A data process of human knee joint kinematics obtained by motion-capture measurement

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Abstract

Background: The motion capture has been used as the usual method for measuring movement parameters of human, and most of the measuring data are obtained by partial manual process based on commercial software. A data process was developed for kinematics data obtain by programming on MATLAB software in this paper.

Methods: The coordinate data of markers on human lower limb measured by motion capture system were firstly read and repaired through the program. Then the coordinate data of anatomical points in the movement of human lower limb were obtained by program processing. The local coordinate systems of human femur and tibia were established with anatomical points. After that the flexion/extension, abduction/adduction and internal/external rotation of human knee tibiofemoral joint in the movement of lower limb were obtained by coordinate transformation. Lastly, the motion capture and measurement of healthy volunteers were carried out and the MATLAB program was used for data process.

Results: Using the above methods, motion capture measurements and batch data processing were carried out on squatting and climbing stairs of 29 healthy volunteers to obtain the motion characteristics of the knee joint. As

followed, the maximum angle of internal and external rotation in squatting was 30.5 degrees, and the maximum angle of internal and external rotation in climbing stairs was 14 degrees, etc. The results of this paper also were respectively compared with the results processed by other research methods, and the results were basically consistent, thus the reliability of our research method was verified.

Conclusion: The kinematics data of human knee joint could be processed accurately and effectively with the method programmed in MATLAB software, and the kinematics characteristics of human knee tibiofemoral joint were obtained. The processing method provided a reference for the designing and optimization of knee prosthesis, and the program can be modified for different purposes. At the same time, it is helpful to study knee joint movement of patients after total knee arthroplasty.

Keywords: Knee joint, Motion capture measurement, MATLAB, Kinematics

Background

Total Knee Arthroplasty (TKA) is a routine operation used to treat knee-related diseases in humans [1-3]. It replaces the diseased tissue of the knee joint with an artificial joint prosthesis to restore the normal function of the knee joint and improve the quality of life of patients. By measuring the lower limbs of healthy volunteers of a certain species, the anatomical characteristics and movement parameters of the knee were obtained, which can provide reference for the design and optimization of artificial knee prosthesis in line with the characteristics of this species. With the development of motion capture technology [4-6], some scholars carry out motion capture measurement of human gait [7-9], some scholars have made motion capture measurement and analysis of human knee joint squatting [10-11], and some scholars use the motion capture system to measure and analyze the motion characteristics of the lower extremity joints during the stair climbing process [12-15]. Most of them use the commercial motion capture systems such as

Visual3D (C-Motion, USA) and Vicon (Oxford Metrics Limited, UK) to calculate and analyze the kinematic parameters of the human knee joint; These methods need to be manually processed one by one, which are time-consuming and labor-intensive [16]. However, by using MATLAB (MathWorks, USA), according to the preparation, calibration, measurement process and characteristics of motion capture measurement, a special program for motion capture measurement can be written, which can batch process motion capture data and customize relevant data tables [17].

In this paper, the motion capture system is used to measure the squat and stairs-climbing of healthy volunteers, and the coordinate data of the body surface markers are obtained; The MATLAB software is then used to design a method for reading and processing the knee joint motion data. The kinematic parameters of the tibiofemoral joint during the movement of the lower limbs are obtained by processing data.

Methods

Subjects

There were 29 experimental volunteers, including 17 males and 12 females within 150-178cm height (average 165.5cm) and 47-81kg weight (average 63.9kg). The population of Shanghai urban area was selected as volunteers: 15 young volunteers aged 22-28 years old and 14 middle-aged volunteers aged 41-71 years old.

Instrumentation

The experiment of motion capture measurement was carried out in Shanghai Sixth People's hospital. The experiment used the Optotrak Certus (NDI, Canada) motion capture system with two position sensors, as shown in **Fig. 1**.

