

The Three-Dimensional Morphology of the Patellofemoral Joint and the Normal Predicted Value of Tibial Tuberosity-Trochlear Groove Distance In Chinese Population

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Research article

Keywords: Patellofemoral joint, tibial tuberosity-trochlear groove distance, knee morphology, LASSO regression

Posted Date: November 23rd, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-100152/v1>

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Abstract

Our objective was to obtain normal patellofemoral measurements so as to provide a reference for prosthetic design. Besides, the absolute values and indices of TT-TG distances are still controversial in clinical application. A better method to enable precise clinical applications is still needed.

Methods:

78 knees of 78 subjects without knee pathologies were included in this cross-sectional study. A CT scan was obtained from all subjects and three-dimensional knee models were constructed using Mimics and SolidWorks software. We measured and analyzed 19 parameters including TT-TG distance and dimensions and shapes of patella, femur, tibia, and trochlea. LASSO regression was used to predict the normal TT-TG distances.

Results:

The dimensional indexes, TT-TG distance, and femoral aspect ratio of the males were significantly larger than those of females (all P values <0.05). However, after controlling the bias from age, height, and weight, there were no significant differences in TT-TG distances, PAL, and anterior-posterior dimensions between genders (all P values >0.05). The Pearson correlation coefficients between the AFO and other indexes were consistently below 0.3, indicating a none or weak relationship. Similar results were observed for the SA and the Wiberg index. Using LASSO regression, we obtained four parameters to predict TT-TG distance ($R^2=0.5612$, $P<0.01$) to achieve the optimal accuracy and convenience.

Conclusion:

The anterior-posterior dimensions of the females were thicker than those of males for the same medial-lateral dimensions. More attention should be paid to not only gender differences but individual differences, especially the anterior condyle and trochlea. Besides, this study provided a new method of predicting TT-TG distance to enable precise clinical diagnoses and guide the medial transfer of the tibial tuberosity.

Introduction

Although total knee arthroplasty (TKA) has proven to be a successful surgical procedure for alleviating pain and improving function in patients with knee osteoarthritis, patient satisfaction rates after TKA vary between 75% and 89% [39]. Anterior knee pain is a major reason for the dissatisfactions, which may be caused by a variety of abnormalities, including patellofemoral pathologies [44]. More and more researchers have observed mismatches of the patellofemoral joints after TKA. Matz *et al.* reported that the probabilities of changes in anterior femoral offset, anteroposterior size of the femur and anterior patellar offset after TKA were 40%, 60%, and 71%, respectively, compared with those before TKA[34]. Kalichman *et al.* suggested that increased trochlear angles were associated with exacerbated functional

impairments [30]. Moreover, Jan *et al.* highlighted that the patellofemoral geometry was of great importance in TKA, but was often overlooked[29]. Finally, most of the endoprosthetic designs of the knees are based on the anatomical data of Caucasians, and less relevant for Asians and may result in component mismatches[33, 51].

In the last few decades, researchers reported the shape differences of knees between ethnicity and gender. An extensive study from Mahfouz *et al.* analyzed 1000 normal adult knees to identify differences in three-dimensional knee morphology among Caucasian, African American, and East Asian populations, which calculating 11 femoral and 9 tibial measurements[33]. Asseln *et al.* comprehensively analyzed 412 pathological knees following TKA using 33 femoral and 21 tibial features to investigate gender differences and they indicated that large inter-individual variations should also be important for specific implant design despite gender differences [3]. Yue *et al.* investigated the morphologic measurements of femur and tibia in healthy Chinese and white subjects and described the differences in knee anthropometry between gender and ethnicity [51]. Although most of the literatures affirmed gender differences between knee morphology, several literatures suggested no gender differences regarding anterior condylar anatomy and posterior condylar offset [15, 49]. Meanwhile, relative fewer studies on gender differences of patellofemoral morphology were investigated and most of them analyzed the patella, but not the anterior and posterior condylar of the femur or entire patellofemoral joint [31, 35, 40]. In conclusion, the sexual dimorphism of the entire patellofemoral morphology is still controversial.

The tibial tubercle-trochlear groove (TT-TG) distance is a well-established reliable index that evaluates tibial tubercle lateralization and patellofemoral instability. Increased TT-TG distance is generally implicated as a risk factor for patellofemoral instability and used as an important criterion to make decisions in surgical procedures[27, 46]. The TT-TG value of > 15 mm is recommended as abnormal, and the value of > 20 mm is the threshold for performing tibial tubercle osteotomy[12, 37]. However, this absolute value does not respect the anatomic differences between gender and ethnicity, and it was hypothesized that TT-TG distance is highly correlated to the knee size [13, 25, 38]. Hernigou *et al.* indicated that the normal TT-TG distances varied as the knee sizes and predicted the normal TT-TG value of Greek using the femoral width and tibial width for the first time. However, the mediolateral width of the femur and tibia might not be the best parameters to describe the knee sizes, and similar parameters also included the height and weight of the patient [23]. Thus, it is still needed to analyze appropriate parameters to predict the normal TT-TG distance and to create the reference criterion in Chinese.

Therefore, our objectives were (a) to obtain normal patellofemoral measurements and identify gender differences to provide a reference for prosthetic design; (b) to determine the normal predicted TT-TG value to enable precise clinical diagnoses and prediction of medial transfer of the tibial tuberosity.

Materials And Methods

Subject demographics

78 subjects (38 females) were recruited at the Second Affiliated Hospital of Xi'an Jiaotong University from May 2017 to October 2017. The local ethics committee of the hospital approved the project. Only the normal and nonpathological joints were included in this research, which was verified through clinical examination and CT images. Pregnant women or family planners and those with any knee abnormality were excluded. Informed consent was obtained from all included subjects. Female subjects were younger (29 ± 5 years vs 34 ± 3 years, $P < 0.01$), shorter (165 ± 3 cm vs 177 ± 5 cm, $P < 0.01$), and weighed significantly less than males (57 ± 6 kg vs 70 ± 9 kg, $P < 0.01$). Only one side of the knee was chosen to be studied and the left or right knee was chosen by random to maintain the independence of the data.

CT Protocol and creation of 3-Dimensional knee model

A CT scan of the lower limb was obtained using a helical CT scanner (120 kV, 200 mA, reconstruction thickness 0.6 mm, reconstruction spacing 0.4 mm, GE revolution CT, General Electric Company, Milwaukee, Wis). All subjects were supine and non-weightbearing as per protocol with the extension of all knees. All DICOM images were imported and segmented in Mimics software (version 17.0, Materialise Inc., Leuven, Belgium), which exported the 3-Dimensional reconstructions of tibia, femur, and patella. The reconstructed models were then processed with SolidWorks engineering software (version 2017, Dassault Systemes Company, Concord, Massachusetts). Appropriate coordinate systems were established to obtain standard radiographic views including lower and lateral views of the patella and femur, axial views taken in 30° knee flexion of the femur, and upper view of the tibia.

Definitions and measurements of parameters

In the lower view of the patella, the following parameters were measured in this study.

1. patella width (PW): the distance between the tangent line of the medial margin and the tangent line of the lateral margin of the patella.
2. patella lateral facet width (PLFW): the distance between the most prominent point of the central ridge and the tangent line of the lateral margin of the patella.
3. patella thickness (PT): the distance between the most prominent point of the central ridge and the tangent line of the anterior margin of the patella.
4. patella facet thickness (PFT): the distance between the most prominent point of the central ridge and the tangent line of the deepest margin of the patella facet.

Meanwhile, the Wiberg index (PLFW/PW) was calculated[17], and the morphology of the patella was determined by the Wiberg classification as modified by Baumgartl and Ficat[45].

In the lateral view of the patella, the following parameters were measured in this study.

1. longitudinal length of the whole patella (PLL): the distance between the most prominent point in the upper pole and the most prominent point in the lower pole of the patella.
2. longitudinal length of the articular surface of the patella (PAL): the distance between the upper margin and the lower margin of the articular surface of the patella. (Fig. 1)

In the lower view of the femur, the following parameters were measured in this study.

The mediolateral (fML) and anteroposterior (fAP) sizes of the femur: taking the posterior condylar line (PCL, the line along the most posterior margins on each condyle) as a reference, a rectangular bounding box that fitted the distal femur was created. And the fML and fAP values were measured using the bounding box. Meanwhile, the femoral aspect ratio (fML/fAP) was calculated.

In the upper view of the tibia, the following parameters were measured in this study.

1. the mediolateral width of the tibia (tML): the maximum width of the tibia plateau in the mediolateral direction.
2. the anteroposterior size of the tibia (tAP): the maximum length of the tibial plateau in the anteroposterior direction, through the midpoint of the intercondylar eminence (Fig. 2).

The TT-TG distance was defined as the distance between the most anterior point of the tibial tuberosity and the deepest point of the trochlear groove, with parallel and reference to PCL (Fig. 3). CT images were observed in Mimics software and the transverse picture of the most anterior point of the tibial tuberosity was firstly selected. Next, the transverse picture of the proximal trochlea at the level of the "roman arch" was selected. The two pictures were proceeded and merged using the ImageJ software (the National Institutes of Health, Bethesda, MD, USA) and the TT-TG distance was measured in the final merged picture. All transverse pictures were kept perpendicular to the vertical axis of the lower limbs, implemented through online reslice of Mimics software, to maintain the accuracy and consistency of the obtained data.

In the lateral view of the femur, the following parameters were measured in this study.

1. anterior femoral offset (AFO): the distance between the anterior edge of the femoral cortex and the anterior aspect of the anterior femoral condyle.
2. posterior femoral offset (PFO): the distance between the posterior edge of the femoral cortex and the posterior aspect of the posterior femoral condyle (Fig. 4).

In the axial views taken in 30°knee flexion of the femur, the following parameters were measured in this study.

