The muscle standardized femur: a step forward in the replication of numerical studies in biomechanics

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Abstract: The standardized femur is the computer aided design (CAD) solid model of a synthetic human femur, commonly used in experiments *in vitro*, available in the public domain through the International Society of Biomechanics Finite Element Mesh Repository. Currently used by hundreds of researchers, it was made available to simplify the experimental cross-validation of numerical studies as well as their replication by other researchers. One aspect that the standardized femur left uncovered is the definition of muscles and ligaments. In particular, for a variety of simulations it would be extremely useful to map on to the femoral surface the insertion of the principal muscles. The aim of the present study was to create a new solid model, called the muscle standardized femur, where the femoral insertion of each muscle is mapped on to the surface of the femur. Published data on muscle insertion morphometry were registered to the model by applying an affine scaling defined on bone landmarks. Good agreement was found with another similar study in which only the insertion centres were defined. The new model will be made available in the public domain for no-profit uses. When combined with published data on the direction and intensity of muscular forces this model is expected to make a useful contribution to the steadily growing library of models and data sets made available to the biomechanical community.

Keywords: muscle anatomy, standardized femur, finite element analysis

1 INTRODUCTION

The quantitative anatomy of the musculo-skeletal apparatus presents considerable intersubject variability [**1**, **2**]. Whether such variability must be considered or not in a particular study largely depends on the question the study aims to answer. Many research questions, to be properly addressed, require such intersubject variability in order to be considered. In many other cases, however, it is sufficient to model one generic anatomy when investigating a specific biomechanical problem (e.g. see references [**3**] to [**9**]).

Because of this, as well as to simplify the experimental cross-validation of numerical studies, a computer aided design (CAD) solid model of a synthetic human femur, commonly used in experiments *in vitro*, was made available in the public domain [**10**]. The scientific community found this model to be very useful. Between 1998 and 2002 more than 1200 researchers downloaded the model, called the 'standardized femur', from the International Society of Biomechanics (ISB) Finite Element Mesh Repository [**11**].

One aspect that the standardized femur left uncovered was the definition of muscles and ligaments. In particular, for a variety of simulations it would be extremely useful to map the insertion of the principal muscles on to the femoral surface. Because the reference femur used to create the model is a synthetic bone, no direct definition of the muscle geometry is available. The insertion mapping may only be derived on the basis of similarity with cadaver specimens.

To the authors' knowledge, only in one published study were muscle insertions mapped on to the standardized femur model [**4**]. In order to investigate the influence of the muscle forces on the femoral strain distribution the coordinates of the muscle attachment centroids [**12**] were scaled to the standardized femur model. A finite element model was created from the standardized femur geometry and the resultants of the muscle actions for a specific motor task [**13**] were applied as nodal forces.

While the coordinates of the muscle attachment centroids may be sufficient for many purposes, in some other cases it would be useful to have the whole area of the muscle insertions identified on the standardized femur surface. Some examples are as follows:

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1. In experimental studies, it is possible to accurately machine the insertion of the straps used to simulate muscles.
2. In finite element studies, it is possible to investigate the effect of the load distribution on the insertion surface by spreading the load over all nodes falling inside the insertion patch.
3. In computer modelling, the model can be used as a registration template to model muscle insertions from MRI data.

The aim of the present study is to create a new solid model, called the muscle standardized femur (MuscleSF), in which the femoral insertion of each muscle is mapped on to the surface of the femur. Rather than trying to represent an average anatomy, which in the present context is not univocally definable, the MuscleSF model was designed to reproduce one particular but generic human femur and its muscle insertions.

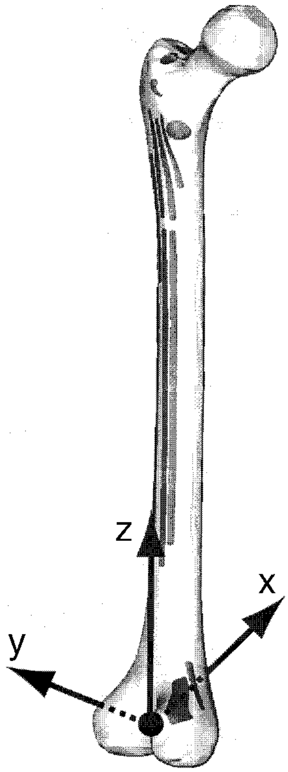

Fig. 1 The reference system used in reference [**12**] and also adopted in this study

2 MATERIALS AND METHODS

A variety of resources were used in the present study. The model is based on the current version of the standardized femur (version 2.2) and on the published data from six cadaver specimens [**12**]. Additional anatomical data were derived from anatomical atlases [**14**, **15**], a three-dimensional computer atlas [**16**], a mapped skeleton (3B Skeletons, Kappa Medical, USA) and the data from the Visible Human Project [**17**].

