extent possible. These methods are:

- GCM (Gravity Center Method) which conforms to the anatomical, morphological and geometrical properties of the femur,

Symbols/Oznake

AN	- (Anatomical – Neck) axis angle, ° - kut između anatomske osi i osi vrata	*FNA*	- Femoral neck axis - Os vrata femura
AM	- (Anatomical – Mechanical) axis angle ° - Kut između anatomske i mehaničke osi	*FSA*	- Femur Shaft Axis - Os tijela femura
AP	- Anterior Posterior plane - Ravnina koja odvaja prednji i zadnji dio	*GCM*	- Gravity Center Method - Metoda gravitacijskih centara
CPM	- Curve Projection Method - Metoda projiciranja krivulje	*LM*	- Lateral Medial plane - Lateralno medijalna ravnina
DC	- Distal Condylar angle, ° - Distalni kondilarni kut	*RGEs*	- Referential Geometrical Entities - Referencijalni geometrijski entiteti

– CPM (Curve Projection Method) which conforms to the position, topology and geometrical properties of the femur.

1.1. The current research in this field

The methods for developing femur anatomical axis are presented and adequately described by Cong-Feng Luo in [5], and Morland JR et al. in [6]. These methods use two points for anatomical axis definition. One point is defined as the center of the femur shaft, while the other can be the center of a knee, or the point which is 10 cm away from the surface of knee joint, midway between the medial and lateral surfaces [5]. The curve created between two points is always linear; thus, it does not follow the shape of the femur shaft in a natural way. The methods presented in this paper use more points on the femur shaft for the creation of the 3D curve, and enable creation of a more natural anatomical axis. 3D curve created in this manner may have a complex shape, but it can be approximated with the linear curve which can be more precise than the line created through two points only.

In [2], the authors present a cost- and time-effective computational method for generating a 3D bone shape from multiple X-ray images. Starting with a predefined 3D template bone shape that is clinically normal and scaled to an average size, their method scales and deforms the template shape until the deformed shape gives an image similar to an input X-ray image when projected onto a two-dimensional (2D) plane. The hierarchical freeform deformation method is used to scale and deform the template bone. That research provided a good example of 3D template bone shape creation and application in preoperative planning.

The 3D reconstruction process which is based on anatomical properties is presented in [3]. The purpose of that study is to create a 3D human femur model by using multiple X-ray images and anatomical properties of the femur. For the 3D reconstruction, the 2D shape and specific parameters of the bone were firstly measured in X-ray images. Then, the corresponding CT model was modified as it follows: the axial scaling, shearing transformation and radial scaling. This research provides excellent view on mathematical approaches and modeling procedures in defining the adaptable model geometry.

The creation of solid (surface) models from data acquired from medical imaging methods (in this case MRI) is well described in [7] by Stephen Fening. The principles described in that thesis, are general principles for geometrical modeling based on medical data, and they can be applied for various types of models creation, as it is the case in this research.

2. MATERIALS AND METHODS

The geometry analysis of the femur shaft included 10 scans of femur samples. Samples were scanned by computer tomography (CT) in the resolution of 0.5mm. The samples were obtained from European adults, intentionally including different gender and age: 4 women samples, both right and left, age 25, 33, 45, 67; 6 men samples, both right and left, ages from 22 to 72. It was assumed that this diverse set of samples could present quite a diverse morphology of the very same bone.

2.1. The process of geometrical models creation

The creation of geometrical models is based on the reverse modeling of the scanned samples by CAD (computer-aided design) software. The use of CAD application in bioengineering is presented in [8]. The authors of the paper present a method which enables creation of a precise dragonfly wing geometrical model.

The reverse modeling begins with importing the point coordinates of scanned tissue (from CT) into the appropriate CAD software. The next step is to create a valid polygonal model by using CAD software features and to define referential geometrical entities (detailed explanation of RGE in [9] by Stojković et al.). The final step is to apply methods for the creation of valid geometrical models of femur anatomical axis and shaft surface.

