Proceedings of the International Conference on Biomedical Engineering and Systems
Prague, Czech Republic, August 14-15, 2014
Paper No. 73

Investigation of the Role of Quadriceps Forces and Joint Contact Pressure in Loading of the ACL - In-Vitro Simulation

Ariful Bhuiyan, Stephen Ekwaro-Osire
Texas Tech University
Lubbock TX 79409
ariful.bhuyian@ttu.edu; stephen.osire@ttu.edu

Javad Hashemi
Florida Atlantic University
Boca Raton FL 33431
jhashemi@fau.edu

Abstract **-** Instrumented cadaveric knees were used to quantify the association between quadriceps muscle force, ground reaction force, tibiofemoral contact pressure/area and strain in anterior cruciate ligament (ACL) through in vitro simulation of a vertical jump-landing process in a dynamic loading simulator. The research question for this project was set: "Can the ACL strain be influenced by the tibiofemoral contact pressure/area, the unopposed quadriceps force (QMF), low knee flexion angle, and constant ground reaction force (GRF)?" Fourteen cadaveric knees were mounted in the custom made dynamic loading simulator to measure strain on the anteromedial bundle of the ACL using a differential variable reluctance transducer (DVRT). An I-Scan pressure transducer (Model 4000) was used to measure contact pressure and area in the tibiofemoral joint. It was observed that the tibia rotates internally prior to landing and during landing. During the landing phase, the peak pressure on the lateral compartment is very high, compared with the medial compartment. During the landing phase, both the contact area and pressure increases in the tibiofemoral joint. The influence of pressure induced joint conformity is also justified. It can be concluded from the obtained results of the experimental works that the unopposed quadriceps muscle forces coupled with ground reaction force at low knee flexion angle cannot cause ACL injury. Joint compressive loads induced by large muscle forces and GRF introduces the joint conformity, and this joint conformity produces the primary restraint against anterior tibial translation at low flexion angles along with menisci.

Keywords**:** Anterior cruciate ligament, Tibial plateau, Tibial slope, Joint compressive force.

1. Introduction

The knee joint is one of the largest and most complex joints in the human body; it is situated between the body's two longest bones (the femur and the tibia). One of the four major ligaments in the knee joint is anterior cruciate ligament (ACL). This ligament connects these longest two bones. The knee joint sustains high forces and moments every now and then from the daily life activities or sports related activities, which makes the soft tissue, ACL susceptible to be torn.

Anterior cruciate ligament (ACL) injury is a serious, common, and costly injury in sports and creates a deterioration in the quality of life (Bing, William 2007). ACL reconstruction is a commonly performed procedure (Garret, 2004), with approximately 300,000 new ACL injuries estimated to occur annually in the USA [(Griffin et al., 2006; Renstrom, 2008). These ACL injuries require surgical reconstruction and lengthy rehabilitation at a cost of almost $3 billion USD (Renstrom, 2008; McLean, 2010). The ACL injury also induces subsequent indirect cost such as loss of time from work, school, or sports (Griffin et al., 2006). Even when ACL reconstruction is performed, there is a high likelihood that the injury predisposes the knee to the early onset of osteoarthritis in the secondary stage. It also induces other pathological knee conditions, including knee instability, as well as damage to menisci and the chondral surface (Finsterbush et al., 1990). The treatment of these secondary damages also incurs additional significant costs.

ACL injury that occurs without physical contact with another person or object is referred to as non-contact ACL injury (Ireland et al., 1997). Approximately 70 to 80% of ACL injuries occur during non-contact sports events. These sports events involve different types of manoeuvers: sudden deceleration, an abrupt change in direction, or jump landing. These manoeuvers are common in soccer, basketball, handball, and volleyball (Boden et al., 2000; Boden et al., 2009; Krosshaug et al., 2007). The growing number of people in sports, especially the increased participation of young females has resulted in an increase in the number of ACL injuries. Female ACLs are typically smaller compared with males; as they do not grow in proportion to the body height and are of lower mechanical quality (Beynnon et al., 2010). It is reported that female athletes are 2-8 times more likely to sustain a non-contact ACL injury than males (Yasuharu et al., 2009; Ireland, 2002)

One of the most cited mechanisms is quadriceps pull mechanisms (QPM). As per QPM, the contraction of QMF results in a significant anterior proximal tibial translation at low knee flexion angles, and thus puts the ACL under tension. Sometimes this mechanism is termed as “anterior shear force mechanisms.”

