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Loss of ACL Function Leads to Alterations in Tibial Plateau Common Dynamic Contact Stress Profiles

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Abstract

It has been suggested that the repetitive nature of altered joint tissue loading which occurs after anterior cruciate ligament (ACL) rupture can contribute to the development of osteoarthritis (OA). However, changes in dynamic knee joint contact stresses after ACL rupture have not been quantified for activities of daily living. Our objective was to characterize changes in dynamic contact stress profiles that occur across the tibial plateau immediately after ACL transection. By subjecting sensor-augmented cadaveric knees to simulated gait, and analyzing the resulting contact stress profiles using a normalized cross-correlation algorithm, we tested the hypothesis that common changes in dynamic contact stress profiles exist after ACL injury. Three common profiles were identified in intact knees, occurring on the: I) posterior lateral plateau, II) posterior medial plateau, and III) central region of the medial plateau. In ACL-transected knees, the magnitude and shape of the common dynamic stress profiles did not change, but their locations on the tibial plateau and the number of knees identified for each profile changed. Furthermore, in the ACL transected knees, a unique common contact stress profile was identified in the posterior region of the lateral plateau near the tibial spine. This framework can be used to understand the regional and temporal changes in joint mechanics after injury.

Introduction

The anterior cruciate ligament (ACL) is the primary stabilizer to anterior translation, and a secondary stabilizer of internal rotation of the tibia (Andriacchi and Dyrby, 2005; Chaudhari et al., 2008; Georgoulis et al., 2003; Micheo et al., 2010). When the ACL is torn, a decrease in external rotation is observed (Andriacchi and Dyrby, 2005) and an increase in internal rotation of the tibia relative to the femur occurs (Chaudhari et al., 2008; Defratre et al., 2006; Gao and Zheng, 2010; Georgoulis et al., 2003; Keene et al., 1993). This offset, also evident

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in dynamic MRI studies (Barrance et al., 2006), is thought to occur due to the loss of the screw home mechanism at the end of the swing phase, leading the femur and tibia to be offset relative to each other (Georgoulis et al., 2010). This alteration in the magnitude and location of joint contact has been theorized to contribute to the development of knee osteoarthritis (OA) (Andriacchi et al., 2006; Andriacchi and Mundermann, 2006).

Clinical observations have shown that regardless of whether an ACL reconstruction is performed, nearly half of patients with ACL injuries will progress to symptomatic OA within 12-14 years of the initial injury (Lohmander et al., 2004; Micheo et al., 2010; von Porat et al., 2004). There is certainly a biological component to the progression of OA (Goldring et al., 2008), but given the mechanical role of the ACL in maintaining joint stability (Kanamori et al., 2002; Solomonow et al., 1987), mechanical factors are likely to play an important role. It is not well understood whether the early onset of OA is due to excessive mechanical forces at the incipient injury event, or altered loading that occurs repetitively during use of the limb after injury, or a combination of both.

Previously, our group (Bedi et al., 2013) has quantified changes in peak contact stress magnitude and contact area in cadaveric knees after ACL transection. While increased peak contact stress in the posterior medial aspect of the medial plateau occurred, the analysis was focused *only* on the medial plateau and *only* at two points in the gait cycle at which axial forces were highest. Because the knee experiences millions of gait cycles each year (Sechriest et al., 2007; Shepherd et al., 1999; Silva et al., 2002), the repetitive nature of contact stresses to which the articular cartilage surfaces are subjected to throughout a complete gait cycle needs to be characterized. The objective of this study was to characterize alterations in dynamic contact stress profiles that occur *throughout* gait after ACL transection. By applying the normalized cross-correlation algorithm developed and described in Wang et al. (2014a) to the previously performed ACL study (Bedi et al., 2013), we tested the hypothesis that there exist quantifiable common changes in contact stress profiles after ACL transection.

Materials and Methods

As described in Bedi et al. (2013), nine human cadaveric knees from 6 donors (Table 1) were aligned, pinned, and potted on a Stanmore Knee Simulator (Bedi et al., 2013; Gilbert et al., 2014; Wang et al., 2014b). The simulator controlled axial force, anterior-posterior force, internal-external torque and flexion-extension profiles to mimic the activity of walking (ISO #14243-1; (DesJardins et al., 2000). Contact stress perpendicular to the surface of the tibial plateau was measured using an electronic sensor (Tekscan 4010N; South Boston, MA), sealed in Tegaderm (3M; St Paul, MN), augmented with tabs, and equilibrated and calibrated as previously described (Bedi et al., 2013; Gilbert et al., 2014; Wang et al., 2014b). The sensors were placed on the tibial plateau under the meniscus in both compartments and anchored to the anterior tibial footprint of the ACL and posterior capsule. The sensor consists of 422, 2×2mm sensing elements (“sensels”) which dynamically record the applied normal stress at a frequency of 9.8 Hz for 40 seconds. Knees were tested intact for 20 cycles, then flexed on the simulator and the ACL was transected at the footprint of the femoral

attachment site. The knee was subjected to an additional 20 gait cycles and data from the last 5 cycles for both conditions were analyzed.