Fig. 1 Position sensors of motion capture system

The experimental process

In this experiment, only the right leg movement of the volunteers was measured. Then the calibration of the motion capture was performed, which includes: initial calibration the determination of the coordinate system, the calibration of the seven bone markers and the ground reference point. The seven bone markers are respectively the femoral trochanter, the femoral medial-lateral condyle, the medial-lateral tibial plateau, and the medial-lateral condyles of ankle joints. In this experiment, the detailed processes, from registering volunteer information and calibration to finally saving data, were shown in **Fig. 2** below.

Fig. 2 Motion capture measurement flow chart

As shown in the **Fig. 3**, there are 4 markers placed respectively on the thigh and calf, which were used for motion capture; meantime there are 7 anatomical feature points and 1 ground

reference points on the lower limbs, which were used for calibration to determine the coordinate systems. In order to avoid the measurement error, which caused by skin movement during movements and the bony point being occluded, virtual markers were generally used for calibration measurement [18], these 7 anatomical feature points are virtual markers for measurement. The coordinates of virtual-markers in the experiment can be determined by the coordinates of 3 or 4 marker points photographed on the rigid body. Therefore, the real-time coordinates of anatomical feature points of human lower limbs in the movement can be obtained by measuring the coordinates of markers pasted on volunteers' thighs and calves.

Fig. 3 The position of markers and anatomic feature points in human lower extremity

Spatial 3D (three-dimensional) coordinate data of marker points and bony points were saved by the motion capture system in a file in xls format. Volunteers of the motion capture and measurement of the knee joint squatting and the parts were shown in **Fig. 4**. **Figure 4a** shows the initial squat measurement position when the lower limbs remain upright. **Figure 4b** is the position with the largest knee flexion angle in the squat. The rest marker points shown in the figure are coincident markers for other motion measurement, which have no direct relationship with the motion capture measurement in this paper.

Fig. 4 (a) Site Map of Squatting Motion Measurement (orthostatism). (b) Site Map of Squatting Motion

Measurement (maximum of knee joint flexion)

Data processing method

MATLAB software was used to write the program to obtain and analyze the 3D coordinate data of markers. If the collected data were missing, the original data should be firstly interpolated and repaired reasonably before further data process. If the data were intact, it could be read and processed directly. Secondly, the data were processed to obtain the coordinates of 7 anatomical feature points (**Fig. 3**) in the movement of lower limbs, and the local coordinate systems of femur and tibia were established based on these 7 markers. Finally, the kinematic parameters of the knee tibiofemoral joint during the movement of the lower limbs were obtained by using coordinate transformation. The kinematic parameters respectively were below: the flexion and extension of femur relative to tibia, adduction and abduction, and internal and external rotation. The data processing flow chart is shown in **Fig. 5**.

Fig. 5 Data processing flow chart

Reading and preprocessing of the original coordinate data of the marker points

The original data measured in the experiment included coordinates during calibration below: markers on the probe tool and markers pasted on the leg for motion capture. And the coordinates of human lower limb movement: the coordinates of marker points on the leg. The data read function 'xlsread' was used in the MATLAB software to directly read coordinate data.

Fig. 6 The coordinate values in Y direction of markers in thigh and shank in a squat

Figure 6 shows the change of the coordinate value of the marker points on the squat legs in

the up and down direction. The horizontal coordinate represents the number of frames. Markers 5-8 are on the thigh, markers 9-12 are on the lower leg, and the data of markers on the lower leg has a small change because of the small amplitude of the calf in the movement. It could be seen that in the first 50 frames, the data remains unchanged. Within these 50 frames, the volunteers do not move, and then the squatting action begins. After reaching the lowest point, the knee began extending and the data appears to be increasing firstly and then decreasing. Finally, the volunteers remained stationary and the data remained unchanged.