2.2. Geometrical accuracy of the models

Adequate dimensions were chosen to check the integrity of the developed method, and the comparison was made with the already established and determined values in anatomy, orthopedic surgery and practice (presented by Cong-Feng Luo in ([5] and [10]). Two analyses were done, one for anatomical axis and other for femur shaft surface.

To test the geometrical accuracy of anatomical axis geometrical model three angles were measured and compared:

- Anatomical Axis – Neck axis (AN), mean value about 126°
- Distal condylar angle – (DC) , mean value about 81°
- Anatomical axis – Mechanical axis (AM), mean value about 6° - 8°

Angles were measured in Anterior Posterior plane (AP) [6] of the femur bone model, Figure 1. The AN angle is measured between the projected neck axis and the line tangent to the anatomical axis projection in AP plane. AM angle is measured between the projected mechanical axis and the line tangent to the anatomical axis in the point of its intersection with the mechanical axis. DC angle is measured between the tangential line of distal femur and the projected anatomical axis. These angles were chosen since they are often used in clinical anatomy and surgery to determine the proper position and orientation of lower limb bones. One of the advantages of using these angles is a possibility for acquiring their values from the X-ray images. That is important because X-ray scanning is an important part in the patient recovery processes (to check whether the bone is healing well). Some example of X-ray image processing is presented in [11]. Industrial application of X-ray imaging is presented in that paper, but the applied image processing techniques can be used in medicine also.

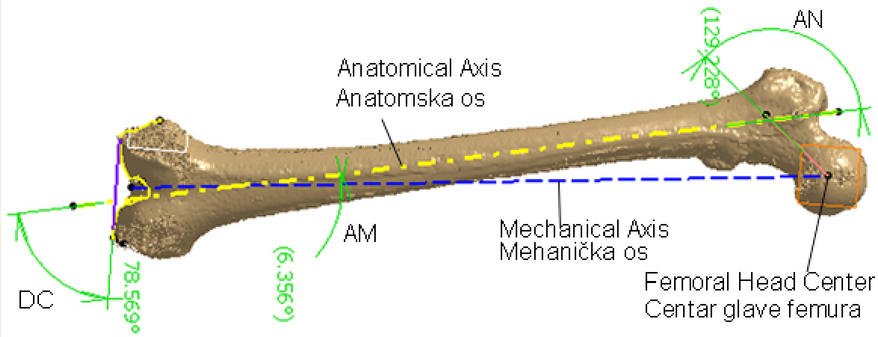

Figure 1. Adequate Femur dimensions (angles) defined on the femur polygonal model

Slika 1. Adekvatne dimenzije (kutovi) femura definirane na poligonalnom modelu femura

To test the geometrical accuracy of femur shaft surface model three cross sections were analyzed. Cross sections were created by intersection of planes normal to the LM (Lateral Medial) [9] and AP planes, and shaft geometrical models, Figure 2. The position of cross sections was defined by femur shaft anatomical landmarks. Cross sections were defined on three different types of femur shaft geometrical models and these models are:

- Imported polygonal model (from CT scans),
- Surface models created by using anatomical axis which was constructed by applying GCM and CPM on femur polygonal model.

In every cross section plane three spline curves were created. The first is a cross section boundary curve of imported model from CT scans, the second is a surface cross section boundary curve obtained by applying GCM, and the third is a surface cross section boundary curve obtained by applying CPM. Maximum and minimum deviations were measured between the curves from created and imported models, and the results are presented in this study. Measurements were done in AP and LM directions, together with maximum deviations between curves at adequate positions. By using these approaches, one can see advantages and disadvantages of a certain method (GCM and CPM) for the creation of patient adapted femur shaft surface model.