1. sulcus angle (SA): the angle between the two lines connecting from the highest points of the medial and lateral condyles to the lowest point of the femoral sulcus, respectively.
2. lateral and medial trochlear inclination (LTI, MTI): the angle between the PCL and the line connecting from the highest points of the lateral and medial condyles to the lowest point of the femoral sulcus, respectively. And SA, LTI, and MTI add up to 180°.
3. trochlear angle (TA): the angle between the PCL and the line passing along the most anterior edge of the medial and lateral trochlear facets (Fig. 5).

Two readers who had many years' experience of radiography took the measurements and repeated the measurements after two weeks.

Statistical analysis

All statistical analyses were performed using R (version 3.5.1, R Foundation for Statistical Computing, Vienna, Austria), and p values less than 0.05 were considered significant. The intraclass correlation coefficient (ICC) was performed to determine intrarater and interrater reliability, and the intrarater and interrater reliabilities were good to excellent (all ICCs > 0.85, Table 1).

Table 1
Reliability assessment

Variable	Interrater (ICC)	Intrarater (ICC)
PT(mm)	0.987	0.988
PFT(mm)	0.959	0.962
PW(mm)	0.935	0.974
PLFW(mm)	0.989	0.992
PLL(mm)	0.990	0.991
PAL(mm)	0.858	0.958
fML(mm)	0.967	0.971
fAP(mm)	0.956	0.959
tML(mm)	0.987	0.991
tAP(mm)	0.988	0.991
TTTG(mm)	0.923	0.956
AFO(mm)	0.959	0.973
PFO(mm)	0.988	0.988
SA(°)	0.976	0.984
LTI(°)	0.973	0.981
MTI(°)	0.973	0.982
TA(°)	0.979	0.979
PT = patella thickness, PFT = patella facet thickness, PW = patella width, PLFW = patella lateral facet width, PLL = longitudinal length of the whole patella, PAL = longitudinal length of the articulating surface of the patella, fML = mediolateral size of the femur, fAP = anteroposterior size of the femur, tML = mediolateral size of the tibia, tAP = anteroposterior size of the tibia, AFO = anterior femoral offset, PFO = posterior femoral offset, SA = sulcus angle, LTI = Lateral trochlear inclination, MTI = medial trochlear inclination, TA = trochlear angle.		
ICC = intraclass correlation coefficient.		

For normally distributed data, the two-sample Student's t-test was performed to determine the significance of the difference between the genders, otherwise, the Mann–Whitney U test was used. Next, multiple variable linear regression analysis was used to analyze the significant difference between the genders again after controlling the bias from age, height, and weight. The Pearson correlation coefficients were performed to explore the relationship among all parameters.

The LASSO (Least Absolute Shrinkage and Selection Operator) regression models were constructed to predict the normal TT-TG distances. Firstly, the boxplot was generated to determine the outliers from the

distribution of TT-TG in males and females, respectively. After deleting the outliers, the remaining data were both normally distributed. The LASSO regression models were created using the “glmnet” package of R software. We selected the directly measured parameters above the moderate correlation coefficient with TT-TG distance to enter the model for coefficient progression. And sex also entered the initial model. The LASSO regression introduces λ as a tuning parameter on the basis of linear regression, which controls the overall strength of the penalty. The greater the penalty is, the fewer parameters are retained in the model. Then the independent variable that has a great influence on the dependent variable is selected and a relatively simplified model can be obtained. We used the mean squared error (MSE) as the selection criterion to describe the performance of the model. 10-fold cross-validation was automatically performed to calculate the λ value and MSE for a varying number of independent variables. We used the λ at which the minimal MSE is achieved (lambda.min) and the largest λ at which the MSE is within one standard error of the minimal MSE (lambda.1se) to select the optimal model.

Results

Demographic data

78 knees were included in the study. The means and standard deviations for all parameters, as well as age, height, weight, and BMI, are shown in Table 2. Regarding the Wiberg classification as modified by Baumgartl and Ficat, type I, II and III accounted for 7.5% (n = 3), 90% (n = 36) and 2.5% (n = 1) in males; and for 10.5% (n = 4), 89.5% (n = 34) and 0 (n = 0) in females, respectively. No other type was found. This indicates that most of the selected patellas were stable.

Table 2
Demographic statistics and Gender differences (n = 78 knees)

	male	female	overall	P value	P' value
Age(y)	34 ± 3	29 ± 5	32 ± 5	< 0.01	
Height(cm)	177 ± 5	165 ± 3	171 ± 8	< 0.01	
Weight(kg)	70 ± 9	57 ± 6	64 ± 10	< 0.01	
BMI	22.37 ± 1.79	20.98 ± 2.18	21.70 ± 2.09	< 0.01	
PT(mm)	22.42 ± 1.57	19.80 ± 1.29	21.15 ± 1.94	< 0.01	0.188
PFT(mm)	11.77 ± 0.93	10.94 ± 0.96	11.36 ± 1.03	< 0.01	0.935
PW(mm)	46.94 ± 2.50	40.51 ± 2.34	43.81 ± 4.03	< 0.01	< 0.01
PLFW(mm)	27.18 ± 2.18	23.34 ± 1.59	25.31 ± 2.71	< 0.01	< 0.01
Wiberg index	0.58 ± 0.03	0.58 ± 0.03	0.58 ± 0.03	0.797	NA
PLL(mm)	45.21 ± 2.75	38.84 ± 2.64	42.11 ± 4.17	< 0.01	< 0.01
PAL(mm)	30.75 ± 2.43	26.82 ± 1.81	28.83 ± 2.91	< 0.01	0.089
fML(mm)	86.35 ± 3.99	74.14 ± 3.11	80.40 ± 7.10	< 0.01	< 0.01
fAP(mm)	66.78 ± 3.30	60.15 ± 2.81	63.54 ± 4.52	< 0.01	0.107
fML/fAP	1.29 ± 0.05	1.23 ± 0.05	1.26 ± 0.06	< 0.01	< 0.01
tML(mm)	80.46 ± 2.83	70.16 ± 2.52	75.44 ± 5.82	< 0.01	< 0.01
tAP(mm)	55.75 ± 3.13	48.72 ± 2.29	52.32 ± 4.47	< 0.01	< 0.01
TTTG(mm)	14.29 ± 2.11	12.92 ± 0.86	13.62 ± 1.76	< 0.01	0.090
AFO(mm)	6.37 ± 1.39	5.62 ± 1.37	6.01 ± 1.42	0.019	NA

PT = patella thickness, PFT = patella facet thickness, PW = patella width, PLFW = patella lateral facet width, PLL = longitudinal length of the whole patella, PAL = longitudinal length of the articulating surface of the patella, fML = mediolateral size of the femur, fAP = anteroposterior size of the femur, tML = mediolateral size of the tibia, tAP = anteroposterior size of the tibia, AFO = anterior femoral offset, PFO = posterior femoral offset, SA = sulcus angle, LTI = Lateral trochlear inclination, MTI = medial trochlear inclination, TA = trochlear angle.

P values represent the significant differences between genders applying the two-sample t-test for independent samples.

P' values represent the significant differences between genders after controlling the bias from age, height, weight using the multiple variable linear regression model.

Data are presented as mean ± SD.

NA represents no linear relationship or not meeting the condition for linear regression analysis.

	male	female	overall	P value	P' value
PFO(mm)	26.77 ± 2.05	24.62 ± 1.78	25.73 ± 2.19	< 0.01	0.291
SA(°)	139.44 ± 4.95	138.20 ± 4.55	138.83 ± 4.77	0.254	NA
LTI(°)	20.92 ± 2.82	21.61 ± 3.71	21.25 ± 3.28	0.358	NA
MTI(°)	19.65 ± 3.58	20.20 ± 3.15	19.92 ± 3.37	0.473	NA
TA(°)	2.66 ± 1.97	2.93 ± 2.28	2.79 ± 2.11	0.587	NA
PT = patella thickness, PFT = patella facet thickness, PW = patella width, PLFW = patella lateral facet width, PLL = longitudinal length of the whole patella, PAL = longitudinal length of the articulating surface of the patella, fML = mediolateral size of the femur, fAP = anteroposterior size of the femur, tML = mediolateral size of the tibia, tAP = anteroposterior size of the tibia, AFO = anterior femoral offset, PFO = posterior femoral offset, SA = sulcus angle, LTI = Lateral trochlear inclination, MTI = medial trochlear inclination, TA = trochlear angle.					
P values represent the significant differences between genders applying the two-sample t-test for independent samples.					
P' values represent the significant differences between genders after controlling the bias from age, height, weight using the multiple variable linear regression model.					
Data are presented as mean ± SD.					
NA represents no linear relationship or not meeting the condition for linear regression analysis.					

Gender differences of patellofemoral measurements

When using two-sample t-test for independent samples for gender comparison, PT, PFT, PW, PLFW, PLL, PAL, fML, fAP, femoral aspect ratio, tML, tAP, TT-TG distances, AFO and PFO of males were significantly larger than those of females, and the differences were statistically significant (all P values < 0.05). After controlling the bias from age, height, and weight, there were no significant differences in TT-TG distances, PAL, and anterior-posterior dimensions including PT, PFT, fAP, and PFO between genders (all P values > 0.05). Meanwhile, PW, PLFW, PLL, fML, femoral aspect ratio, tML, tAP of males were still significantly larger than those of females (all P values < 0.05). No significant differences between males and females were identified for the Wiberg index, SA, LTI, MTI, and TA (all P values > 0.05).