In the experimental process, some of the coordinate data of markers were missing due to some of them being obscured, and the missing data needs to be repaired. The patch function was programed in Matlab based on the number of missing data and the missing position. As shown in **Fig. 6**: within 1-50 frames in the beginning and the last 200 frames, the volunteers were stationary, so the lack of data in these two stages has no effect on the results. It takes 2.5 seconds for 50-300 frames to complete the collection from squatting to standing, in which the data-loss will be caused by marker points being obscured or falling during the movement. When one of the 4 markers points (which were on the thigh or calf, as shown in **Fig. 3**) missed, it can be repaired. However, it cannot be repaired and should be discarded when 2 or more markers of the 4 markers missed.

The positional correlation among markers during the movement and the overall movement trend are all references for data repair. For example, this relation can be obtained according to the real-time coordinates of the upright position and the maximum flexion position shown in **Fig. 4a** and **Fig. 4b** respectively, and the real-time coordinates of the anatomical feature points of the upright position were shown in **Fig. 3**. When the patch program was written, cubic spline interpolation function was used for interpolation repair [19]. The curve after interpolation by this

method is second-order continuous and differentiable, with high precision and smooth curve transition. The detailed introduction of cubic spline interpolation function is described in literature [19], and its principle is shown in **Appendix. 1**.

The written patch flowchart is shown in **Fig. 7** below. In the experiment, as shown in **Fig. 4**, there are 4 markers attached to the thighs and calves of the volunteers respectively. If there is 1 marker data missing in the nth frame in the motion measurement, then according to the data of 4 markers in the previous frame or the nearest frame and the remaining three markers data of the nth frame, the transformation matrix and a translation matrix between the two sets of coordinates were established, thereby the coordinate data of missing markers in the nth frame were solved.

Fig. 7 Patch program flow chart

Solution of Coordinate Data of Bone Markers in Lower Limb Movement

Two sets of three-dimensional point sets $\{p_i\}$ and $\{p_i'\}$ are known, $i=1, 2, \dots, N$, N is the number of

markers, $\{p_i\}$ and $\{p'_i\}$ are 3×1 column matrix, then there is $p'_i = Rp_i + T$, where R is the 3×3 rotation matrix, and T is the 3×1 translation vector of the column matrix, The transformation matrix R and the translation matrix T can be solved based on the known two sets of points based on the singular value decomposition method.

Figure 8 shows the probe and probe local coordinate system, the tip of the probe was defined as the local coordinate system origin. According to the coordinate data of 4 marker points on the probe obtained by measurement and the parameters of the probe itself (coordinate data of 4 marker points in local coordinate system), then the transformation matrix and translation matrix between two sets of coordinate data were established. Finally, the coordinate data Z (probe-tip's coordinates) of the bony-markers (also known as anatomical feature points) was obtained. According to the coordinate data of the marker points on the thigh and calf respectively in the calibration of bony-markers and ground reference points, the transformation matrix and the translation matrix between the two sets of coordinate data were established, it was used to calculate the coordinate data of bony-markers points in the calibration of ground reference points. Finally, according to the coordinate data of marker point on the leg in the calibration of ground reference point and the coordinate data during the movement of human lower limb, the transformation matrix and translation matrix between the two sets of coordinate data were established. Thereby, the coordinate data of the bony-markers in the lower limb movement of the human body was obtained.

Fig.8 The probe and its local coordinate system

Establishment of local coordinate system of femur and tibia

This study defines and establishes the local coordinate system of the femur and tibia according to the seven bony-markers of the lower extremities. In 1983, Grood et al. [20] first introduced the method of establishing the joint coordinate system for the 3D motion of joints. Later, other scholars redefined the method of establishing the local coordinate system of various parts of the human body [21-25]. Dane et al. [26] modified the coordinate system definition method proposed by Grood et al. [20]. Of course, some scholars have proposed the definition method of the coordinate system of human lower limbs and knee joints [2]. This paper refers to the above scholars' research and establishes the human femur and tibia local coordinate system in combination with the actual situation. As shown in **Fig. 9**, the femur and tibia coordinate systems are established. The method is as follows:

Fig. 9 Knee joint femur and tibia local coordinate system

The local coordinate system of the femur: the line connecting the lateral femoral condyle and medial femoral epicondyle is the X axis, the direction is pointing to the outside, and the midpoint of the line is the origin. The X-axis multiplied by the line being connected the femur greater trochanter and the origin to obtain the Y-axis with the direction facing forward. The X-axis multiplied by the Y-axis to obtain the Z-axis with the direction facing up.