In this research, using in-vitro techniques, we investigate the role of a combination of factors including tibial plateau contact pressure, an unopposed quadriceps force, low knee flexion angle, and a dynamic ground reaction force on ACL strain.

2. Methods

A novel landing simulator apparatus was used to load the a cadaveric knee/ACL under simulated athletic activities (Figure 1). Prior to testing, cadaveric knees were thawed at room temperature for 8-10 hours, and were dissected to the capsule level. The knee was placed in the simulator at a pre-determined flexion angle. At that position, a DVRT was placed in anterior bundle of the ACL. A thin pressure sensor was inserted in the space between the femur and the tibia. A pre-determined quadriceps force was then applied through an actuator connected to a 75mm long woven nylon strapping which was attached to the patella with annealed steel wire just after the dissection. An impulsive ground reaction force was applied at time=0. The soft tissue surrounding the knee, specifically the ACL, were kept moist by applying 0.1N saline solution in 5 minutes intervals.

Initially, the knee was positioned at approximately $20^{o\ of}$ flexion angle. The quadriceps force was applied at various load levels including 25N, 75N, 175N, 200N, and 300N. After application of the quadriceps force, the strain value in the ACL and joint contact pressure values were recorded using the DVRT and the pressure sensor readouts. Following the measurements, an impulsive ground reaction force, GRF, was applied to the knee and the strain in the ACL as well as the contact pressure was measured again. Overall, fourteen different knees were tested and the set of tests for each individual knee were conducted on the same day to control for temperature and humidity.