Pearson correlation coefficient analysis

As was shown in Fig. 6, the height, weight, the dimension of the patella, the dimension of the femur, the dimension of the tibia, and TT-TG distance were moderately-highly positively correlated with each other (r: 0.32 ~ 0.96, all P values < 0.05). Similarly, PFO exhibited medium correlation to the upper indexes (r: 0.34 ~ 0.63, all P values < 0.05) except TT-TG distance (r = 0.14, P = 0.22). The femoral aspect ratio was moderately correlated with the most of the dimensions including the height, weight, PW, PLFW, PLL, PAL, fML, tML, tAP, and TT-TG distance (r: 0.33 ~ 0.60, all P values < 0.05), but none correlated with PT, PFT, fAP, AFO, PFO, and all angles (r < 0.3, all P values > 0.05). Besides, the angles exhibited a none or weak correlation to the dimensional indexes (r < 0.3) except that SA was moderately correlated with PLFW (r =

0.33, $P < 0.05$). And medium-high correlation was found among angles ($r: -0.49 \sim -0.73$, all P values < 0.05), except the none correlation between MTI and LTI ($r = 0.03$, $P = 0.79$), SA and TA ($r = -0.07$, $P = 0.57$). In conclusion, the dimensions generally exhibited positive correlations with each other, but the none or weak correlation to the angles.

Interestingly, the Pearson correlation coefficients between the AFO and other indexes were consistently below 0.3, indicating a none or weak relationship between AFO and all other indexes. However, AFO trended to be positively correlated with height, PT, PLL, PAL, fML, fAP, tML, tAP, TT-TG distance, LTI, and TA ($r: 0.23 \sim 0.29$, all P values < 0.05). Similar results were observed for the SA and the Wiberg index. SA exhibited a none or weak correlation with most of the indexes ($r < 0.3$), except PLFW, the Wiberg index, LTI, and MTI ($r = 0.33, 0.32, -0.71, -0.73$, respectively, all P values < 0.05). The Wiberg index exhibited a none or weak correlation with most of the indexes ($r < 0.3$), except PLFW and SA ($r = 0.49, 0.32$, respectively, all P values < 0.05). Taken together, the AFO, SA, and the Wiberg index all varied greatly, and only none or weak correlations with most of the indexes were found.

LASSO regression to predict normal TT-TG distance

LASSO regression model was constructed to analyze the prediction of the normal values of TT-TG distances. 14 indexes were selected into the model. Coefficient progression was shown in Fig. 7. Taking lambda.min as a reference, 12 indexes were included and only PW and PLL were excluded ($R^2 = 0.7064$, $P < 0.01$), which was not convenient to clinical application. Thus we took lambda.1se as a reference, and the height, fML, tML, and tAP were included in the final model ($R^2 = 0.5612$, $P < 0.01$). The formula is defined as:

$$\text{"TT - TG distance = height * 0.029 + fML * 0.069 + tML * 0.005 + tAP * 0.010 + 2.307"}$$

The height is expressed in cm, while the fML, tML, and tAP in mm. In this study, only data with the height ranging from 160 to 185 cm, fML ranging from 67.51 to 94.36 mm, tML ranging from 64.37 to 87.73 mm, and tAP ranging from 44.27 to 63.15 mm were included. Thus this formula might not be available to the populations beyond that range. Sex was excluded in this model, which indicated that sex had little influence on the predictive performance of model. Taken together, on the premise of ensuring high model quality, we reduced the parameters to the minimum and established a formula that is convenient for clinical application.

Table 3
Comparison of the patella thickness (mm) with the data from literature

Population studied	male	female	study
Caucasian	23.9*	21.8*	Baldwin <i>et al.</i>
Caucasian	26.1*	22.6*	Chmell <i>et al.</i>
Caucasian	25.3*	22.5*	Hitt <i>et al.</i>
Caucasian	24.9*	21.0*	Rooney <i>et al.</i>
Korean	22.7	20.4	Yoo <i>et al.</i>
Indian	20.3*	16.2*	Muhamed <i>et al.</i>
Chinese	22.42	19.80	Present study
* P < 0.01, data are presented as mean.			

Discussion

In the past few decades, TKA has achieved great development, but there is a high rate of dissatisfaction, often due to patellofemoral pathologies. In addition to surgical techniques, inappropriate prosthetic design often results in mismatches of the patellofemoral joints [10, 28]. It has been reported in the literature that even a millimeter-level error in TKA can lead to serious consequence [43]. In this study, we made comprehensive measurements of patellofemoral joints as a whole, obtained gender differences, and exploratively found some morphological characteristics, which provided a reference for prosthetic design. Meanwhile, we used LASSO regression model to predict the normal values of TT-TG distances so as to enable precise clinical diagnoses and predict medial transfer of the tibial tuberosity accurately.

Many studies have reported on the measurements of patella thickness. The comparisons of patellar thickness with those measured in other studies are shown in Table 3. We used student's t test to determine the significant differences between present results and those reported in other literatures. The result indicated that the patella thickness of Chinese tended to be smaller than that of the Caucasians, while comparable to that of the Korean and greater than that of the Indian [4, 9, 26, 35, 40, 50]. This finding is consistent with the results from previous studies [31, 35, 50]. The re-establishment of original thickness and adequate residual bone thickness is considered as key surgery guidelines in TKA [22]. However, due to the mismatch of the patellar implants, the surgeons had to choose between the re-establishment of original thickness and adequate residual bone thickness. By choosing the former, the low residual bone thickness likely causes fracture and instability; by choosing the latter, the increased thickness of patella causes overstuffing of the patellofemoral joint and leads to anterior knee pain [1, 41]. Although several studies have shown that adverse clinical outcomes were not likely to occur if the overall and residual bone thickness of patella was maintained in a reasonable range (postoperative thickness within 3 mm of the original thickness of the patella, and residual thickness between 10 and 15 mm), the

changes of the patella might affect the patellofemoral contact pressures, thus leading to complications of the patellofemoral joint [31]. Therefore, the patellar prostheses with more available choices should be designed according to patellar characteristics.

We explained many gender differences from this study. The result showed that the dimensional indexes of the males were generally larger than those of females, which was consistent with previous studies [33, 40]. In terms of the shape, the patella and the femur of the females were thicker than those of males in the anterior-posterior direction for the same medial-lateral dimensions, which was consistent with the relatively small femoral aspect ratio in females. Therefore, the shape of the distal femur of the males was more "flat" compared to females, while females had a narrower distal femur than males. These results were comparable to those reported in previous studies [5, 19, 33, 51]. We found that the Wiberg index and the shape of the trochlear exhibited no dimorphisms between gender. Gillespie et al reported that no significant difference between gender was found in the medial and lateral flange, which was similar to our results [19]. Based on these features, gender-specific prostheses should be designed in consideration of gender characteristics. However, more and more studies focused on not only gender differences but individual differences [3, 5]. Taking this issue into account, we exploratory analyzed the correlation coefficient between all parameters.

This study found that AFO, SA and the Wiberg index all varied greatly among individuals. These three indexes are the primary description of the patellofemoral shape and thickness. To avoid overstuffing and notching of patellofemoral compartment, the AFO should be treated appropriately. Matz et al reported that the probabilities of changes in AFO after TKA were 40% compared with those before TKA [34]. Although some previous studies showed no significant differences between restoration of AFO and clinical outcomes, there was a trend toward improved outcomes [34, 42]. Other studies showed that if the AFO increased after TKA and there was a risk of overstuffing due to the mismatch of the prosthesis, the pressure of the patellofemoral joint would increase, and then there would be complications such as anterior knee pain and decreased knee motion [20]. If there was a risk of notching of the patellofemoral joint, it led to cause instability in knee flexion [6]. Taking these issues into account, more and more studies analyzed the shape and variance of the distal femur. Lonner and Gillespie et al indicated that the overall variability of the anatomy of the distal femur should be taken into account but not gender difference [19, 32]. According to the individual differences, Everhart et al proposed a binary classification system to describe the shape of the distal femur and five binary categories were selected based on the aspect ratio, trochlear width, trochlear tilt, the ratio of medial and lateral trochlear width, and trochlear groove angle [14]. Besides, Varadarajan et al reported that the laterally oriented proximal part and medially oriented distal part formed the intact trochlear groove, and there was a turning point to distinguish these two parts [48]. Moreover, Chen et al proposed a quaternary system based on the position of the turning point [8]. Due to the greatly individual variance of the distal femur, more studies on different shapes of the femoral components should be focused, and prosthetic implants with greater varieties in sizes and shapes of anterior femoral condyle needed to be designed.

The TT-TG distance had significant positive correlation with tubercle sulcus angle (TSA) and Q-angle, and was considered to be objective and reliable in the quantification of extensor mechanism malalignment and patellar instability[21, 23]. In the previous studies, the measurement of the TT-TG distance was mainly used in image overlapping technology based on CT and MRI. However, several literatures have reported the inaccuracy of the current measurement[2, 21], and we found that mild adduction or abduction of the lower extremity resulted in a greater change in this value. In this study, we took this issue into account, and used the online reslice of the mimics software to standardize the selection of images, so that the collected transverse picture was as perpendicular to the mechanical axis of the lower limb as possible, which greatly ensured the accuracy of measurement.

