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In-Vivo Analysis of Flexion Axes of the Knee: Femoral Condylar Motion during Dynamic Knee Flexion

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Abstract

Background—Transepicondylar axis and geometrical center axis are widely used for investigation of the knee kinematics and component alignment in total knee arthroplasty. However, the kinematic characteristics of these knee axes are not well defined in literature. This study investigated the femoral condylar motion during a dynamic flexion of the knee using different flexion axes.

Methods—Twenty healthy knees (10 males and 10 females) were CT scanned to create 3D anatomic models. The subjects performed a single leg flexion from full extension to maximal flexion while the knees were imaged using fluoroscopes. The femoral condyle translations in anterior-posterior and proximal-distal directions were described using clinical transepicondylar axis, surgical transepicondylar axis and geometrical center axis.

Findings—The subjects achieved -9.4° (SD 3.0°) hyperextension at full extension and 116.4° (SD 9.0°) at maximal flexion of the knee. The anterior-posterior translations of the three flexion axes were different for the medial condyle, but similar for the lateral condyle. Substantial variations of the condylar motion in proximal-distal direction were measured along the flexion path using these axes. While the surgical transepicondylar axis maintained condyle heights from full extension to 60° of flexion, geometrical center axis showed little changes in condyle heights from 30° to maximal knee flexion. The condyles moved distally beyond 90° flexion using both transepicondylar axes.

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Interpretation—The femoral condylar motion measurement is sensitive to the selection of flexion axis. The different kinematic features of these axes provide an insightful reference when selecting a flexion axis in total knee arthroplasty component alignment.

Introduction

A flexion axis is important for measurement of the knee joint kinematics (Asano et al., 2005; Eckhoff et al., 2007; Li et al., 2013; Most et al., 2004; Victor et al., 2009) and for component alignment in total knee arthroplasty (TKA) (Colle et al., 2012; Matziolis et al., 2011; Victor et al., 2009). The transepicondylar axis (TEA) and the geometrical center axis (GCA) are widely used in knee joint kinematics analysis (Asano et al., 2001; Berger et al., 1993; Eckhoff et al., 2007; Li et al., 2013; Matsuda et al., 2003; Most et al., 2004; Oussedik et al., 2012; Victor et al., 2009). A TEA could be referred to the clinical TEA (c-TEA) or surgical TEA (s-TEA) based on the different bony landmarks used to define the axes on the medial femoral epicondyle (Berger et al., 1993; Griffin et al., 2000; Victor et al., 2009; Yoshino et al., 2001). Geometric differences between these axes have been compared in various studies (Berger et al., 1993; Eckhoff et al., 2001; Most et al., 2004; Victor et al., 2009). However, the differences of femoral condylar motion measured using these axes are still not well defined during dynamic motions of the knee (Gromov et al., 2014; Victor, 2009).

Few studies have compared the anterior-posterior (AP) femoral condyle translation calculated using different flexion axes for the same knee motion in vitro (Eckhoff et al., 2007; Most et al., 2004; Walker et al., 2011) and in vivo (Kozanek et al., 2009; Li et al., 2013; Tanifuji et al., 2013). These studies were mainly concerned about the c-TEA and GCA, and reported that the AP translations of the femoral condyles measured using the c-TEA and GCA could be different at different ranges of knee flexion (Most et al., 2004; Tanifuji et al., 2013; Walker et al., 2011). However, in TKA component alignment, the TEAs were mostly adopted for component alignment (Berger et al., 1993; Victor, 2009), therefore, the condyle position in the proximal-distal (PD) direction is critical for gap balance in medial and lateral compartments (Manson et al., 2009; Mihalko et al., 2009). Little is known about the proximal and distal translations of the femoral condyles during knee joint motion (Asano et al., 2005; Mochizuki et al., 2014). No study has compared the femoral condyle translations in the PD direction measured by using these different flexion axes.

The objective of this study was to investigate the femoral condylar motion during a dynamic flexion motion using a two-dimensional to three-dimensional (2D–3D) fluoroscopic tracking technique. The femoral condylar motion was described using three flexion axes: c-TEA, s-TEA and GCA axes. In addition to the traditionally reported AP femoral condyle translation, the PD femoral condyle translation was specifically analyzed. We hypothesize that these three axes of the knee will result in different motion patterns of the femoral condyle along the dynamic flexion path of the knee.

