Computer Investigation into the Anatomical Location of the Axes of Rotation in the Normal Knee

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Abstract. The purpose of this paper was to investigate the anatomical location of the main axes of rotation of the knee. The study was performed as follows: joint motion registration by an electrogoniometer; joint digitization by the same electrogoniometer; computer reconstruction of motion and bone geometry; comparison of 4 hypotheses on correlation between the axis of flexion–extension and the femoral anatomy and between the axis of longitudinal rotation and the tibial anatomy in 6 human knees using an original geometrical interpolation. Our results suggest that: (a) the axis of flexion-extension lies in a cone spanned by the transepicondylar line and the so called FFc line [1]; (b) the axis of longitudinal rotation can be represented by a line parallel to the tibial anatomical axis intersecting the flexion axis in the medial compartment. Such a simplified frame for the representation of knee rotations may be useful and easily computed in computer-assisted knee reconstruction.

Keywords: knee, axes, rotation, anatomy, kinematics, motion, PROM

1 Introduction

The increasing number of computer assisted surgical procedures have allowed surgeons to demand more information about the knee biomechanics and kinematic predictions. Therefore new methods to evaluate the knee motion are necessary, based on quantitative evidence and functional acquisitions.

Despite agreement in literature about the identification of the two main components of knee kinematics (the flexion – extension and the longitudinal rotation), there is still no agreement about the anatomical location of the axes of rotation and therefore the method to identify them. Many authors have identified the axis of flexion-extension in relationship to the femoral anatomy. [1], [2], [3], [4], [5], [6], [7], [8], [9] Similarly many authors have identified the axis of longitudinal rotation in relationship to the tibial anatomy, most reporting its orientation to be parallel to the tibial anatomical axis [2], [3], [5], [7] in the medial compartment, [1], [4], [5], [6], [7], [8], [10], [11], [12], [13] sometimes proposing an anterior-posterior slope [10], [11] or complex pattern of motion in the tibial plateaux. [1], [2], [11], [14]

At present most scientists represent the 3D nature or the 6 degrees of freedom of the knee in a reference frame made of the flexion – extension axis fixed to the femur, the longitudinal axis fixed to the tibial anatomy, and a third axis to complete the definition of a suitable joint reference frame. [2], [7], [15], [16], [17] Therefore the anatomical location of the axes of the knee can improve not only geometrical measurements but also the kinematic evaluation in computer-assisted applications.

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The goal of this work is to verify some hypotheses on the location of the main axes of rotation of the knee during passive motion.

2 Material and Methods

2.1 Experimental Data Acquisition

6 normal knee specimens were examined.

A 6 degrees-of-freedom electrogoniometer, FARO Arm (FARO Technologies, Lake Mary, FL, USA), was used to record passive motion and digitize the articular surfaces (0.3 mm / 0.3° accuracy in 1.8 m^3), as follows (protocol in patent pending state):

1. The tibia was rigidly fixed to the experimental desk by screws while the Faro Arm was secured to the experimental desk and rigidly connected to the mobile femur (like in the set-up of robot-assisted knee surgery in [18]). The mobile bone was held consecutively by two expert orthopaedic surgeons, who performed a passive range of motion and recorded the neutral position of the intact knee at 0°, 10°, 30°, 60°, 90° and 120°. Also the internal–external rotation at 45° and 90° was recorded with the knee in the neutral position at 45° of flexion, in the maximal internal rotation possible at 45°, in the maximal external rotation at 45°, at 90° neutral position, 90° internal rotation, 90° external rotation. The motion were repeated twice for each knee.
2. Then the FARO Arm was detached from the mobile bone and equipped with a point–probe, three landmarks were implanted on the femur and on the tibia and the joint was dissected. One surgeon digitized the shape of femur, tibia (on the cartilage surface) and ligament insertions (on the external border of the insertion areas).
3. Data about knee anatomy and motion were processed off-line by dedicated software, allowing the 3D reconstruction and display of the bone shape and of the relative position of the two segments during the recorded trajectories in an anatomical coordinates system. Surfaces were represented as clouds of points and motion was represented tracking the positions of all structures in the 3D space or in 2D projections or sections corresponding to the standard sagittal, frontal and transversal planes.

