Three-dimensional *in vivo* motion analysis of knee joint laxity under torsional loading

Andrea Hemmerich[1], Willem van der Merwe[2], Christopher L. Vaughan[1]

[1] Department of Human Biology, University of Cape Town, South Africa

[2] Sports Science Orthopaedics Clinic, Sports Science Institute of South Africa, Cape Town, South Africa

Introduction

Excessive knee joint laxity is often used as an indicator of joint injury, such as rupture of the anterior cruciate ligament (ACL). Although the ACL has been shown to contribute to rotational stability [1, 3], clinical assessment devices are currently limited to anterior-posterior drawer measurements. The objective of this work was to design a non-invasive procedure whereby *in vivo* knee joint kinematics could be evaluated in 3D using magnetic resonance imaging (MRI) to view the underlying bone and soft tissues.

3D Knee Loading Device Kinematics

Figure 1 shows a subject lying on the MRI patient table with her lower limb rigidly connected to the knee loading device. Adjustments in three planes can be made to ensure the correct knee flexion, ab-adduction, or rotation angles in the neutral (no load) position. Up to 80° of flexion and 15° of varus-valgus motion can be accommodated. The boot was in the extended position in order to ensure the knee was in the MRI coil field of view.

Figure 1: Subject in knee loading device. Knee is at 30° of flexion.

Measuring the Applied Torque

The applied torque is normalized to each subject's body mass in order to objectively compare results between individuals. The magnitude of the applied torque is measured using a strain gauge mounted onto a load cell. Figure 2 shows an exploded view of the main components of the load cell. The calibration data acquired while applying 80% and 20% of the maximum allowable load is shown in Figure 3.

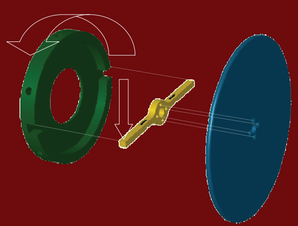

Figure 2: Exploded view of torque mechanism.

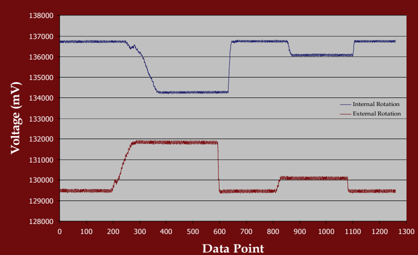

Figure 3: Calibration data used to determine equivalent torque in Nm.

Magnetic Resonance Image Acquisition

MR images were acquired using the 0.2 Tesla dedicated open-MR system (E-Scan XQ, Esaote, Italy). A 3D T1-weighted sequence with a 256 × 256 matrix was used to generate contiguous slices of less than 2 mm thickness. Three sets of images are acquired in the no-load, externally torqued and internally torqued positions. Figure 4 shows femoral and tibial slices in the two torsionally loaded positions.

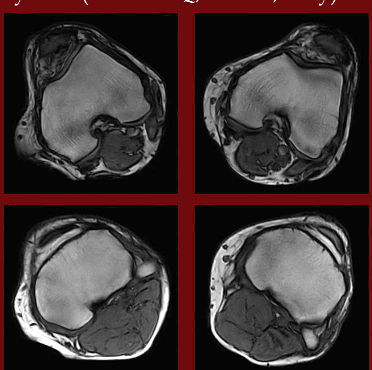

Figure 4: MRI scans of femur (top) and tibia (bottom). Left: internal rotation. Right: external rotation.

3D Kinematic Description of Motion

The definitions of the segment coordinate systems are shown in Figure 5. Positions of bony landmarks in 3D are determined from the three planes of the MR images, shown in Figure 6. Rotation and translation measurements follow the convention developed by Grood and Suntay [2]. The flexion-extension axis is defined as the x-axis of the femoral coordinate system, the internal-external rotation axis is defined as the tibial z-axis, and abduction-adduction occurs about the floating axis which is perpendicular to the preceding two axes.

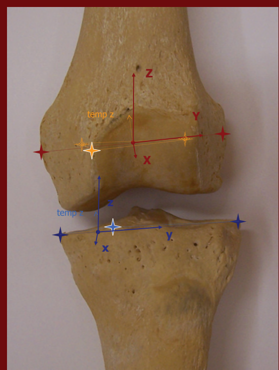

Figure 5: Femoral and tibial coordinate systems.

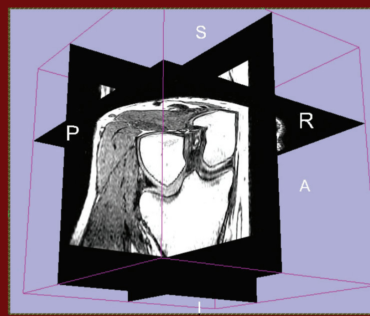

Figure 6: Magnetic resonance images of the three planes of the knee.

Device Validation

The accuracy to which relevant landmarks can be identified on the MR images at various flexion and rotation angles is within 2 mm. Figure 8 shows the phantom model of the femur and tibia that was used to determine the accuracy to which translation and rotation can be measured from the MRI scans. The phantom tibia was set at 0°, 30°, and 60° degrees of flexion and 0°, 15°, and 30° degrees of rotation relative to the femur. The measurements calculated from the MR images shown in Figure 7 were within 1.5 degrees of rotation of the known values.

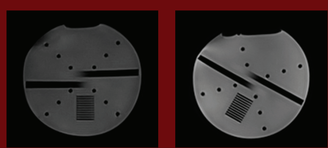

Figure 7: Transverse views of the phantom knee model at 30° rotation.

Figure 8: The phantom model simulating tibia at 30° of flexion in the MRI coil.

Conclusion

This torsional knee loading methodology, which enables us to measure kinematics of the non-weight-bearing knee joint *in vivo*, is non-invasive, eliminates soft tissue artefact during 3D measurements, and permits soft tissue visualization which is beneficial in clinical assessment.

Acknowledgments

The authors would like to acknowledge Charles Harris, Iekraam Fakier, Melissa Dagnin, Merle Neethling du Toit, Christopher Ball, and Sarah Dawson for their work on the device design and data collection. This study was financially supported by the Natural Sciences and Engineering Research Council of Canada and UCT.

References

[1] Georgoulis AD et al., Am J Sports Med 31:75-79, 2003

[2] Grood ES, Suntay WJ, J Biomech Eng 105:136-144, 1983

[3] Scopp JM et al., Arthroscopy 20:294-299, 2004