Noninvasive Assessment of Sagittal Knee Kinematics After Total Knee Arthroplasty

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Abstract
Normative and arthroplasty knee joint kinematics have been studied extensively using a wide range of instrumentation and methodologies. Many of the methods used to assess knee mechanics after total knee arthroplasty (TKA) have failed to create realistic testing conditions in terms of joint load and range of motion. In contrast, motion capture studies facilitate knee assessments during functional, weight-bearing activities. Using motion capture techniques, this study aimed to examine differences in sagittal tendon kinematics between TKA and normative individuals. The relative positions of the patellar tendon and quadriceps tendon, as a function of knee flexion-extension, were estimated during step down and bilateral deep knee bend tasks. To assess the validity of this technique, motion capture data were compared to radiographic data for each TKA patient. Sagittal knee tendon angles were measured directly from the radiographs and compared to corresponding points in the dynamic data. Results of the patellar and quadriceps tendon angles showed good agreement between the two methods, with absolute errors ranging from 2.9º to 5.6º, suggesting that noninvasive motion capture is a suitable method for evaluating knee mechanics.

INTRODUCTION
While one of the main goals of total knee arthroplasty (TKA) is to restore normal knee function, sagittal plane kinematics after TKA are known to differ from normal knee kinematics [1,2]. As a result, normative and TKA knee joint kinematics have been studied extensively using a wide range of instrumentation and methodologies [3]. One such technique is motion analysis, which provides numerous advantages to traditional imaging methods. Motion analysis allows researchers to noninvasively quantify knee kinematics in TKA and normative participants during functional, weightbearing tasks, including gait [4], sit-to-stand [5], and stair climbing [6]. In addition, motion analysis permits the measurement of the patellofemoral joint across a range of knee flexion angles. The major limitation of this technique is soft tissue movement, which may cause errors in the estimation of the position and orientation of the underlying bone [7]. As a result, few studies have attempted to track sagittal tendon geometry after TKA using this method.

Measurement of sagittal knee tendon angles is an established method for assessing normal and TKA joint kinematics [8-10]. These tendons play a critical role in determining the orientation of the patella and provide an indirect assessment of knee function. This paper uses a two-dimensional model of the lower extremity to describe movements of knee structures in the sagittal plane of individuals with TKA. Using motion capture techniques, the relative positions of the patellar tendon and quadriceps tendon, as a function of knee flexion-extension, were estimated during step down and bilateral deep knee bend tasks. Data were compared to an age-matched normative group. To assess the validity of this technique, motion capture data were compared to radiographic data for each TKA patient.

METHODS
PARTICIPANTS
Eight individuals (3F, 5M), with a total of 15 TKA’s were recruited for the study. The age range of the patients was 60 to 76 years and all patients were at least 6 months postoperative. These individuals were patients of two orthopaedic surgeons at the Dr. Everett Chalmers Hospital in Fredericton, New Brunswick. All implants were Zimmer NexGen knees with resurfaced patellas. The normative group consisted of 11 individuals aged 55 to 81 years old. Individuals were recruited through advertisements and presentations at local senior centers. Individuals reported no known knee pathology or knee pain. Each participant was provided details of the study and asked to sign an informed consent form.
consent form. This study was approved by the University Research Ethics Board and the River Valley Health Ethics Committee.

INSTRUMENTATION/APPARATUS

Data collection for the TKA patients occurred at the Dr. Everett Chalmers Hospital in Fredericton, New Brunswick. Normative data was collected at the motion analysis lab at the Institute of Biomedical Engineering, University of New Brunswick. A 6-camera Vicon 512 motion capture system was used to collect the three-dimensional locations of reflective markers placed on the lower extremity of each patient (25 mm markers). Movements were sampled at a frequency of 60Hz. Radio-opaque markers (4 mm) were also used to identify bony landmarks about the knee joint on lateral weight bearing radiographs. A 20cm high step with a support handle was used for the step down task. Calipers were used to obtain joint width measurements.

PROCEDURES

Data collection occurred during routine clinical evaluations at the Orthopaedics Clinic at the Dr. Everett Chalmers Hospital. A physical exam and radiographs are a routine part of this evaluation. Prior to the radiographs, the examining surgeon placed radio-opaque markers over specific anatomical landmarks on both lower extremities. These landmarks were the: 1) mid-femur, 2) lateral femoral epicondyle, 3) tibial condyle, 4) tibial tubercle, 5) distal tibia, 6) superior pole of patella, and 7) inferior pole of patella (Figure 1a). Each patient then had lateral weight-bearing radiographs taken with their knees slightly flexed.

Figure 1

Figure 1 – a) Sagittal view of participant with reflective markers performing the step down task, b) a lateral weight-bearing radiograph of a total knee arthroplasty with radio-opaque markers.

