

MEASURING GEOMETRIC PARAMETERS OF PROXIMAL FEMUR BY USING REVERSE ENGINEERING

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Today, total hip replacement surgery can be performed at many Vietnamese hospitals. However, all total hips in Vietnam are now imported from foreign countries. These hips are expensive and their designs do not accurately match with most Vietnamese patients. Designing total hips for Vietnamese patients is a demand at the moment. This paper presents a method to get some important geometrical parameters of Vietnamese proximal femur by using reverse engineering. In this method, the CT images of the femur were used as input data for 3D modelling in Mimics to get the 3D model of the femur. CATIA V5 was used to determine the geometric parameters of the proximal femur. The measured data can be used to design femoral stem in the standardized size set of total hip for Vietnamese patients.

KEYWORDS

Total Hip, Proximal Femur, Vietnamese Patient, Reverse Engineering, CAD

1 INTRODUCTION

Hip replacement surgery is a procedure in which a painful hip joint is replaced with an artificial joint. A normal hip joint is a ball-and-socket joint as shown in Fig. 1a. The ball is the head of the femur, called the femoral head. It is supported by the femoral neck. The socket, called the acetabulum, is a cup-shaped component of the pelvis. In total hip replacement, the diseased ball and socket are removed and replaced with an artificial ball and stem inserted into the femur bone and an artificial cup socket, as illustrated in Fig. 1b. To fix the stem in the medullary canal of the femur, a bone cement can be used. Alternatively, a cementless stem is used. This kind of stem has porous surfaces which allow bony ingrowth from the femur into the stem. This cementless hip has a longer duration and is suitable for younger patients. Generally, cemented total hip is preferred for old patients, while cementless total hip is preferred for young patients with high physical activity [Hailer 2010].

Nowadays, total hip replacement is on the rise in Vietnam. However, all total hips which are available in Vietnam are imported from foreign countries. Besides, most commercial total hips are designed and manufactured entirely to suit the geometrical considerations of the western population [Bagaria 2012], [Baharuddin 2011], [Baharuddin 2013] and they do not accurately match with most Asian patients [Mahaisavariya 2002]. Using a prosthesis that does not match with the anthropometry of the patient can cause complications such as aseptic loosening, improper load distribution, and discomfort

[Rawal 2012]. The need for design and manufacture total hips which match for Asian patients have stressed by some researchers [Bagaria 2012], [Baharuddin 2014a], [Mahaisavariya 2002]. Baharuddin and colleagues [Baharuddin 2014a] emphasized the differences between Asian and Western femoral morphology and pointed out that these differences should be used as a guide to improve the design of commercially available femoral stems particularly for Asian populations. This paper presents a method of using reverse engineering to get the 3D geometrical data of proximal femurs of Vietnamese people. These data can be used to design femoral stems of total hips for Vietnamese patients.

