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IDENTIFYING THE EFFECTS OF KNEE ANATOMY VARIATION ON THE ENVELOPE OF KNEE MOTION (VARUS-VALGUS) USING PRINCIPAL COMPONENTS

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INTRODUCTION:

The motion patterns of the human knee joint depend on its passive motion characteristics, which are described by the ligamentious and articular constraints. Since active motions, like walking and squatting are believed to fall within a passive envelope, the basis for the understanding of the knee joint kinematics lies in the description of its passive constraint characteristics [1]. Although several authors studied passive envelope characteristics of a knee, it is not clear from the literature which anatomical structures guide the knee in passive or active motion and how their geometric arrangement produces the unique path of passive knee motion [1-3]. A few mathematical models have been developed to study the structures that guide the passive knee motion [1, 2]. However, their hypotheses were not supported by a sufficiently detailed ligament bundle model, soft tissue properties, ligament insertion-origin sites and their intra-subject variability. To explain the relationship between knee anatomy and its variability with three-dimensional knee motion completely, new methodology must be developed. The objective of the present study was to estimate the effects of variation in knee anatomical factors on the tibiofemoral passive envelope using a multivariate analysis technique, principal component (PC) analysis.

MATERIALS AND METHODS:

Sixteen fresh frozen cadaver legs (Age: 63.3±11.5, BMI: 26.7±3.6) were thawed at room temperature and then dissected. For each leg, the femur and tibia were sectioned 28cm proximal and 18cm distal to the epicondylar axis. All soft tissue within 10cm of the knee joint was left intact to prevent the dehydration of the tissue. Soft tissue more than 10cm from the epicondylar axis was removed. The remainder of the tibia and femur were cleaned and cemented into tubular fixtures aligned parallel to the bones' intermedulary canals.

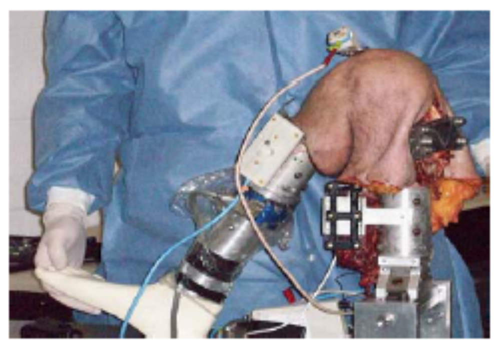

Figure 1. Knee attached to table for the manual evaluation of the passive envelope of motion.

Each knee went through the manual assessment of the passive envelope of motion (Fig. 1). An assessment was performed manually by moving the tibia though the flexion-extension (F-E) range of motion (ROM) from full extension to full flexion. During F-E ROM, loads and torques were applied until the tibial varus-valgus (V-V) motion was constrained. Applied V-V torque magnitudes were within 10-15Nm. Care was taken while applying the loads in order to avoid damaging the soft tissue constraints.

The motions of the tibia and femur during the evaluations were tracked using an Optotrak 3020 system (Northern Digital Inc., Canada). Tibiofemoral kinematics were estimated using a modified Grood and Suntay knee kinematics description [4]. Additionally, the following anatomical landmarks were identified and their locations captured using a digital stylus, medial and lateral epicondyle and origin and insertion locations of the MCL and LCL. Epicondylar points were later used to estimate the epicondylar width (EpW) and frontal (FPA) and transverse plane angle (TPA) of an epicondylar axis.

A PC model was developed [5] for the V-V envelope boundaries, femoral epicondylar width and the MCL and the LCL origin-insertion points. For each knee, the mid-point of the envelope boundaries at full extension was subtracted from the rest of the envelope to normalize the results. PC model results included the PCs and the variance explained by them. Models were deformed (within $\pm 3\sigma$) along each PC axis with all other PCs fixed at the mean, to identify the variation associated with that specific PC. Anatomical factors associated with first PC would be responsible for the corresponding change in the passive envelope. This PC interpretation process was continued until 80% variation in the input data matrix was explained.

RESULTS:

The first four PCs accounted for 83.7% of the total variation. PC1, explained almost 39% of variation and was due to the change in relative position of the envelope (Fig. 2). The envelope variation was tied with the epicondylar axis FPA and S-I location of the MCL and the LCL insertion sites. Deformation along the PC1 axis showed that the increase in FPA shifted the V-V envelope more valgus without affecting its ROM (Table 1). The change was also coupled with the medial-superior positioning of MCL and the lateral-inferior positioning of the LCL insertion; as the MCL insertion shifted medial-superior, the LCL insertion shifted lateral-inferior. PC2 (29.5%) was caused by the varying size of the envelope without affecting its relative position, coupled with the EpW and the location of MCL and LCL origin (Table 1). Increase in EpW was observed with the increase in envelope size and the superior location of the MCL and LCL origin. PC3 (9.6%) was due to the variation in the envelope size after 30º of flexion coupled with TPA of epicondylar axis. PC4 (5.7%) captured variation in the relative position of envelope at early flexion.

