Journal of Biomechanics 48 (2015) 3551–3558

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Characterising knee motion and laxity in a testing machine for application to total knee evaluation

Peter S. Walker*, Sally Arno, Ilya Borukhoy, Christopher P. Bell

Department of Orthopaedic Surgery, New York University - Hospital for Joint Diseases, United States

ARTICLE INFO

Article history:
Accepted 17 June 2015

Keywords:
Knee laxity
Total knee replacement
Knee motion
Total knee design
Knee function

ABSTRACT

The goal of this study was to determine knee motions in specimens under combined input forces over a full range of flexion, so that the various flexion angles and loading combinations encountered in functional conditions would be contained. The purpose was that the data would act as a benchmark for the evaluation of TKR designs using the same testing methodology. We measured the neutral path of motion and laxity about the neutral path. The femur was flexed in a continuous movement, rather than at discrete flexion angles, using optical tracking. The motion of the femoral circular axis relative to the tibia was determined, as well as the contact patches on the tibial surfaces. The neutral path of motion was independent of compressive load, and consisted of a relatively constant medial contact and steady posterior displacement laterally, in agreement with previous studies. The anterior–posterior laxities of the lateral and medial condyles were similar whether AP forces or torques were applied. The lateral laxity was predominantly anterior with respect to the neutral path, while on the medial side, the laxity was less than lateral and predominantly posterior of the neutral path. Contact on the anterior surface of the medial tibial plateau only occurred in some cases in 5° hyperextension and at 0° flex when an anterior femoral shear or an external femoral torque were applied. The method can be regarded as a development of the ASTM constraint standard, with the addition of the benchmark, for the evaluation of total knee designs.

1. Introduction

An important requirement in designing any type of knee replacement, ranging from modular components to total knees, is a method for evaluating the kinematics. The two main approaches have been computer modeling (Amiri et al., 2011; Baldwin et al., 2012; Fitzpatrick et al., 2012a; Galloway et al., 2012; Liu et al., 2012; Willing and Kim, 2012) and experimental methods (Atarod et al., 2014; DesJardins et al., 2000, 2007; Fitzpatrick et al., 2012a, 2012b; Halloran et al., 2010; Moran et al., 2008; Patil et al., 2005; Yildirim et al., 2014, 2009; Varadarajan et al., 2009; Walker et al., 2014). Modelling has the advantage that many different activity scenarios can be simulated and different design variations can be evaluated. Experimental methods can include implantations into knee specimens and also provide direct observation of the mechanics of the knee as it is being tested, often providing insights into potential problems or design modifications. Whatever the method of testing, a benchmark is required against which to evaluate the replacement, representing as many functional conditions as possible. The benchmark can be based on laboratory studies using knee specimens, or from in vivo data of normal knees.

In this study, the pre-clinical testing methodology was to characterize the motion of the knee in specimens by determining the neutral path of motion, where the knee was flexed and extended with only a compressive force acting along the tibial axis, and the laxity about the neutral path when shear forces and torques were superimposed. This approach can be regarded as being based on the ASTM constraint test (ASTM, 2008; Moran et al., 2008; Halewood et al., 2010; Heim et al., 2001). However the test method would be enhanced if there was a benchmark based on the normal intact knee, against which a particular total knee construct could be compared.

Hence, the focus of the present study was to generate a benchmark by obtaining the neutral path of motion and the laxity data for knee specimens under different compressive forces as well as shear forces and torques, during continuous flexion. The hypothesis was that the neutral path of motion would be independent of compressive force and be close to a medial pivot action; while anterior–posterior (AP) laxity would occur primarily on the lateral side, with the medial side being AP stable.