The local coordinate system of the tibia: the connection between the medial and lateral tibial plateau is the X axis, the direction is pointing to the outside, the midpoint of the line is the origin, and the X-axis multiplied by the line being connected the origin and the midpoint of the inner and outer ridges to obtain the Y-axis, the direction is forward. The X-axis multiplied by the Y-axis to obtain the Z-axis with the direction facing up.

Solving knee kinematic parameters

According to the above method, the local coordinate systems of femur and tibia were established according to the bony-markers [27]. The femoral coordinate system was rotated and translated to

obtain the tibia coordinate system. According to the order of coordinate rotation, coordinates transform can be divided into two categories [28]. One type is that the three axes were different for the three rotation transforms to rotate, the other type is that the first and third rotations axes are the same one, and these two types all have six rotation transformation orders. In this paper, the order of X-Y-Z is used for Euler rotation, and its transformation matrix is R:

$$R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \quad (1)$$

The femoral coordinate system were orderly rotated α angle around the X axis, rotated β angle around the Y axis, rotated γ angle around the Z axis, and coincides with the tibia coordinate system. According to the coordinate transformation principle, the rotation transformation matrix R is as follows:

$$\begin{cases} \alpha = \arctan(-R_{32}, R_{33}) \\ \beta = \arctan(R_{31}, \sqrt{R_{11}^2 + R_{12}^2}) \\ \gamma = \arctan(-R_{21}, R_{11}) \end{cases} \quad (2)$$

$$\arctan 2(x, y) = \arctan(x / y)$$

According to the local coordinate system, the follows were respectively defined: the flexion and extension angle of the femur relative to the tibia is the angle α of the femoral coordinate system rotating around the X axis, and the adduction and abduction angle is the angle β of the femoral coordinate system rotating around the Y axis. The internal and external rotation angle is the angle γ of the femoral coordinate system rotating around the Z axis, as shown in Figure 10 below. The kinematic parameters of the knee joint during the lower limb movement are obtained by calculating the α , β and γ angle.

Fig. 10 Joint angles are defined by rotations occurring about the three joint coordinate axes.

Figure 11 is the flow chart of the main program for obtaining relative motion parameters of tibiofemoral joint, which were programed in MATLAB. The program starts reading the data by calculating the coordinates of the bony-markers firstly. Secondly, marker data when the reference-points were calibrated is read and the coordinates of the bony-markers under the reference-points posture were calculated, then the marker data in the motion is read to calculate the coordinates of bony-markers in the movement; meantime, the local coordinate system of the femur and tibia were established according to the bony-markers. Finally the coordinate transformation was used to solve the kinematic parameters of the knee joint.

Fig. 11 Main program flow chart of obtaining relative motion parameters of femorotibial joint

Result

The method described in this paper is applied to capture and measure the subjects' motion and process the data, so as to obtain the flexion-extension, adduction-abduction, and internal-external rotation data of the knee joint femur relative to the tibia during the movement of the lower limbs. As shown in **Fig. 12** and **Fig. 13**, respectively, the x-coordinate is knee flexion angle, and the y-coordinate is adduction-abduction and internal-external rotation.

(a) abduction/adduction (b) internal/external rotation

Fig.12 The relative rotation motion of femur vs tibia under different flexion during squat

Note: B/D/F/H/J respectively represent the motion data of internal/external rotation and abduction/adduction of five different volunteers in this study.