2.2 Computer Evaluation of the Axes of Rotation

Four different definitions of the axis of flexion–extension were compared (Fig. 1):

- F1, the line joining the most posterior points of the posterior condyles [2], chosen on a central section of the medial and lateral femoral condyles at full extension;
- F2 the line joining the most distal points on femoral condyles in extension [3], chosen on a central section of the medial and lateral femoral condyles at full extension;
- F3 (transepicondylar line), the line joining the centres of the femoral insertion areas of medial and lateral collateral ligaments [4], [5], [6], [7];

- F4, the line joining the centres of the posterior femoral condyles, computed as the centres of the circle fitting the posterior part of the femoral profile in a central section of the medial and lateral compartment at extension (the so called "flexion facet centres" (FFc) in [1]). [4], [8], [9]

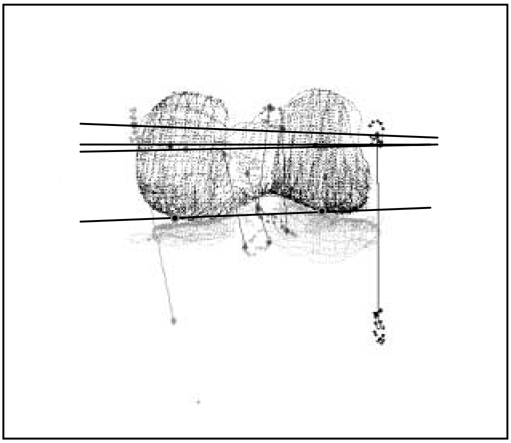

Fig. 1.

Similarly four definitions of the axis of longitudinal rotation were compared. All axes have the same orientation (parallel to the tibial shaft), but different location and patterns of motion with respect to the joint:

- T1, the vertical line passing through the centre of the medial posterior condyles, i.e. intersecting F1;
- T2, the vertical line passing through the centre of the medial anterior condyles, i.e. intersecting F2;
- T3, the vertical line passing through the centre of the medial collateral ligament, i.e. intersecting F3;
- T4, the vertical line passing through the centre of medial femoral flexion facet, i.e. intersecting F4.

To verify the hypothesis that the knee rotates around one of the known axes, we used a geometrical method inspired by the one presented in [9], [11], [19], that we realised through computer elaboration and statistical evaluation.

As all points in a mobile rigid body rotate around the instantaneous axis of rotation, the projection of their positions during the motion onto a plane perpendicular to the axis will track a circle or part of a circle. In this study we chose 10 points (named P1 to P10) distributed in the two compartments at increasing distances from the presumed axis of rotation; we tracked their projection during the recorded motion onto the plane perpendicular to the axis of rotation; then we computed the circle with its centre on the projection of the axis and radius equal to the mean distance from the tracked positions of the point (Fig. 2). The residual of this fitting was considered as an indication of how correct the identification of the axis of rotation is (the less the residual, the better the circularity of the motion of the tracked point).

We used this method to verify the hypothesis that the knee rotates around the axes F1/T1, F2/T2, F3/T3 or F4/T4, during passive range of motion (PROM) and maximal internal – external rotation at 45° and 90°.

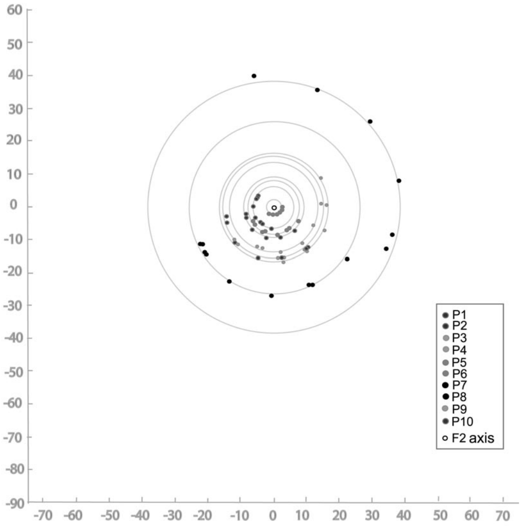

Fig. 2.