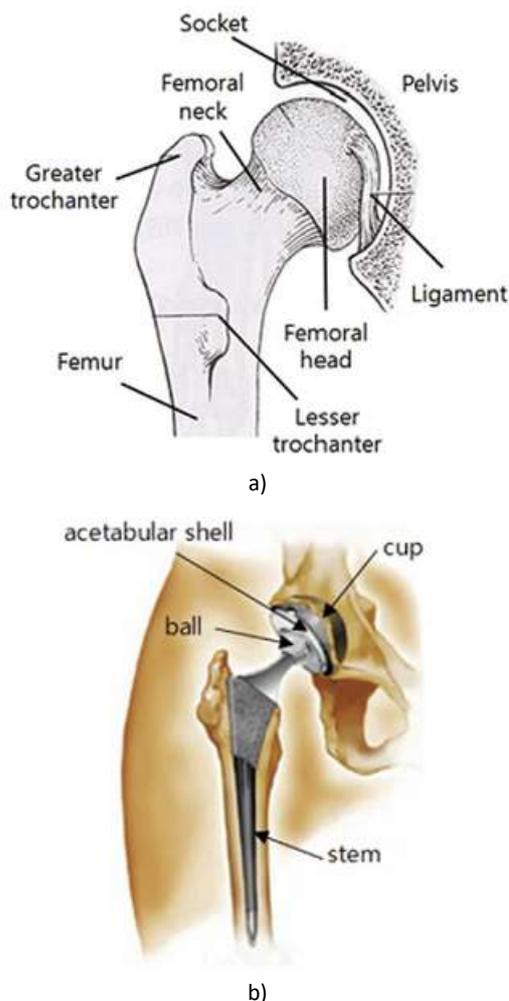


Figure 1. Bones of the hip joint: (a) Bones of the normal hip form a femoral head and socket; (b) The artificial cup is embedded in the pelvis bone and the stem is inserted into the femoral canal [Jun 2010].

2 MATERIALS AND METHODS

2.1 Femur geometrical parameters

To specify the overall shape of the hip joint, many geometrical parameters of the hip joint must be defined. These parameters can be used to design total hip. Some standard parameters of the proximal femoral geometry have been presented in [Mahaisavariya 2002], [Noble 1988], and [Rawal 2012]. Similarly, in this study, a set of 11 parameters was used to determine the proximal femur geometry, as presented in Fig. 2, including:

- Femoral head offset (A),
- Femoral head diameter (B),
- Femoral neck diameter (d),
- Position of shaft isthmus (l),

- Neck-shaft angle (J),
- Anteversion angle (K),
- Femoral neck length (P),
- Canal width at 20 mm above the lesser trochanter (D),
- Canal width at the level of the lesser trochanter (E),
- Canal width at 20 mm below the lesser trochanter (F),
- Canal width at the isthmus (G).

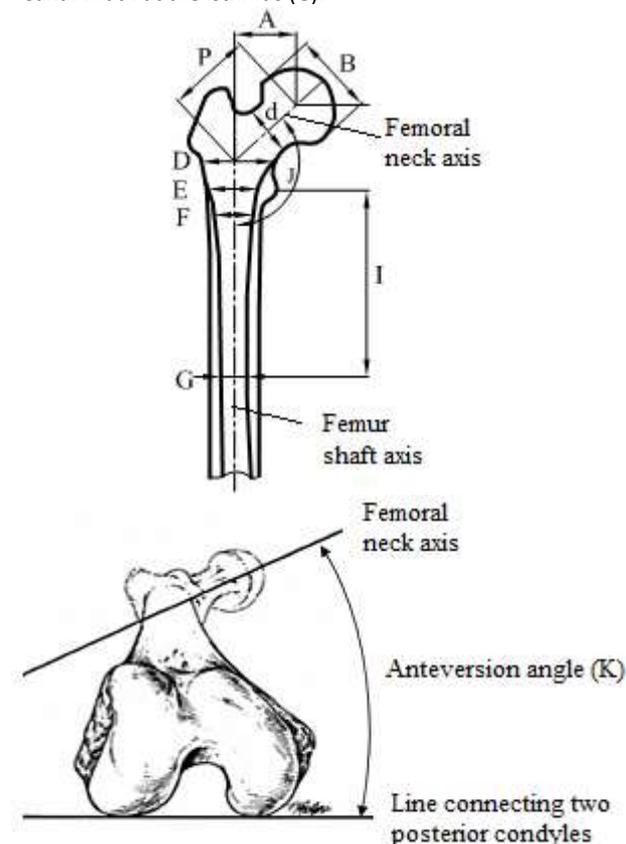


Figure 2. Measurement of anatomical parameters of femur bone [Jun 2010], [Rawal 2012].

2.2 Medical image acquisition and processing

The prerequisite of designing a femoral stem is to determine the geometric parameters of proximal femur. These parameters as well as the shape of the femur can be determined by femur reconstruction based on X-ray films, CT (Computed Tomography) images [Baharuddin 2014b], [Galibarov 2010], [Lee 2009], [Mahaisavariya 2002], [Otomaru 2012], [Ruyu 2005], [Rudek 2017]. Compared to CT images, X-ray films have some advantages. For example, it is more convenient, faster, and cheaper to take X-ray films than CT images, and there is less harm from radiation taking X-ray films than CT images. However, a more exact femoral model could be built according to CT images [Ruyu 2013].