Figure 12 showed the adduction-abduction and internal-external rotation of the human knee joint femur relative to the tibia at different flexion angles during squatting for five healthy subjects. During the squatting, the femur was abducted relative to the tibia from 0 degrees to about 40 degrees; From 40 degrees flexion on, the femur was adducting relative to the tibia until the knee reached the maximum flexion of 100 degrees. As the knee flexion angle deepened, the femur was abducted firstly and then adducted relative to the tibia, and the femur continued to rotate externally relative to the tibia. It can be seen from the figure that the maximum flexion angle of the knee joint in the squat was between 79 and 98 degrees in this experiment.

(a) abduction/adduction (b) internal/external rotation

Fig.13 The relative rotation motion of femur vs tibia under different flexion during stairs climbing.

Note: B/D/F/H/J respectively represent the motion data of internal/external rotation and abduction/adduction of five different volunteers in this study.

Figure 13 showed the adduction-abduction and internal-external rotation of the femur relative to the tibia during stairs climbing of five healthy subjects. It can be seen from the figure that the maximum flexion angle of the knee joint of the subject was between 23 and 44 degrees. Due to the higher mobility of the knee joint on the anterior-posterior axis, as the knee flexion angle increased, the femur with respect to tibia has a larger difference in adduction and abduction movements; and the femur was abducted firstly and then adducted overall. At the same time, in the process of going up the stairs, the femur continued to rotate externally relative to the tibia as a whole. However, the femur was rotated internally at the end of knee flexion in some subjects.

Discussion

In this paper, the motion capture measurement of the squat and stairs-climbing of the subjects was carried out. The relative movements of femoraltibial joint of the human knee joints in the lower limbs movements were analyzed.

Verification and analysis

And the results of this paper were compared with those of other researches (as shown in Fig (14) and Fig (15)).

Fig.14 The data of abduction/adduction and internal/external rotation in this paper and data obtained by other researchers

Note: B/D/F/H/J respectively represent the motion data of internal/external rotation and adduction/abduction of

five different volunteers in this study. The motion data of internal/external rotation and adduction/abduction of other researchers, which were compared with the data in this paper, were taken from the K.E.Moglo[29]、Michal Kozanek[33]、Azhar M[31]、Silvia Pianigian[30]、Chih-Hui Chen[32]、Yasayuki Mizuno[34].

As shown in Fig. 14(a), for the adduction-abduction of the knee joint in the squat, K. E. Moglo et al. [29] showed that the femur was abducted relative to the tibia from -10 to 0 degrees flexion and adducted from 0 to 80 degrees flexion. The results of Silvia Pianigian et al. [30] and Azhar M et al. [31] showed that the femur was abducted firstly and then adducted relative to the tibia. The research in this paper also showed that the femur was abducted firstly, and the femur was adducted relative to the tibia at 40 degrees flexion. However, Chih-Hui Chen et al. [32] showed that the femur was adducted and then abducted relative to the tibia, Michal Kozanek et al. [33] have shown that the femur was abducted continuously relative to the tibia, while Yasayuki Mizuno et al. [34] have shown that the femur was adducted continuously relative to the tibia. The scope of adduction-abduction angle obtained in this paper was largely consistent with the comparison of other literatures. In summary, for different researchers and different test objects, the results of adduction and abduction in the process of knee flexion are different, which may be related to individual diversity.

As shown in Fig. 14(b), for the internal-external rotation of the knee joint in the squat, the results of this paper showed that the femur was rotated externally relative to the tibia when the knee flexion increased, and the femur was rotated internally relative to the tibia around 70 degrees flexion of the knee joint. The results of Silvia Pianigiani et al. [30] and Azhar M et al. [31] also had the similar changes in the knee flexion, and the result of Silvia Pianigiani et al. [30] indicated that the femur was changed from external rotation to internal rotation at about 50 degrees; The result of Azhar M et al. [31] indicated that the femur was changed from external rotation to internal rotation at about 70 degrees. The results of this paper indicated that the femur was

generally in external rotation relative to the tibia, which was generally consistent with the results of K.E. moglo et al. [29], Michal Kozanek et al. [33] and Yssayuki Mizuno et al. [34]. In the research of Schmitz et al. [10], the squat (the flexion angle of the knee joint to 60 degrees) of 15 healthy people was measured by the motion capture system, and the data was processed by Visual 3D software. The results showed that in a squat cycle, from the beginning to the flexion angle of the knee joint reaching the maximum, the knee joint was always in external rotation. This was consistent with the trend of movement in this squat measurement.

