A torn anterior cruciate ligament (ACL) is one of the more frequently occurring knee injuries plaguing both athletes and the general population [1]. This injury typically results in severe knee instability thereby limiting the activities the injured is able to perform. Currently, surgical reconstruction is the most common option to restore knee stability and allow the injured subject to return to full functionality (i.e. participation in athletic and recreational activities as desired). However, small populations of individuals who rupture their ACL forego surgery yet still remain fully functional [2]. We hypothesize that these subjects, referred to as "copers", alter the control strategy of the muscles crossing the knee joint to compensate for their ACL-deficient knee.

REVIEW AND THEORY

The high frequency and lasting effects of ACL tears has resulted in a number of studies on the knee joint in the past ten years. For example, Besier et al. [3] designed an experiment to compare the external flexion and valgus loads at the knee joint resulting from both pre-planned and unanticipated cutting movement. They suggest that subjects activate muscles crossing the knee joint earlier in order to provide additional stabilization. The muscle activation signals needed to verify this difference were not measured during their experimentation. However, the suggestion of altered control strategy implies that knee stabilization may not rely solely on the ligaments. Another study, performed by Long et al. [4], demonstrated that ACL deficient knees show less hamstring activation, thereby decreasing knee joint stability. Other studies have shown that increased anterior shear force applied on the tibia may increase the potential for an ACL tear if the hamstring does not apply a compensating force [5,6]. These studies indicate the importance of the hamstrings in both knee stabilization and the prevention of ACL tears. Thus, based on literature, we hypothesize that greater hamstring activity is suspected in the alternative control strategy implemented by copers.

PROCEDURE

Six test subjects (3 normals, 2 post-operation ACL, 1 coper) were prepared with 39 surface markers to quantify joint motion using a five camera motion capture system (Motion Analysis) and bi-polar surface electrodes to measure the muscle activity for five muscles: Rectus Femoris, Vastus Lateralis, Vastus Medialis, Semitendinosis, and Gastrocnemius. EMG signals were band-pass filtered from 20 – 200 Hz, low-pass filtered at 2 Hz, and then normalized to the maximum value for the respective muscle and leg found during the trials. Subjects were asked to perform a series of running cutting trials consisting of approximately three steps and a 30 to 60 degree, preplanned side-step cutting maneuver. Ground reaction forces created by the foot to initiate the cutting maneuver were measured with a six degree-of-freedom force plate (Bertec). Force plate signals were low-pass filtered at 60 Hz. Subjects repeated these cutting trials until three acceptable trials were obtained for each leg. Trials were deemed “acceptable” based on pre-established standards used to maintain consistency between trials for both intra-subject and inter-subject comparisons. Unacceptable trials were discarded and re-attempted. The first test subject was used as the basis for these pre-established standards. The standards were as follows:

- **Foot Placement:** The subject’s entire foot had to make contact with the force plate while cutting.
- **Cutting Angle:** The side-step cutting maneuver had to be performed at an angle between 30 and 60 degrees.
- **Horizontal Velocity:** To maintain natural stride length, each subject’s horizontal speed was scaled their leg length. Acceptable speeds ranged from 2.24 to 3.36 m/s per meter of leg length.
- **Ground Reaction Forces:** Ground reaction forces were scaled to the subject’s weight, \( W \). \( F_x \) (force perpendicular to direction of motion) ranged from 225% to 330% of \( W \), \( F_y \) (force parallel to direction of motion) ranged from 150% to 220% of \( W \), and \( F_z \) (vertical force) ranged from 400% to 600% of \( W \).
RESULTS

The following data analysis was limited to the half second before and after the maximum vertical force (max $F_z$) at the force plate. This one-second envelope served as the reference window for all subsequent comparisons. The knee flexion angle was similar among all subjects, varying a maximum of 15 degrees for the dominant leg. EMG signals were numerically integrated resulting in average activation values and were used for both intra-subject comparisons between the normal and ACL affected leg and for inter-subject comparisons.

Figure 1 summarizes coper activation differences for three primary muscles in the normal and ACL affected legs. This comparison indicates a 53% increase in the Semitendinosis activity; a 26% decrease in Rectus Femoris activity; and an 18% decrease in the Gastrocnemius activity in the ACL affected leg versus the normal leg.

![Figure 1. Intra-Subject Comparison (Coper)](image)

Figure 2 summarizes the inter-subject muscle activity for the Semitendinosis and the Rectus Femoris for the normal and ACL affected legs. This comparison indicates a 35% increase in average activation of the Semitendinosis for the ACL affected leg for the coper versus normal subjects. The Rectus Femoris shows 56% increase for both post-operation and coper subjects versus normal subjects. Intra-subject differences seen in normal and post-operation subjects are unaccounted for by this experiment.

Further research is being performed increasing both the sample sizes and developing a dynamic model of the knee joint. This dynamic model, which includes the femur, patella, tibia, five muscles, and the knee ligaments, estimates ligament forces based on estimated muscle forces and measured body kinetics. This model provides a critical tool for comparing the affects of muscles and ligaments on knee joint motion and stability.

![Figure 2. Inter-subject Comparisons](image)

DISCUSSION

Preliminary data indicates that muscle control strategy does vary for an ACL deficient knee. Both intra-subject comparison (coper) and inter-subject comparison (coper vs. normal) indicate increased Semitendinosis activity (53% and 35% respectively). This finding, along with the intra-subject (coper) decrease in Rectus Femoris activity (26%) is in agreement with previous research [2,4]. Intra-subject differences seen in normal and post-operation subjects are unaccounted for by this experiment.

This data both confirms and enhances the hypothesis by Besier et al. [3] that muscles assist ligaments in overall joint stability. These results imply potential improvements to both athletic training for the prevention of knee injuries as well as enhancing rehabilitation programs either implemented post-operatively or in place of surgical ACL reconstruction.

REFERENCES


ACKNOWLEDGMENTS

This research was supported in part by equipment provided by NSF-CCLI Grant (DUE-0087898). Special thanks to the Undergraduate 2001-2002 Biomedical Engineering Team at LeTourneau University.