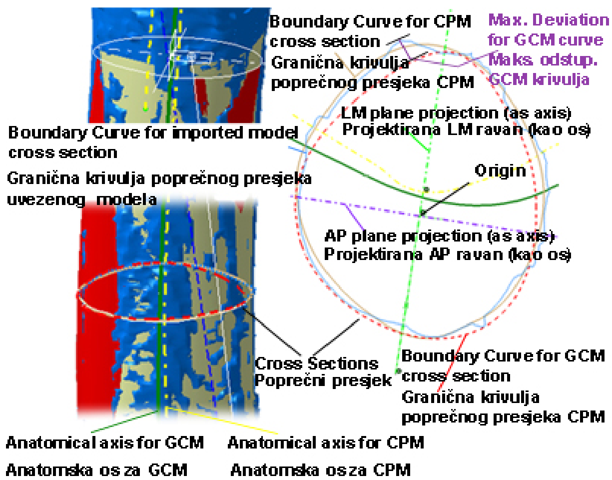

Figure 2. Cross sections boundary curves defined on femur shaft geometrical models

Slika 2. Granične krivulje poprečnih presjeka definirane na poligonalnom modelu tijela femura

Besides that, the 3D curve and the surface model of the femur shaft can be used to analyze the use of different aspects of implants in surgery of the skeletal system [12].

2.3. The anatomy of femoral shaft and its correlation with applied method

The body of the femur (or shaft), almost tubular in form, is a little broader above than in the center, broadest and somewhat flattened from before backward below. It is slightly arched, so as to be convex in front, and concave behind, where it is strengthened by a prominent longitudinal ridge, the linea aspera. The linea aspera is a prominent longitudinal ridge or crest, on the middle third of the bone, presenting a media (first third of the femur shaft) and a lateral lip (last third of the femur shaft), and a narrow rough, intermediate line. Concerning the shape one can say that femur shaft is slightly twisted and curved. The middle third of femoral shaft is almost cylindrical in the form. The anatomy and morphology of femoral shaft are used as the foundation for the methods presented in this study.

Figure 3 presents a polygonal model of femur with defined cross-sections. Cross-sections are created in planes normal to the anatomical axis of the femur. Basic planes are defined on anatomical boundaries of the femur shaft, e.g. the plane on the medial lip boundary. This enables defining anatomical regions of femur shaft to either create individual surface models, or a surface model of the whole femur shaft. The lower border of the lesser trochanter up to its transition into a medial lip on the proximal side, and the end of the medial supercondilar line on the distal femur side, serve as borders of the surface model. The basic sections aren't the only ones used to create the surface model; also the adequate number of sections (fifteen to be exact) among border sections is used to create the most geometrically and topologically accurate model of femur shaft possible. Accuracy of the surface model is tested on three middle control sections which are positioned mid anatomical regions (each third contains one control cross-section).

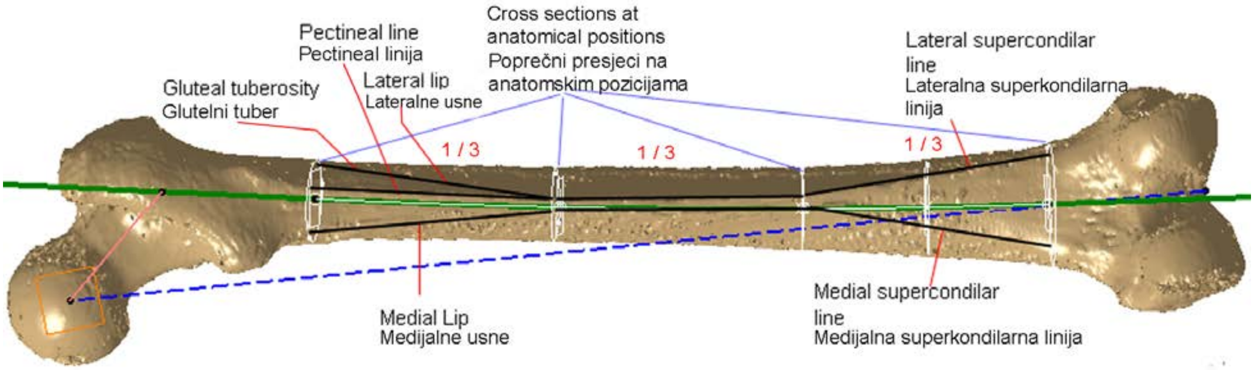

Figure 3. Cross sections defined on femur polygonal model, together with defined anatomical regions.