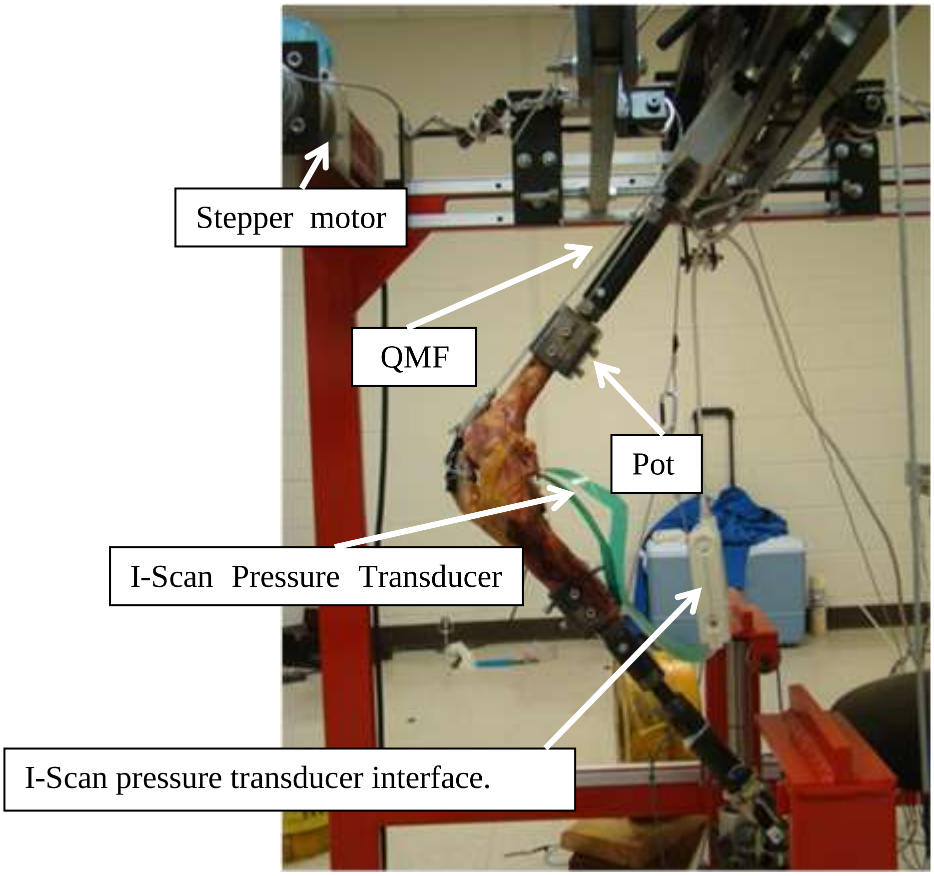

Fig 1. Potted knee and other necessary items used for the experimental work. It shows the knee right after applying the ground reaction force (GRF).

3. Results

The average values of ACL strain at each level of quadriceps pre-activation is given in Figure 2. The correlation for the pooled results (14 knees) was found to be significant and positive; as quadriceps pre-activation increases so does the ACL strain.

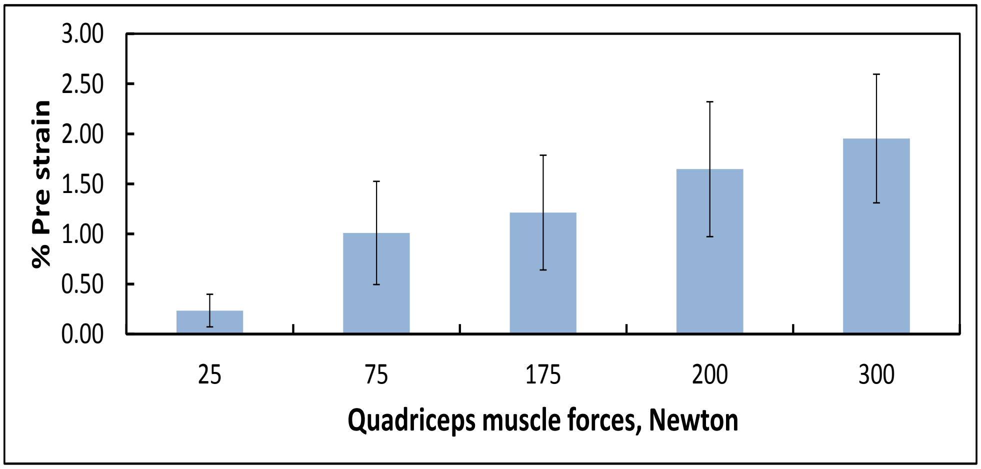

Fig 2: Percent Pre strain versus QMFs for pool of all knees (strains measured prior to landing).

The total strain observed in the ACL (the summation of pre strain and landing strain) does not vary considerably with increasing QMF (Figure 3).