All cadaver data were expressed in a right-handed reference system originating from the femoral insertion of the posterior cruciate ligament (PCL) (Fig. 1) [**12**]. The Z axis points to the most proximal point of the greater trochanter. The X axis is perpendicular to a line passing through the most medial and the most lateral point on the condyles and is oriented frontally. The Y axis is oriented laterally [**18**]. Thus, the first step was to locate the same points on the standardized femur model. The bone landmarks were accurately measured. The PCL insertion was defined using results from a study where its position is expressed with respect to the other bone landmarks [**19**]. To verify the accuracy of the procedure, the locations of the synthetic bone landmarks were also measured on a physical specimen.

The coordinates of the bone landmarks were compared to those reported for the cadaver specimens by computing the root mean square difference between the coordinates of bone landmarks on the composite femur and on each cadaver specimen. Adopting the same numbering conventions used in the original study, it was found that among the six specimens, specimen 2 was the most similar to the composite femur.

Thus, the coordinates of the muscle attachment centroids reported for specimen 2 were scaled to the standardized femur model (scaled insertion centroids) using a least-squares solution for an affine scaling transformation [**20**, **21**] computed with the single value decomposition [**22**]. The affine model requires that lines that are parallel before transformation remain parallel after transformation. Affine models cannot register large differences of femoral anteversion. However, more complex elastic registration would require a number of bone landmarks much larger than those available.

The shape of each muscle insertion area was derived from a three-dimensional computer model of the Visible Human Project male data, verified on the atlases and reproduced as a B-spline contour projected on to the SF external surface. Contours were placed with their centroids (insertion area centroids) as close as possible to the scaled insertion centroids. For some muscles, anomalies and regional overlapping were found. An expert anatomical drawer, on the base of the anatomical atlases, manually adjusted the shape of the insertion areas for these muscles. Thus, the resulting insertion area centroids were not exactly centred at the scaled insertion centroid coordinates. Once muscle insertions were mapped on the standardized femur model, the coordinates of the insertion area centroids were compared to those reported in reference [**12**]. An error propagation model was used to evaluate the effect of the initial measurement uncertainties on the final results.

3 RESULTS

The current version of the SF computer model replicates the geometry of the synthetic femur with an average accuracy of 1.1 mm. The location of the synthetic bone landmarks, as measured on a physical specimen, differed from those located on the computer solid model, with less than this accuracy. The only exception was the landmark at the tip of the greater trochanter, where there is a layer of epoxy resin that did not appear in the computed tomography (CT) images used to create the model. Thus, for this point, the coordinates derived from the physical model were used.

The coordinates of the SF landmarks, expressed in the anatomical reference system, were found to be comparable to those of the cadaver specimen 2 (Table 1), with an average root mean square (r.m.s.) difference of 25.5 mm. After rigid scaling the average difference was reduced to 4.5 mm.

Two adjustments were necessary. Since the femoral PCL insertion is located medially, contrary to what was reported in the original data [**12**], the coordinate Y (medial-lateral direction) of landmark M2 (lateral femoral epicondyle) should be greater in absolute value than that of landmark M3 (medial femoral epicondyle). This is clearly visible in one of the illustrations of reference [**1**]. It was assumed that the two numbers were erroneously inverted. The coordinates Z (proximal–distal direction) of points M2 and M3 were not considered in computing the rigid registration because the standardized femur presents relatively flat epicondyles that make this coordinate unreliable.

The insertion areas were visualized as colour-coded patches on to the SF surface (Fig. 2). The coordinates of the insertion area centres were compared to those of the scaled insertion centres and to those computed by Duda *et al.* using the average of the six cadaver specimens (Table 2). The two capi of the gluteus maximus as well as the insertion of the gluteus medius and of the adductor brevis were described in the previous study with two separate insertions to account for the large insertion area. For these muscles the average between the two points was compared with the centre of the insertion area of the MuscleSF model.