3 Results

The relative location of the examined axes was compared by computing the 3D angle made by pairs of F1, F2, F3, F4 axes (Table 1) and the distance among pairs of T1, T2, T3, T4 projected onto the horizontal plane (Table2).

All tracked points appeared to move around the mentioned axes in a 120° arc of a path looking quite circular. However a more detailed analysis of the circularity of these paths (reported in Table 3) showed some statistical differences in the behaviour of F1, F2, F3 and F4.

Table 1. Angles (in degrees) between the couples of axes reported in the heading of each column, computed as the arcosin of the dot between the unitary vectors of axes

	F4-F3	F4-F2	F4-F1	F3-F2	F3-F1	F2-F1
Knee 1	11.6	10.5	3.7	4.6	8.2	8.2
Knee 2	5.6	15.1	5	9.8	4.6	13.8
Knee 3	4	5.2	2.5	3.3	5.9	5.8
Knee 4	8.1	8.8	3	5.6	6.2	8.9
Knee 5	8.4	9.9	0.9	5.8	9	10.7
Knee 6	5.6	14.6	2.1	11.1	4.3	15
MEAN	7.2	10.7	2.9	6.7	6.4	10.4
	(2.7)	(3.7)	(1.4)	(3.0)	(1.9)	(3.5)

Table 2. Mean distance (in millimetres) during PROM (average of the recorded PROMs) of the projection of T1, T2, T3, T4 axis onto the horizontal plane. Each column reports the distance between the specified couple

	T4-T3	T4-T2	T4-T1	T3-T2	T3-T1	T2-T1
Knee 1	16.8	18	13.6	24.6	26.1	27.3
Knee 2	18.4	19.9	12.5	26.4	25.4	29.3
Knee 3	20	22.2	16.1	29.2	30.7	33.9
Knee 4	21.2	18.5	13	25.1	25.3	27.6
Knee 5	19.3	19.2	12.4	27.7	24.1	28.8
Knee 6	21.1	22.1	13.7	31.9	27.8	31.4
MEAN	19.5 (1.7)	20.0 (1.8)	13.6 (1.4)	27.5 (2.7)	26.6 (2.4)	29.7 (2.5)

Table 3. Residuals (in millimetres) of the circular fitting for each knee in planes perpendicular to F1, F2, F3, F4. Each value is computed as the mean (and standard deviation) of all sample points (P1 – P10) and all recorded passive ranges of motion

	F1	F2	F3	F4
Knee 1	0.1 (0.07)	0.3 (0.11)	0.1 (0.06)	0.1 (0.07)
Knee 2	0.2 (0.20)	0.4 (0.34)	0.1 (0.13)	0.2 (0.18)
Knee 3	1.2 (0.44)	1.5 (0.39)	0.6 (0.37)	0.6 (0.35)
Knee 4	0.9 (0.32)	1.1 (0.33)	0.4 (0.25)	0.7 (0.39)
Knee 5	1.2 (0.35)	0.8 (0.27)	0.3 (0.21)	0.6 (0.34)
Knee 6	0.4 (0.11)	0.5 (0.14)	0.1 (0.09)	0.2 (0.16)
MEAN	0.67	0.77	0.27	0.40

To identify the optimal axis of longitudinal rotation during IE rotation at 45° and 90° we considered tracks of points during internal – external rotations and during PROM. All points appeared to move around T1, T2, T3 and T4 in a 29° ± 2° arc of a circular path. However no significant differences could be found among the compared axes, as all tracks were fitted by a circle with a mean residual (over the six knees and the 10 sample points) of 0.45 (0.12) mm at 90° and 0.85 (0.15) mm at 45°.

To identify the optimal axis of longitudinal rotation during PROM (i.e. screw-home mechanism) we must consider that IE rotation is a secondary component of this movement, therefore it can be identified only by splitting it from the simultaneous rotation around the flexion – extension axis. Therefore during PROM we verified the coupled IE rotation around T1, T2, T3 and T4 tracking 10 points on each flexion-extension axis (F1, F2, F3, F4). These points, fixed during pure flexion, revealed a circular pattern around the tibial axis during the PROM, without the artefacts present in the tracking of random points, but a detailed analysis of the circularity of these paths showed no significant statistical differences in the behaviour of T1, T2, T3 and T4.