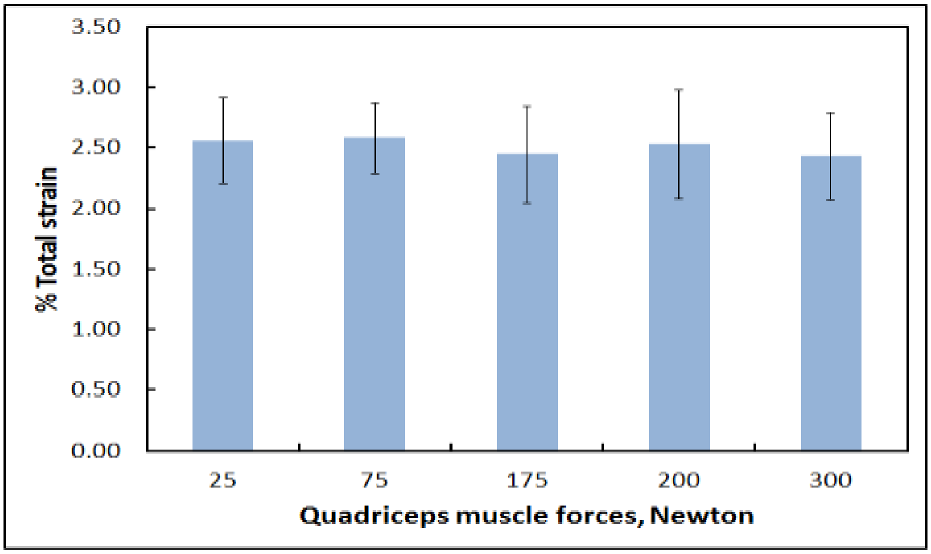

Fig 3: Total strain (pre strain + landing) versus QMF for pool of all knees

Figure 4 shows the typical GRF and QMF patterns. Both GRF and QMF are normalized by their respective peak values during the landing phase. GRF takes approximately 10 ms to reach its peak value, and it starts to decrease from the peak point immediately. QMF starts with the applied QMF of 175N (normalized by 350N) just prior to landing time. All quadriceps muscle forces in this study showed the same pattern of increase and decrease. The ACL reached its peak strain 10 to 20 ms after ground contact.

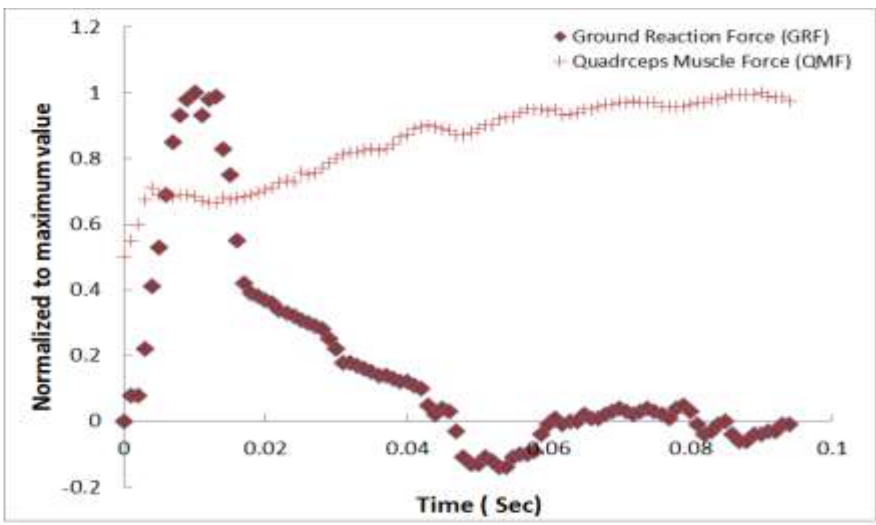

Fig 4: Normalized input to the experimental work of a knee (Exp Sub # 60103L): Applied normalized impact force and normalized quadriceps muscle force.

Figure 5 and 6 show the mapping of contact pressure distribution on the lateral and medial compartment of a knee (Exp Sub #1, 60103L) for five different QMFs while the knee is under various quadriceps loads. The peak contact pressure for QMF 25N is 0.303Mpa in the medial compartment and increases with increasing initial quadriceps force beyond 75 N. The location of the peak contact pressure shifts from the medial aspect to the lateral aspect for all knees above 75 N of quadriceps force.