The left and right femurs of 32 males and 33 females in the age range of 20 to 35 were evaluated in this study. The femurs of the normal patients were scanned by a SOMATOM Definition AS+ CT scanner (Siemens Healthcare, Germany). CT scans were taken at 1 mm intervals. After scanning, the CT images of the femur, saved in DICOM format, were imported to Mimics environment (Materialise, Belgium) in order to generate a 3D (three-dimensional) model of the femur. In Mimics, the 3D model of the femur was developed by a thresholding and region growing techniques to get the boundaries of the proximal femur. The 3D model was then exported to STL (Stereolithography) format. The STL file of the 3D femur model can be processed in CAD (Computer-Aided Design) software systems to determine the femur geometrical parameters.

2.3 Method of determination of femur geometrical parameters

Mahaisavariya and colleagues proposed a method of using computerized tomography images combined with reverse engineering technique to obtain and analyse the three-dimensional inner and outer geometry of the proximal cadaveric femur [Mahaisavariya 2002]. They approximated the shape of specific portions of the proximal femur with geometric configurations such as circle, ellipse or sphere that have the best fit to the real geometry in order to get 10 parameters of the proximal femoral geometry. The following are some main steps of this method:

- First, create a sphere that approximates the femoral head portion. From this sphere, the femoral head diameter and femoral head center can be defined.
- Second, find the smallest circular cross section and its center of the femoral neck, and then create the femoral neck axis which connects this center with the femoral head center.
- Third, create circles that fit the outer and inner surfaces of the femoral shaft and find out the smallest circular cross-section of the intramedullary canal (shaft isthmus).
- Last, create the proximal shaft axis that goes through the centre of each circle from the shaft isthmus level in proximal direction.

In this study, the above method was used to determine 11 parameters of proximal femur as follows: femoral neck length, femoral head diameter, femoral neck diameter, femoral head offset, neck-shaft angle, anteversion angle, canal width at the level of the lesser trochanter, canal width at 20 mm above and below the lesser trochanter, canal width at the isthmus, and position of shaft isthmus. After simplification of the CAD femur model, the dimension of each femur geometrical parameter can be measured in CAD environment.

Medical image processing software and commercial CAD software can be used to process the CAD model of proximal femur to get its geometrical parameter. Rahmati et al. used Mimics to reconstruct the canal of the proximal femur for edge-detection of the canal based CT image data to design the custom-made stem [Rahmati 2010]. Lee and Chang used Unigraphics NX to build a custom-made femoral stem from a group of geometric data of the femur measured from X-ray [Lee 2009]. Mahaisavariya and colleagues used Surfacer (Imageware Division, SDRC Inc.) to process the IGES files of CAD femur models in order to get 10 parameters of the proximal femoral geometry [Mahaisavariya 2002]. Other software such as IDEAS (Siemens AG, Germany), SolidWorks, CATIA (Dassault Systemes, France), Pro/ENGINEER, Creo Parametric (PTC, USA) can also be used to reconstruct the femur model from its point clouds [Hidayati 2018], [Jette 2018], [Li 2010], [Mandala 1991], [Tabakovic 2012].

In this study, the above method was used to determine the proximal femur dimensions. CATIA V5 was used to read this STL file and to perform measurement tasks in order to get the geometrical data of the proximal femur. The detailed description of determining of some femur geometrical parameters is as follows:

a. Femoral head center and radius

The femoral head can be approximated by a sphere. Its geometry parameters are head radius and head center. Then, the head offset length can be measured. Figure 3 presents some main steps to get the geometry parameters of the femoral head in CATIA V5. First, choose the femoral head surface, Fig. 3a. Second, create an approximated sphere from the chosen surface, Fig. 3b. Last, define the head center and the head radius, Fig. 3c.

