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An Automatic Method to Measure the TT-TG Distance Using 3D Slicer Software

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Abstract. The tibial tubercle-trochlear groove distance (TT-TG) is an essential indicator of the lateral forces on the patellofemoral joint, which is valuable for evaluating tibial tuberosity lateralization and diagnosing patellar instability. The orthopaedic surgeons mainly used the image overlay technique to measure the TT-TG distance manually, but this method was prone to inaccuracy due to the nonstandard position and subjectivity of surgeons. In this study, we proposed an automated method for measuring TT-TG on 3D models of the femur and tibia. Firstly, the average model is automatically calculated from a set of the femur and tibial models to be measured, And the orthopaedic surgeon labels the markers on the average model. Next, the Bayesian coherent point drift (BCPD) algorithm is used to register the average model with the model to be measured and calculate the corresponding makers on the model to be measured and make some optimization of the markers. Specifically, we used the markers on the undertested femur to calculate the lowest point of the trochlear groove. We used the lowest point of the trochlear groove and the mark point on the tibia to be measured to calculate TT-TG. We have measured TT-TG distance for a total 56 subjects and compared them with the values measured manually by the physician; the mean error is 0.645 mm for 33 male subjects and 0.690mm for 23 female subjects. This method can aid physicians in measuring TT-TG.

Keywords: TT-TG, BCPD algorithm, average model, automated method for measuring

1. Introduction

TT-TG [1-2] is a well-established and reliable parameter for evaluating tibial tuberosity lateralization and diagnosing patellar instability and is considered to have better accuracy and clinical significance than the Q angle in clinical practice [3].

TT-TG is measured clinically using the image overlay technique commonly as follows: Firstly, the two CT images at the most prominent point of the tibial tuberosity and the "arch" shape of the posterior femoral condyle were selected. Next, the two images were overlapped to one image, and the posterior condylar line (PCL) was drawn. Finally, two vertical lines across the most prominent point of the tibial tuberosity and the deepest point of the trochlear groove, respectively, were determined with PCL as the reference. The distance between the two vertical lines was the TT-TG distance. However, there are many reports of varying results in clinical applications and literature, which suggested the inaccuracies in current measurement methods [4-8]. In addition to the sample variation, the non-standard position of the CT scan, the surgeon subjectivity, and the non-repeatability of the manual measurements all contributed to the inaccuracy of the measurement of the value. Even a mild degree of varus or valgus could cause a large change in TT-TG.[9] In addition,the manual measurement of TT-TG was time-consuming for the surgeons, and therefore the automatic and accurate measurement of TT-TG by computerized methods was of great clinical importance.

To solve the problem of automating TT-TG measurements, the automatic calculation of the mark points on the model to be measured was transformed into a registration problem. The registration problem was the study of the point correspondence between 3D point cloud models. We use the registration method to calculate the point correspondence between a model with mark points marked in advance and the model to be measured. We could obtain the mark points required for the model to be measured through correspondence. The bayesian coherent point drift (BCPD) [10-11] was an algorithm for solving registration problems, and it was an improvement of the coherent point drift (CPD) [12] algorithm, which combined rigid and non-rigid registration into one algorithm ensuring convergence and enhanced robustness to target rotation [10]. Choosing the right model to register with the model to be measured was also an important issue. In order to avoid individual important issue. In order to avoid individual differences affecting the registration results, we proposed a method for calculating the average model using the set of models to be measured. The method of finding the exact mark points on the model to be measured employing the averaging model and the BCPD algorithm was ideally suited for measuring TT-TG.

We, therefore, proposed an automated method for measuring TT-TG based on a combination of the averaging model and the BCPD algorithm. Firstly. We calculated the average model for the set of models to be measured. Next, the model to be measured was registered with the average model using the BCPD algorithm to calculate the mark points required for the measurement and optimize them. Then, the cross-section was created by mark points on the femur model to be measured. We used the cross-section to cut the femur model to be measured and obtained the marginal contour line of the femur section after it had been cut. Finally, Theposterior condylar line and the lowest point of the trochlear groove were established on the marginal contour line, and the posterior condylar line is used as a reference for the measurement of TT-TG using the lowest point of the trochlear groove and the mark point on the tibia to be measured.

