EVALUATION OF ACL AND MCL STRAIN UNDER NON-CONTACT LOADING OF LOWER EXTREMITIES USING A HYBRID CADAVERIC SYSTEM

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The purpose of this study was to determine the strain in the ACL and MCL under simulated athletic activities using a novel hybrid robotic/cadaveric simulator. Four cadaveric knees, with ACL and MCL instrumented with strain transducers, were tested under simulated jump landing conditions from a height of 30 cm with various degrees of valgus orientation (fixed hamstring and quadricep forces) and various Quadriceps (Q) and Hamstring (H) force levels (fixed degrees of valgus). The response of Anterior Cruciate Ligament (ACL) and Medial Collateral Ligament (MCL) were monitored and assessed during the dynamic loading conditions. 4 – 5 tests were completed for each cadaveric leg, totalling 48 – 64 total tests. Analysis of data revealed that muscle activation (Q&H), in anticipation of landing, reduces the ACL strain even under severe valgus orientations. However, MCL strain is not influenced heavily by muscle activation.

KEYWORDS: ACL, MCL, strain, muscle activation

INTRODUCTION: ACL non-contact injuries are among the most common injuries that occur in the knee; this is typically caused by excessive tensile loading of the ACL during athletic activities (Griffin et al., 2006; Shimokochi & Suhlz, 2008; Yu & Garrettt, 2007). The non-contact injuries are especially perplexing because although very common, the cause or causes of such injuries are still unknown. There are numerous theories for such injuries including the excessive quadriceps force, excessive dynamic valgus, excessive anterior shear force, a combination of all of the above, and a recently proposed Hip Extension – Knee Flexion Paradox. However, for obvious reasons, none of these theories can be verified through human subject testing during the actual athletic activities. The ACL injury event is unpredictable, happens under short transient conditions (50-70 ms after ground contact), and involves a complex set of biomechanical, anatomical and biological factors. Thus, the most effective method of experimentation, analysis, and understanding is through development of hybrid (robotic-cadaveric) systems that can simulate simple athletic activities. In this research we present one such system that was used to simulate the landing from a jump activity under various kinematic and kinetic conditions. The main objective was to determine the impact of anticipatory muscle activation on the state of strain in the ACL and MCL.

METHODS: Full cadaveric legs that included a significant portion of the femur (8 to 10 inches), the knee joint, the ankle joint, and the foot were procured, instrumented, and installed in a novel robotic system that simulates landing from the jump, Figure 1. The ACL and MCL on the freshly thawed cadaveric legs were instrumented with strain transducers (DVRTs); the hamstring and quadriceps muscles forces were attached to loading actuators via cables; the full assembly was raised to a desired height; the position of the hip was manipulated using a mechanically designed hip that was connected to the femur using a threaded rod; the hip, knee, and ankle, were positioned at the desired orientations using applied muscle forces and the mechanical hip (controlling for knee flexion, valgus alignment, and hip flexion). The leg was then released under the action of the gravity and allowed impact on a force plate. The resulting strains, forces, ground reaction forces, and changes to kinematic variables were measured.