Common contact stress profiles were identified using a modified version of the algorithm described in Wang et al. (2014a). Briefly, a custom Matlab program (Mathworks Inc, MA) was used to first normalize the location and size of the meniscal footprint before extracting the contact stress profile as recorded by each sensel for each specimen. Then, a 'within' knee analysis was conducted: To establish if characteristic contact stress profiles existed across the tibial plateau of each knee, the contact stress profile from the sensel located at matrix location [1,1] was used as a 'template'. This 'template' was then compared to the contact stress profile as recorded by every other sensel within that knee using normalized cross-correlation (NCC). Sensels with NCC values greater than 0.93 were considered similar and their profiles were grouped. The next sensel in the row was then used as the template and the process was repeated until all sensels had been compared. To allow for a 'between' knee analysis, the average of the grouped profiles was compared to profiles from itself and the remaining 8 knees using the same NCC algorithm, with the threshold value set to 0.92. A validation of the 'within' and 'between' knee analysis was performed using sinusoidal loading on the sensors and is provided in the supplemental data (Supplement I & II). The average magnitude of the common profile was calculated by weighting the average stress profile at each sensel by the number of knees that contained the profile at that location – this analysis resulted in common dynamic profiles with stress magnitudes that were bias to sensels with the most overlap amongst knees. An overview of the process is given in Fig 1. The rationale by which the threshold values were chosen is given in Supplement III.

Results

Common Dynamic Stress Profiles of Intact Knees

Common dynamic stress profiles were identified in the intact knees. One common profile (Profile 1, Fig 2A) was located in the posterior region of the medial plateau and diffusely along the circumference of the menisci. This profile consisted of a single prominent peak in contact stress that occurred at 14% of gait with 4 to 7 knees identified with this profile. Another common profile (Profile 2, Fig 2A) was identified with 5-9 knees having this profile located on the posterior lateral aspect of the tibial plateau. Profile 2 consisted of two peaks in contact stress, the timing of which corresponded to that of the peak externally applied axial forces at 14% and 45% of gait. Finally, a common profile (Profile 3, Fig 2A) occurred in the central region of the medial plateau where cartilage-cartilage contact occurs with 4 knees exhibiting this profile. This profile consisted of a prominent single peak during the late stance phase of gait (45%).

Common Dynamic Stress Profiles of ACL Resected Knees

The shape and magnitude of the common dynamic stress profiles for the ACL-transected knees were similar to the intact condition (Fig. 2B). However, the number of knees that exhibited the common profiles and their locations were altered. Profile 1 which was evident in 5-8 knees was more localized to the posterior and central footprint of the meniscus (Profile 1', Fig 2B). Fewer knees (5-7) were identified for Profile 2 (Profile 2', Fig 2B).

Interestingly, Profile 3 occurred over a larger number of sensels with 4 knees consistently exhibiting this profile (Profile 3', Fig 2B). Additionally, a fourth profile, containing 4 knees, was located in the posterior lateral plateau near the tibial spine (Profile 4', Fig 2B).

Discussion

By way of a dynamic, multidirectional cadaveric test that simulates gait, we have demonstrated that there are common identifiable contact stress profiles acting across the tibial plateau in the intact knee. While no changes in profile shape or magnitude of the common profiles was observed with ACL transection, a new common profile located in the posterior lateral plateau near the tibial spine was identified. Changes in the location of the remaining common contact stress profiles and in the number of knees exhibiting those common profiles was also identified (Fig. 2C).

Quasi-static and dynamic biomechanical cadaveric studies have previously analyzed the effect of ACL rupture on joint contact mechanics (Bedi et al., 2013; Imhauser et al., 2013; McCarthy et al., 2013). The main outcome is typically reported as the magnitude of peak contact stress and as such can represent a change in mechanics over a focal area, at a single instant in time. It was our intent to represent joint contact stresses *throughout* a simulated gait cycle. Moreover, we wanted to capture changes in contact stress that occurred across the plateau, rather than at a single site. Thus, while large changes in aberrant peak loads have been reported to occur after ACL rupture (up to 4.8 MPa, Bedi et al., 2013), the changes reported herein represent average changes in common dynamic contact stress profiles that are distributed over a larger area of the tibial plateau.