Materials and Methods

Subject recruitment

Twenty healthy subjects (10 males and 10 females) were recruited for this study with approval of the IRB and informed consents. The mean age was 26.4 (SD 4.4) years. The mean body mass index was 21.8 (SD 2.7) kg/m². All subjects have a right dominant limb and no history of knee injury, surgery or systemic diseases. Knee pathology was ruled out upon physical and radiographic (CT and X-ray) examination. The motion of the right knee was analyzed in all subjects.

Creation of three dimensional knee model

Computed tomography scan (SOMATOM[®] Sensation; Siemens, Munich, Germany) of the femur and tibia was obtained for each subject with a slice thickness of 1mm and a pixel size of 0.625 mm by 0.625 mm. The CT images were imported into the 3D modeling software (Rhinoceros, Seattle, WA, USA). The bony edges were outlined and used to reconstruct the 3D models of the femur and tibia. The accuracy of the 3D models was estimated at 0.4 mm according to the imaging resolution (DeVries et al., 2008).

To quantitatively describe the femoral condylar motion, 3 axes (the c-TEA, s-TEA and GCA) were established using the 3D bony models of the knee (Fig.1). The c-TEA was defined as a line connecting the most prominent points of both lateral and medial epicondyles of the femur (Berger et al., 1993; Yoshioka et al., 1987). The s-TEA was a line connecting the lateral epicondylar prominence and the medial sulcus of the medial epicondyle (Berger et al., 1993). The geometric center axis (GCA) was a line connecting the centers of the spheres fitting to the lateral and medial posterior femoral condyles (Asano et al., 2001). The long axis was defined as parallel to the femoral shaft. The AP axis was perpendicular to the other two axes (Kozanek et al., 2009; Most et al., 2004). For the tibia, a long axis was parallel to the posterior wall of the tibial shaft. Two circles were created to cover the edges of the medial and lateral tibial plateaus, respectively. The centroids of the two circles were projected onto the surface of tibial plateaus along the tibial long axis. A line connecting the two projected points was defined as the mediallylateral axis and its midpoint was defined as the origin of the tibial coordinate system. The AP axis was perpendicular to the other two axes (Kozanek et al., 2009; Most et al., 2004). To describe the relative angular relationship between the knee flexion axes, the angles between any two axes among the 3 flexion axes of the knee were quantified in 3D space. The projection angles between the axes on the coronal and transverse planes of the femoral coordinate system were also reported.

Measurement of in vivo knee kinematics

The dynamic images of the knee during the single-legged lunge were captured using a fluoroscopic imaging system (Philips, WA, USA) at a frame rate of 30 Hz following a published protocol (Feng et al., 2015). Participants were asked to stand with feet apart at shoulder width and toes forward without any supporting devices. The subject was then instructed to flex the knee from full extension position to maximum comfortable flexion. The other leg was only used to maintain body stability. The mean duration of the knee

flexion was 4.7 seconds. The mean angular velocity and sampling rate were 26.7°/second and 1.1 images/degree of knee flexion.

After experiment, the fluoroscopic images were imported into the modeling software (Rhinoceros, Seattle, WA, USA) that reproduces the fluoroscopic set up during the testing. The 3D CT-based knee model was also imported into the software and manipulated in 6 degrees-of-freedom (DOF) until the projections of the model matched the outlined silhouettes of the bones captured on the fluoroscopic images. Therefore, the dynamic knee motion was represented by a series of 3D knee models along the flexion path (Feng et al., 2015; Zhu and Li, 2012). Spline interpolations with 5° flexion increments were used to resample the knee kinematics. Then we measured the motion of medial and lateral femoral condyles with respect to the tibia using the three flexion axes (Kozanek et al., 2009; Most et al., 2004). A center of each condyle was determined on the c-TEA, s-TEA, and GCA axes. The condylar centers were then projected onto the sagittal and transverse plane of the tibial coordinate system. The AP and PD femoral condylar motions were quantified as the movement of these condylar centers with respect to tibia.

