Correlations Between Knee Anatomy and Joint Laxity Using Principle Component Analysis

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Introduction: Knee joint kinematics depend highly on bone morphology, knee alignment, and soft tissue properties. Statistical models examined variation in shape and relative alignment of the knee structures [1-3]. Knee joint laxity, specifically varus-valgus (VV) and internal-external (IE) rotations, across the knee flexion range is well documented in the literature [4, 5]; however, the relationships between anatomical shape measure, alignment, and knee laxity are less understood. Identifying the relationship between anatomical measures and knee kinematics could improve the diagnosis and treatment of pathologies as well as the development of orthopedic implant design. The objective of this study was to examine, in vitro, the correlation between knee anatomy and tibiofemoral (TF) laxity shape using principle component analysis.

Methods: Magnetic resonance images were collected on seventeen fresh frozen cadavers (all male, mean age 65 years: range 52-78, average BMI 25.7: range 22.3-29.7) prior to testing. The femur, tibia, patella bones, and associated cartilage were segmented using ScanIP (Simpleware, Virginia). The segmented bones were then meshed in Hypermesh (Altair, Alabama) using a tri template mesh. A nodal correspondence for each bone and cartilage were developed using an iterative closest point algorithm. Both the femur and the tibia were potted into aluminum fixtures. A laxity envelope was then preformed on each knee with the femur rigidly attached to a table in the inverted position and the tibia unconstrained (Fig. 1). An IE and VV torque, ranging between 0-10 N-m, were applied onto the tibia as the knee went through the flexion range. An Optotrak Certus and a JR3 tri-axial load cell were used to capture the kinematics and the loads.

A principle component analysis (PCA) was performed using VV and IE kinematics and the X, Y, Z coordinate of the nodes representing the bone and cartilage of the femur and the tibia. The results of the first four modes of variations were then perturbed by ±3 standard deviation to explain the variation and the correlation between the envelope of laxity kinematics and the anatomy.

Results: The first 10 modes of the PCA accounted for 91.5% of the variations. Mode 1, 2, and 3 explained 21.8%, 15.92%, and 12.1% respectively. Mode 1 was largely correlated with the knee size, envelope size, and VV and IE alignment of the knee (Fig. 2). Perturbing the first mode showed that there is a positive correlation between the VV and IE envelope size and the relative geometry of the bone and cartilage size. Variability in the thickness of the femoral and tibial medial condyle cartilage and varus laxity was captured by mode 2 (Fig. 3). An increase in cartilage thickness was associated with a decrease in varus laxity; however, it had minimal effect on the IE and valgus laxity ranges. The third mode was associated with the tibial plateau angle and conformity. A smaller less conforming tibial plateau angle correlated with a decrease in varus laxity and an increase in IE laxity. A smaller less conforming tibial plateau angle correlated with a decrease in varus laxity and an increase in IE laxity. Variability in the femoral sagittal
condylar radius (J-curve) and femoral epicondyle width were captured by mode 4 and 5 (not shown). An increase of these parameters was associated with an increase in IE and VV laxity.

**Discussion:** The correlation between knee anatomy and the laxity envelope has been investigated using a statistical model. The initial alignment of the knee plays a major role in shifting the position of the VV laxity envelope. The knee size did not have a large effect on the size of the VV and IE envelope. These results suggest that the constraint in the VV and IE directions is more dependent on soft tissue structures than bone geometries. Variations in cartilage thickness change the geometry interaction in the frontal plane, in which the VV rotation occurs; therefore, its effect on VV envelope was expected, since VV is the rotation in the frontal plane. Cartilage thickness variation had no influence on IE. This can be explained as changes in cartilage thickness do not change the contact mechanics in the coronal plane.

Femoral epicondyle width, J-curve and tibia plateau flatness had an influence on the size of IE and VV envelope. An increase in these variables will results in a less conforming geometry of the tibiofemoral joint; therefore, allowing more motion for the same applied load. The statistical model does not take into account the influence of variation in soft tissue parameters such as attachments site and free length; therefore, some of the variable seen in the model can be related to the contribution of the soft tissue. The lack in specimen variations (all males, low BMI) was another limitation of the study; however, more specimens can be included in the model which in turn will improve its accuracy.

**Significance:** The study provides a novel framework into understanding and quantifying the correlation between knee joint anatomy and laxity. Identifying the dependencies between the anatomical measures and knee kinematics can play a major role in the development of orthopedic implant design and diagnosis and treatment of pathologies.

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**Figure 1:** Experimental setup. The proximal femur was rigidly attached to a surgical table, and a load cell with an analog foot was attached to the distal tibia.
Figure 2: The effects of perturbing the first three modes of variation onto Varus-valgus (top) and internal-external laxity (bottom), the show as mean (blue) ± 3 standard deviation (red and green).

Figure 3: Representation of the mean bones and cartilage (blue) and the variation of the first principle component. The knees are shown at ±3 standard deviation.

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