Using the error propagation model, the effect of the initial measurement uncertainties on the final results was calculated. The estimated error is equal to 25 mm on each coordinate. Comparing the insertion area centres to the coordinates reported by Duda *et al.* for a few muscles, namely gluteus maximus, psoas major, iliacus, adductor magnus cranial, adductor minimus and vastus medialis, the differences were found above this threshold and thus could not be explained simply by uncertainty of the measurements.

4 DISCUSSION

The present study was aimed at the creation of a computer geometric model, based on the standardized femur geometry, of a human femur complete with muscle insertions. Each step of the procedure used to create such a model was qualified in terms of accuracy. A few experts accurately inspected the resulting model and it was found that the muscle insertions were consistently in agreement with well-known anatomical atlases [**14**,**15**]. However, a direct validation of the model described here is not possible.

An indirect validation can be achieved with respect to the literature; the centres of the insertion areas can be compared to those reported in a previous study [**4**]. Because the two studies used different approaches, perfect agreement cannot be expected. However, for most of the muscles the observed differences can be explained by the uncertainty of the original measurements. For a few insertions the differences were much larger. For these muscles the insertions on the MuscleSF seemed anatomically correct when compared to anatomical atlases [**14**–**16**]. This was not true for the insertions provided in the previous study:

1. The femoral insertion of the gluteus maximus is normally distal to the lesser trochanter, while the insertion of the gluteus medius is usually located 30–50 mm more proximally [**14**–**16**]. Using the data from reference [**4**] the gluteus maximus inserts on to the greater trochanter and the gluteus medius inserts very close to the gluteus maximum.

Table 1 Bone landmark coordinates of cadaver specimen 2 of the standardized femur and of specimen 2 after being rigidly scaled to match the standardized femur. Coordinates marked by * were excluded. See text for details

		Femur 2			Standardized femur			Femur 2 scaled		
Landmark	Number	X	Y	Z	X	Y	Z	X	Y	Z
Greater trochanter	M1	0.0	0.0	465.7	0.0	0.0	401.3	0.0	0.0	399.0
Lateral femoral epicondyle	M2	3.1	48.7	39.6	−1.8	41.1	*	1.9	42.7	35.7
Medial femoral epicondyle	M3	3.1	−39.0	17.1	−0.5	−30.7	*	1.9	−34.1	13.0
Centre of the femoral head	R1	19.5	−54.2	468.5	−2.6	−55.3	398.2	12.1	−47.3	398.7
Femoral PCL insertion	R2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