Immediately after completion of the radiographs, patients were asked to enter a separate room containing the Vicon 512 motion capture system. Reflective markers were applied directly overtop of the radio-opaque markers (Figure 1b). The motion capture system was used to track the locations of these markers during weight bearing bilateral knee bend and stair descent tasks. A 20cm high step with a support handle was positioned within the calibrated workspace for the stair descent task. The order of tasks was randomized across individuals. Both activities produced high loads at the knee joint and are typical activities of daily living. Patients were asked to perform 6 bilateral knee bends to the best of their ability. Patients were permitted to position their arms in front of their trunk to aid with balance. For the stair descent task, patients were asked to perform 3 trials with the left leg leading off the step, and 3 trials with the right left leading off the step. If necessary, patients were permitted to hold onto the support rail for stability.

DATA ANALYSIS

DYNAMIC TASKS: TKA Versus Age-Matched Normative Data

All coordinate data was transferred to Matlab for processing. For each of the two tasks performed, 3 sagittal angles and anteroposterior displacement of the patella were computed for each trial. Sagittal angles were computed using the three-dimensional locations of markers and dot products. The angle between the patellar axis and patellar tendon (PA/PT) was defined by the vector representing the patellar tendon (inferior pole of patella to tibial tuberosity) and the vector representing the longitudinal axis of the patella (inferior to superior pole of patella). The angle between the femoral axis and the longitudinal axis of the patella (PA/PT) was defined by the vector representing the patellar tendon (inferior pole of patella to tibial tuberosity) and the vector representing the longitudinal axis of the patella and the vector representing the femur (lateral femoral epicondyle to mid-femur). This angle approximates the orientation of the quadriceps tendon. Both of these angles were examined with respect to knee flexion, which was calculated using the vectors representing the femur and the tibia (tibia condyle to distal tibia). The anteroposterior motion of the center of the patella, as a function of knee flexion, was determined with respect to the longitudinal axis of the tibia. As the range of knee joint motion was different for each individual, data was cropped at the lowest and highest common knee flexion value. This conservative approach ensured that error was not introduced into the linear and angular displacement data by approximations (i.e. polynomials).
VALIDATION OF THE MOTION CAPTURE SYSTEM

Accuracy of the motion capture system was determined by comparing data obtained during the dynamic tasks (bilateral deep knee bend and stair descent) to the static data obtained from the lateral weight-bearing radiographs. For each individual, the surgeon estimated the 3 angles manually on each radiograph using the radio-opaque markers as reference points. For each individual, the angles were measured three times by the surgeon and the average of each angle was used for analysis. For each individual, the knee flexion angle obtained from the radiograph was matched to the occurrence of the same knee flexion angle in the dynamic motion data. For the dynamic data, the average of each sagittal tendon angle, measured across the three trials for each task, was calculated for each participant. The tendon angles corresponding to the instantaneous knee flexion value obtained from the radiographs were extracted from the waveforms. The mean absolute differences between the angle values obtained from the radiographs and the motion capture system were computed.

RESULTS

TKA VERSUS AGE-MATCHED NORMATIVE DATA

The results for the bilateral deep knee bend and the step down task were very similar. Therefore, only the deep knee bend data is provided here. As the knee flexed from 30°-70° during the bilateral deep knee bend, the orientation of the patellar tendon was calculated relative to the longitudinal axis of the patella (Figure 2) and relative to the longitudinal axis of the tibia (Figure 3). For both the TKA and normative group, the mean range of motion of the patellar tendon angle with respect to the patella was relatively small. This indicates that the tendon maintains a relatively fixed position with respect to the patella in the sagittal plane. Age-matched data was more variable than the TKA data and showed differences in amplitude for the patellar tendon angle (Figure 2). The mean relative angle between the tibia and the patellar tendon did not change as expected in the TKA group as a function of knee flexion (Figure 3). The patellar tendon angle was directed anteriorly throughout the task. At higher values of knee flexion, the tendon will be directed posteriorly, yet this transition is not apparent by 70° of knee flexion. The normative group demonstrated a more acceptable pattern of motion, showing a negative slope with increasing knee flexion.
Figure 4
Figure 3a – Mean ± one standard deviation for patellar tendon and tibial axis for TKA group

Figure 5
Figure 3b – Mean ± one standard deviation for patellar tendon and tibial axis

In the TKA group, the relative angle between the longitudinal axes of the femur and patella (an approximation of the quadriceps tendon) increased linearly from 27° to 52° during flexion of the knee from 30°-70° (Figure 4a). Similar ranges and pattern of motion were noted in the age-matched normative data (Figure 4b). However, the normative group showed lower amplitudes and higher variability for this angle compared to the TKA group.

The midpoint of the patella translated an average of 1.5 cm posteriorly as the knee flexed in the TKA group. Similar results were noted for the normative group (average of 1.3 cm). Again, the TKA group showed more consistent results than the normative group (Figure 5).