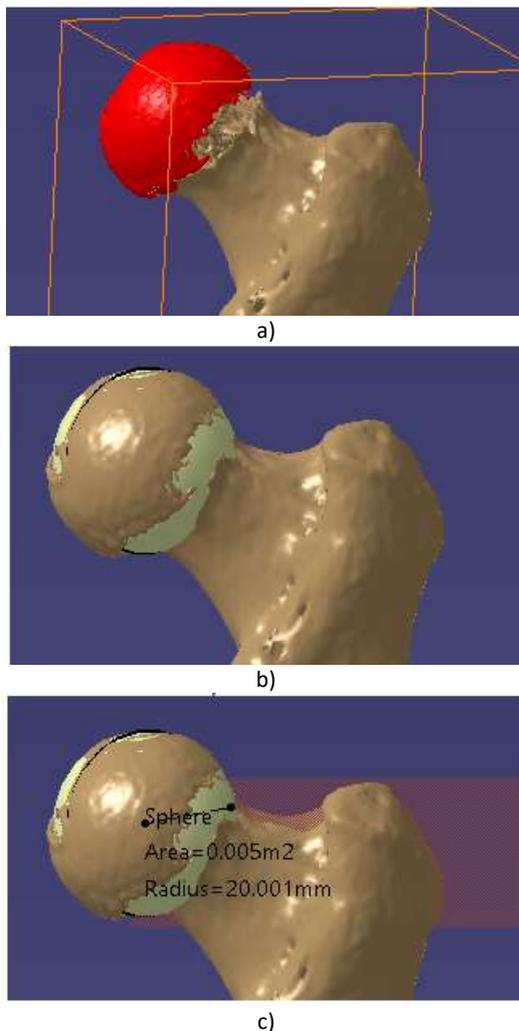


Figure 3. Three main steps to define the head center and its radius: (a) Choose the femoral head surface ; (b) Create a approximated sphere ; (c) Define the head center and the head radius.

b. Femoral neck axis

The femoral neck axis is a line connecting the center of the femoral head and that of the isthmus of the neck. Compare to other portions of the proximal femur, the femoral neck portion is more complicated in structure. The cortical bone of the femoral neck has an asymmetric cross-sectional distribution. This complex structure thus complicates the determination of the femoral neck axis.

To find the smallest circular cross section and its center of the femoral neck, Mahaisavariya et al. used the fit ellipse, fit circle and fit line functions to derive the position and diameter of the femoral neck isthmus and the orientation of the femoral neck axis. This method is quite complicated. In [Jun 2010], the femoral neck was sliced to find the femoral neck isthmus where the sliced circle has the smallest radius value. The orientation of slicing planes has 450 with a plane formed by the femoral shaft axis and an axis which passes through the femoral head center and is perpendicular to the femoral shaft axis. This fixed angle could be not suitable for any situation.

In this study, a novel and simple method to determine the femoral neck axis was developed with the following steps in CATIA V5 environment:

1. Choose the femoral neck surface (Fig. 4a).
2. Create a cylinder that approximates the chosen surface and draw the axis of the cylinder (Fig. 4b).
3. Create 15 equally spaced planes (perpendicularly to the cylinder axis) at 1 mm intervals on the middle portion of the

neck, then create the approximated circle of each section on each slicing plane (Fig. 4c).

4. Define the cross section with smallest perimeter then approximate it by a circle. Draw a line that goes through the center of approximated circle and the approximated sphere of the femoral head. This is the femoral neck axis (Fig. 4d).