This study reported the average CT-based TT-TG distance to be 13.62 ± 1.76 mm. The average TT-TG distance from the research of Hernigou et al. was 13 mm, which was measured based on CT data and was similar to our results[23]. Tse *et al.* showed by MRI that the average TT-TG distance was 10.1 mm in healthy Chinese[47]. In a research conducted in New Zealand, Pandit *et al.* reported the average MRI-based values to be 9.91 mm for males and 10.04 mm for females[37]. Hinckel et al reported that the MRI-based TT-TG distance was 3.1–3.6 mm smaller than CT-based TT-TG distance, which explained the inconsistency of the above results[24]. At present, more and more literatures recognized the limitation of the absolute threshold of TT-TG distance. Although 20 mm was the main diagnosis threshold for surgical application, there are some disputes about the value. Franciozi et al reported that tibial tubercle osteotomy combined with medial patellofemoral ligament reconstruction (MPFLR) resulted in better outcomes compared with MPFLR alone in the treatment of recurrent patellar instabilities in patients with a TT-TG distance of 17 to 20 mm[18]. Graf et al reported the inaccuracy of surgical intervention, and demonstrated the need for combining the TSA and the TT-TG distance to avoid overcorrection during medial tibial tubercle osteotomy[21]. Our result reported that the TT-TG distance had a positive correlation with height and the knee size, which was comparable to other literatures[11, 16, 23]. Moreover, several literatures described that application of the TT-TG indices (ratio of the TT-TG distance to the tibial maximal mediolateral axis) obtained more reliable and standardized results[7, 16]. Hernigou et al used fML and tML to establish normal values of TT-TG distances in Greek. However, they also raised doubts about whether the two parameters were applied as the best predictors[23]. Taking these questions into account, the present study applied LASSO regression model to analyze the best predictors of the normal TT-TG distances. LASSO regression is a machine learning method that can shrink the coefficients of variables that do not contribute information to the model to zero and is well suited to feature selection for high-dimensional data[36]. Using this method, we obtained four parameters to predict normal TT-TG distance, namely height, fML, tML and tAP, to achieve the best accuracy and convenience. The prediction formula obtained by us provided a more accurate reference for clinical determination of patellar instability, rather than the absolute values or TT-TG indices. Meanwhile, the formula can play a guiding role in the more accurate localization of the tibial tubercle during the tibial tubercle osteotomy.

Insufficiency of the study

Limitations of the present study include the relatively small sample size. With all measurements derived from knees with extension, there was no data from the knees with 30° of flexion. Thus, the patellar tilt, patellar height, bisect offset, and other factors could not be obtained. We are continuing to study additional subjects and to acquire data from knees with a flexion angle of 30°. Another limitation of the present study was that the formula for predicting TT-TG distance has not been clinically verified, and more studies on the clinical effectiveness of the formula need to be performed.

Conclusion

In summary, the dimensional indexes of the males were generally larger than those of females. In terms of the shape, the patella and the femur of the females were thicker than those of males in the anterior-posterior direction for the same medial-lateral dimensions. Moreover, the AFO, SA, and the Wiberg index all varied greatly among individuals. More attention should be paid to not only gender differences but individual differences. Besides, using LASSO regression, we obtained four parameters to predict normal TT-TG distance, namely height, fML, tML and tAP, to achieve the best accuracy and convenience. This study provided a reference for prosthetic design and a new method of predicting TT-TG distance to enable precise clinical diagnoses and guide the medial transfer of the tibial tuberosity accurately.

Declarations

Acknowledgments

The authors gratefully acknowledge the support of National Natural Science Foundation of China (No. 81672173). Especially Thanks to the technical and financial support provided by Chunli Zhengda Medical Equipment Co., Ltd.

Conflict of interest

The authors declare that they have no conflict of interest.

Author contributions

All authors contributed to the study conception and design, especially Kunzheng Wang, Pei Yang, and Zhe Li. Material preparation was performed by Ning Kong, Yue Li, and Yiyang Li. Data collection was performed by Run Tian and Pei Yang. Data analysis were performed by Zhe Li, Guanzhi Liu. The first draft of the manuscript was written by Zhe Li and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and materials

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

Ethics approval and consent to participate

The local ethics committee of the Second Affiliated Hospital of Xi'an Jiaotong University approved the project. Informed consent was obtained from all included subjects.

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Figures

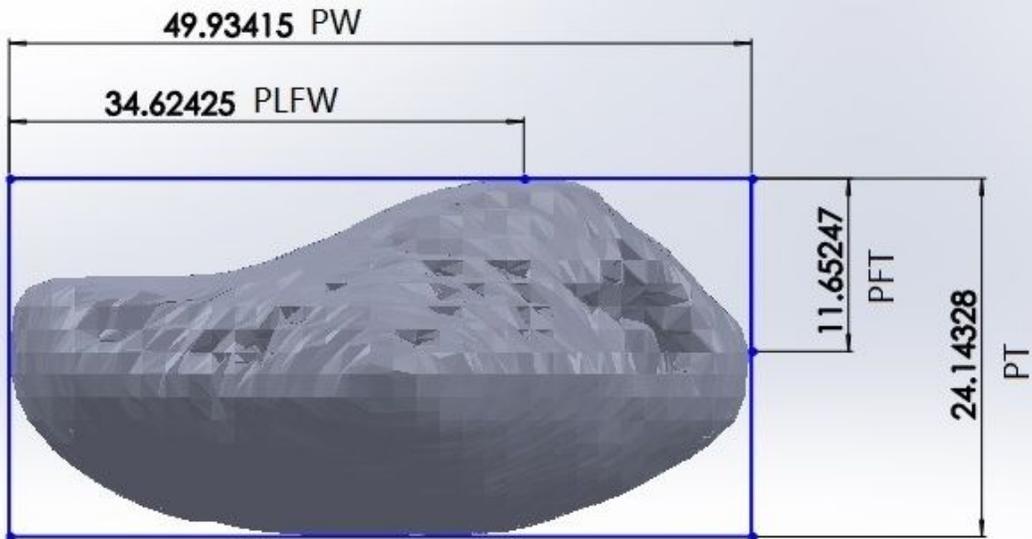
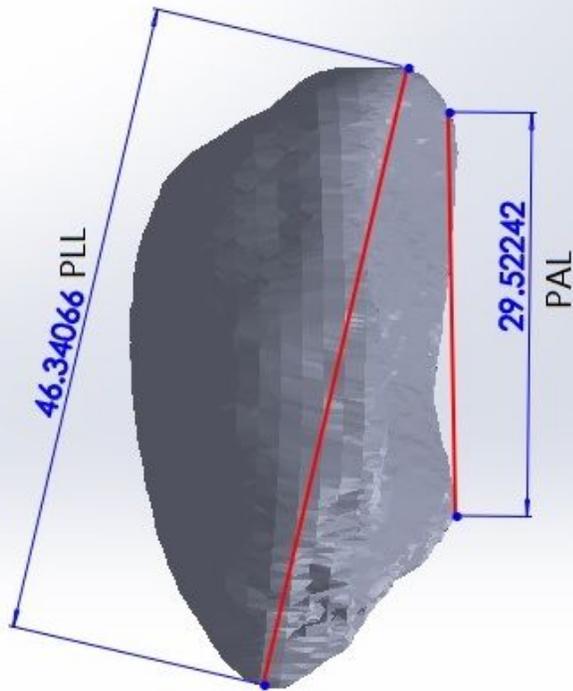
A**B**

Figure 1

A. patella thickness (PT), the patella facet thickness (PFT), patella width (PW), patella lateral facet width (PLFW); B. longitudinal length of the whole patella(PLL), longitudinal length of the articulating surface of the patella(PAL).

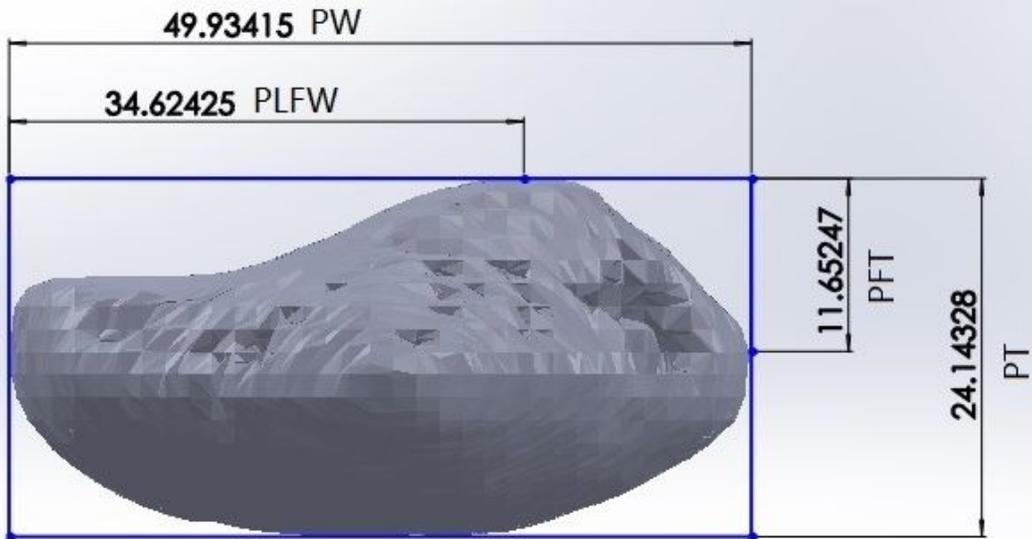
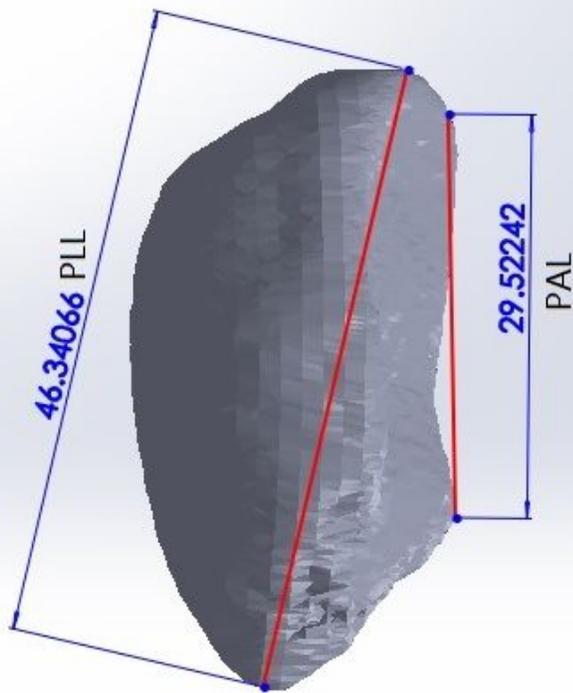
A**B**