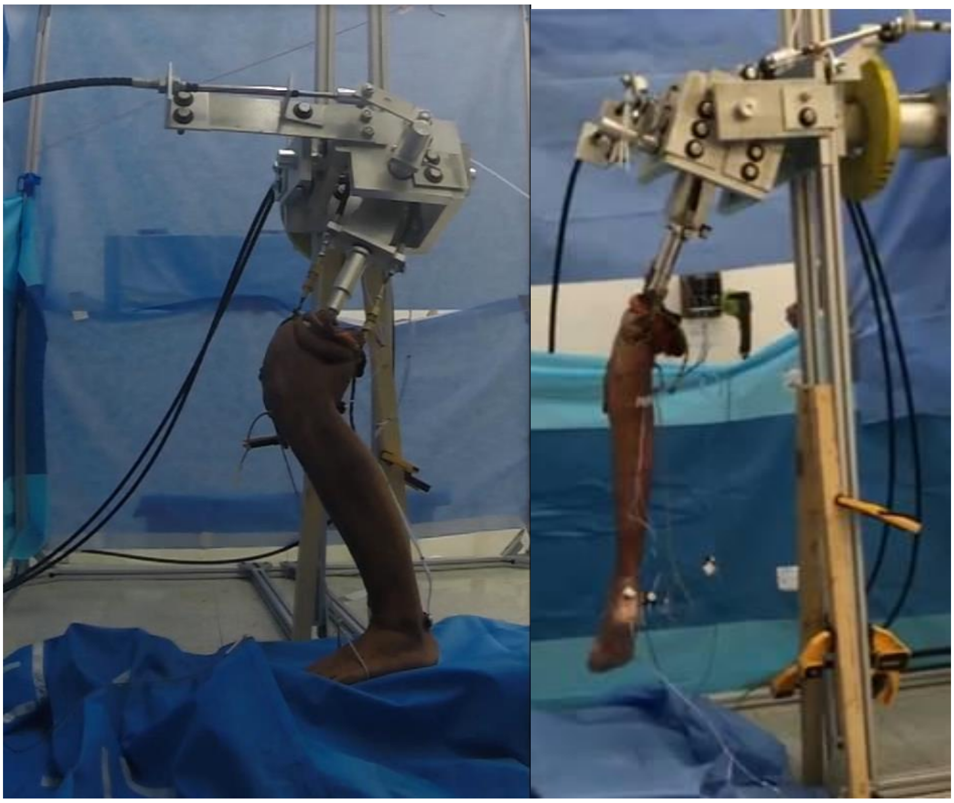

Figure 1. Two views showing integration of the cadaveric leg into the mechanical hip, forming a hybrid simulator.

Four cadaveric legs were tested, each specific test was repeated 4 - 5 times for a total of 48 – 64 tests. The cadaveric legs were tested in three positions: 1- knee positioned at 5^{o} of valgus, with quadriceps force varying from 0 to 300 N and hamstring force varying from 0 to 100 N; 2- knee positioned at 15^{o} of valgus and muscle forces varied as in position 1; 3- knee positioned at 25^{o} of valgus and muscle forces varied as in position 1. Each test was completed with constant parameters of 15^{o} of knee flexion and a 30 cm drop height. Results were analysed via MATLAB using a one-way ANOVA Bonferroni.

RESULTS: Under high valgus alignments extending from 15^{o} to 25^{o}, the observed ACL strain reduced as quadricep (Q) & hamstring (H) activation increased however statistical significance was only observed at 15^{o} of valgus alignment. At 15^{o} of valgus, considered a dangerous injury alignment, ACL strain was found to be lower when comparing 0 N quadriceps – 0N hamstring activation versus 300 N quadriceps - 0 N hamstring activation levels ($p = 0.0035$). At the same valgus alignment, ACL strain was also found to be lower when comparing 0 N quadriceps – 0 N hamstring activation conditions versus 300 N quadriceps - 100 N hamstring activation levels ($p = 0.004$) The ACL strain values at valgus alignments of 5^{o}, 15^{o}, and 25^{o} and at various quadriceps and hamstring activation levels are presented in Figure 2 through Figure 4 respectively. No statistical significance was found for MCL strain at the varying levels of knee valgus with differing levels of quadricep and hamstring activation forces (n of 52 – 33 for knee valgus levels). A typical figure for MCL strain at 25^{o} of valgus and various muscle forces is shown in Figure 5.