Slika 3. Presjeci definirani na poligonalnom modelu femura prikazani zajedno s anatomskim regijama

2.4. Identification of referential geometrical entities of femur

The geometrical analysis of the proximal femur is based on the reverse modeling of the scanned samples by CAD. The reverse modeling starts with importing the coordinates of the points of scanned tissue into appropriate CAD software. For this particular case, CATIA V5 R19 CAD software and its reverse engineering modules are used. In the next five phases, the previously developed reverse modeling procedure [9], customized for femoral geometry is being applied. The most important phase in reverse modeling of a human bone's geometry (and the femur) is the identification of the so-called *referential geometrical entities* (RGEs). Usually, these RGEs include characteristic points, directions, planes and views. All other elements of the redesigned bone's geometry (curves, surfaces and solids) should be referenced to RGEs. The basic subset of RGEs is related to the femoral overall geometry as it was described in [9]. This subset includes the most prominent points of the femur:

- 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 the reverse modeling procedure P_CFH, P_LEc, and P_MEc are used as referential points for creation of another crucial RGE of the femur: AP plane and the so-called AP view, *mechanical axis* of the femur (FMA), LM plane as well as *LM view*, femoral ***shaft axis*** (FSA) and femoral neck axis (FNA) [9].

2.5. GCM (Gravity Center Method)

This method uses same principle as the one described in [2], although with some differences. Instead of using only two points for anatomical axis creation, more points are used in this method. These points are gravity centers of the femur's body cross sections, Figure 4.

The procedure for creating anatomy axis of the femur is somewhat complex, and contains several steps, which are:

1. Creating basic RGE's (Referential Geometrical Entities) on the femur model. This procedure is described in [9] in more detail.
2. Creating plane of intersection (POI) which is a plane normal to the AP plane. The process of creating the AP plane is explained in [9].
3. Creating femur's body cross-sections, which are cross-sections between planes parallel to POI and femur's polygonal model, Figure 4.
4. Defining gravity centers of each cross section, Figure 4.
5. Creating 3D spline curve using near operator, with gravity center points as reference, Figure 4.
6. Extrapolating curve at end points towards the hip and tibia (tangent extrapolation).

The result of this process is a 3D spline curve which is actually the model of femur anatomical axis in 3D space. The measuring of three angles is done in AP plane, with projected anatomical and mechanical axis.

To confirm that this method is usable, the procedure is performed on ten femur specimens. The values for three defined angles are presented in Table 1.

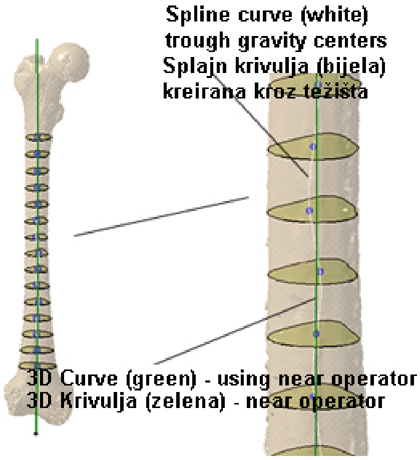

Figure 4. 3D spline curve (anatomical axis) created by using GCM

Slika 4. 3D splajn krivulja (anatomska os) kreirana pomoću GCM

Data in Table 1. show that angles are in the appropriate range (compared to study in [8]). Conclusion follows that this is an adequate procedure for creation of the femur's anatomical axis. For some bone models there is a possibility for vast angle(s) deviation; however, this is usually the case when a bone model is inadequate, perhaps due to: bone illness, wrong input data, osteoporosis, etc.

Table 1. Angle values for ten different femur models (GCM)

Tablica 1. Vrijednosti kuta za deset različitih modela femura (GCM)

Angle[°]\ Femur/ Kut \ Femur	1	2	3	4	5	6	7	8	9	10	Mean / Srednja vrijednost
AN	127.1	129	127	127	126	124.9	127.2	126.4	127.20	129.23	127.10
AM	8.36	7.61	7.86	8	3.4	7.8	8	7.6	7.56	6.36	7.26
DC	81	80.54	82.22	78.96	80.86	79.9	79.7	82	80.33	78.57	80.41

To confirm that this method is usable, another test was performed, and that test is a surface creation test. The geometrical model of the anatomic axes (3D curve) is used as a spine curve, for the creation of the femur shaft surface model, by using the loft feature. Curves which were used for loft feature are boundary curves of cross sections created by intersection of imported polygonal model and planes normal to the anatomical axis at adequate points. For this test fifteen (15) curves were created and used. The created surface is presented in Figure 5 and it can be seen that there are minor deviations from the original femur's body surface, which is something that this research is trying to achieve.