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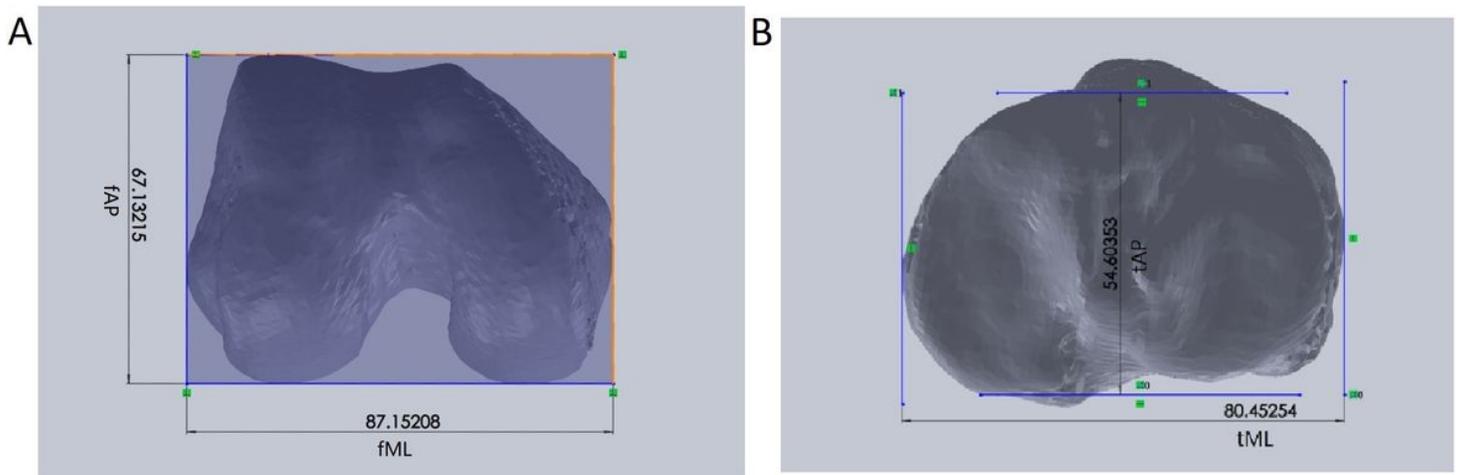


Figure 2

A. the mediolateral (fML) and anteroposterior (fAP) size of the femur; B. the mediolateral (tML) and anteroposterior (tAP) size of the tibia

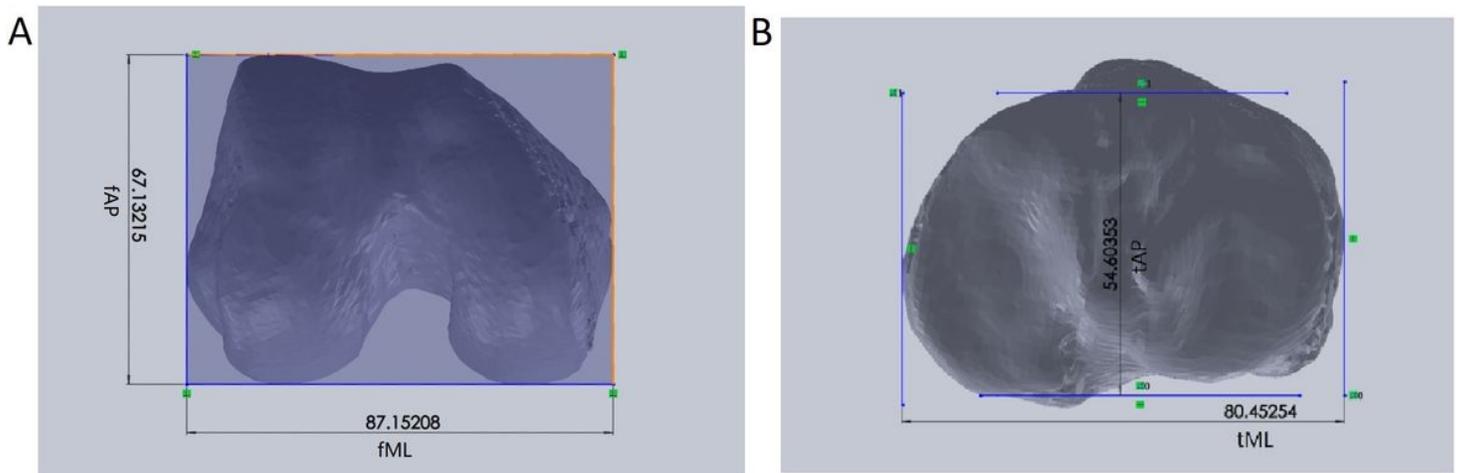


Figure 2

A. the mediolateral (fML) and anteroposterior (fAP) size of the femur; B. the mediolateral (tML) and anteroposterior (tAP) size of the tibia