2. Related Work

Several studies proposed new methods of measuring TT-TG distances. Li et al. proposed a manual measurement method to eliminate the nonstandard shooting position errors by re-cutting the CT data. However, the steps were all done manually and consumed a lot of time [9]. Brehler et al. provided an automatic measurement method by creating an atlas of femoral and tibial models and marking feature points. However, due to individual differences, the method of using matched correspondence points may have large errors for some highly variable points, such as the lowest point of the trochlear groove [13]. Chen et al. implemented a dynamic semi-automatic measurement of TT-TG distance on 4D CT. However, its sample size of 8 was too small to characterize the accuracy of the results [14].

3. Materials and Methods

This section described a method for measuring TT-TG by automatically marking mark points on the model to be measured. This whole process is described in the following four parts and is shown in Figure 1. The collection and processing of data before measurement are described in part A. The method for solving the average model is described in part B. The procedure for calculating the mark point on the model to be measured using the registration algorithm and the method for optimizing the mark point on the tibia model to be measured as described in part C. The method of measuring TT-TG on the femur model and the tibial using the mark points obtained in part C was described in part D. The specific measurements (part C, part D) were implemented and tested in the 3D Slicer software.3D Slicer was an open-source software platform [15] for medic imagery informatics, image processing, and 3D visualization widely used in medicine and research [16-18]. 3D Slicer offered a programming interface for customization and had the advantage of being highly scalable and easy to develop twice. Therefore, we developed the 3D automatic measuring TT-TG system on 3D Slicer software.

Data Collection and Processing

We retrospectively collected lower limb CT data from May 2019 to May 2021 from 56 subjects from the Second Affiliated Hospital of Xi'an Jiao tong University and desensitized these data. Using a CT scanner (GE revolution CT, General El-citric Company, Milwaukee, Wis) we collected 0.625mm*0.625mm voxels and reconstructed a CT dataset with a thickness of 1mm. We included only intact femurs and tibias, excluding any disease affecting the morphology of the femur or tibia, such as fractures, bone defects, bone tumors, etc. Before calculating the average model, these CT scan slices were imported into Mimics software (version 17.0, Materialise Inc.,Leuven, Belgium) and used this software to generate 3D models and to save these 3D models as files of stl format.

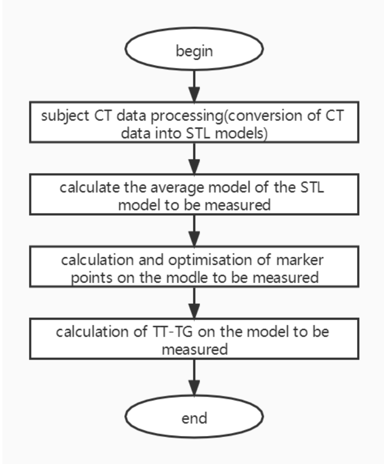

Fig.1. Overall flow of the automatic measurement of the TT-TG distanc

Average Model

The average model is a model where the 3D models of all subjects were pooled and averaged in order to avoid the degradation of registration result caused by individual differences. The algorithm of calculating the average model is shown below.

```
The process of calculating the average model
Input:
Y= {Y1, Y2, Y3, ...YK} Y: the set of point coordinate matrices for all models; YM (1≦M≦K) :coordinate matrix of all points of the Mth model
Output:
average model X (X is the matrix of coordinates of all points of the average model)
-----------------------------------------------------------------
begin:

    1 Ys← point coordinate matrix for the model with the largestnumber of points in Y.
    2 G= [].
    3high_point_number← number of points in Ys.
    4 for i=1 to K step=1:
            if Yi== Ys then:
                starting the next loop
            else:
                Yi← BCPD (Ys as target point cloud,Yi as source point cloud ) using BCPD algorithm to register Yi withYs and
              calculating the matrix of point coordinates after Yi change.
                Yi'' ←[].
                for j=1 to high_point_number step=1:
                    p← calculating the coordinates of the pointnearest to the jth point of Ys among all
                        points in Yi'.
                    Yi'' ← Yi'' append p.
                G← G append Yi''.
   5 G← G append Ys.
   6 X← calculating the mean matrix of the coordinate matrix of all
   points in G.

end
```

We used CloudCompare software to generate the average model according to the X and saved the average models as files of stl format.

