Design, Construction, and Validation of a Cadaver Knee Motion Testing Device

THE OHIO STATE UNIVERSITY DEPARTMENT OF MECHANICAL ENGINEERING

Undergraduate Honors Research Project

Julie Ann Thompson

Advisor: Robert A. Siston, Ph.D.

Introduction

The knee joint is a complex and important part of the human body. It also plays an important role in many everyday activities, including walking, running, and kneeling, making it vulnerable to injuries and diseases such as ACL injury and osteoarthritis. Surgical procedures, such as ACL reconstruction and total knee arthroplasty, commonly are required to alleviate pain and restore more normal joint function. There is a need to understand how these surgeries affect knee kinematics so that normal knee motion and function can be restored post-operatively. Knee kinematics are best investigated in actual knees; however, since it is unethical to simulate surgery in living subjects, there is a need to utilize cadaver specimens. Researchers have used a variety of mechanical devices to look into the complex ways in which the knee moves. The work of Wilson et al. [2], for example, has investigated how knee translation and rotation during passive motion are coupled to flexion angle.

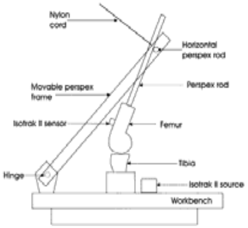

Figure 1: Passive motion rig of Wilson and colleagues [2]. The tibia is held fixed on a workbench and the femur is flexed and extended by manually rotating a rod inserted in the femur's distal end.

Li et al. [1] used a robotic testing system (Figure 2) to determine the motion of cadaver knee specimens in response to external loads.

Figure 2: Robotic testing system of Li and colleagues

There is great utility for these devices, but each has important limitations which have motivated this project. The goal of this project was to design, construct, and validate a cadaver knee motion testing device using passive motion for the purpose of understanding how surgical procedures affect knee kinematics.

Mechanism Design

The design is based on a continuous passive motion (CPM) machine, a device often used on patients who have undergone knee surgery. I used anthropometric data to determine the link sizes necessary for my device to accommodate a range of leg lengths. Using this data, I created a solid model of the design (Figure 3).

Figure 3: Design solid model. The base at the lower left of the mechanism is stationary while the slider at the lower right of the mechanism is able to translate back and forth.

I used kinematic vector loop equations to determine the slider position and speed at any given knee flexion angle and angular velocity. The variables in the vector loop equations are based on the angles and lengths of each link in the device (Figures 4 and 5).

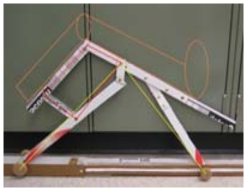

Figure 4: Cardboard prototype of design. Mechanism is a combination of a slider-rocker and 4-bar linkage.

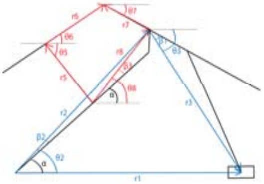

Figure 5: Lengths and angles of each link in the slider-rocker (blue) and 4-bar mechanism (red).

General vector loop equations (for slider-rocker):

$$r_{slider} = r_1 = r_2 + r_3$$

$$r_3 \cos\theta_3 = r_1 \cos\theta_1 - r_2 \cos\theta_2$$

$$r_3 \sin\theta_3 = r_1 \sin\theta_1 - r_2 \sin\theta_2$$

$$r_3^{\,2} = r_1^{\,2} + r_2^{\,2} - 2r_1r_2\left(\cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2\right)$$

$$A\cos\theta_2 + B\sin\theta_2 + C = 0$$

$$A = -2r_1r_2\cos\theta_1$$

$$B = -2r_1r_2\sin\theta_1$$

$$C = r_1^{\,2} + r_2^{\,2} - r_3^{\,2}$$

Simplifying with Trigonometric identities:

$$A(1-t^2) + B(2t) + C(1+t^2) = 0$$

$$t = \tan\left(\frac{\theta_2}{2}\right)$$

$$t = \frac{-B \pm \sqrt{B^2 - C^2 + A^2}}{C - A}$$

$$\theta_2 = 2\tan^{-1} t$$

To obtain the linear motion at the slider, I selected a lead screw. I calculated the required diameter, length, material, and other characteristics of the lead screw and nut assembly using machine design concepts.