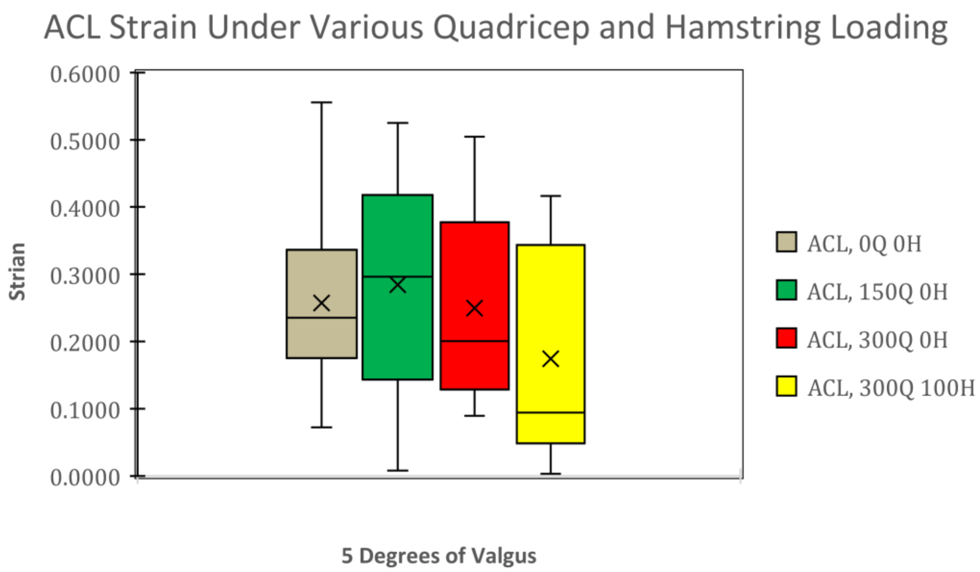

Figure 2. ACL strain data at 5º of valgus with various muscle preactivation levels (n = 53).

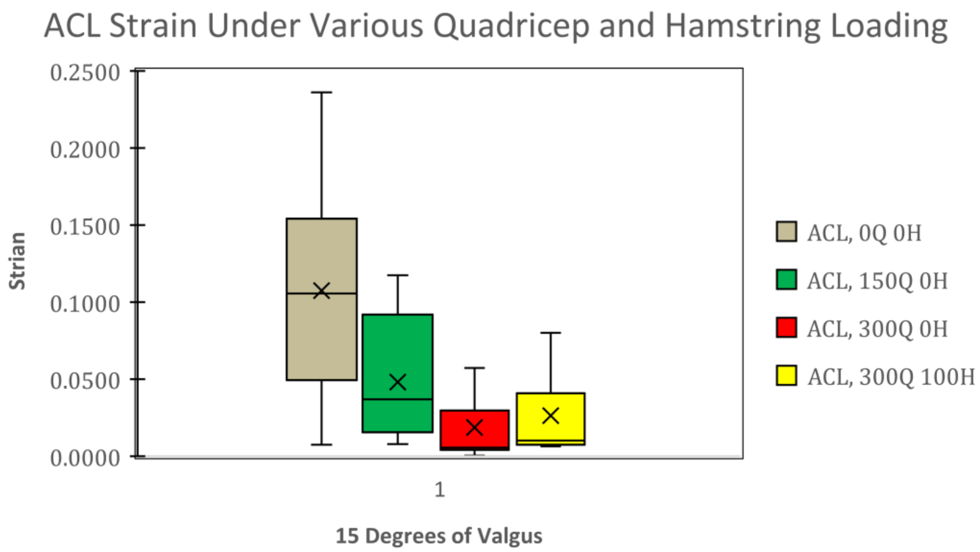

Figure 3. ACL strain data at 15º of valgus with various muscle preactivation levels (n = 32).

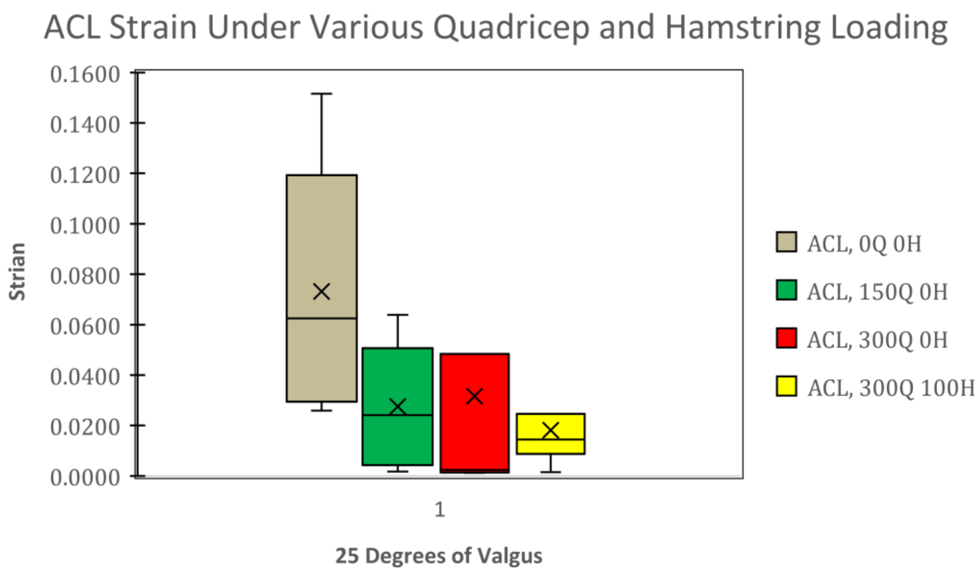

Figure 4. ACL strain data at 25º of valgus with various muscle preactivation levels (n = 26).