Calculation and Optimization Of mark points

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1) Calculation Of mark points.

Three mark points are required for our measurement, and we denote them as MarkerPoint1, MarkerPoint2, MarkerPoint3. MarkerPoint1 is located at the most prominent central part of the tibial tuberosity; MarkerPoint2 and MarkerPoint3 are located on either side of the distal femur. Firstly, the orthopaedic surgeon manually marked these markers points on the average model. Then, we used the bcpd [10-11] algorithm to register the average model with the model to be measured. The result of registration is shown in Fig.2. Finally, We used these mark points on the average model after registration to calculate the mark points on the model to be measured.

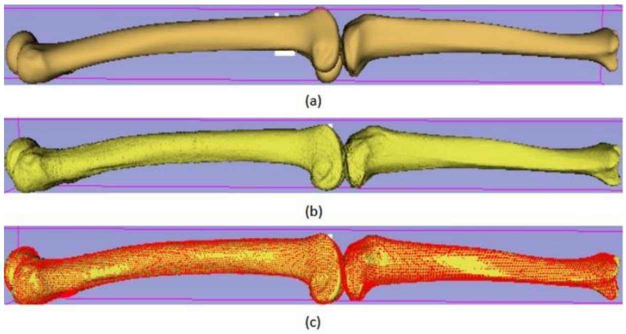

Fig.2. The registration of the average model and the model to be measured(a) the average model of the femur and tibia (b) the model to be measured of the femur and tibia (c) the result of registration, the red part represents (a) the result of average model transformation.

2) Optimization Of mark point On the Measured Tibia

There is a large deviation between the position of MarkerPoint1 on the model to be measured for the tibia derived in C.1 and that defined in C.1. This deviation would cause inaccuracy of final measurements. We proposed a procedure for optimizing the MarkerPoint1 on the tibial to be measured. The optimization process is shown below.

The optimization process of MarkerPoint1

Input:

x_poly: the vtkpolydata object representing the average tibia model

y_poly: the vtkpolydata object representing the measured tibia mode

p_1: coordinates of the MarkerPoint1 on the average tibia model

p_2: coordinates of the MarkerPoint1 on the measured tibia model

Output:

Optimized MarkerPoint1

begin:

1 x_array, y_array← converting x_pcd, y_pcd to x_arry, y_arry (x_arry, y_arry mean the coordinate matrix of all points of the model).
2 x_pcd, y_pcd← converting x_poly, y_poly to pcd objects(x_pcd, y_pcd) of the Open3d library.
3 n← number of coordinate points extracted.
4 x_part_arry, y_part_arry← get_point_cloud(x_pcd,y_pcd,p_1,p_2,n) with p_1 and p_2 as the center, point cloud coordinate matrix x_part_arry and y_part_arry are calculated from x_pcd and y_pcd, and the number of points in both x_part_arry and y_part_arry is n.
5 high_point← find_high_point(y_part_arry) calculating thehighest point in y_part_arry.
6 y_part_arry_new← get_point_cloud(y_pcd, high_point, n) withhigh_point as the center point cloud coordinte matrix y_part_arry_new are calculated from y_pcd, and the number of points in y_part_arry_new is n.
7 y_res← BCPD(y_part_arry_new as target point cloud,x_part_arry as source point cloud) using BCPDalgorithm to register y_part_arry_new with x_part_aand calculating the matrix of point coordinates (y_res)after x_part_arry change.
8 Markpoint1← findclosepoint(y_res): using y_res to calculate thenew MarkerPoint1 on the tibia model to be measured.