Anterior changes in tibial position of up to 2.8 mm occurred after ACL transection (Bedi et al., 2013), which correspond to anterior translation and internal rotation of the tibia found to occur in the knees of ACL deficient patients (Andriacchi and Dyrby, 2005; Defrate et al., 2006; Gao and Zheng, 2010; Van de Velde et al., 2009). As the tibial position changed, we found a corresponding enlargement of the common dynamic contact stress profile in the cartilage-cartilage contact region (Profile 3 & 3'). Additionally, a new characteristic contact stress profile was observed in the posterior lateral tibial plateau (Profile 4') along with increased number of knees containing the profile in the central and posterior footprint of the medial meniscus. These changes could be caused by the increased femoral external rotation observed with ACL deficiency (Gao and Zheng, 2010; Zhang et al., 2016). The offset in external rotation of the femur after ACL transection causes changes in the contact point on the tibia which may attribute to the increase in the number of knees with common profiles in the central portion of the medial meniscus, the increased profile area from Profile 3 to 3' and the identification of the new profile on the lateral plateau. Moreover, such changes in contact stress profiles in areas covered by the meniscus correspond to the increased incidence of medial meniscus damage in chronic ACL deficient knees (Bellabarba et al., 1997; Hagino et al., 2015). The altered rotational mechanics can lead to significant cartilage loss in the posterior medial tibial plateau, observed in Andriacchi et al. (2006), and offloading of areas that were highly loaded (Andriacchi et al., 2006; Andriacchi and Mundermann, 2006; Chaudhari et al., 2008) – as was observed with fewer knees identifying with Profile 2 to 2' after ACL transection.

This study had limitations. ACL injury patients have been shown to alter their kinematics to a more “quadriceps avoidance” gait profile (Andriacchi and Dyrby, 2005; Berchuck et al., 1990; Gao and Zheng, 2010), but such changes were not mimicked in this study. Our approach of keeping force inputs constant allowed us to better isolate changes *only* due to sectioning the ACL - altered input forces will be studied in the future. Variations in the location of the pinned flexion axis could cause changes in the motion of the joint on the simulator and lead to variations in contact stress. While this variation is not accounted for, 2 profiles have been identified in a majority of the knees tested. The sampling frequency of 9.8 Hz was the maximum sampling frequency available to us at the time of the study, but this value is less than the Nyquist rate (12 Hz). We conducted a back analysis of data recorded from intact knees at a higher sampling rate (100 Hz, (Wang et al., 2014a)), and found similar characteristic contact stress profiles identified when focusing on areas where there are more than 4 knees containing the pattern (Supplement III). It should be recognized that the back analysis was only performed on the intact knees and not on the ACL transected knees. Finally, our analysis was restricted to the tibial plateau.

In summary, we have demonstrated consistent identifiable common contact stress profiles acting across the tibial plateau in intact and ACL-transected knees subjected to simulated gait. While no difference in common stress shape or magnitude was noted with ACL transection, the locations of the common profiles on the tibial plateau and the number of knees identified for each profile changed. The analysis framework described in this study can be used to understand the effect of different knee-related injuries on the spatial and temporal dynamic contact stresses across the tibial plateau and the efficacy of repair techniques to restore these contact stress profiles to the intact state.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Figure 1. Flow diagram of knee joint contact profile identification

Specimens were first tested intact and then after the ACL was transected at the femoral insertion. The data acquired from the electronic sensor was independently processed through the NCC algorithm and common profiles ‘within’ a knee were identified. The identified profiles within all specimens were then compared ‘between’ each other using the same algorithm resulting in a map of the common dynamic stress profile locations and the identified common profiles.

Figure 2. Common dynamic loading profiles in intact and ACL transected knees

4 common loading profiles were found in both the A) intact and B) ACL transected knees. Profile 1 was localized in the posterior medial aspect of the tibial plateau with both the intact and ACL transected knees having a single peak during early stance. Profile 2 was localized in the posterior lateral aspect of the tibial plateau both intact and ACL transected knees. Profile 3 was localized to the central region of the medial tibial plateau for both intact and ACL transected knees. The ACL deficient knees showed a fourth profile location at the posterior lateral plateau. Shaded regions with a solid line represent the upper and lower 95% confidence interval for the intact knees. The shaded regions surrounding the dotted lines represent the upper and lower 95% confidence intervals for ACL transected knees. C) Representation of tibial plateau with the location of characteristic profiles for intact and ACL deficient knees. The pink regions represent the menisci, the white regions the cartilage, and the blue regions the bone. The size of the shapes indicates the number of knees found at that location with larger circles representing more knees.

Table 1**Specimen Demographics**

Knee #	Age	Gender	Height (in)	Weight (lb)
1R	55	Male	70	100
1L	55	Male	70	100
2R	57	Male	70	105
2L	57	Male	70	105
3R	54	Female	67	90
4L	53	Male	72	135
5R	49	Female	67	110
6R	55	Male	66	80
6L	55	Male	66	80