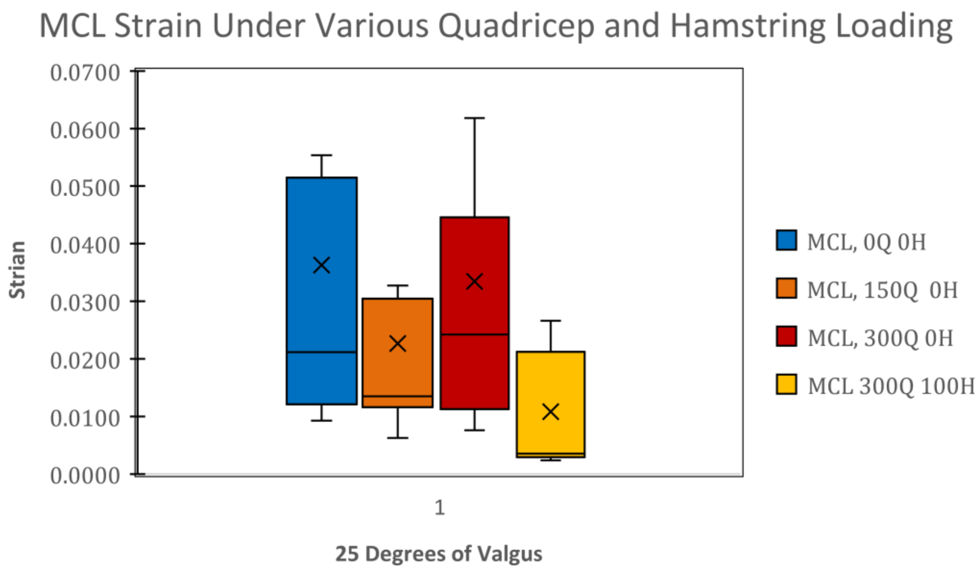

Figure 5. MCL strain data at 25º of valgus with various muscle preactivation levels (n = 33).

DISCUSSION: In the ACL injury literature, the impact of muscle forces on the state of strain in the ACL is not well understood. Some researchers suggest that increasing forces in the quadriceps muscle force increase the strain in the ACL and others suggest that it enhances the deleterious impact of valgus alignment at landing (Besier et al., 2001; Ford et al., 2001; Markolf et al., 1995). The existing literature suggest that increasing muscle force combined with valgus alignment causes ACL injury (Shimokochi et al. 2008; Bates et al., 2017). Some researchers using static robotic simulators have suggested that ACL injury occurs routinely under the combined action of quadriceps force, anterior shear force, internal rotation, and valgus alignment (Bates et al., 2017). These assertions are provocative and need verification from the scientific community. Accordingly, our results here consistently suggest that as quadriceps and hamstring force increase the strain in the ACL, at landing, decreases at all valgus alignments. Our results, although preliminary, suggest that increasing muscle forces do not cause ACL injury and are protective. In fact, our results suggest that even at extreme valgus levels, activation of Q & H reduce strain levels in the ACL. The results suggest that valgus alignment in the presence of sufficient knee and hip muscle forces is not a cause of concern related to ACL injury. Concurrently, the strains in the MCL were maintained under control although a decreasing trend was not always observed. This indicates the trivial conclusion that as long as ACL's integrity is maintained the strains in the MCL remain under control. One Limitation of this study is that the number of legs could be increased to increase the power of prediction. Additionally, other factors should be taken into account in future research including foot flare, pronation and supination of the foot and ankle, active verse passive ankle response to landing, and timing of muscle activation within the ground reaction loading.

CONCLUSION: There are two major conclusions: 1) the hybrid robotic/cadaveric simulator can be a useful tool in studying the knee ligaments with various muscle forces and under impulsive loads during ground impact. And 2) The preliminary results here suggest that increasing pre-activation of quadriceps and hamstring muscle forces, reduce ACL strain during landing from a jump however significantly more tests with more legs must be performed to achieve stronger results. The authors plan to perform a series of studies to identify conditions that will result in ACL injury. The developed system can be used to test key ACL failure theories.

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