end

The final position of these three mark points is shown in Fig.3

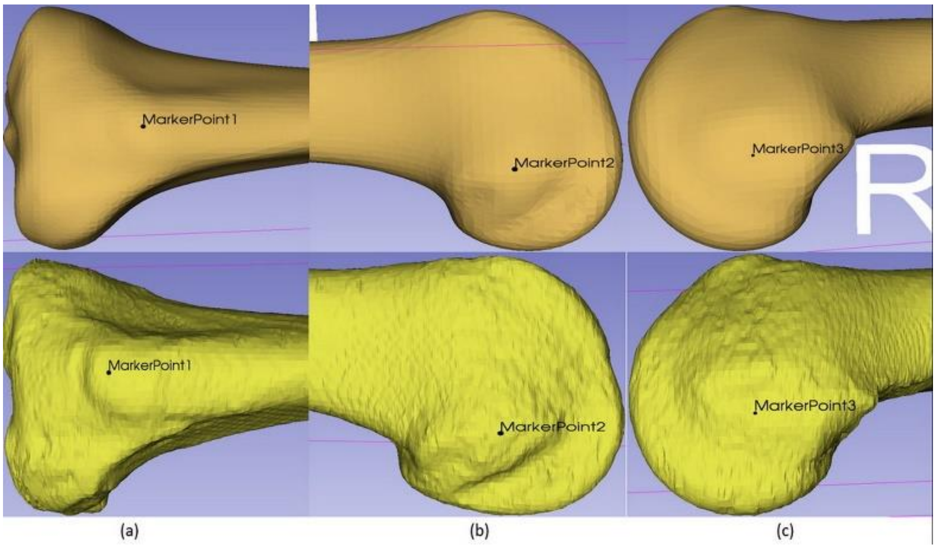

Fig.3. Mark points on the` average model and the model to be measured (a) diagram of MarkPoint1(above is average model and below is measured model) (b) diagram of MarkPoint2(above is average model and below is measured model) (c)diagram of MarkPoint3(above is average model and below is measured model)

Specific Measurement Method

1) Creating Cross-Sections And Obtaining Contour Lines

In this section, the method of creating a cross-section on the femur model to be measured and obtaining contour lines using mark points obtained in C.2 was described. The process is shown below. (see Fig.4)

The process of creating cross-sections and obtaining contour lines
Input: M_2: coordinates of the MarkerPoint2 on the femur model to be measured M_3: coordinates of the MarkerPoint1 on the femur model to be measured fe_poly: the vtkpolydata object representing the femur model to be measured Outpput: L_1: contour lines
begin: 1 Plane P_0← CreatPlane(M_2, M_3) using the direction vector of the lineconnecting M_2, M_3 as the normal vector and the midpoint of M_2, M_3 as the center to create the Plane P_0. 2 n1← [0,0,1] setting the vector by RAS coordinate system of 3D Slicer. 3 center_point← GetCenterPoint(fe_poly) calculating the center of mass of the femur model to be measured. 4 cross-sectionP1, crosssectionP2← CreatClipPlane(fe_poly, center_point,n1) using n1 as normalvector and center point as thecenter to create cross-section P1.Then moving P1 along its normaltowards the distal femur to obtain the cross-section P2. 5 o1, o2← GetCircleCenterPoint(P1, P2, fe_poly) using P1, P2 to cu the fe_poly and calculating edge contour lines of t section generated by P1 an P2 on fe_poly respectively,Then using circles to fit the edge contour lines and calculating the circles as o1, o2. 6 c1, c2← PointToPlane(o1, o2, P0) calculating the projection pointsc1, c2 of o1, o2 on the Plane P0. 7 cross-section P3←CreatPlane(c1, c2, M2, M3) using the direction vector of the line connecting c1, c2 as the normal vector and the midpoint of M2, M3 as the center to create the plane, and moving this plane along its normal towards the distal femur to obtain the cross-section P3. 8 contour line L1← Clip(P3, fe_poly) using P3 to cut the fe_poly ,and calculating the edge contour line L1 of the section generated by P3 on fe_poly. end

