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Knee Joint Analysis for Optimal Ligament Surgical Reconstruction Using Three Dimensional Motion Model

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Abstract. Anterior cruciate ligament(ACL) is liable to a major injury that often results in a functional impairment requiring surgical reconstruction. The success of reconstruction depends on such factors as attachment positions, initial tension of ligament and surgical methods of fixation. The purpose of this study is to find isometric positions of the substitute during flexion/extension. A three-dimensional knee model was constructed from CT images and was used to simulate length change during knee flexion/extension. The results showed that minimum length changes were 1.9~5.8 mm(average 3.6±1.4 mm). The proposed method can be utilized and applied to optimal reconstruction for ACL deficient knee.

Introduction

Anterior cruciate ligament(ACL) is functionally subdivided into AMB(anteromedial band) attached on anteromedial side of tibia part and PLB(posterolateral band) attached on posterolateral side of femur part. When the knee joint does extension exercise, PLB suffers a tensile force. When the knee joint does flexion exercise, AMB suffers a tensile force and PLB is relaxed and appears the twisted shape. A normal ACL secures firstly knee stability by constraining the knee joint with the role of AMB and PLB that maintains a tensile force in flexion and extension exercise. ACL of ligament in knee joint endures 87% of the force restricting excessive knee extension. If ACL is ruptured, the stability of knee joint is functionally lost with severe pain. In this case, the reconstruction in the position of ACL using the ligament of one's own or the same kind is operated. The largest motion in knee occurs at mediolateral axis that flexion-extension occurs. When flexion-extension occurs, internal-external rotation about major axis is accompanied, and degree of freedom of varus-valgus on anterior-posterior axis of knee exists. The motion of knee joint with 6 degrees of freedom is very complicated. Because isometry of the ACL was directly related to the knee joint motion, the studies of the precise measurement of three dimensional motion and length change of ligament have been performed to analysis it[1]. The purpose of this study was to analysis isometry of the ACL by obtaining computationally length change from the measurement of flexion-extension of human body's knee three-dimensionally and selection of the points on tibia and femur.

Methods

Measurement of three-dimensional flexion-extension of knee joint. To measure the knee joint motion, Fastrak(3SPACE, Polhemus), three dimensional motion measurement system with magnetic sensor, was used. Fastrak system consists of the transmitter, receiving sensor and central controller. In Fastrak, the global coordinate system is the coordinate of transmitter detecting magnetic signal, and values of three axis rotation and translation were measured in local coordinate system of sensor receiving the signal of position. Fastrak system was set up to record 120 times per a second.

The movement of the right knee joint from 5 male subjects was measured. Table 1 presents data from subjects. To find out the initial position of knee joint prior to recording motion, Fastrak sensors were attached on the control points, from which three-dimensional position of each region was obtained. Control points were selected at five spots in upper regions of tibia and five spots in femur. After recording control points, subjects moved repeatedly up and down the lower leg 5 times for their strength. The motion of knee joint was reproduced from 90° of flexion angle of knee joint to the position of full extension by contraction of quadriceps femoris.

Table 1 Anthropometric measurements for five subjects.

ID	Age [years]	Height [cm]	Weight [kg]	Femur width [mm]	Tibia width [mm]
1	31	163	60	86	85
2	32	170	80	91	88
3	25	169	65	90	87
4	25	168	85	94	91
5	26	174	70	84	82

The position of sensor attached on tibia was fixed at 2 cm below the tuberosity of tibia that was unaffected by muscle or shifting of surrounding tissue. The direct attachment of sensor on skin surface of this position may cause the shifting of skin. In order to minimize the shifting, the fixing tool made of wood was so manufactured that the movement of tibia was regarded as that of a rigid body by connecting medial malleolus and lateral malleolus of ankle joint. The top end of the fixing tool became the position of sensor to attach on tibia, and flexion-extension was measured at the position.

Three-dimensional knee joint model. For the computational simulation, the shape of the right knee joint obtained from CT photograph Korean grown-up male was used in this study[2]. CT image was taken at intervals of 2.5 mm. The three dimensional shape was constructed by piling up each cross-section image three-dimensionally. Each of the constructed three-dimensional shapes of femur and tibia was scaled to fit the size of subjects by using the measurement of subjects' bone and the data of initial position measured in the measurement of the movement. By scaling, the analysis models of tibia and femur with different sizes were constructed.