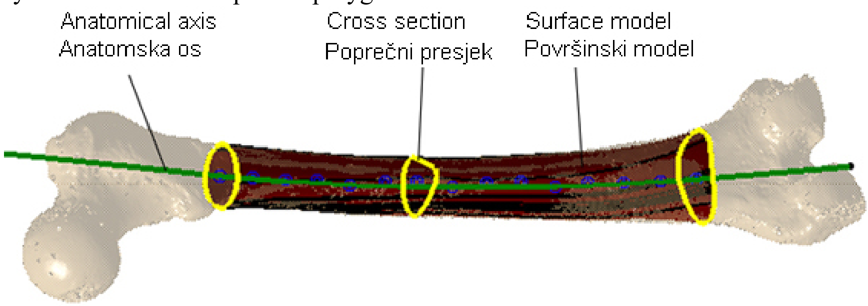

Figure 5. Femur shaft surface model created by using anatomical axis constructed by applying GCM on polygonal model

Slika 5. Površinski model tijela femura kreiran pomoću anatomske osi izgrađene primjenom GCM na poligonalnom modelu

2.6. CPM (Curve Projection Method)

This method uses a different procedure for defining femur's anatomical axis than standard methods do ([5] and [10]). Generally, the idea for this procedure emanated from the GCM when cross sections geometry was analyzed. The analysis shows that topology and geometry of cross section curves are very similar to the deformable ellipsis, Figure 2. Using that as a starting point for analysis, one can say that cross sections can be projected into two normal planes. These planes contain axes of ellipse, and they are normal to the cross section plane. In the normal plane, cross section is projected as a line, which is actually the axis of ellipse. Middle point of the line is actually the center of ellipse, and end points are the end points of the ellipse axes in appropriate directions, Figure 6. The procedure for this method is:

1. Defining position and orientation for the plane of intersection (POI). This plane is one of the initial planes (PX, PY, PZ) of the imported polygonal model.
2. Creating femur's body cross sections, which are cross sections between planes parallel to POI and femur's polygonal model, Figure 6.
3. Projecting cross section curves to the two perpendicular planes.
4. Finding middle points of the projected curves (lines).
5. Creating 2D spline curves in the normal planes using near or through operator (which depends on quality of curves) with middle points as reference, Figure 7.
6. Extrapolating 2D curves in tangent directions, Figure 7.
7. Creating surfaces as extended 2D spline curves in directions normal to the perpendicular planes, Figure 7.
8. Defining 3D spline curve as a result of the surfaces intersection, Figure 7.