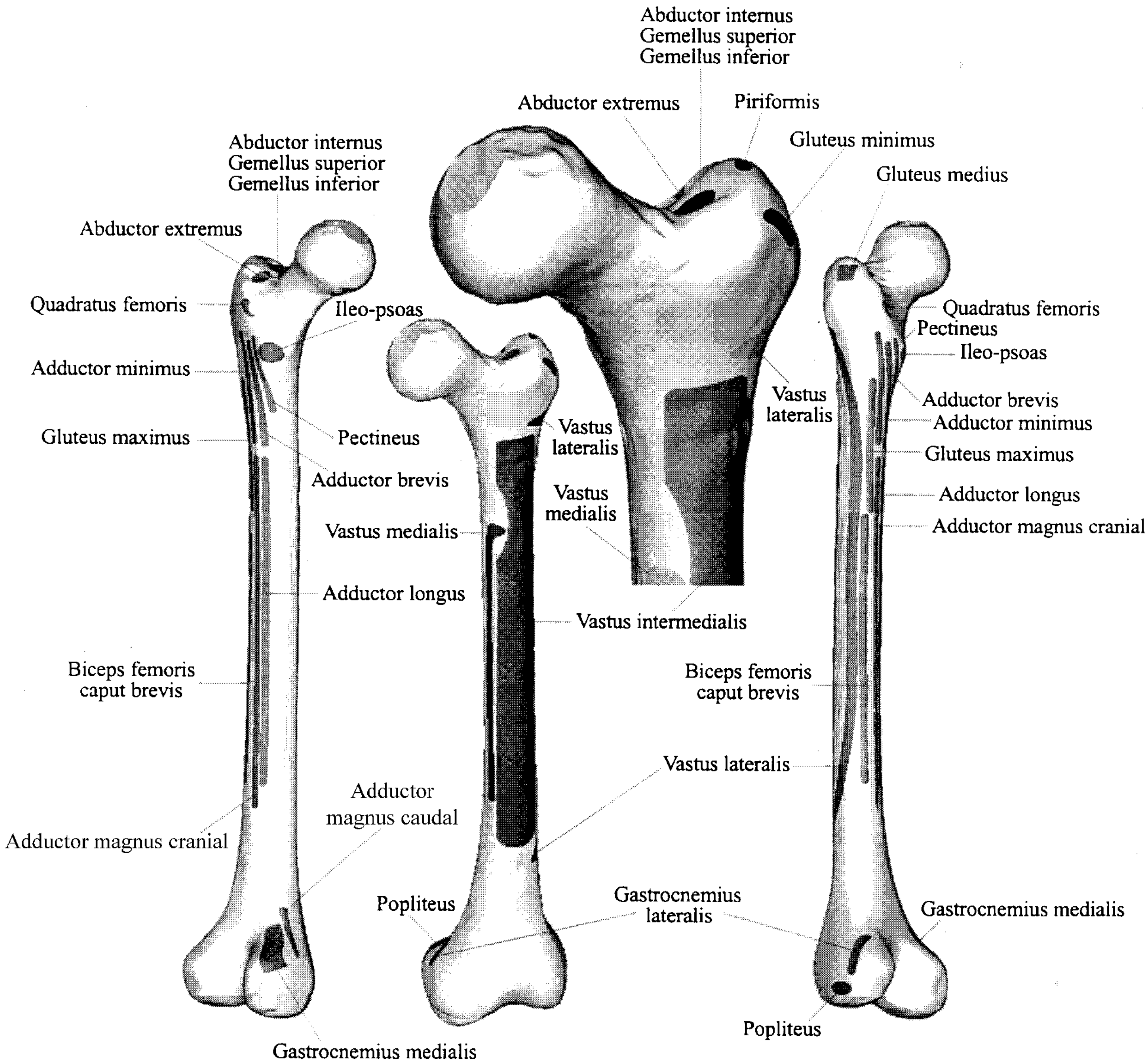

Fig. 2 The muscle standardized femur as seen from various points of view. The muscle insertions are visualized as colour-coded patches on the model surface

2. The common insertion of the psoas major and of the iliacus muscles is usually located on the lesser trochanter [**14–16**], but using the data from reference [**4**] the insertion falls proximal to it.
3. The insertion of the adductor minimus is usually proximal to that of the adductor magnus cranial proximal [**14**, **15**], but using the data from reference [**4**] the minimus is situated distal to the magnus.
4. In reference [**4**] the insertion of the vastus medialis seems far too distal from its anatomic location. In all cadaver specimens investigated in reference [**12**] the insertion of this muscle was found to be more proximal than the location they reported for the SF anatomy.

The muscle standardized femur will soon be made available in the public domain through the ISB Finite Element Mesh Repository [**11**]. Although the MuscleSF will probably be very useful to many researchers in the field, it is important to stress some inherent limitations of this model.

As for the standardized femur [**10**], the MuscleSF is not meant to model every human femur or the average human femur, but only to model one generic human femur. The intersubject variability of bone and muscles anatomy is considerable [**1**, **2**]. Whether such variability must be considered in a particular study largely depends on the question the study aims to answer. There are many research questions in which the anatomy of the muscle insertions cannot be presumed to be constant. In these cases the use of the MuscleSF would be inappropriate.