Statistical analysis

A two-way repeated measures analysis of variance (ANOVA) and a post hoc Student Newman-Keuls test were used to detect whether axis choice had a significant effect on the kinematic characteristics of the tibiofemoral joint. Independent variable was flexion axes and knee flexion angle / the range of knee flexion angles (Full extension-30°, 30°–60°, 60°–90°, 90°–115°). The dependent variables were defined as changes in the anteroposterior and proximal-distal translations. The Student's t-test was used to compare angular relationship of three different flexion axes of the knee. The level of statistical significance was set at $p < 0.05$.

Results

During the dynamic flexion, the knees achieved -9.4° (SD 3.0°) hyperextensions at full extension position and 116.4° (SD 9.0°) at the maximal knee flexion. The 3D angle between the c-TEA and GCA was 8.2° (SD 1.7°); between the c-TEA and s-TEA was 4.8° (SD 1.1°); and between the s-TEA and GCA was 4.0° (SD 1.3°), respectively (Table 1). The angles between these axes in coronal and transverse planes of the femur were significantly smaller than those in 3D space (Table 1, $p < 0.05$).

Anterior-posterior translation

The medial femoral condyle of these axes showed different trends in anterior-posterior translation (Figs. 2A & B). For the c-TEA, the medial condyle translated slightly anteriorly from full extension to 10° (~ 1.9 mm) and then posteriorly after 10° of flexion (~ 15.0 mm). For the s-TEA, the medial condyle gradually translated anteriorly from full extension to 30° (~ 4.1 mm) and then posteriorly after 30° of flexion (~ 8.4 mm). For the GCA, the medial condyle gradually translated anteriorly from full extension to 60° (~ 9.4 mm) and then posteriorly after 60° of flexion (~ 3.1 mm). The total excursions of the medial condyle were 19.4 (SD 2.5) mm for the c-TEA, 17.4 (SD 3.5) mm for the s-TEA and 18.1 (SD 3.1) mm

for the GCA, respectively. There was no statistically significance among these 3 axes ($p > 0.05$).

However, the lateral femoral condyle of these three axes showed similar trends and translated posteriorly with flexion of the knee consistently (Figs. 2A & C). The mean translation of the c-TEA, s-TEA, and GCA were 27.5 (SD 4.2) mm, 25.6 (SD 4.4) mm and 19.6 (SD 5.0) mm, respectively. Both TEAs were significantly larger than the GCA ($p < 0.01$).

Proximal-distal translation

The medial femoral condyle of these axes showed different trends in proximal-distal translation ($p < 0.01$, Fig. 3A, Table 2). According to the degree of the mean translation along the flexion path, the sequence decreasingly was c-TEA, s-TEA and GCA. However, the lateral femoral condyle of both TEAs showed similar trends ($p > 0.05$) and were significantly larger than the GCA ($p < 0.01$, Fig. 3B, Table 2).

For the c-TEA, the medial femoral condyle gradually translated proximally from full extension to 60° (3.4 [SD 1.6] mm) and then translated distally (5.3 [SD 2.1] mm) (Fig. 3A, Table 2). The lateral femoral condyle changed height slightly from full extension to 60° (mean translation: 2.2 [SD 1.0] mm) and then consistently translated distally beyond 60° of flexion (4.7 [SD 1.7] mm) (Fig. 3B). The medial condyle is 1.4 mm, 4 mm, 4.3 mm and 4.3 mm more proximal than the lateral side at full extension, 60°, 90° and 115°, respectively ($p < 0.05$).

For the s-TEA, the medial femoral condyle slightly changes height from 0° to 60° (1.7 [SD 1.3] mm), then gradually translated distally beyond 60° of flexion (3.0 [SD 1.9] mm) (Fig. 3A). The lateral condyle also showed little change in height from full extension to 60° (1.9 [SD 1.0] mm) and then translated consistently distally after 60° of flexion (4.1 [SD 1.5] mm) (Fig. 3B). At full extension, the medial condyle was 0.2 mm more distal than the lateral condyle, but is 0.7 mm, 1.7 mm and 2.5 mm more proximal than the lateral side at 60°, 90° and 115°, respectively.