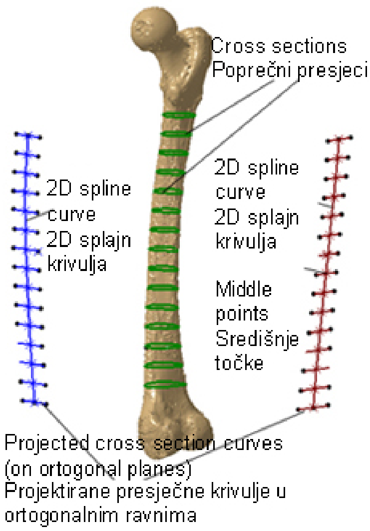

Figure 6. 2D Spline curves and projected cross section curves

Slika 6. 2D splajn krivulje i projiciran poprečni presjek krivulja

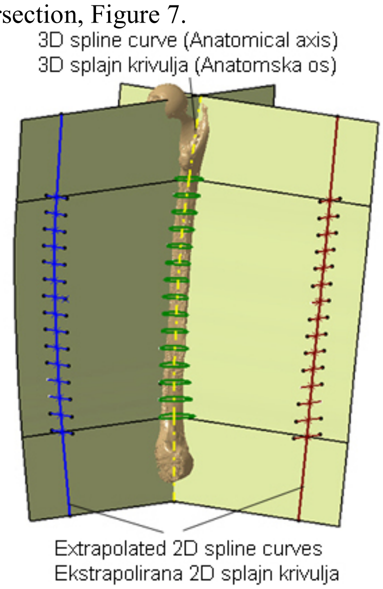

Figure 7. 3D spline curve (anatomical axis) created by using CPM

Slika 7. 3D splajn krivulja (anatomska os) kreirana pomoću CPM

Table 2. shows that angles are in the adequate range, with some deflections (compared to study in [5]). Conclusion follows, that this method is appropriate for anatomical axis creation.

The same procedure for surface model creation was performed as it was for a GCM method. The resulting surface model is presented in Figure 8.

Table 2. Angle values for ten different femur models (CPM)

Tablica 2. Vrijednosti kuta za deset različitih modela femura (CPM)

Angle[°] \ Femur / Kut \ Femur	1	2	3	4	5	6	7	8	9	10	Mean / Srednja vrijednost
AN	129.93	131.14	126.93	137.56	133.59	124.9	127.2	126.4	128.12	132	129.78
AM	6.36	8.78	11.21	8.85	5.94	7.8	8	7.6	7.82	9.6	8.20
DC	78.27	79.4	79.47	78.12	78.31	79.9	79.7	82	79.12	79.5	79.38

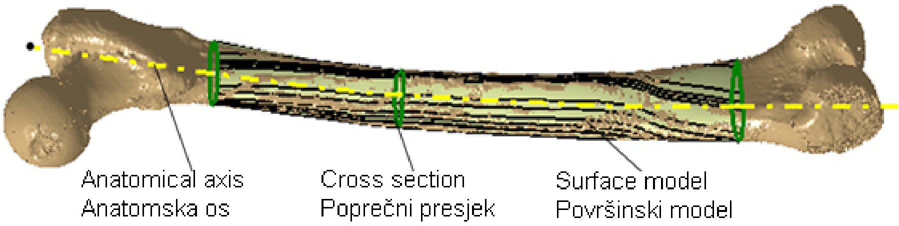

Figure 8. Femur shaft surface model created by using anatomical axis constructed by applying CPM on femur polygonal model

Slika 8. Površinski model tijela femura kreiran pomoću anatomske osi izgrađene primjenom CPM na poligonalnom modelu femura

3. RESULTS AND DISCUSSION

3.1. Measurement of anatomical axes deviations

Table 1. and Table 2. show different values for defined angles of ten femurs. It can be seen from the tables that values are in good range, with some deviations. For example in Table 2, there is a major digression in AN angle, 137.56 (CPM). This kind of digression can occur with some femurs due to: a defective femur model, an unhealthy or a deformed femur, etc. That's why arithmetic mean is used for calculating angle values, since it can describe general case, and not an individual occurrence. According to the measurement results (Table 3.), a conclusion follows that GCM method has an advantage in Anatomical axis – Neck axis angle, and in Distal Condylar Angle (but much less difference compared to the Anatomical axis – Neck axis angle).

Table 3. Angle mean values for GCM and CPM

Tablica 3. Srednje vrijednosti kuta za GCM i CPM

Angle[°] \ Method / Kut \ Metod	GCM	CPM	Known Values / Poznate Vrijednosti
AN	127.10	129.78	126
AM	7.26	8.20	6 - 8
DC	80.41	79.38	81

3.2. Measurement of surfaces deviations

As previously mentioned, the geometrical accuracy of created surfaces is assessed through three cross sections positioned mid the anatomical regions of the femur shaft. Both the values of boundary curves deviations in LM and AP direction, and the values of maximum deviation in relation to boundary curve of the cross-section of the entry model are measured. Figure 9. presents one of the cross-sections used to measure the correct deviation values.