4 Discussion and Conclusion

This study confirms that the axis of flexion- extension of the knee lies in a cone made by the transepicondylar line and the line joining the femoral flexion-facet centres. Table 3 shows that there is no significant difference between these two axes, if we consider an error on anatomical data of around 1.5 mm (i.e. a residual of 0.5 mm with a 99.7% probability), mostly assessed in in-vivo applications. The equivalence between the transepicondylar line and FFc line, and therefore all lines in-between, may be explained by the uncertainty about anatomical data (bone shapes, ligaments' insertions), by an equivalent contribution of ligaments and bone shapes in guiding PROM, or by small changes in the position of the instantaneous axis in different sub-ranges of flexion. It is interesting to notice that the orientation of F1, F2, F3, F4 is very similar (less than 11°, Table 1), but the position of the axis around the condyles' centre instead of the surface appears more satisfactory.

Therefore our study suggests that a kinematic frame of the knee with reference axes aligned with transepicondylar or FFc line, as proposed by Pennock [7], Hollister [11] or Pinskerova [1], may be more correct than the reference frame proposed by Grood and Suntay [2] or Lafortune [3] and reduce cross-talk errors in kinematic computations due to axes misalignment. [20], [21]

This study also confirms that the longitudinal rotation occurs around a vertical axis located in the medial compartment, both during forced rotation at 45° and 90° and during PROM. It can be noticed that the residuals (and standard deviation) measuring the circular paths in both motions around T1, T2, T3, T4 are higher than the residuals measuring the circular paths around F1, F2, F3, F4. This was due to the fact that the amount of longitudinal rotation (and the arc fitted) is much smaller than the amount of flexion (30° versus 120°), and therefore the computation of the circle is more unstable from a numerical point of view. The higher residuals obtained during the forced internal–external rotation with respect to PROM and IE rotation at 90° with respect to 45°can be due to the fact that this movement is performed manually and may be affected by a non-negligible flexion during the manoeuvre, producing artefact in the circular tracks. Probably for these reasons this method was not able to discriminate the exact location of the longitudinal axis in the medial compartment (for example the central position with respect to location on the medial tibial spine). However, it showed that the location of the axis is in the medial compartment, in the central or posterior area of the tibial plateau (the T2 residual is higher than the others in Table 2) and moves with the femur keeping the orientation fixed with respect to the tibia.

We can conclude that our results are compatible with a kinematic model of the knee rotating around the transepicondylar line and an axis parallel to the tibial one through the centre of MCL or around the FFc line and an axis parallel to the tibial one through the centre of the medial femoral flexion facet. The former (F3/T3) is similar to the model proposed by Hollister [11], but simplifies the description of the axis of longitudinal rotation. The latter (F4/T4) is similar to the model suggested by Pinskerova [1], who deduced the location of FE axis from anatomical observations and measured a small displacement of the medial flexion facet centre (i.e. the intersection of F4 and T4), but applies both in PROM and IE rotations. In both models the correlation between the longitudinal axis and the flexion – extension axis is simpler than previous models in literature.

This model simplifies the computation of the knee reference frame from anatomical data, provide a unique the kinematic description in passive motion and forced IE rotations and a fix and predictable correlation between the main axes of rotation. This representation of the knee motion could be easily applied in navigated surgery and computer-assisted procedures.

Moreover, the similarity of our results with Churchill's study [4] in the loaded motion of the knee (although with a different technique), could suggest a similar behaviour also in active flexion. A finer validation of a 2 degrees-of-freedom knee kinematic model, and maybe a better discrimination between F3/T3 and F4/T4, if any, is not possible with the reported geometrical method. A mathematical representation of proposed model of the knee motion, as a double rotation around quasi–perpendicular axes intersecting in the medial femoral condyle or the implied presence of an origin behaving as a fixed point during motion, will be investigated by the author in the future, to find a simple, clinically interpretable and complete representation of the knee kinematics and to use in computer evaluation of the joint.

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