For the GCA, the medial femoral condyle gradually translated distally from full extension to 30° (2.6 [SD 1.5] mm) and then showed little change in height after 30° of flexion (1.9 [SD 0.8] mm) (Fig. 3A). The lateral condyle translated distally from full extension to 30° (2.0 [SD 1.2] mm) and then showed a nearly consistent height from 30° to 90° of flexion (1.4 [SD 0.8] mm) and then translated distally until maximal flexion (1.5 [SD 0.9] mm) (Fig. 3B). At full extension, the medial femoral condyle was 0.9 mm more distal than the lateral condyle, and is 2.2 mm and 1.0 mm more distal than the lateral side at 60° and 90° of flexion, respectively. At maximal flexion, the medial condyle is 0.5 mm more proximal than the lateral condyle.

Discussion

This study investigated femoral condylar motion during a dynamic weightbearing flexion of the knee using three different flexion axes. The results showed that the femoral condylar

motion measurement was sensitive to the flexion axis. The anterior-posterior translations of the three flexion axes were different for the medial condyle, but similar for the lateral condyle. The proximal-distal translations of the three flexion axes were different for the medial condyle. However, the lateral femoral condyle of both TEAs showed similar trends and were significantly larger than the GCA. Specifically, the femoral condyle showed little changes in proximal-distal direction from full extension to 60° knee flexion using the s-TEA, but from 30° to 90° knee flexion using the GCA (Table 2). These data proved our hypothesis that different flexion axes will result in different motion patterns of the femoral condyle along the dynamic flexion path of the knee.

The data of this study should be explained under several limitations. The 2D–3D registration technique using single-plane fluoroscopy showed limited out of plane accuracy (Zhu and Li, 2012). However, the AP and PD femoral condyle translations investigated in this study are in plane motions with respect to the image intensifier. In addition, only a flexion motion of the knee was investigated. Many studies have shown that the knee kinematics is activity-dependent (Hill et al., 2000; Komistek et al., 2003; Moro-oka et al., 2008). Therefore, various dynamic daily activities such as gait, up or down stairs should also be investigated to examine the knee joint motion characteristics using different flexion axes.

Many studies have investigated the femoral condylar motion using different flexion axes, and a few have compared the condylar motions in AP direction using these flexion axes (Eckhoff et al., 2007; Kozanek et al., 2009; Li et al., 2013; Most et al., 2004; Tanifuji et al., 2013; Walker et al., 2011). In a study of passive knee flexion from full extension to 150° using the c-TEA and GCA (Most et al., 2004), the medial condyle of the TEA was shown to move anteriorly at low flexion and posteriorly beyond 30° flexion. The medial condyle of the GCA moved anteriorly until 120°. The lateral condyle demonstrated consistent posterior translation throughout the knee flexion (Most et al., 2004). In a study of in vivo dynamic kinematics of normal knees (Tanifuji et al., 2013), the medial condyle of the c-TEA translated anteriorly by 3.6 mm from full extension to about 30° flexion and then posteriorly by 18.1 mm after 30° flexion. The medial condyle of the GCA moved anteriorly from full extension to about 100°, followed by a posterior translation of 3.9 mm with higher flexion. In our study, the trends of the AP femoral condylar translations using the c-TEA and GCA were similar to those observed in previous studies (Most et al., 2004; Tanifuji et al., 2013; Walker et al., 2011). The notable differences using different flexion axes were the peak of anterior translation and the amount of posterior translation of the medial condyle. “Medial pivoting” motion characteristics depends on the selection of flexion axis and the range of knee flexion (Fig. 2A). These studies revealed that the medial femoral condylar motions measured using different axes were different, but similar in lateral femoral condyles. Our data indicated the lowest anterior translation of the medial condyle when using the c-TEA, but the highest anterior translation when using the GCA. The total excursion of the medial femoral condyle was much smaller than the lateral femoral condyle.