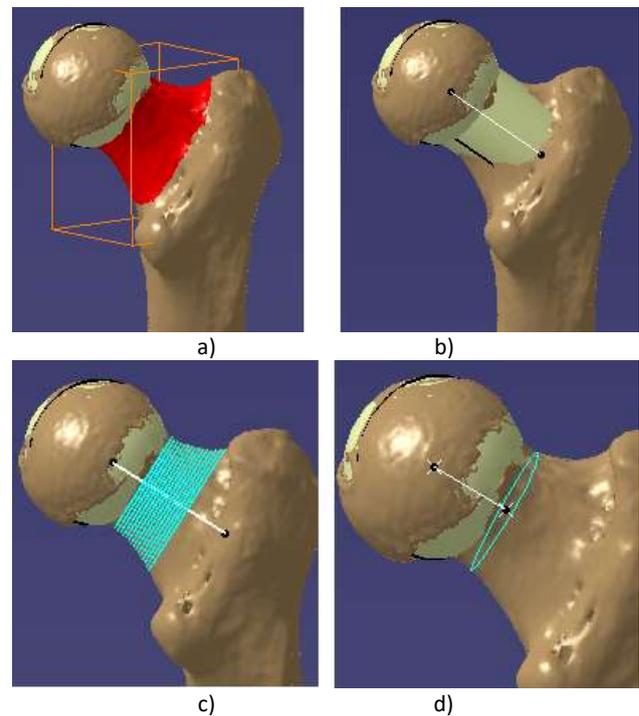


Figure 4. Some basic steps to define the femoral neck axis: (a) Choose the femoral neck surface; (b) Create a cylinder and its axis; (c) Create 15 circles on 15 equally spaced planes; (d) Draw the femoral neck axis.

c. Femur shaft axis and isthmus

The femur shaft axis is an axis through the center of the femoral canal. It can be defined by interpolating the center point of the approximated circle on each slicing planes of the femoral canal. The approximated circle can be determined by approximating the boundary section of the medullary cavity. The femur shaft isthmus is the location of the smallest circle along to the femoral canal. It is directly used to derive the anatomical femoral axis parameter which is the reference coordinate system of the hip joint [Jun 2010]. The following are some main steps to determine the femur shaft axis from a femur model in CATIA V5:

1. Remove the periosteum of the femur bone, keep the marrow of the femur bone; define an assumed axis of the femur shaft, (Fig. 5a).
2. Create 50 equally spaced planes at 1 mm intervals on the middle portion of the femur; these planes are perpendicular to the primary axis, then create the approximated circle of each section on each slicing plane, (Fig. 5b).
3. Measure the diameter of each circle and define the isthmus at the smallest circle, (Fig. 5c).
4. Choose the marrow from the isthmus to the lesser trochanter, (Fig. 5d).
5. Create an approximate cylinder from the chosen portion of the marrow to define the true femur shaft axis, (Fig. 5e).

2.4 Statistical analysis

In the study, Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) was used for statistical analysis. The data of various measured parameters were tabulated with the mean, standard deviation, and range of observations.

3 RESULTS AND DISCUSSION

Table 1 presents the measured data of 130 femurs with the mean, standard deviation, and range of observations. These

data are also relatively compared with those of from Thailand, India, Japan and Malaysia.

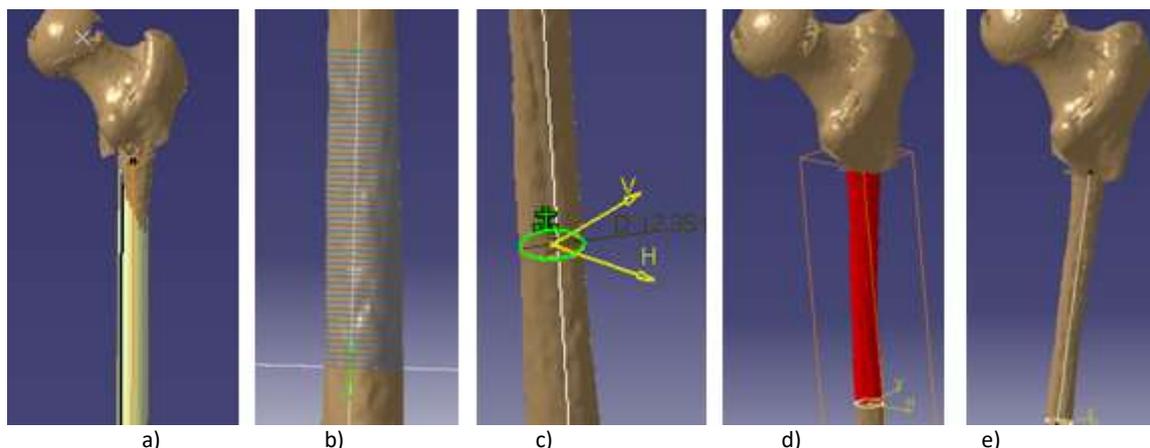


Figure 5. Main steps to determine the femur shaft axis: (a) Define an assumed axis of the femur shaft ; (b) Create 50 approximated circles on the middle portion of the femur; (c) Define the isthmus ; (d) Choose the marrow from the isthmus to the lesser trochanter; (e) Define the true femur shaft axis.