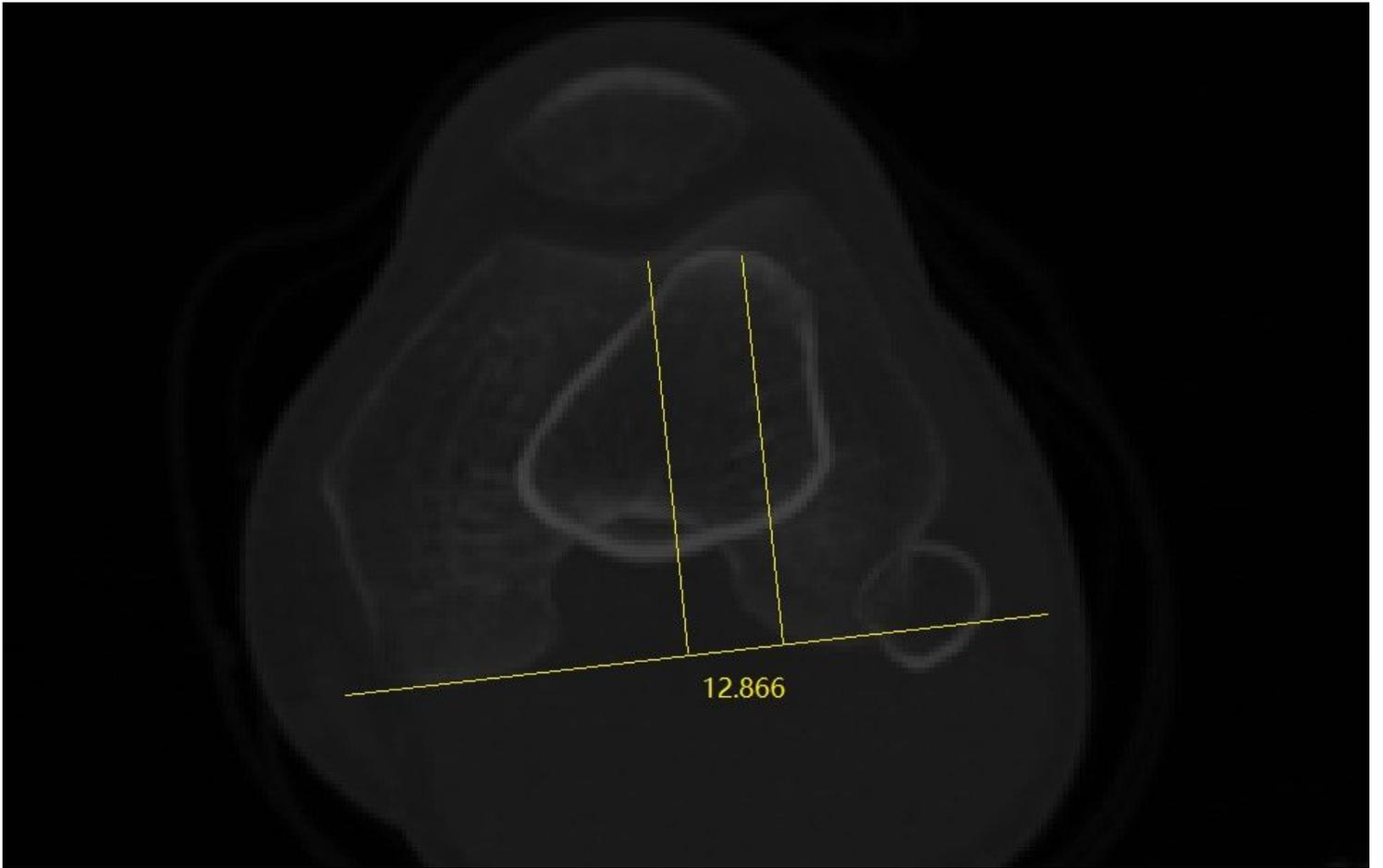


Figure 3

TT-TG distance

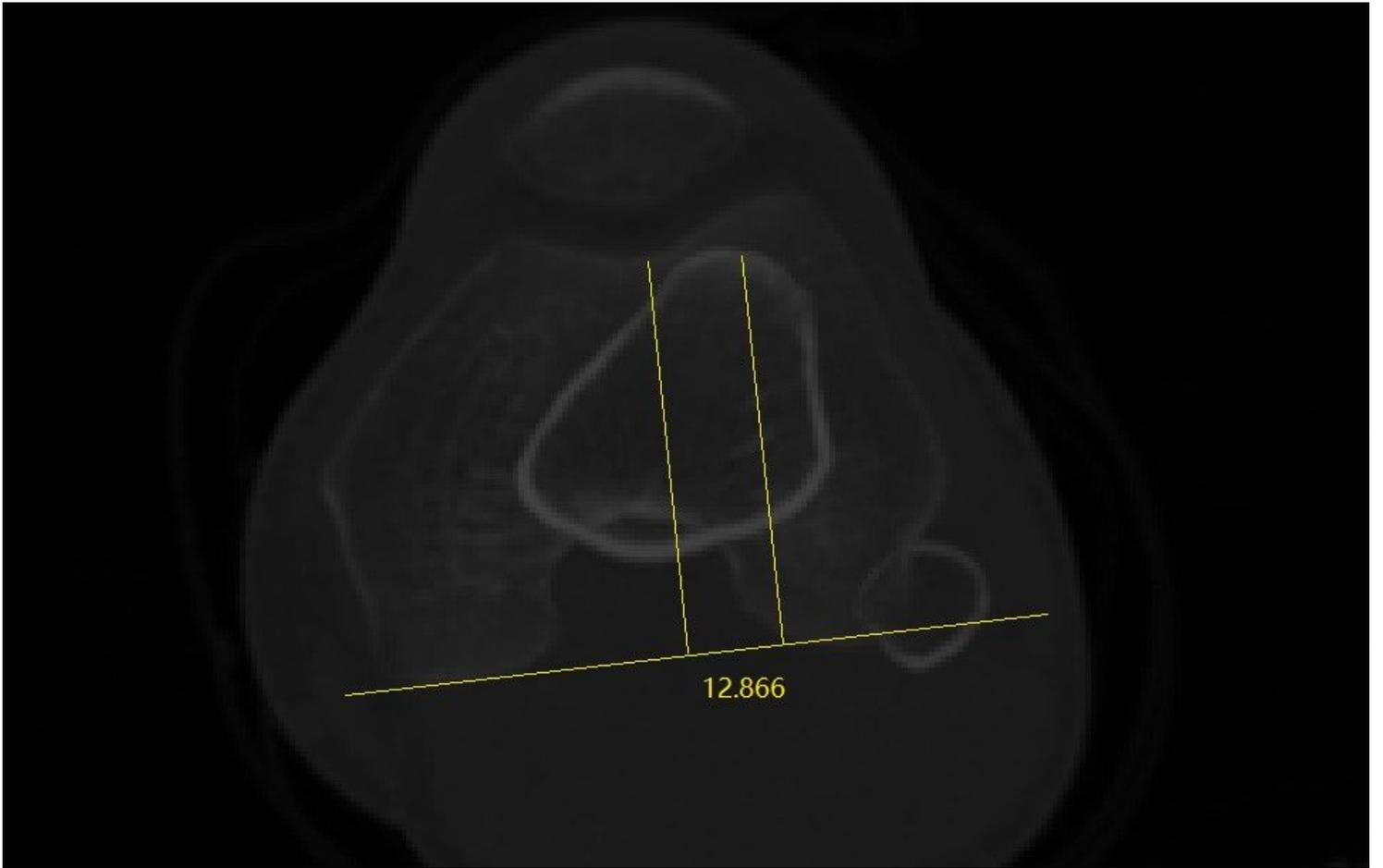


Figure 3

TT-TG distance

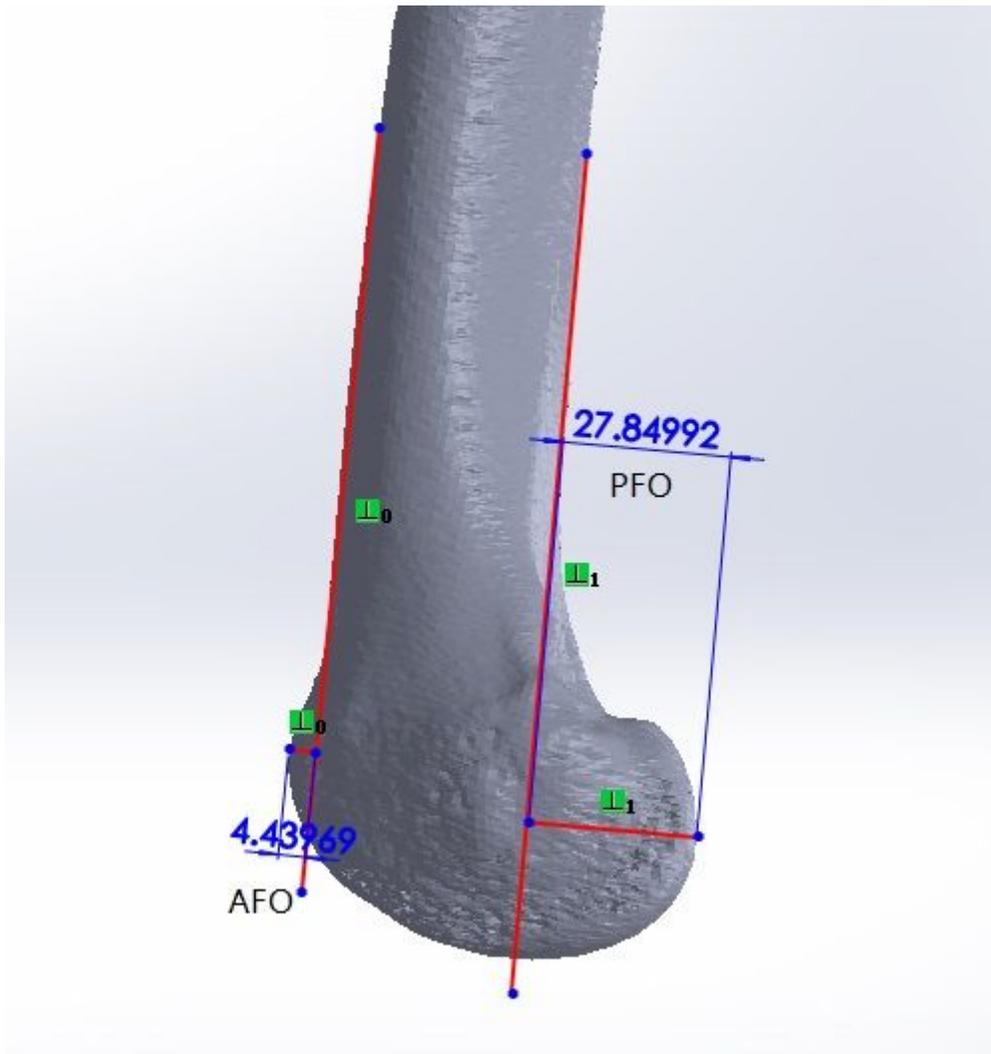


Figure 4

anterior femoral offset (AFO) and posterior femoral offset (PFO)

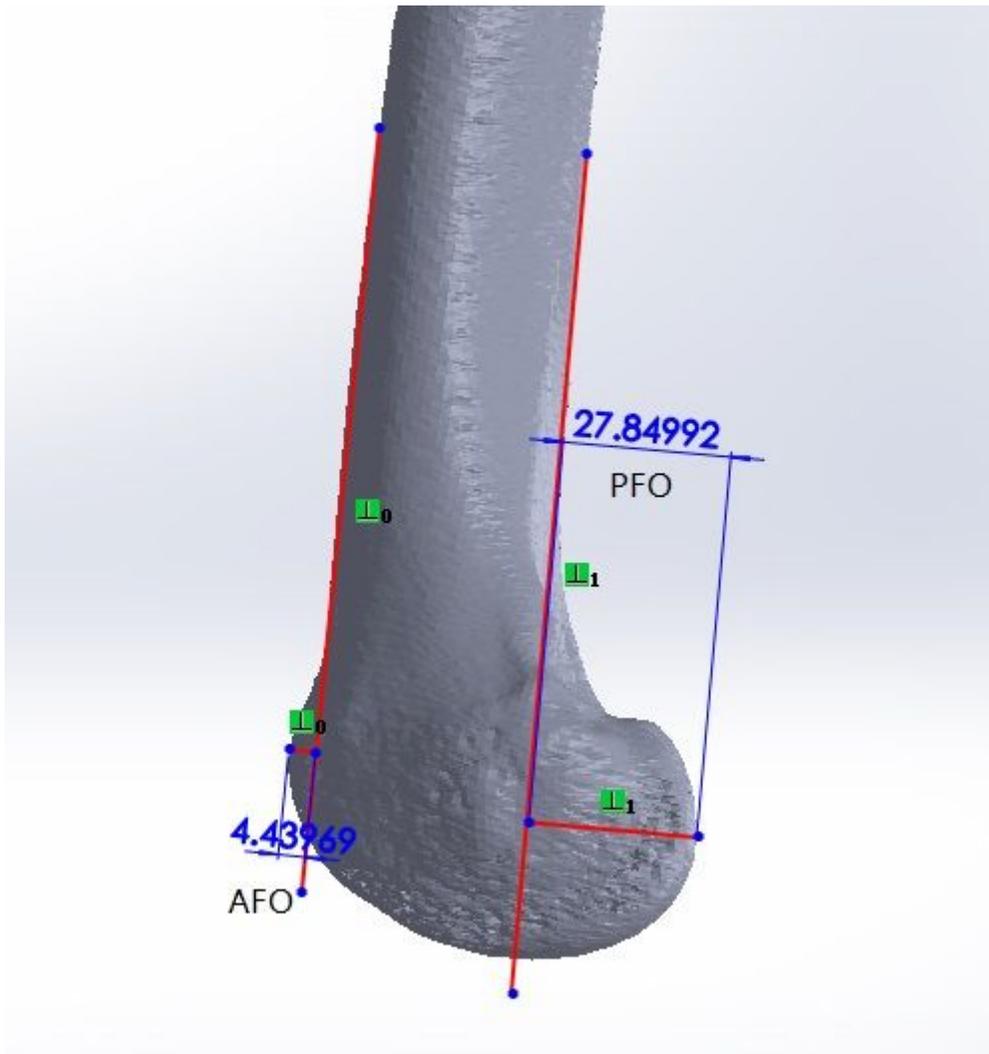


Figure 4

anterior femoral offset (AFO) and posterior femoral offset (PFO)