Few studies have reported the femoral condylar motion in the PD direction (Asano et al., 2005; Mochizuki et al., 2014). Mochizuki et al. (Mochizuki et al., 2014) reported that the medial condyle of the c-TEA had a proximal translation of 7.5 mm from 0° to 100° knee flexion followed by a distal translation of 5.0 mm beyond 100° knee flexion, while the

lateral condyle demonstrated nearly consistent distal translation of 8.2 mm throughout the entire range of flexion. This finding is similar to that of our study using the c-TEA. However, no study has compared the femoral condyle translations in the PD direction measured using different flexion axes. Our data showed that the c-TEA had a larger range of motion in the PD direction than both the s-TEA and GCA. The medial condyle of the s-TEA had little change in height from full extension to 90° of flexion, but the lateral condyle maintained height only up to 60° and then consistently reduced heights with flexion beyond. The differences between the medial and lateral condyles were less than 0.5 mm before 60° of flexion, but increased with further flexion. It is interesting to see that both condyles reduced heights at high flexion angles with lateral lower than the medial condyle. The GCA remained almost stationary in the PD direction from 30° to 90° of knee flexion, but the lateral condyle is around 2 mm higher than the medial side before 90° of flexion. Both condyles were similar in height beyond 90° of flexion.

The condylar motion data revealed that the knee motion characteristics are different using different flexion axes (Fig. 4). Previous in vitro study showed that the c-TEA lies anterior and superior to the GCA. The two axes formed an angle of 4.0° (Most et al., 2004). The c-TEA and s-TEA were shown to form an angle of 3.2° (SD 1.0°) in transverse plane (Yoshino et al., 2001). This result was similar to data of 3.4° (SD 1.4°) measured in our study. The differences between the TEA and GCA axes were also shown to be 4.6° (SD 1.6°) in 3D space (Eckhoff et al., 2007). This data was smaller than that of our study (8.2° [SD 1.7°]). Churchill et al. (Churchill et al., 1998) and Asano et al. (Asano et al., 2005) suggested that both the c-TEA and s-TEA could be used to represent the functional flexion axis, while Eckhoff et al. (Eckhoff et al., 2005) suggested that the cylindrical axis (GCA; found by purely anatomic) could be used as a functional axis of the knee. The differences in axis orientations among different studies may be due to the different methods used to establish the TEA and GCA axes. For example, Eckhoff et al. (Eckhoff et al., 2007) established the TEA by extending the cylinders along the cylindrical axis until only a spot of bone was visible on the medial and lateral aspects of the condyles, while anatomical landmarks were used by others. Therefore, reporting of femoral condylar motion data needs to clearly describe the definition of the flexion axis.

Flexion gap balance using a TEA has been widely accepted in TKA since bony landmarks are readily identifiable (Berger et al., 1998; Berger et al., 1993). The condylar motion in PD direction is critical for gap balance in medial and lateral condyles and at full extension and 90° of flexion (Manson et al., 2009; Mihalko et al., 2009). During surgery, the c-TEA has been frequently used since bony landmarks are readily identifiable, due to the difficulty of the reproducibility of identifying the s-TEA for the patients with knee osteoarthritis (Berger et al., 1993; Yoshino et al., 2001). However, it is still arguable on the optimal reference for the femoral component positioning (Gromov et al., 2014; Victor, 2009). Our findings revealed that it was necessary to seek precise positioning method because the knee kinematics measured using the 2 TEA axes were different. Using the s-TEA, our data indicated that an even gap between medial and lateral compartment may only be achievable from full extension to 60°, and beyond 60°, the medial condyle is increasingly higher than the lateral condyle. To maintain an even gap at 90° or higher flexion using s-TEA may need to consider the condyle height differences of the medial and lateral condyles. Recently, the

GCA has been suggested as a reproducible and reliable reference to optimize femoral component positioning during TKA (Colle et al., 2012; Doro et al., 2008; Howell et al., 2013; Matziolis et al., 2011; Oussedik et al., 2012), since it is believed that the alignment of TKA with GCA could replicate normal knee kinematics, such as medial pivot motion, and could produce an appropriate ligament balance after TKA (Blaha, 2004; Blaha et al., 2003). The different height of the GCA at full extension and 90° of flexion may need to be considered for gap balance at the two position of the knee. In addition, the medial compartment is ~2.0 mm lower than the lateral side in middle range of flexion. It is unknown if this kinematic feature will affect the TKA motion at the middle range of flexion. Long-term clinical outcomes of TKAs are necessary for evaluation of using different flexion axes for component alignment.