Fig.15 The data of abduction/adduction and internal/external rotation in this paper and data obtained by other researchers

Note: B/D/F/H/J respectively represent the motion data of internal/external rotation and abduction/adduction of five different volunteers in this study. The motion data of internal/external rotation and abduction/adduction of other researchers, which were compared with the data in this paper, were taken from the K.E.Moglo[29], Michal Kozanek[33], Azhar M[31], Silvia Pianigiani[30], Chih-Hui Chen[32], Yasayuki Mizuno[34].

As shown in Fig.15(a), for the adduction-abduction of the knee joint during the stairs-climbing, five subjects' data was collected in this paper, one of them continued to abducted relative to tibia with the flexion of the knee joint, which was consistent with the results of Michal Kozanek et al. [33]. Two of the five subjects in this paper were that the femur was abducted firstly relative to the tibia, and then from 17 degrees flexion on, the femur was adducting relative to the tibia until the knee reached the maximum flexion. The results of Silvia Pianigiani et al. [30], K.E.Moglo et al. [29] and Azhar M et al. [31] et al. showed that the femur was abducted firstly and then adducted

relative to the tibia, which was consistent with the results in this paper. However, a few researchers have different results, for example the results of Chih-Hui Chen et al. [32] showed that the femur was adducted firstly and then abducted relative to the tibia, and the results of Yasayuki Mizuno et al. [34] have shown that the femur was adducted continuously relative to the tibia. All in all, the above results indicated that adduction-abduction of the knee joint was unstable.

As shown in Fig. 15(b), for the internal-external rotation of the knee joint during the stairs climbing, five subjects' data was collected in this paper, three of them continued to rotate externally relative to the tibia with the flexion of the knee joint, which was generally consistent with the results of K.E. moglo et al. [29], Michal Kozanek et al. [33] and Yssayuki Mizuno et al. [34]. One of the five subjects in this paper was rotated interally relative to the tibia in the late stage of knee joint flexion, which was generally consistent with the results of Azhar M et al. [31] and Silvia Pianigiani et al. [30]. Besides, Riener [12] measured the upstairs movements of 10 normal people on the steps with different slopes, and analyzed the joint movement of the lower limbs. The results showed that the joint angle was significantly related to the step slope, and the larger the step slope was, the greater the maximum flexion angle of the knee joint during movements was. Tang Gang et al [15] used a staircase with 160 mm in height to analyze the changes of the lower limb joint angle of healthy volunteers during the stairs climbing. It was pointed out that the maximum knee flexion range was 91.4 degrees, and the adduction-abduction range was -3.2—8.9 degrees, and the internal-external rotation range was 20.5 degrees. The height of the stair used in this paper was 100mm, and the greatest knee flexion angle during stairs climbing was 44 degrees. Meantime, the maximal range of the knee joint adduction-abduction was -6—6.8 degrees, and the maximum angle of internal-external rotation was 14 degrees, which was

in line with the research results in literature [12], but lower than that in literature [15]. It showed that adduction-abduction and internal-external rotation angle were within a reasonable range, and indicates the reliability and rationality of the experimental results in this paper.

Limitation analysis of verification experiment

In this experiment, the patients having been operated shortly after TKA were conducted the same measurement. Considering the difference in knee joint motion function of patients after surgery, the height of stair steps was required to be low. Besides, RSA (Roentgen Stereophotogrammetric Analysis) and high-speed photographic experimental measurements were also carried out in this experiment to perform the contrastive analysis of the data. During the experiment, due to the limited shooting space of experimental equipment and the space limitations caused by the simultaneous measurement of multiple systems, the volunteers' motion range was small and the shooting time could not exceed 5 seconds. Based on the above two main reasons, the maximum flexion of knee joint in the stair climbing and squatting experiment in this paper was small.