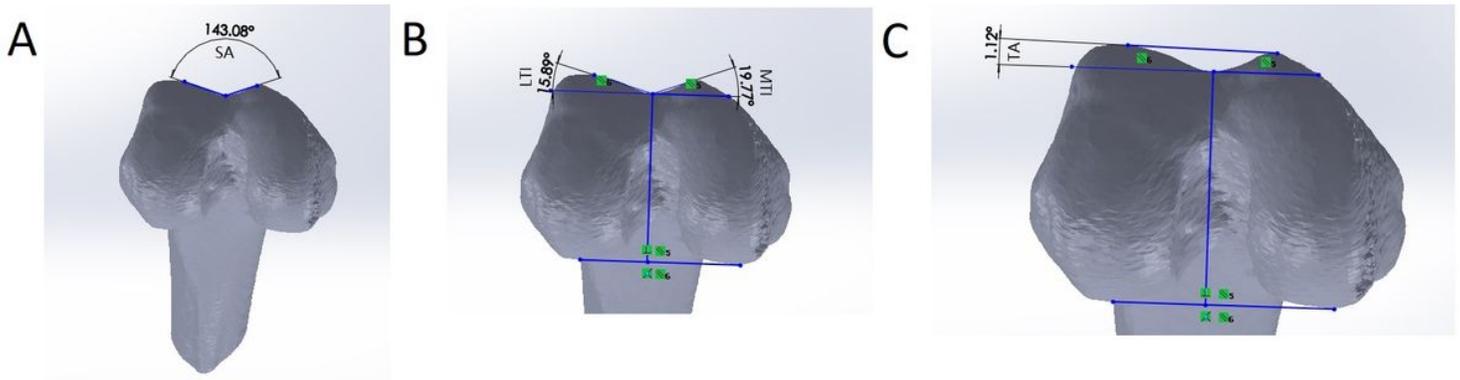


Figure 5

A. sulcus angle (SA); B. lateral trochlear inclination (LTI), medial trochlear inclination (MTI); C. trochlear angle (TA)

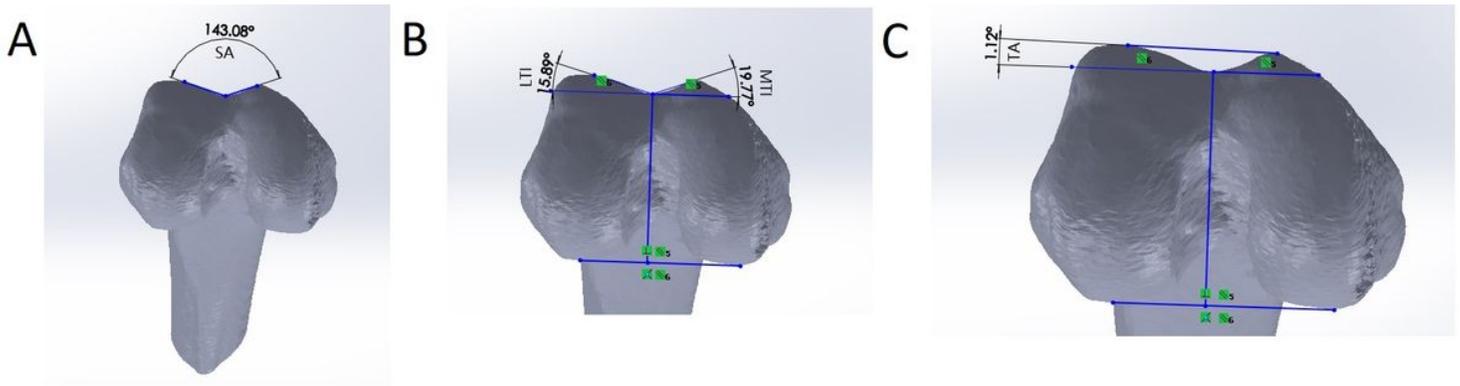


Figure 5

A. sulcus angle (SA); B. lateral trochlear inclination (LTI), medial trochlear inclination (MTI); C. trochlear angle (TA)

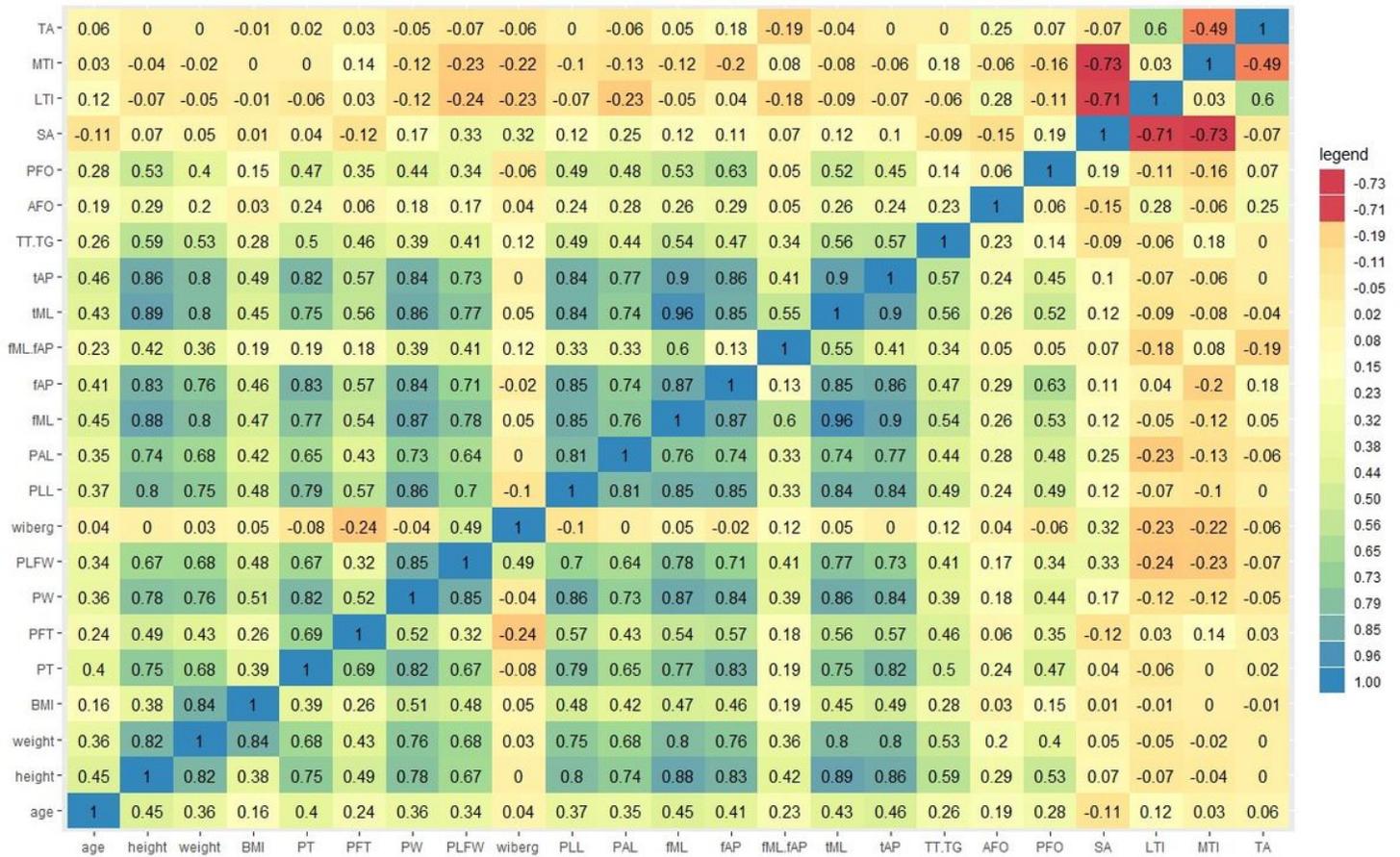


Figure 6

The Pearson correlation coefficients of all variables.