In conclusion, this study quantitatively described the differences on femoral condylar motion using the c-TEA, s-TEA and GCA during a dynamic weightbearing flexion motion. The results revealed that the knee kinematics measurement is sensitive to the selection of flexion axis. The different kinematic features of these axes should be considered when selecting a flexion axis in TKA component alignment.

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Highlights

- Geometrical center axis was used to describe condyle motion during flexion.
- Clinical and surgical transepicondylar axes were measured for condyle motion.
- Condyle height of geometrical center axis showed little changes beyond 30° flexion.
- Surgical transepicondylar axis maintained condyle heights below 60° flexion.
- Both transepicondylar axes moved distally beyond 90° flexion.

Figure 1.

(A) Axial view of the right femur and (B) coronal view of the right tibia. The clinical transepicondyle axis (c-TEA) connects the most prominent points of the lateral and medial epicondyles. The surgical transepicondyle axis (s-TEA) connects the lateral epicondylar prominence and the medial sulcus of the medial epicondyle. The geometric center axis (GCA) connects the centers of the spheres fitting to the lateral and medial posterior femoral condyles.

Figure 2.

(A) Movement patterns of medial and lateral femoral condyles relative to tibia during a dynamic flexion motion measured using three different flexion axes. Anterior-posterior translations of (B) medial and (C) lateral femoral condyles using three different flexion axes. (c-TEA: clinical transepicondylar axis; s-TEA: surgical transepicondylar axis; GCA: geometric center axis)

Figure 3.

Proximal-distal translations of (A) medial and (B) lateral femoral condyles during a dynamic flexion motion measured using three different flexion axes. (c-TEA: clinical transepicondylar axis; s-TEA: surgical transepicondylar axis; GCA: geometric center axis)

Figure 4. Movement patterns of (A) medial and (B) lateral femoral condyles in three dimensional space during a dynamic flexion motion measured using three different flexion axes. (c-TEA: clinical transepicondylar axis; s-TEA: surgical transepicondylar axis; GCA: geometric center axis)

Table 1

Angular relationship of three different flexion axes of the knee

Difference between axes (°)	3D Space	Coronal Angle	Transverse Angle
c-TEA and GCA	8.2 (1.7)	4.4 (1.7) *	6.7 (1.8) †
c-TEA and s-TEA	4.8 (1.1)	2.9 (1.5) *	3.4 (1.4) †
GCA and s-TEA	4.0 (1.3)	1.7 (1.5) *	3.3 (1.3) †

* Significant difference of angles with that of 3D space;

† Significant difference of angles with that of 3D space; c-TEA = clinical transepicondylar axis; s-TEA = surgical transepicondylar axis; GCA = geometric center axis; 3D = three dimensional.

Table 2

Averages (standard deviations) of proximal-distal translations of the femoral condyle of the three different flexion axes were reported in different flexion ranges.

Proximal-Distal Translation (mm)	FE-30°	30°-60°	60°-90°	90°-115°	FE-115°
c-TEA					
Lateral Condylar	1.4 (0.9)	1.0 (0.5)	2.1 (0.9) [†]	2.8 (0.9) ^{*†‡}	5.5 (2.4)
Medial Condylar	2.5 (1.0)	1.0 (0.5) [*]	1.9 (1.1) [†]	3.5 (1.4) ^{*†‡}	6.3 (2.1)
s-TEA					
Lateral Condylar	1.3 (0.9)	0.9 (0.4)	1.8 (0.8) [†]	2.5 (0.9) ^{*†‡}	5.0 (2.1)
Medial Condylar	1.2 (0.8)	0.7 (0.4)	1.0 (0.7)	2.1 (1.3) ^{*†‡}	4.0 (2.0)
GCA					
Lateral Condylar	2.0 (1.2)	0.7 (0.4) [*]	0.9 (0.6) [*]	1.5 (0.9) ^{†‡}	3.8 (1.9)
Medial Condylar	2.6 (1.5)	0.8 (0.6) [*]	0.7 (0.4) [*]	0.9 (0.8) [*]	3.8 (1.9)

^{*} Significant difference of translations with that of FE-30°;

[†] Significant difference of translations with that of 30–60°;

[‡] Significant difference of translations with that of 60–90°; c-TEA = clinical transepicondylar axis; s-TEA = surgical transepicondylar axis; GCA = geometric center axis; FE = full extension.