This experiment calibrates the anatomical feature points under the guidance of a professional orthopedist. Multiple calibrations were required prior to formal testing to ensure accurate position of the anatomical feature points. Volunteers require training for actions to enable them to perform as specified. In the formal experiment, each action was measured multiple times, and then the normal behavior of the most normal state was selected for analysis. However, the method described in this paper also has some limitations, for example, the motion capture measurement of human lower extremity motion and the calculation of kinematic parameters of the knee joint need to use the seven anatomical feature points to establish the coordinate system of the femur and tibia. Therefore, the determination of the anatomical feature point position has certain influence on the

experimental results.

Comparative analysis of processing methods

At present, there are a variety of methods for the processing of kinematics data measured by motion capture system and special software for data processing, including the de-noise processing of data, the matching of scattered data and the repair of missing points. Wu sheng [30] proposed a data processing algorithm based on the piecewise linear model of modules, which can effectively carry out global hierarchical prediction and tracking of 3d motion data modules, carry out module-based denoising processing of noise data, and put forward piecewise Newton interpolation operation based on missing motion data to make reasonable supplement. In this paper, cubic spline interpolation function is used to repair the interpolation program. The interpolated curve of this method is second-order continuous and differentiable, and the interpolation operation method of piecewise Newton interpolation has high accuracy and smooth curve transition. AlonsoF.J. Et al. [31] proposed to use the inverse dynamics model of human skeleton for motion data processing, where the complement algorithm based on rigid body requires that there should not be too many defects in the rigid body. For example, for the four waist points, matching complement points can be obtained only when one point is missing, which is the same idea as the repair data in this paper. When one of four marker points missed, it can be repaired; when two or more marker points missed, it cannot be repaired, so it needs to be abandoned. Liu [32] et al. used piecewise linear PCA technology to estimate the missing points and introduced statistical theory into motion data processing for statistical analysis. In terms of motion data processing software, as mentioned in literature [10], Visual3D commercial software and Vicon optical infrared motion capture system [33] were used for data processing of the experimental data of lower limb motion measurement by

motion capture system. At the initial step of data processing in commercial software, every testee's columnar motion model needs to be constructed manually by using the 'BodyBuilder' module of commercial software, which need costing much time and energy. After this initial manual process, although these software can automatically analyze and report motion capture data, if there are some occluded points and points being not captured during the movement measurement, the data need to be processed manually one by one in these software. Due to the data was large sample size, it also consumes a lot of time and energy. In this paper, MATLAB software is used as a tool to process human knee motion capture data. MATLAB program written by this paper can read kinematics data in batches and repair data. The local coordinate systems of tibia and femur can be established by using bone markers in the program. At last, according to the coordinate transformation, the kinematic parameters of knee femur relative to tibia in the movement of human lower limbs are quickly calculated, and the spatial coordinate curve of tibia and femur in the movement process also can be obtained. Therefore, human motion can be processed quickly by batch processing, and the program can be modified to meet different special requirements of motion function analysis. In the future, more accurate kinematics data will be obtained by increasing the sample size and continuously improving the program.

Conclusions

A set of methods was designed to process human knee motion data in this paper, and programs are written in MATLAB software. The kinematic parameters of the tibiofemoral joint of the knee joint during squatting and stairs climbing were obtained. For the squat movement, when the knee joint reaches the maximum flexion (79-98 degrees) from the beginning of flexion to the maximum flexion angle, the knee tibiofemoral joint is always in the external-rotation state during the whole

process, and the maximum external rotation is 30.5 degrees. In this paper, the maximum flexion angle of knee joint in the process of stairs climbing is 44 degrees, and the tibiofemoral joint is also in external-rotation all the time with a maximum of 14 degrees, and the range of adduction-abduction is 12.8 degrees. The results of other researchers are consistent with the movement trend of knee squat and stairs climbing in this paper, which also verifies the validity and rationality of the data processing method in this paper. It could be fast, convenient and accurate in processing human knee motion data by using the method in this paper; and the program can be modified according to different research purposes. It can provide data support for the design and optimization of artificial knee prosthesis, provide reference and help for the study of knee movement of patients after TKA and provide data processing for kinematics research of human body.