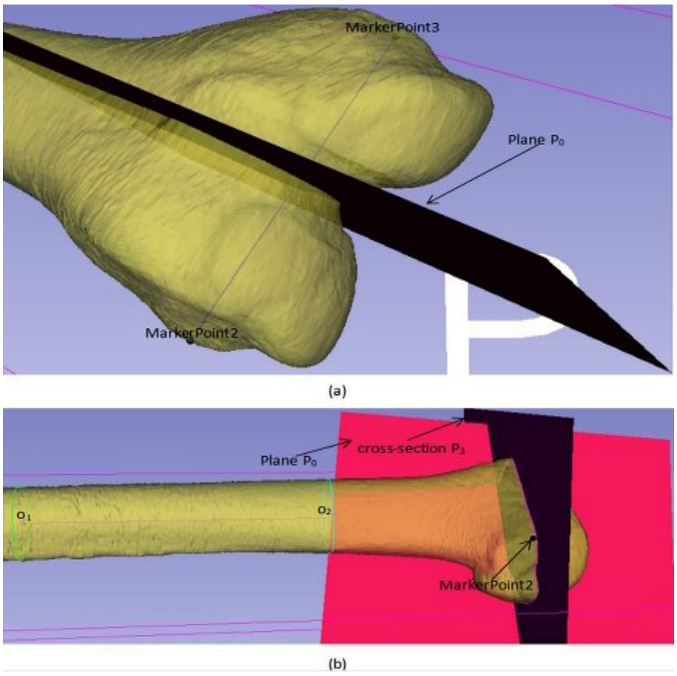

Fig.4. The process of contour calculation (a) showed the Plane P0 in the above process (b) showed the point o1, o2, and the cross-section P3 in the above process

2) Calculation Of TT-TG From Contour Lines

In this section, the method of calculating TT-TG by the contour line L1 in D.1 was described, as shown below (see Fig.5)

The process of calculating TT-TG distance

input:
    contour line L_1
output:
    TT-TG distance

begin:
- 1 Calculating the center of mass of L1 noted as c3.
- 2 Choosing two points on the L1 located furthest below c3thatdistribute on both sides of c3 noted as fc1, fc2.
- 3 Connecting fc1, fc2 to produce a line noted as the posterior condyleline pc1.
- 4 Choosing two points on the L1 located furthest above c3 thatdistribute on both sides of c3 noted as hp1, hp2.
- 5 Connecting hp1, hp2 to produce a line noted as the anterior condyleline ac1.
- 6 The contour line segment from hp1, hp2 on L1 is noted L2.
- 7 Calculating the furthest point on L2 to ac1 and denote it as t1.
- 8 Calculating the furthest point on L2 to pc1 and denote it as t2.
- 9 if t1 is to the left of t2 and distance between t1and t2>1.8mm then:
    - Taking t1 as the lowest point of the trochlear groove.
- Otherwise:
    - Taking t2 as the lowest point of the trochlear groove.
- 10 Calculating the point of perpendicularity from the lowest point of the trochlear groove to the posterior condyle line pc1 noted as k1.
- 11 Calculating the point of perpendicularity from MarkerPoint1 to theposterior condyle line pc1 noted as k2.
- 12 The Euclidean distance between k1 and k2 is the TT-TG.

end

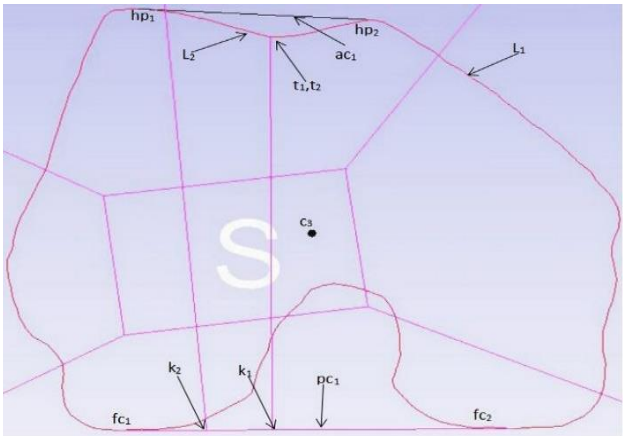

Fig.5. The process of TT-TG calculation on the contour

4. Experiments And result

Comparison of tibial mark point to be measured before and after optimization

We applied the proposed MarkerPoint1 optimization method in 3.3.2 to the 56 tibial to be measured. Fig.6 showed the results of the optimization of MarkerPoint1 on the tibial in three of these subjects.