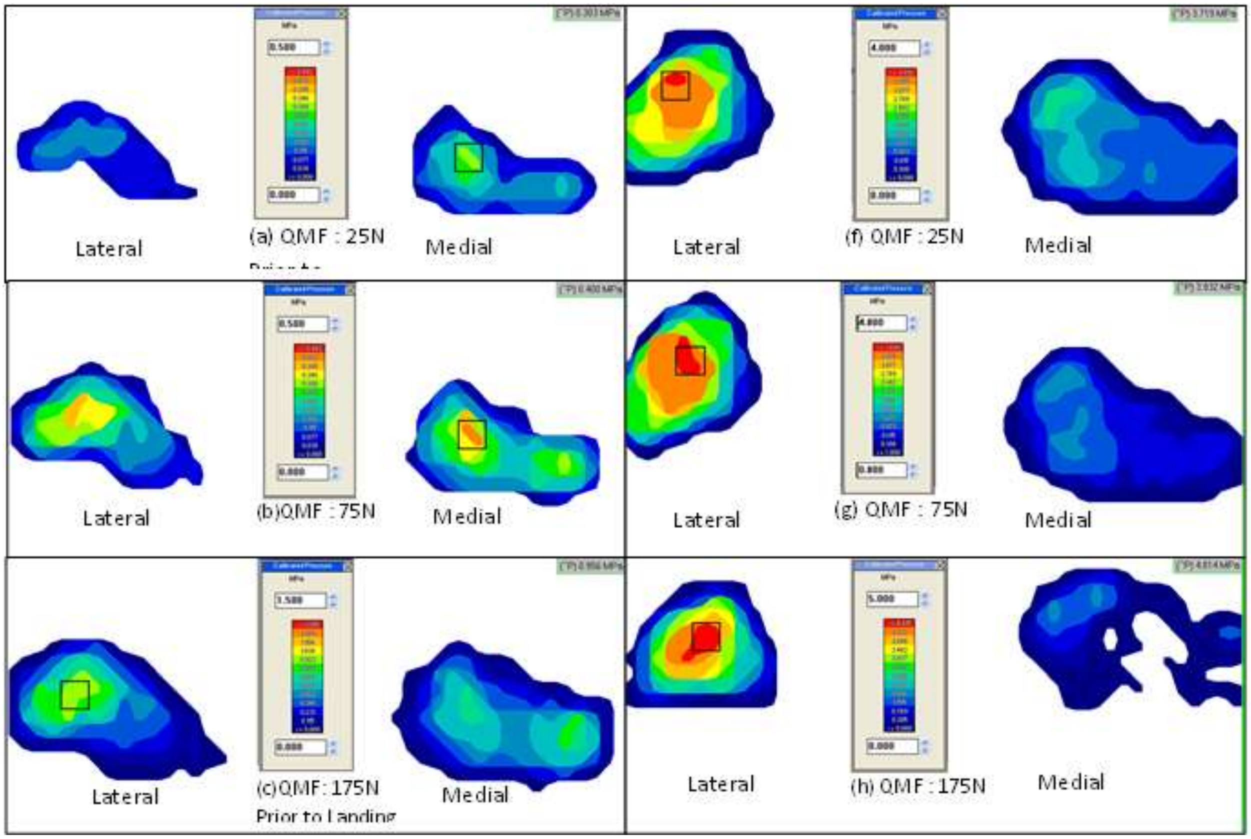

Fig.5. Peak contact pressure (MPa) and its associated area details (mm^2) both for prior to landing [(a), (b), (c)] and after landing [(f),(g), (h)].