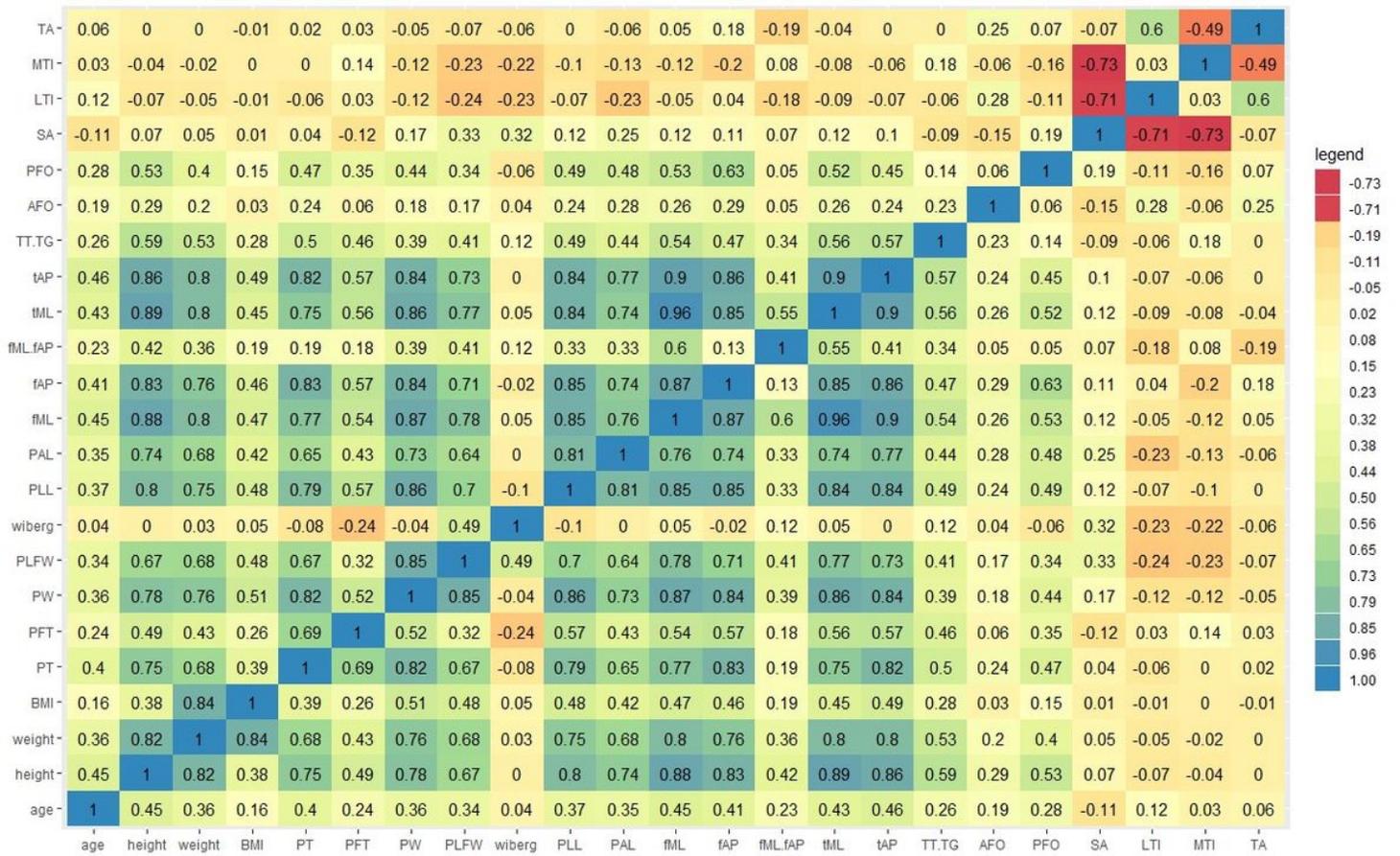


Figure 6

The Pearson correlation coefficients of all variables.

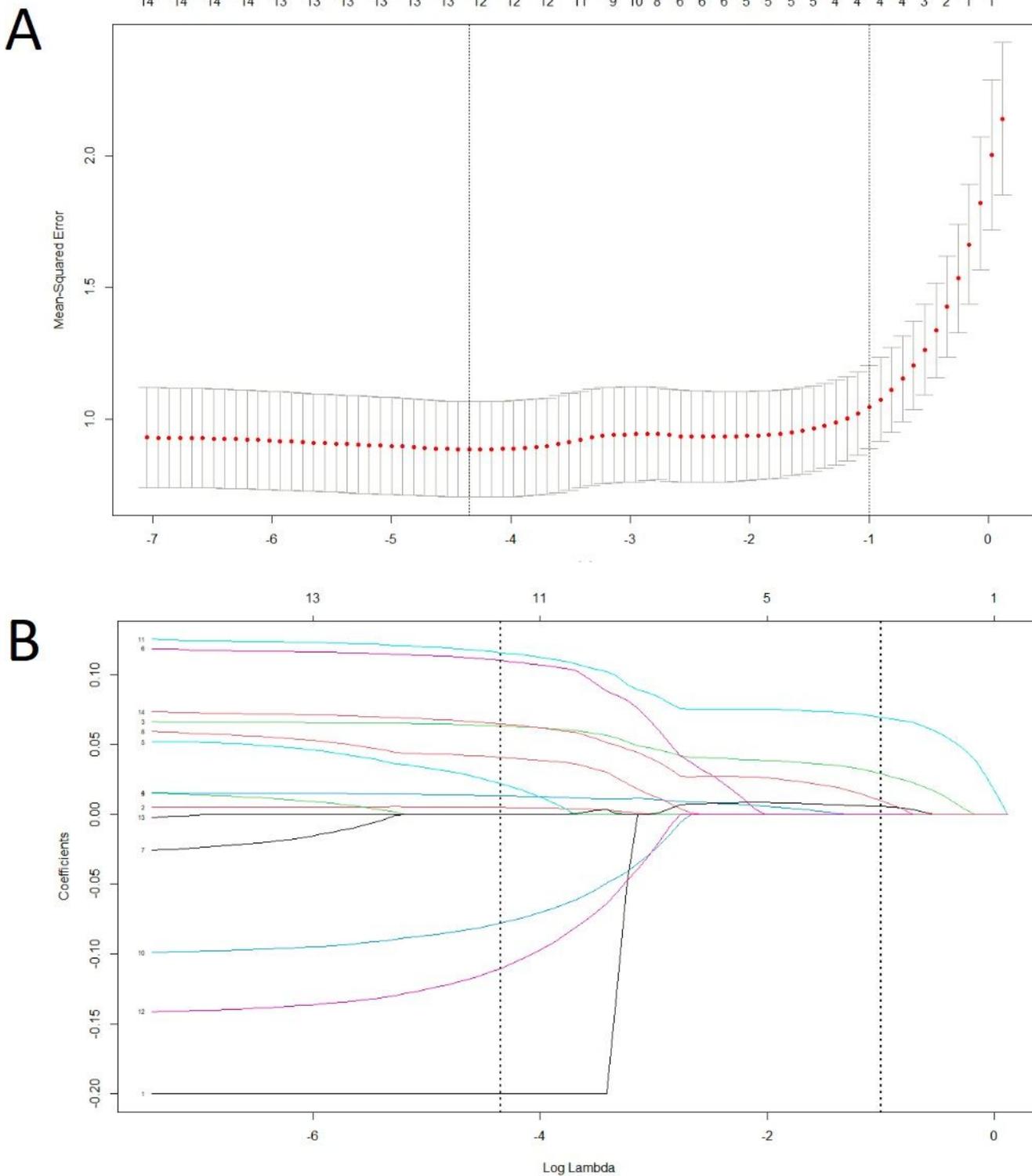


Figure 7

Coefficient progression with LASSO. The first dotted line means that we used the λ at which the minimal mean squared error (MSE) is achieved (lambda.min) to select the optional model. The second dotted line means that we used the largest λ at which the MSE is within one standard error of the minimal MSE (lambda.1se) to select the optional model. The latter was selected as the final model in this study.

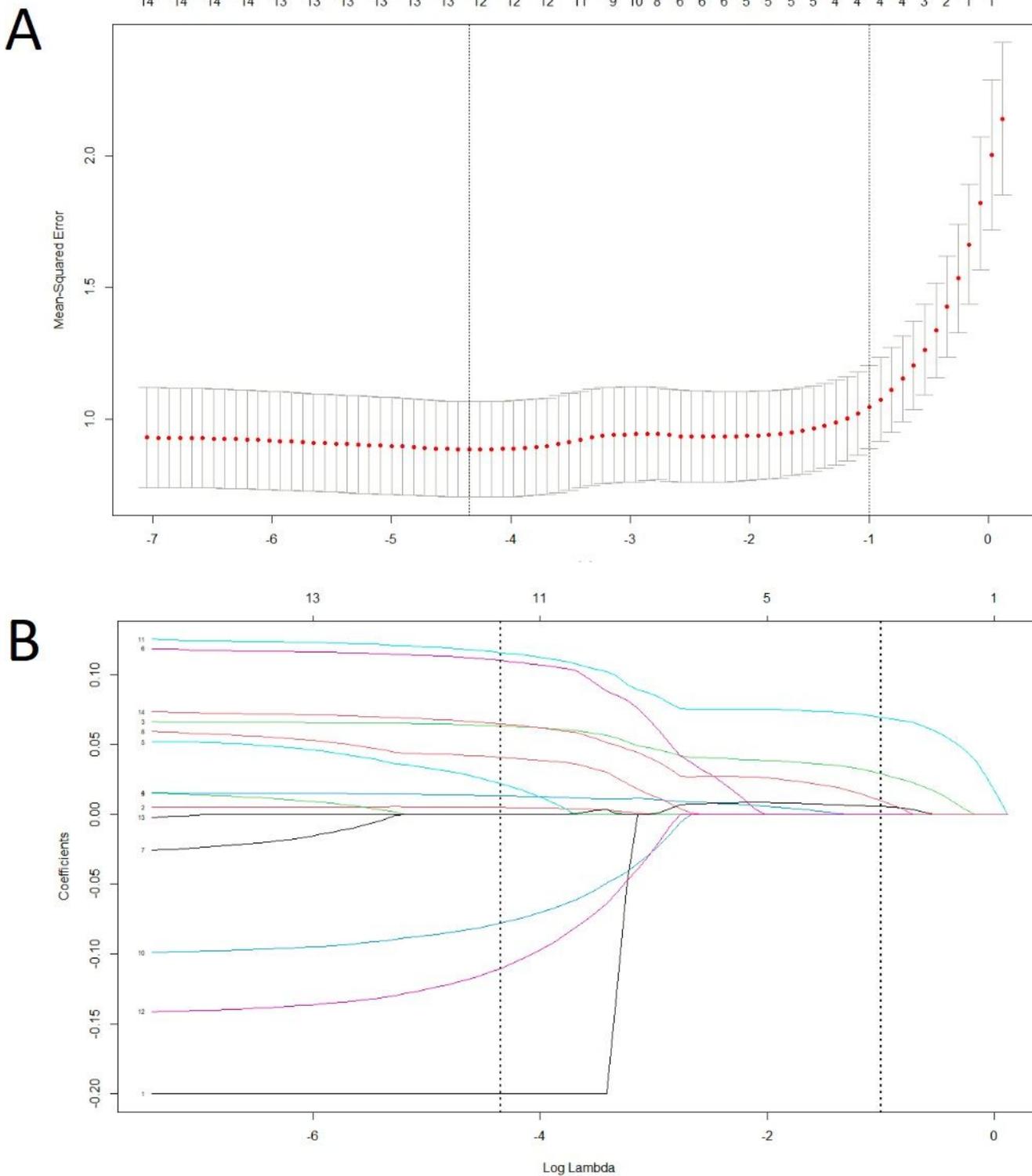


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