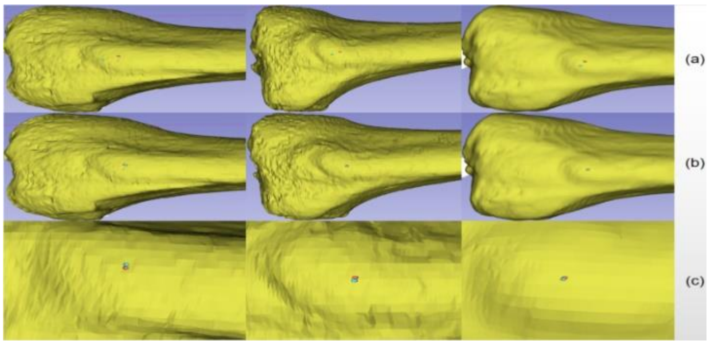

Fig. 6. Results of the optimization, ed point means the manually marked MarkerPoint1, blue point means the automatic marked MarkerPoint1 by programe.(a)the manually marked MarkerPoint1 vs the automatically marked MarkerPoint1 before optimization(b) the manually marked MarkerPoint1 vs the automatically marked MarkerPoint1 afteroptimization.(c) a local enlargement of (b).

Fig.7(a) showed the error of the automatically marked male MarkerPoint1 versus the manually marked male MakerPoint1.The average error before optimization was 3.78mm, and the average error after optimization was 0.34mm.

Fig.7(b) showed the error of the automatically marked female MarkerPoint1 versus the manually marked female MakerPoint1.The average error before optimization was 4.62mm, and the average error after optimization was 0.24mm.

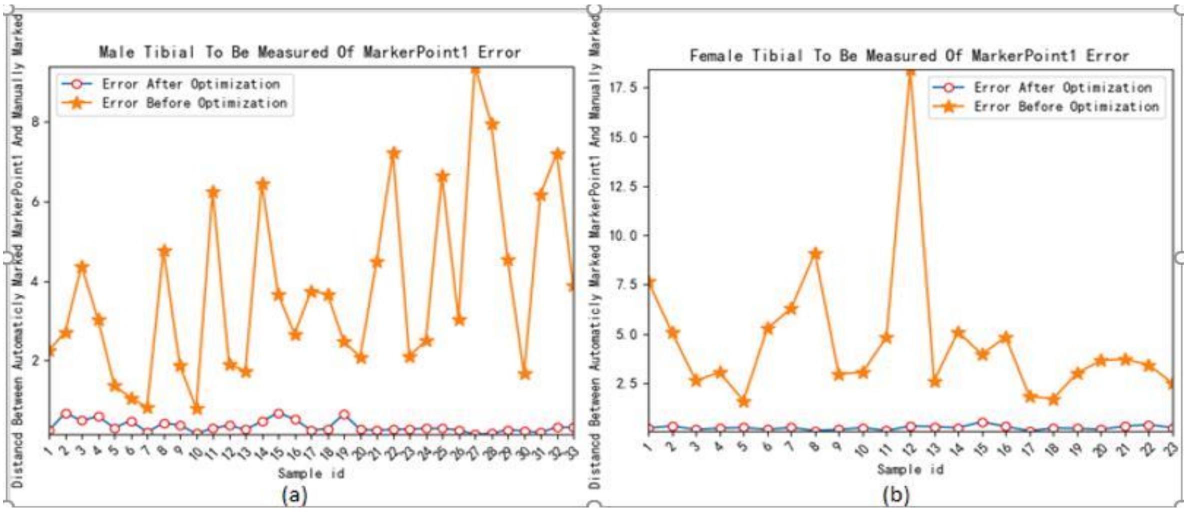

Fig.7. Comparison of MarkerPoint1 error before and after optimization(a)comparison of MarkerPoint1 error of male before and after optimization(b)comparison of MarkerPoint1 error of female before and after optimization