The measurement procedure is performed as following:

1. Femur shaft geometrical models (imported, GCM, CPM) are divided into thirds, for each individual femur.

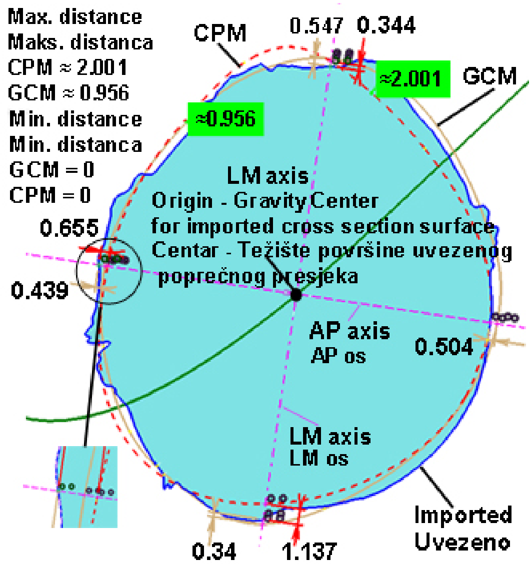

Figure 9. Characteristics dimension values between boundary spline curves (shaft proximal part)

Slika 9. Karakteristične vrijednosti dimenzija između graničnih splajn krivulja (proksimalni dio tijela)

2. Cross sections are created, one in the middle of each third of the femur shaft.
3. Values of correct dimensions are measured in each cross-section.
4. Mean of deviation is calculated based on both deviation in LM, AP direction, and maximum deviation for each cross-section.
5. Results of measurement and data processing are presented in Table 4.

The Table 4. shows that deviations are within acceptable limits. Maximum deviation is less than 2 mm for CPM, while means of deviation in LM and AP direction for both methods are less than and around 1 mm.

Table 4. Deviation values for GCM and CPM

Tablica 4. Vrijednosti odstupanja za GCM i CPM

Mean value for deviation in AP direction / Srednja vrijednost odstupanja u AP smjeru	**GCM**		**CPM**	
	Max. (proximal third / proksimalna trećina)	Min. (middle third / središnja trećina)	Max. (proximal third / proksimalna trećina)	Min. (middle third / središnja trećina)
	0.71	0.003	0.52	0.01
Mean value for deviation in LM direction/ Srednja vrijednost odstupanja u LM smjeru	**GCM**		**CPM**	
	Max. (proximal third / proksimalna trećina)	Min. (middle third / središnja trećina)	Max. (last third / zadnja trećina)	Min. (middle third/ središnja trećina)
	0.65	0.1	1.04	0.05
Mean value for maximal deviation / Srednja vrijednost maksimalnog odstupanja	**GCM**		**CPM**	
	1.2		1.85	

3.3. General discussion of results

Considering the results regarding anatomical axes and created surfaces, general conclusion follows that both methods can be applied for the creation of presented geometrical models. However, if precision is the most important condition, then the GCM is a better choice. This conclusion stems from the results shown in Table 3. and 4., where it can be seen that the mean deviations are less than deviations for CPM. If the speed of surface model creation is the main factor, then the second method ought to be used. One of the main reasons for this claim is that there is no need for RGE's definition, which can be a time consuming process.

Although the results of measurements show that both methods are correct, it is necessary to carry out analysis on more bone specimens. Only in that case a definitive opinion can be made on whether the methods are fully applicable and in which cases.

4. CONCLUSION

The presented research describes a new approach that help to clearly comprehend the geometry of the femur's shaft region (especially the cross section geometry) and, therefore, the geometry of the femur, too. This can improve the design of new implants, taking into consideration their anatomical landmarks, structure and distribution of their bony tissue, and stresses (as presented in [13] by Hsu RWW et al.).

Finally, the new way of looking at femur shaft can improve the surgery preparation and make it more efficient ([14],[15] and [16]). The methods described in this paper will be tested on more femur specimens. This does not imply only the amount of specimens, but, more values that can be compared, different geographical regions, various age groups, etc,. The main reason for further testing is creation of one universal method for femur anatomical axis definition, which will produce accurate results regardless of the input data.

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