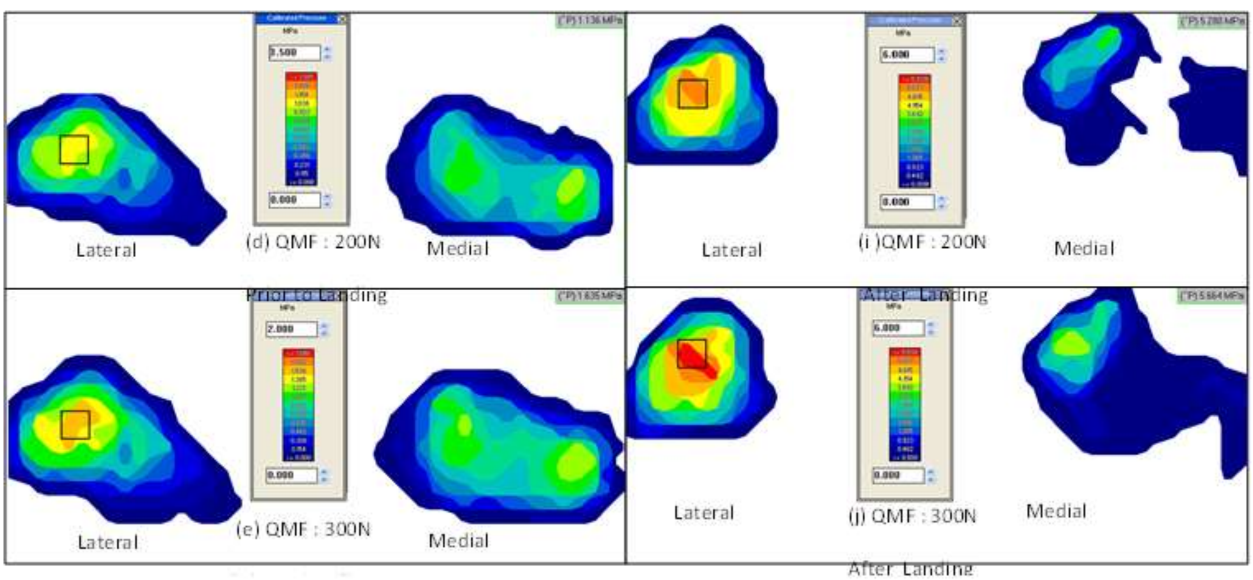

Fig 6: Continuation of figure 7. Peak contact pressure (MPa) and its associated area details (mm^2) both for prior to landing [(d), and (e)] and after landing [(i), and (j)].

4. Conclusion

Increasing value of quadriceps forces prior to landing increases the ACL strain. However, the total strain including pre-landing strain and landing strain remains constant. The joint contact pressure is initially maximum in the medial compartment as the quadriceps load is applied but location of maximum shifts to the lateral plateau as landing takes place. This shows a systematic shift in the pressure distribution during load on the lateral side. This shift in pressure also indicates internal rotation of the tibia during the landing phase.

Acknowledgements

The authors acknowledge the support of Texas Tech University and Florida Atlantic University in funding this work.

References

Beynnon B. D., Mansouri H., Chandrashekar N., J. H., Hardy D., and Slauterbeck J. R., 2010, “Age, sex, body anthropometry, and ACL size predict the structural properties of the human anterior cruciate ligament,” Journal of Orthopaedic Research.

Bing Y., and William E. G., 2007, “Mechanisms of,” British Journal sports of medicine, **41**, pp. i47–i51.

Boden B. ., Torg J. S., Knowles S. B., and Hewett T. E., 2009, “Video Analysis of Anterior Cruciate Ligament Injury,” American Journal of SPorts Medicine, **37**, pp. 252–259.

Boden B. P., Dean G. S., Feagin A. J., and Garrett W. J., 2000, “Mechanisms of anterior cruciate ligament injury,” Orthopedics, **23**, pp. 573–578.

Finsterbush A., Frankl U., and Matan Y. et al., 1990, “Secondary damage to the knee after isolated injury of the anterior cruciate ligament.,” American Journal of sports Medicine, **18**(5), pp. 475–479.

Garrett W. E., 2004, “Anterior cruciate ligament injury: pathophynology and current therapeutic principles.,” Paper presented at : 71st Annual Meeting of the American Academy of Orthopaedic Surgeons.

Ireland M. L., 2002, “The female ACL: why is it more prone to injury?,” Orthopedic Clinics of North America, **33**, pp. 637–651.

Ireland M. L., Gaudette M., and Crook S., 1997, “ACL injuries in the female athlete.,” Journal of Sports Rehabilation., **6**, pp. 97–110.

Krosshaug T., Nakamae A., Boden B. P., Engebretsen L., Simth G., and Slauterbeck J. R. et al., 2007, “Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases.,” American Journal of sports Medicine, **35**(3), pp. 359–67.

Letha Y Griffin, Marjorie J Albohm, Elizabeth A Arendt, Roald Bahr B. D. B., 2006, “Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005,” American Journal of Sports Medicine, **34(9)**, pp. 1512–1532.

McLean S. G., 2010, “Complex integrative morphological and mechanical contributions to ACL injury risk,” Exercise sports science Reviews, **38**(4), pp. 192–200.

Renstrom P., 2008, “Non-contact ACL injuries in female athletes,” British Journal of sports medicine, **42**, pp. 394–412.

Yasuharu Nagano, Hirofumi Ida, Masami Akai T. F., 2009, “Biomechanical charateristics of the knee joint in female athletes during tasks associated with anterior cruciate ligament injury,” The Knee, **16**, pp. 153–158