VALIDATION OF MOTION CAPTURE DATA
Comparisons of radiographic and motion capture results for patellar tendon angle (PA/PT) and quadriceps angle (PA/FEM) showed good agreement for both step down and knee bend tests. Average absolute differences in angles between the two methods for the step down task were 2.9° (± 0.1°) for PA/PT and 5.6° (± 0.2°) for PA/FEM. For the bilateral deep knee bend task, the average absolute differences in angles were 2.6° (±0.1°) for PA/PT and 5.9° (±0.2°) for PA/FEM. Radiographic and motion capture data for a typical patient is shown in Figure 6.

Figure 6
Figure 4a – Mean ± one standard deviation for quadriceps tendon and patellar axis for TKA group

Figure 7
Figure 4b – Mean ± one standard deviation for quadriceps tendon and patellar axis for Normative group
Figure 8
Figure 5a – Mean ± one standard deviation for anteroposterior patellar displacement for TKA group

Figure 9
Figure 5b – Mean ± one standard deviation for anteroposterior patellar displacement for Normative group

Figure 10
Figure 6. Comparisons of radiographic (*) and motion capture tendon angle data (+) versus knee flexion for one participant.

DISCUSSION
Tracking the patellar and quadriceps tendon angles, as they vary with knee flexion, provides a simple assessment of knee function. This study examined sagittal plane knee kinematics during functional, weight-bearing tasks using motion capture techniques.
For both groups, the patellar tendon angles were similar to those reported by Van Eijden et al. (1986), demonstrating a relatively fixed angle with respect to the longitudinal axis of the patella throughout knee flexion. Previous research has shown that, with respect to the tibia, the patellar tendon is typically directed anteriorly during the first 70° of knee flexion and posteriorly for the remainder of flexion [8,10]. While the normative group shows an anteriorly directed patellar tendon that is gradually shifting towards neutral as knee flexion increases, the TKA group did not show this pattern. Instead, the patellar tendon remained in a fairly consistent anterior position throughout knee flexion.

For this study, it was assumed that the longitudinal axis of the femur approximated the orientation of the quadriceps tendon during knee flexion. Previous research has shown that during 30°-70° of knee flexion, the quadriceps tendon maintains a relatively fixed angle with respect to the longitudinal axis of the femur [8]. In both groups, the mean relative angle between the longitudinal axes of the patella and femur increased linearly with flexion of the knee (Figure 4). For the normative group, results were similar to Van Eijden et al. (1986), despite differences in knee load between the studies. The TKA group showed a similar pattern and range of motion to the normative data; however, the amplitude of the signal was higher suggesting a different tendon orientation.

Linear displacements of the patella demonstrated a similar pattern of motion across the two groups (Figure 5). Higher variability is noticeable as the knee approached extension for both TKA and normative data. Results for this parameter were similar to those provided by Van Eijden et al. (1986).

The second objective of this study was to validate the use of a Vicon motion capture system to measure sagittal knee tendon angles. The motion capture system used in this study was a passive optoelectronic device that used infrared cameras to track skin-mounted reflective markers as the person moved. Average absolute differences between the two methods revealed that the motion capture system was able to approximate the patella tendon angles more accurately than the quadriceps tendon angle for both tasks. Average absolute differences were 2.9° (±0.1°) for PA/PT and 5.6° (±0.2°) for PA/FEM for the step down task. For the bilateral deep knee bend task, the average absolute differences in angles were 2.6° (±0.1°) for PA/PT and 5.9° (±0.2°) for PA/FEM.

The larger error for PA/FEM for both motor tasks is likely due to several reasons. First, the motion capture method used the locations of markers on the mid-femur marker and lateral femoral condyle to estimate the quadriceps tendon angle. However, the mid-femur marker was not always visible on the radiographs of each patient. In these cases, a more proximal femur point of reference was used to measure the PA/FEM angle from the radiographs. As a result, small errors in the angle measures may have been generated. Another factor that may have affected the error results was that the motion capture method used the three-dimensional coordinates of the markers to compute angles. For the radiographic images, if the patient was not aligned properly during the procedure, the measured projection angles would be smaller than the true angle. While the radiographs were subjectively examined to ensure appropriate alignment of the patient, small errors could result from minor malalignment of the patient. Finally, errors may have also occurred through movement of the mid-femur marker relative to the underlying bone during the performance of the motor tasks.

The kinematic model used in this study was limited to the sagittal plane and does not address the other planes of motion for the knee joint or the Q-angle. However, the robust sagittal measures provide a reliable indicator of knee function. Due to subject differences in range of motion, data was cropped to common knee flexion-extension ranges. While the data could have been modeled to provide estimates of tendon angles at certain knee joint angles, we opted for a conservative approach that used only the available raw data.

CONCLUSIONS

This technique provides a method to measure patellar movements after TKA with results comparable to radiographs. Motion capture techniques permit data capture during functional, weight-bearing activities, thereby providing information on knee motion across a range of flexion angles. The results of this study suggest that motion capture is a valid and reliable technique for assessing sagittal plane knee tendon geometry. Further research aims to develop three-dimensional mechanical models of the knee to assess movements in individuals with TKA.

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