List of abbreviations

TKA: total knee arthroplasty;

3D: three-dimensional.

Declarations

Ethics approval and consent to participate

Informed consent was obtained from all individual participants included in the study. And we obtained approval from the Ethics Committee of Shanghai Sixth People's Hospital, China. All subjects provided written informed consent prior to their participation in the study.

Consent for publication

All authors confirmed the consent for publication.

Availability of data and materials

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

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

WJP designed the study, performed the measurements in healthy subjects, analyzed the data, and drafted the manuscript. WSH, ZX, HH, WYQ, LIL, CX and LY participated in performing the measurements of healthy subjects, analyzing the data, and drafting the manuscript. All authors read and approved the final manuscript.

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Appendix 1 Cubic spline interpolation function principle

Figure 14 Block diagram for solving cubic spline interpolation function

The block diagram for solving cubic spline interpolation function is shown in **Fig. 14**. The cubic spline interpolation function can be solved according to definitions and boundary conditions. Given some data point correspondence function values in the interval $[a, b]$, $\{x_1, x_2, \dots, x_n\}$, corresponding function value $\{y_1, y_2, \dots, y_n\}$, $S(x)$ is a cubic spline interpolation function, which satisfies $S(x_j) = y_j (j = 1, 2, \dots, n)$ and has a second-order continuous derivative on $[a, b]$. $S(x)$ determines a cubic polynomial on each subinterval $[x_j, x_{j+1}]$, known $S''(x_j) = M_j, S''(x_{j+1}) = M_{j+1}, h_j = x_{j+1} - x_j (j = 1, 2, \dots, n-1)$, then

$$S(x) = \frac{(x_{j+1} - x)^3}{6h_j} M_j + \frac{(x - x_j)^3}{6h_j} M_{j+1} + \left(y_j - \frac{M_j}{6} h_j^2 \right) \frac{x_{j+1} - x}{h_j} + \left(y_{j+1} - \frac{M_{j+1}}{6} h_j^2 \right) \frac{x - x_j}{h_j}, \quad (1)$$

The system of equations in matrix form was solved finally according to known conditions.

$$573 \quad \begin{bmatrix} 2 & 1 & & & \\ \mu_2 & 2 & 1-\mu_2 & & \\ & \cdot & \cdot & \cdot & \\ & & \mu_{n-1} & 2 & 1-\mu_{n-1} \\ & & & 1 & 2 \end{bmatrix} \begin{bmatrix} M_1 \\ M_2 \\ \cdot \\ M_{n-1} \\ M_n \end{bmatrix} = \begin{bmatrix} \beta_1 \\ d_2 \\ \cdot \\ d_{n-1} \\ \beta_n \end{bmatrix} \quad (2)$$

$$574 \quad \mu_j = \frac{h_{j-1}}{h_{j-1} + h_j}, d_j = 6 \left(\frac{y_{j+1} - y_j}{h_j} - \frac{y_j - y_{j-1}}{h_{j-1}} \right) \frac{1}{h_{j-1} + h_j}.$$

$$575 \quad \beta_1 = \frac{6}{h_1} \left(\frac{y_2 - y_1}{h_1} - y_1' \right), \beta_n = \frac{6}{h_{n-1}} \left(y_n' - \frac{y_n - y_{n-1}}{h_{n-1}} \right).$$

576 The coefficient matrix of equation (2) is a three-diagonal matrix and a diagonally dominant

577 matrix, so there is a unique solution. The interpolation function $S(x)$ on $[a, b]$ is obtained by taking

578 the solution into equation (1).