Assuming $l = p = 0.2''$, $W = 25$ lb, $\theta = 14.5^o$ and a 3/8" steel screw with a plastic nut, the torque required for the screw is:

$$T_R = Wr_p\left[\frac{l\cos\theta + 2\pi r_p\mu_t}{2\pi r_p\cos\theta - l\mu_t}\right] + Wr_c\mu_c$$

with $\mu_t = 0.17$

$$d_r = d_o - 2\left(\frac{p}{2}\right)$$

$$d_r = \frac{3}{8} - 2\left(\frac{0.2}{2}\right) = 0.175''$$

$$r_p = \frac{p}{4} + r_r = \frac{p}{4} + \frac{d_r}{2}$$

$$r_p = \frac{0.2}{4} + \frac{0.175}{2} = 0.1375''$$

So the torque calculation is as follows:

$$T_R = (25\text{ lb})(0.1375\text{ in})\left[\frac{0.2\cos(14.5) + 2\pi(0.1375)(0.17)}{2\pi(0.1375)\cos(14.5) - (0.2)(0.17)}\right] = 1.459\text{ in-lb}$$

Construction

The testing frame is made almost entirely of 6061-T6 aluminum. I machined every individual part of the device myself out of either aluminum tubing, plate, or extruded block in the Scott Laboratory student machine shop. The only non-metal part of the device is the Lexan plate which provides the support surface for the shank and foot of the cadaver leg specimen.

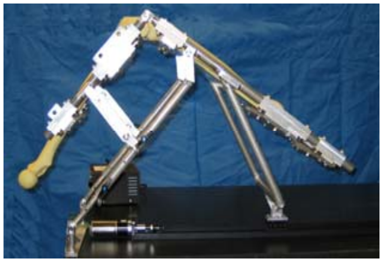

Figure 6: Final assembled device. Sawbones of the femur, tibia, and fibula represent the approximate location of the cadaver specimen.

Motion Control

The lead screw is driven and controlled by a small DC motor. Based on the torque calculations from the lead screw analysis and the speed calculations from the vector loop analysis, I was able to calculate the minimum power requirement for the motor using the following equation:

$$\text{hp} = \frac{T*n}{63025}$$

Using the maximum calculated rotational speed of the screw:

$$\text{hp} = \frac{(1.459\text{ in-lb})(953.15\text{ rpm})}{63025} = 0.0221\text{ hp}$$

The motor power in watts is: $0.0221\text{ hp}\left(745.7\ \frac{watts}{hp}\right) = 16.45\text{ watts}$

Currently, the motor is being controlled using open-loop feedback. Eventually, we will be controlling the motor with closed-loop feedback through the use of a rotary potentiometer. The position and speed results from the vector loop equations will be used as input to the motor.

Contributions

This custom passive motion device will allow us to investigate joint angles and speeds beyond the capabilities of existing devices. This device has the added advantage of being able to simulate motion in both a full cadaver leg as well as a transected knee specimen. The effects of a variety of procedures and surgical parameters on knee motion will be obtained using the device and will be beneficial in motivating possible future improvements in prosthetic design and surgical technique.

Acknowledgments

I would like to thank Dr. Ajit Chaudhari, Dr. James Schmiedeler, Dr. John Bolte, Neil Gardner, Gary Gardner, Caroline Tragni, Mark Reep, my fellow NMBL labmates, and my friends and family.

References

1. Li, G. et al. *Journal of Orthopaedic Research* 2004; *22*:90-95.
2. Wilson, D. R. et al. *Journal of Biomechanics* 2000; *33*:465-473.