Validation of passive kinematics of a physical knee model with simulated soft tissues

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INTRODUCTION

Ligaments and articular surfaces work together to guide passive knee motion. The aim of this study was to design, construct, and validate a physical knee model that has similar kinematics to a real human knee, by incorporating the anterior cruciate, posterior cruciate, medial collateral, lateral collateral, and popliteus ligaments. This model was intended to reproduce typical axial rotation seen during passive knee joint flexion and to allow substitution for cadavers in some kinematic experiments.

METHODS

A physical knee model was designed using Sawbones for a left tibia and femur that had anatomic geometries (1104-1, 1106, Pacific Research Laboratories, Vashon, WA, USA). Potential materials for the soft tissues were evaluated based on tensile elastic stiffness and attachment capabilities. The final ligaments were constructed from braids of low-cost cotton-polyester yarn, such that each had comparable stiffness to the ligaments extracted from three cadavers. Menisci, in contrast, were constructed from elastic impression material (Dentsply, York, PA), without systematically reproducing cadaver menisci material properties, since this knee model was not intended to see high joint loads. Menisci geometry was based on literature and cadaveric samples. These components were integrated according to the functional anatomy of the knee, considering ligament insertion points and tensioning (Figure 1).

The model was analyzed with a standard motion capture protocol (Plug-in-gait, Vicon, Oxford, UK [1]), together with a corresponding size Sawbone pelvis. Reflective markers were fixed on the bones and tracked during multiple manual passive knee flexion trials. Average knee axial rotation was recorded during the full range of passive flexion allowed by the model (Figure 2).

Previously collected in vivo and in vitro reference data were analyzed for comparison. The in vivo reference data came from ten young adult subjects (29±9 years old; 76±20 kg mass; 178±8 cm height) receiving informed consent, and analyzed with Plug-in-gait. They each performed three trials of a non-weight-bearing active flexion-extension motion from 10°-110° knee flexion. The in vitro data came from six cadaver knees from elderly [2]. These had undergone three trials each of passive flexion from 0°-130° as described earlier, but were analyzed with a different standard motion capture protocol [3] that is more accurate than Plug-in-Gait. All data from subjects and cadavers had been previously collected under ethical approval. The ligament insertion point locations and menisci attachments were optimized such that the kinematics of the physical model resembled that of the reference data. Each insertion point and attachment method was systematically changed to result in a more anatomic axial rotation curve. This included testing without individual ligaments. Repeatability of the final optimized model was analyzed by rebuilding it and remeasuring its kinematics three times.

RESULTS

Axial knee rotation is plotted versus flexion angle for the optimized physical model, the in vivo data, and the in vitro cadaver data (Figure 3). Within the common flexion range of 10°-110°, the ranges of average axial rotation were 16.7°±2.0° for the physical model, 19.1°±7.4° for the in vivo data and 13.1°±3.9° for the in vitro data. The graphs show similar shapes in axial rotation. The model was on average 1.0° more externally rotated than the cadaver knees and 1.3° more internally rotated than the in vivo data, but its curve fell within the inter-subject error bars of the reference data. Intra-operator repeatability of the axial rotation curve for the model was good, with average standard deviations of 2° at each flexion angle (not plotted, for clarity).

DISCUSSION

Based on this analysis, the optimized physical model exhibited expected physiologic axial rotation during passive and unloaded flexion, compared to the in vivo and in vitro knee data. However, translations still must be analyzed, and inter-operator reproducibility of the model must be measured. The model could withstand about 20 consecutive motion trials before the ligament braids experienced significant creep, changed knee kinematics, and had to be reattached or remade. Nevertheless, this study confirmed that ligaments and menisci affect knee kinematics during passive motion. It also suggests that a relatively simple yet parametric physical model of the knee can substitute cadaver knees for some kinematics tests. This model can be a research and education tool for analyzing ligament models, interactions among knee soft tissues, total knee arthroplasty designs, and surgical techniques.

REFERENCES