Measurement Results Of TT-TG

The method of measuring TT-TG proposed in this study was applied to 56 femur models to be measured and 56 tibial models to be measured. Fig.6 showed the results of the TT-TG distance measured for these models. The mean error in TT-TG distance measured by this method was 0.6675mm compared to the physician's manual measurements, and the error is calculated as shown below.

$$Average\_Error = \frac{\sum_{i=1}^{K} Error_i}{K}$$

$Where$ (1)

$$Error_i = |length_a - length_m|$$

The K is the number of subjects. The $length_a$indicated the TT-TG distance measured by the method proposed in this study, and the $length_m$indicated the TT-TG distance measured manually by the physician.

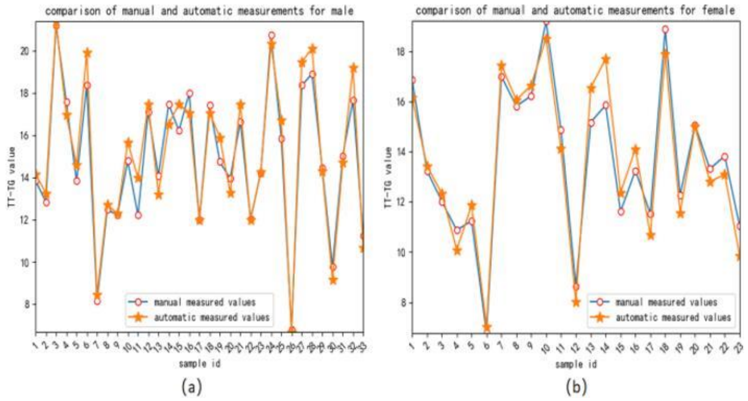

Fig.8. Comparisonof manual measurement and automaticmeasurement

In Fig.8(a), we compared the TT-TG distance obtained by the method in this study with those obtained by the physician's manual measurement for 33 male subjects, and the mean error is 0.645mm. In Fig.8(b), we compared the TT-TG distance obtained by the method in this study with those obtained by the physician's manual measurement for 23 female subjects, and the mean error is 0.690mm.

The analysis of the two TT-TG distances measured is shown in Table I. We performed a one-way ANOVA using SPSS software for the TT-TG distance obtained from the two measurement methods,with significance set at α = 0.05. According to the Table II, the difference between the TT-TG distance measured by the physician and those measured in this study was not statistically significant(male:p=0.769, female:p=0.955), and no significant difference existed, indicating that the method proposed in this study was more accurate for the measurement of TT-TG.

TABLE I. COMPARISON OF TT-TG OF TWO METHODS

methods	gender	number of subjects	max.value	min.value	average	median	standard deviation
manual d	male	33	21.20mm	6.82mm	14.86mm	14.74mm	3.29mm
	female	23	19.21mm	6.78mm	13.68mm	13.32mm	3.01mm
automatic	male	33	21.38mm	6.70mm	15.11mm	14.71mm	3.48mm
	female	23	18.53mm	7.03mm	13.63mm	13.44mm	3.15mm

TABLE II. EFFECT OF DIFFERENT MEASUREMENT METHODS ON TT-TG MEASUREMENTS

influencing factors	gender	F-value	P-value
Different measurement methods	male	0.087	0.769
	female	0.003	0.995

5. Conclusion

We proposed an automated method for measuring TT-TG. Firstly, we used the set of tibial and femur models to be measured to generate their average models. Next, we used the average model and the model to be measured by the registration algorithm to calculate the mark points required to perform measurements on the model and optimize these mark points. Then, we used mark points on the femur model to calculate the lowest point of the trochlear groove. Finally, we used the lowest point of the trochlear groove and the mark point on the tibia model to be measured to calculate the TT-TG distance after comparing the values measured manually by the doctor with the values measured by this method. The mean error was 0.645mm for males and 0.690mm for females. Analysis of the automated and manual measurements by SPSS software revealed no statistically significant difference between the two. Overall, the automated measurement method proposed in this study was important for clinicians to obtain accurate and reliable TT-TG distance, which can further assist in diagnosing conditions such as patellofemoral instability.

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