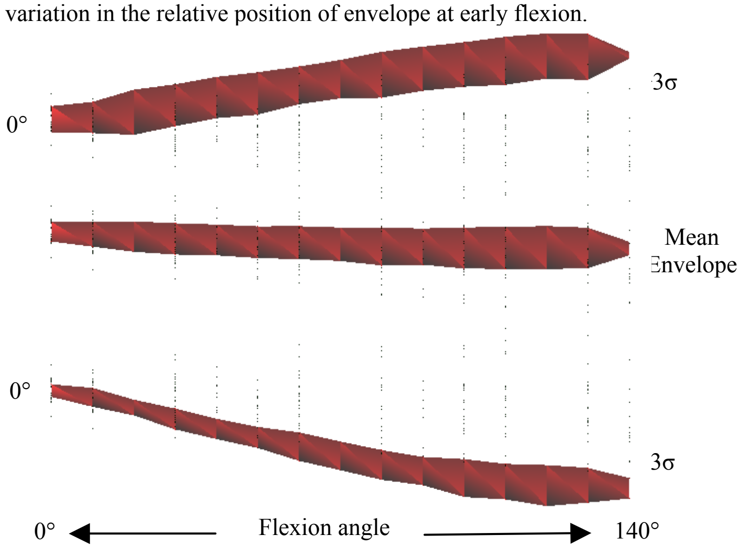

Figure 2: -3σ, mean and +3σ deformation along the PC1 (38.9%) axis of the V-V envelopes as a function of flexion

DISCUSSION:

To observe the effects of variation of anatomical factors on a knee envelope, a PC model was developed. Models were developed for V-V, internal-external and anterior-posterior (AP) knee envelopes; however, only V-V results are documented here. Two-thirds of the variation in -VV envelopes was captured by the first two PCs and caused mainly due to the relative position of the envelope (PC1) and its size (PC2), coupled with the special orientation of the epicondylar axis and EpW. Epicondylar axis orientation affected the relative position of the envelope, whereas EpW affected the envelope size.

Table 1: The percentage variation explained by the first four PCs and their interpretation

Variation %		Total	Interpretation
PC1	38.9	38.9	Relative position of Envelope, S-I location of MCL and LCL insertion,
PC2	29.5	68.4	Envelope Size, Epicondylar width, A-P location of MCL and LCL origin, S-I location of LCL insertion
PC3	9.6	78.0	Envelope size after 30° of flexion, TPA
PC4	5.7	83.7	Relative position of envelope at early flexion (<40°)

Variation in the relative position of the VV envelope (frontal plane motion) occurred with the variation in the FPA. This indicates that the orientation of an epicondylar axis in the respective plane affected the relative position of the passive (envelope) motion occurring in that plane. Also, increase in FPA shifted the V-V envelope more valgus.

Previous studies found a positive correlation between femoral epicondylar width and other femoral linear dimensions and tibial and patellar size variables [6]. Also, representation of various knee dimensions in one measure helps summarize a size and shape trend in one value (PC) that would take several linear measurements to explain. PC2 was mainly associated with the envelope size and the EpW. Increase in EpW was coupled with the increase in envelope size and vice-e-versa. The PC also captured the variation in the AP location of the collateral origins, indicating their contribution to determine the envelope size. Larger EpW along with anterior-superior location of both collaterals was tied with the increase in the EpW. Although the variances of PC3 (9.6%) and PC4 (5.7%) were low, meaningful information of was captured by them. PC3 summarized the increasing envelope size after 30º of flexion, whereas PC4 captured relative position of the envelope at early flexion (<40º). These subsequent PCs could provide insight about the knee stability and it's interaction with anatomical factors during specific flexion ranges.

The study demonstrated the capability of PC modeling to link the V-V tibiofemoral envelope with the variation in certain knee anatomical features. Relative position of the V-V envelope was caused due to the orientation of the epicondylar axis in the frontal plane, whereas the envelope size was coupled with the EpW. The model will be further developed to study active motion waveforms like gait and squat.

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