Table 1. Comparison of the femur geometrical parameters of Vietnamese population with those of the Thai, Malay, Indian and Japanese

Parameters, units	Present study, Vietnam (n = 130)			Thai [Mahaisavari 2002] (n = 108) Mean±SD	Malay [Baharuddin 2014a] (n = 60) Mean±SD	Indian [Rawal 2012] (n = 98) Mean±SD	Japanese [Bo 1997] (n = 100) Mean±SD
	Mean±SD	Min	Max				
Femoral neck length (P), mm	43.02 ±4.63	35.40	53.20	46.22 ±5.14	45.30 ±4.74	48.4 ±5.56	
Femoral head diameter (B), mm	46.66 ±3.92	38.40	54.30	43.98 ±3.47	40.81 ±3.43	45.41 ±3.66	
Femoral neck diameter (d), mm	30.65 ±2.30	24.20	35.30	29.05 ±2.73	28.95 ±3.37	-	
Femoral head offset (A), mm	41.24 ±4.74	28.70	51.40	-	30.35 ±4.26	40.23 ±4.85	31.5 ±5.0
Neck-shaft angle (J), degree	128.18 ±2.53	124.50	135.00	128.04 ±6.14	130.46 ±4.02	124.42 ±5.49	137.4 ±4.8
Anteversion angle (K), degree	10.67 ±2.08	6.40	15.20	11.37 ±7.65	19.10 ±8.67	10.9 ±4.22	27.0 ±14.1
Canal width at the level of the lesser trochanter (E), mm	31.43 ±3.57	23.50	39.70	-	-	23.75 ±4.18	
Canal width at 20 mm above the lesser trochanter (D), mm	35.86 ±3.71	27.20	42.60	-	-	36.78 ±5.32	
Canal width at 20 mm below the lesser trochanter (F), mm	27.77 ±3.74	19.80	36.40	-	-	16.73	
Canal width at the isthmus (G), mm	9.05 ±1.72	12.70	5.40	10.5 ±1.81	-	9.02 ±1.92	
Position of shaft isthmus (I), mm	106.50 ±9.3	142.0	71.0	112.93 ±17.96		107.8 ±9.73	

From Table 1, it can be seen that the average femoral neck length of Vietnamese population is shorter than that of the Thailand, India and Malaysia. On the contrast, the average femoral neck diameter of Vietnamese population is a little bit

higher than that of other populations. The average femoral head offset of Vietnamese population is a little bit higher than that of India population but much higher than that of Thai and Japanese populations. The neck-shaft angle of the Vietnamese

is similar to that of the Thai but smaller than that of the Malay and higher than that of the Indian and the Japanese. There is a little difference, less than 0.9° , between Vietnamese population and other (Thai, Indian) populations in term of the anteversion angle. While the anteversion angle for Malaysian and Japanese populations is much bigger. There is not much difference of the canal width at the isthmus among the reported values and that of the study. The position of shaft isthmus for Vietnamese and Indian populations is shorter than from 5.1 to 6.4 mm compared to that of the Thai population. From the results of this study, it can be said that the femur geometrical parameters of Vietnamese population are different from those of other Asian populations.

This study presents a method for determining geometric parameters of the proximal femur through its 3D model which was created from CT images. In [Mahaisavariya 2002], CT-scanned image was performed with 3 mm and 10 mm slice thickness and reconstruction was done with 1 mm and 5 mm interpolated slice in the two end regions and the femoral shaft of the femur, respectively. Similarly, the scanning intervals were 3 and 5 mm in the study of Jun and Choi [Jun 2010]. It is obvious that when scanned with the larger interval, the number of CT-scanned images is smaller, hence the size of the 3D model file is also smaller. Therefore, it is easy to manipulate the 3D model in CAD environment but the accuracy of the 3D model of the femur is not high. In our study, the scanning interval and the interpolated slice thickness in Mimic are 1 mm. In this case, the size of the femur model is bigger but there is no problem for manipulating the 3D model in CATIA with powerful computers these days.