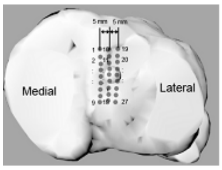


Fig. 1 Tibia insertion points.

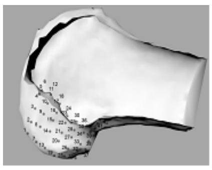


Fig. 2 Femur insertion points.

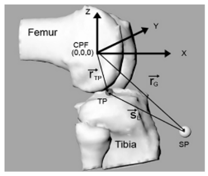


Fig. 3 Target point calculation.

Attachment position of the reconstructed ligament. 69 points on tibia and femur were selected for computational analysis. To consider actual insertion point of ACL, the insertion positions on the top of tibia were selected with 27 points adding up 9 points in anterior-posterior direction and points 5 mm apart from them in the medial-lateral direction as shown in Fig. 1. For femur, 42 points were selected from the medial surface of lateral condyle of femur(the attachment position of actual ACL) as shown in Fig. 2.

Calculation of the attachment position of tibia during flexion-extension. The coordinate system was set to describe the knee joint motion as shown in Fig. 3: X axis to front; Y axis to the inside; Z axis to the top side. Fig. 3 illustrates the center of medial epicondyle and lateral epicondyle of femur, CPF(center point of femur) and measurement position of sensor attached on tibia, SP(sensor position). TP(target point) is the point that represents the relative movement of tibia to femur, and becomes the attachment point of anterior cruciate ligament. If CPF of femur is set to the center of all coordinate system, tibia takes a relative motion to it. At this time, by obtaining the motion of TP according to flexion angle of tibia, the variation of anterior cruciate ligament length can be calculated. In this study, three dimensional coordinates were obtained by loading model to Rhino(three dimensional modeling program) and then activating each node point. By visualization of three-dimensional model, it can be ensured whether knee joint motion was correctly simulated, and ligament length changes on the position to insert can be displayed. To do this, the analysis program was constructed by use of Microsoft Visual C++ programming tool. To analyze isometry, length changes were obtained by connecting 27 points of tibia and 42 points of femur with line. For knee joint motion, the values of interim 3 times motion out of total 5 time flexion-extension were used, and length changes for the case of total 1134 (27x42) were obtained.

Results

Knee flexion-extension. The largest flexion-extension exercise in knee, which appears the rotation of Y axis, occurs as shown in Fig. 4. When the lower leg is raised on the condition that knee is bended to 90° in normal knee joint exercise, internal rotation occurs. When full flexion was reached, screw home movement that appears external rotation occurs. This can be confirmed from the value of X rotation in Fig. 4. The rotation of Z axis indicates internal and external rotation, and the lower leg moves within the region of 10°in flexion-extension of knee.

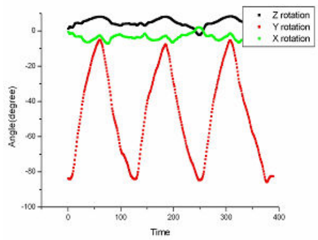


Fig. 4 Rotation data of the tibial motion.

Length change of insertion points. Length changes according to insertion position of all points were calculated by the constructed program during flexion-extension. Length(D) represents the distance of straight line between insertion points of femur and tibia and is defined as follows.

$$D = \sqrt{(x_f - x_t)^2 + (y_f - y_t)^2 + (z_f - z_t)^2}$$

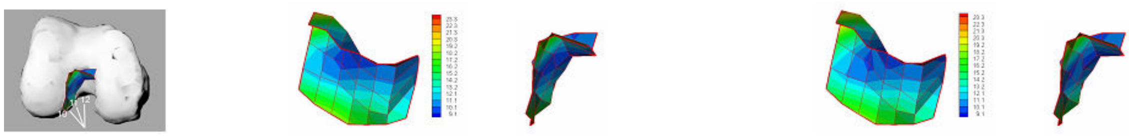
where x_f, y_f, z_f are the coordinates of femur insertion point, x_t, y_t, z_t are the coordinates of tibia insertion point. Table 2 presents minimum values out of length changes calculated by connecting 27 points on tibia and 42 points on femur during knee flexion-extension and corresponding insertion points. Hefzy[3] reported that there was no isometric point without the change of length from their measurement of length change according to the position of ligament. Therefore, the position close to isometric point was investigated. Because insertion points was connected for all cases in Table 2, the positions of insertion points that the length change became a minimum were different for each subject.