* Corresponding author. Tel.: +212 598 2459.
E-mail address: ptrswlkr@aol.com (P.S. Walker).

http://dx.doi.org/10.1016/j.jbiomech.2015.06.013

2. Methods and materials

Ten fresh human cadaveric knee specimens (8 Male and 2 Female) with an average age of 77 years (55–91 years) were used, representing a typical range for total knee patients. Each knee was dissected to the capsule, preserving all ligaments and the quadriceps tendon. Three conical holes were made in the distal femur and proximal tibia to act as fiducial points. The tibia was fixed vertically to the base of the Testing Machine (Fig. 1) with a cemented intramedullary rod and screws. A frame was fixed to the femur using a cemented intramedullary rod such that the lateral and medial transverse rods of the frame were in line with the epicondylar axis of the femur. Axial compressive forces were applied using a pneumatic cylinder, connected to the transverse rods by vertical cables. Horizontal cables from servo motors attached at the four corners of the machine were also connected to the transverse rods, to apply shear forces and torques. The quadriceps tendon was attached by a cable to the femoral frame, which allowed the patella to track in the trochlea during flexion. A pneumatic cylinder connected to the superior aspect of the femoral frame by a cable, flexed the femur dynamically from hyper-extension $-5°$ to $135°$ in 10–15 s. The application of compression, shear, torque, and flexion was controlled through a touch screen and a programmable logic controller. Black and white targets were attached to the femoral frame, whose positions were recorded using an optical motion tracking system (MicronTracker $S \times 60$, Claron Technology Inc., Toronto, Ontario, Canada).

The knees were tested under the following loading conditions: (1) No Load, (2) 100 N compression, (3) 500 N compression, (4) 500 N compression with 100 N anterior shear, (5) 500 N compression with 100 N posterior shear, (6) 500 N compression with 2.5 Nm internal torque and (7) 500 N compression with 2.5 Nm external torque. The ratios of compression-to-shear and compression-to-torque were based on data from instrumented knee studies (D'Lima et al., 2007; Heinlein et al., 2009). The knee was set at 5° hyper-extension and the first loading condition was applied. To record the starting position of the knee, the fiducial points on the femur and tibia, along with the centers of the targets, were digitized using a MicroScribe G2LX digitizer (CNC Services Inc, Amherst, Virginia). The motion tracking system was then initiated and the knee was flexed continuously to 135°. The knee was then returned to hyper-extension and the procedure was repeated with the next loading condition.

After testing, the knee was stripped of all soft tissue and the femur and tibia were scanned using a NextEngine 3D Scanner HD in conjunction with ScanStudio HD software (NextEngine, Inc, Santa Monica, California). After scanning, the point cloud representations of the femur and tibia were rendered into 3D mesh solid body models using Geomagic Design X software (3D Systems, Rock Hill, South Carolina). The 3D solid models of the tibia and femur were aligned to the digitized locations during testing by use of the fiducial points. A custom MATLAB program was written (MathWorks, Inc, Natick, Massachusetts) to extract the coordinates of the motion tracking targets at the starting positions of $-5°$, and in 15° increments between 0° and 135°. These coordinates were then aligned to the location at the time of testing using the digitized target coordinates taken at the start of the test.

To describe the motion of the knee, two parallel and equal circles were fit to the posterior sections of the lateral and medial femoral condyles (Fig. 2). The line connecting the centers of the two circles was defined as the circular axis, which was projected onto the articular surface of the proximal tibia. The anterior–posterior (AP) position of the lateral and medial femoral condyles was defined as the distance between the end-points of the circular axis, and a line across the posterior tibial plateau. The neutral path of motion was defined as the circular axis position through flexion under compression-only loading conditions. Shear AP laxity was defined as the difference in AP position between applying an anterior and posterior shear force. Torque AP laxity was defined as the difference in AP position between applying internal and external torque. Rotational laxity was the total rotation of the circular axis between applying internal and external torque. To display the average neutral path of motion, the lateral and medial AP positions were averaged for all knees and shown over an average tibial surface, generated by aligning the articular surfaces of the proximal tibia for all ten knees using Geomagic Verify and DesignX software (3D Systems, Rock Hill, South Carolina). In addition to tracking the circular axis through flexion, contact patches were depicted on the tibial surface using Geomagic Verify by mapping 0.5 mm deviation of the femoral cartilage from the points of closest approach between the articular surfaces of the tibia and femur.