The present model could have been created, with a higher level of accuracy, by deriving it directly from the

Table 2 Coordinates of the insertion centre of all muscles inserting on the femur. From left to right: computed by rigid scaling to the standardized femur the points collected by Duda [**12**] on cadaver 2; centre of the insertion areas of the muscle standardized femur; centres computed by Duda [**12**] by scaling to the standardized femur the insertions averaged over the six cadaver specimens

	Femur 2 scaled			Areal centres			Duda SF		
	X	*Y*	*Z*	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Gluteus maximus 1	−11.9	18.6	326.3	−7.9	−1.7	295.2	−5.7	10.3	407.5
Gluteus maximus 2	−13.1	8.4	288.6				−13.1	2.6	349.9
Gluteus maximus 3a	−4.6	21.6	405.8	−1.7	18.6	375.6	−11.6	10.9	392.2
Gluteus maximus 3b	−4.6	21.6	405.8				−11.6	10.9	392.2
Gluteus medius 1	5.8	24.3	388.9	−8.7	7.6	392.9	−4.5	8.6	410.6
Gluteus medius 2, 3	−7.8	14.6	392.4				−4.5	8.6	410.6
Gluteus minimus 1, 2, 3	10.7	20.5	380.7	7.3	7.6	390.2	0.0	0.0	413.7
Psoas major	0.4	−20.7	337.1	−19.4	−24.8	344.6	−12.2	−33.5	370.4
Iliacus	−0.2	−22.5	335.9	−19.4	−24.8	344.6	−12.2	−33.5	370.4
Tensor fasciae latae a	5.8	24.3	388.9	−1.7	18.6	375.6	6.3	15.4	393.2
Tensor fasciae latae b	5.8	24.3	388.9	−1.7	18.6	375.6	6.3	15.4	393.2
Piriformis	−7.5	−1.1	404.9	−4.6	0.8	401.4	1.7	−7.5	413.7
Obturator internus	−15.9	−8.8	397.3	−0.3	−11.7	393.6	0.9	−10.4	410.6
Obturator externus	−12.6	−23.3	376.5	−11.4	−10.7	388.4	−5.7	−11.1	407.2
Gemellus superior	−18.3	−4.5	399.4	−0.3	−11.7	393.6	0.9	−10.4	410.6
Gemellus inferior	−15.9	−8.8	397.3	−0.3	−11.7	393.6	0.9	−10.4	410.6
Quadratus femoris	−20.0	−2.0	368.2	−22.0	−8.5	370.9	−17.8	−29.3	367.2
Pectineus	−2.8	−8.2	311.9	−16.7	−17.3	331.7	−16.5	−11.1	339.5
Adductor brevis 1	1.8	−7.9	287.8	−14.7	−12.2	322.3	−15.6	−6.9	339.6
Adductor brevis 2							−11.4	−11.3	311.7
Adductor longus	1.1	−5.8	204.5	1.6	−7.9	194.4	−3.2	−5.7	216.1
Adductor magnus caudal	−5.7	−39.6	22.3	9.2	−22.3	19.5	3.6	−27.7	41.9
Adductor magnus cranial	−4.8	−0.5	268.1	0.7	−2.6	188.3	1.4	−24.0	276.2
Adductor minimus	−3.1	7.6	254.4	−15.2	−5.7	326.2	7.4	−21.5	174.4
Biceps femoris, caput brevis	5.1	2.8	186.4	3.4	5.2	181.5	−0.9	−1.6	204.3
Popliteus	−12.9	18.5	−8.1	9.5	41.0	−9.0			
Gastrocnemius lateralis	−17.5	33.5	22.4	−0.3	36.7	10.5	−17.9	26.8	11.4
Gastrocnemius medialis	−8.3	−18.4	34.0	−3.6	−21.5	9.2	−24.7	−24.5	10.3
Vastus medialis (fem)	5.1	−9.9	248.1	19.2	−16.4	212.1	15.5	−21.9	180.8
Vastus intermedialis (fem)	13.0	1.6	263.0	25.0	−2.2	220.7	21.3	−16.8	199.3
Vastus lateralis (fem)	4.0	11.4	289.5	7.3	8.0	228.5	16.7	1.2	217.3

data made available by the Visible Human Project or by the VAKHUM Project [**23**]. However, the use of the standardized femur as bone geometry is fundamental to ensure the cross-validation of numerical models by means of experimental measurements *in vitro*. Switching to another anatomical reference would have seriously limited the usefulness of the model.

Because of the complexity of the task, the authors cannot exclude *a priori* the fact that errors or omissions may not affect the proposed model. It is hoped that many colleagues will download the model, double-check it and report any problem so that it can be fixed. In doing so, a positive loop will be created, hopefully useful for the entire biomechanics community, especially if the model is combined with published data on the direction and the intensity of muscle forces such as those reported in references [**13**] and [**24**].

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