Jun and Choi [Jun 2010] also used a similar method to determine geometric parameters of the femur. However, they only determined 7 parameters: femoral head center and radius, head offset length, femoral neck, neck shaft angle, anteversion, and canal flare index. The femur shaft is determined by interpolating the center point of the approximated circles on slicing planes which were created at distances of $\pm 10\%$ of the total femoral length. These distances could be large and then the isthmus could not be defined exactly.

The method for defining the geometrical parameters of the proximal femur presented in this study has some advantages as follows: (a) the ability to measure more accurately the 3D parameters of the femur that cannot be performed by a 2-dimensional radiographic measurement; (b) the ability to get more accurately the 3D parameters of the femur compared to those measured by researchers in [Jun 2010] and [Baharuddin 2014a]. However, one of limitations of this study is that it is time consuming to reconstruct the CAD model of the femur and measure its geometrical parameters. On average, it took about 35 minutes to get a set of geometric parameters of a femur.

From the obtained data, a set of 8 sizes of stems for Vietnamese patients was determined. Figure 6 shows a 3D model a stem for Vietnamese patients. This is a double taper stem, narrowed distally in both medial-lateral and anterior-posterior planes. The lower part of stem will be coated with Ti-6Al-4V, which enhances fixation of the implant to the femur. In this study, some stems were machined on a 3-axis machining center for manufacturing trials. The result shows that the designed stems can be machined to meet its engineering requirements by domestic technologies. Fig. 7 presents a real stem of the design without Ti-6Al-4V porous coating.

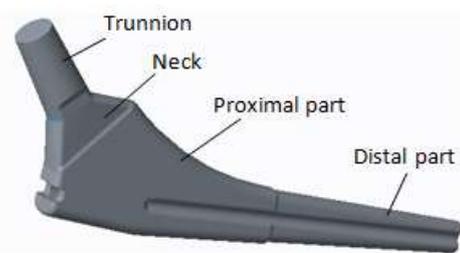


Figure 6. Solid model of a designed stem created in Creo Parametric.

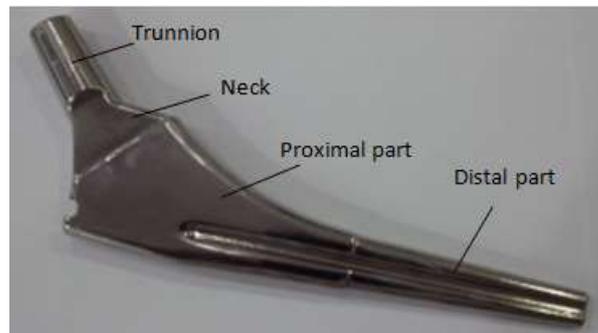


Figure 7. A real stem of the design.

4 CONCLUSION

A method of measuring geometrical parameters of proximal femur is presented. 130 femurs of 65 Vietnamese normal patients were scanned by a CT scanner. The CT images of the femur were used as input data for 3D modelling in Mimics to get the 3D model of the femur. The STL format of this model was then imported to CATIA V5 to determine the geometric parameters of the proximal femur. The following parameters were measured for each proximal femur: femoral head offset, femoral head diameter, femoral neck diameter, position of shaft isthmus, anteversion angle, neck-shaft angle, femoral neck length and canal width at some special positions. The measured results show that there are significant differences in the geometric parameters of the proximal femur between Vietnamese populations and other populations. The morphological data of the proximal femur in this study can be used for the design of proper size and shape of femoral prostheses for Vietnamese patients. However, to get a better design, more more accurately measured data must be obtained. Determining the geometrical parameters of proximal femur of Vietnamese people with higher average age is one of our further study.

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