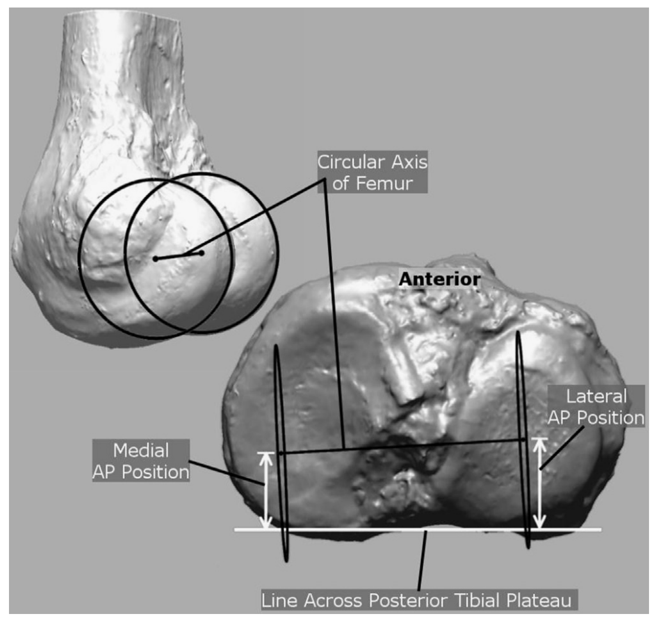

Fig. 2. The circular axis was used to determine the anterior–posterior position of the lateral and medial femoral condyles through flexion for each loading condition. The AP positions of the condyles of the femur on the tibia were described by distances of the circular axis relative to the posterior of the tibia.

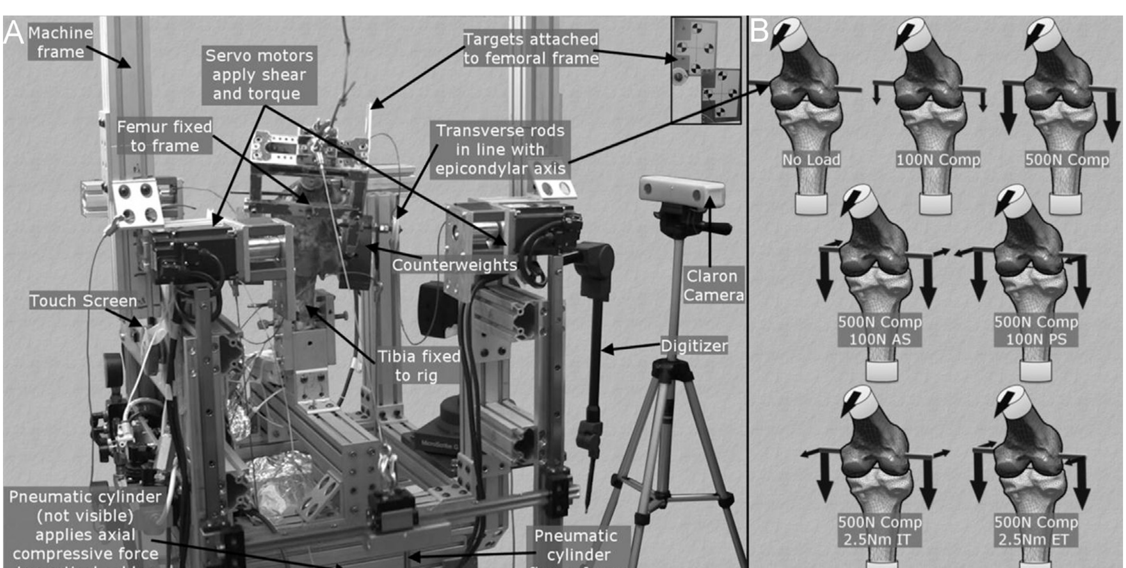

Fig. 1. Knee testing machine with free body diagrams of loading conditions. Flexion and compressive force were applied by pneumatic cylinders, while shear and torque were applied by servo motors. The camera and digitizer for recording the positions of the femur and tibia are shown. AS = Anterior Shear, PS = Posterior Shear, IT = Internal Torque, ET = External Torque.