Table 2 Minimum length changes during knee flexion-extension.

ID	Tibia number	Femur number	Min. length [mm]	Max. length [mm]	Min.Difference [mm]
1	8	36	40.2	42.1	1.9
2	8	29	32.1	37.9	5.8
3	26	15	23.9	27.3	3.4
4	18	5	23.9	27.8	3.9
5	15	40	36.0	39.0	3.0

Isometry analysis. In this study, the tibia part was first selected, and then isometry was analyzed by calculating length changes of the insertion position of femur. To insert graft ligament into tibia and fix it, a tunnel is cut. The center of a tunnel locates at point number 12 ~ 17 of tibia in this study. The point number 12 ~ 17 locate at the place of 40 ~ 55% in anterior-posterior direction of femur. Fig. 5 illustrates average length changes calculated from 12~17 points to 13~16 points.

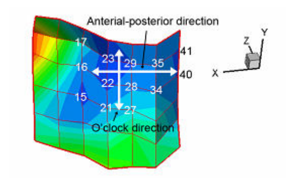
(a) Isometry map at tibia point no.13 (b) Isometry map at tibia point no.14

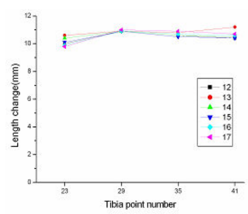


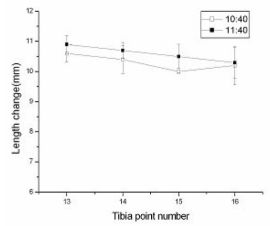
(c) Isometry map at tibia point no.15 (d) Isometry map at tibia point no.16

Fig. 5 Length changes on femoral insertion sites varying tibia point (Anterial-Posterior).

Clinically, by making tunnel of diameter 8~10 mm at 7 mm anterior from over-the-top of lateral malleolus of femur, and then fixing at femur, a ligament is reconstructed in the place. Fig. 5 shows that isometry on anterior-diagonal area along the surface of posterior cortex is high. This region is similar with the one which Hefzy[3] and Sidles have analyzed. Hefzy has studied isometry by causing flexion-extension of knee with dead body. He has considered the region that length change of the linear region connecting insertion point A-A was less than 2 mm as isometric position. Fig. 6 shows the selected points out of insertion points of femur and direction for isometry analysis. The point number 23-29-35-41 of femur in Fig. 6 indicates anterior-posterior points in highly isometric regions. Fig. 7(a) illustrates the results from calculation of length change as these points shift from point number 12 to 17 on femur. When points on femur have moved in anterior-posterior direction, a major change of length at point number 23-29-35-41 was not found, as shown in Fig. 7(a). For o'clock direction in Fig. 6, highly isometric region ranges from 12 to 10(Fig. 5). To analysis isometry in o'clock direction, 15-21-27 points and 17-23-29 points in Fig. 6 were averaged, and then set to 10:40 direction and 11:40 direction respectively. Fig. 7(b) illustrates length changes as the point of tibia moves from 13 to 16 in both directions, and the length changes rate in 10:40 and 11:40 direction are 3.8% and 5.2% respectively.







(a) AP direction (b) O'clock direction

Fig. 6 Analysis points of the femur.

Fig. 7 Length changes with two other directions.

Summary

To investigate the reconstruction position of ligament as ACL was reconstructed, isometry of ligament attachment position was analyzed. In this study, the isometic position has analyzed for the knee joint of a normal person instead of dead body eliminating muscle. It is estimated that this method is more efficient for reconstructing the movement of actual knee joint, compared the experiment using dead body even if it has a low precision due to the influence of muscle. The results shows that isometry of actual knee joint is similar with the results of Hefzy or Sidles that has used the knee of dead body. The result of this study shows that the position to cut tunnel in femur clinically agrees to highly isometric region, and may be useful to find the better clinic reconstruction position for o'clock direction.

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