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Relationship between increased in vivo meniscal loads and abnormal tibiofemoral surface alignment in ACL deficient sheep is varied

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ABSTRACT

The aim of this study was to quantify how abnormal dynamic tibiofemoral surface alignment affects the load bearing function of menisci in vivo. Using a sheep model of ACL deficiency, we tested the hypothesis that increased in vivo meniscal loads correlate with greater tibiofemoral surface alignment abnormality. Stifle kinematics were recorded using a bone-mounted instrumented spatial linkage in four sheep before, and at four and twenty weeks (w) after ACL transection. A parallel robotic manipulator was used to quantify stifle kinetics by reproducing each animal's in vivo kinematics and measuring tissue loads during gait. Meniscal resultant loads were estimated from the change in joint reaction force after sequentially removing load-bearing tissues. Tibiofemoral subchondral surfaces were then traced and modeled using thin plate splines. Proximity disturbance is a surface interaction measure used to quantify dynamic tibiofemoral surface alignment abnormality. ACL transection increased meniscal loads by 30–145% at 20w post-ACL transection, whereas the degree of dynamic tibiofemoral subchondral surface alignment varied between sheep. Positive and significant correlations between increased meniscal loads and proximity disturbance values >10 mm were observed ($R^2=0.04$–0.57; $p\leq 0.05$). Our results suggest that the proximity disturbance measure reflects abnormal meniscal loads following ACL injury; however given the range of R^2 values, perturbations in dynamic tibiofemoral subchondral surface alignment do not explain abnormal joint kinetics entirely, and point to the presence of other dynamic compensatory mechanisms that may have a significant bearing on in vivo joint function and long-term joint health.

1. Introduction

Much work has been done to understand the biomechanical consequences of anterior cruciate ligament (ACL) deficiency, with the view to understand what constitutes abnormal motion, and then to use this knowledge in order to restore joint function as closely as possible in the hope that post-traumatic osteoarthritis (PTOA) can be attenuated (Lohmander et al., 2007). Many have hypothesized that loads borne by the remaining structures of the knee are different following ACL tear (Frank et al., 2004). By and large, in vitro (Allen et al., 2000; Papageorgiou et al., 2001) and numerical (Li et al., 2002) studies have provided significant evidence to support the hypothesis. In vitro robotic studies in particular have demonstrated that the medial collateral ligament (MCL) and menisci function as secondary restraints to anterior tibial translation during a simulated motion path (Allen et al., 2000; Kanamori et al., 2000). Menisci also play a critical role in distributing contact stress uniformly between the tibiofemoral surfaces of the knee (Shrive et al., 1978) and in modulating fluid flow within the load-bearing cartilage regions (Adeeb et al., 2004). Thus impaired meniscal function is likely to result in joint instability and damage to the underlying articular cartilage (Englund and Lohmander, 2004). Despite the known consequences of impaired meniscal function, monitoring the presence of either impaired or abnormal dynamic function in vivo, and the relationship to PTOA onset, has been challenging.

Six degree of freedom (6-DOF) tibiofemoral kinematic abnormalities have been well characterized in both ACL-deficient humans (DeFrate et al., 2006) and in large animal models of ACL

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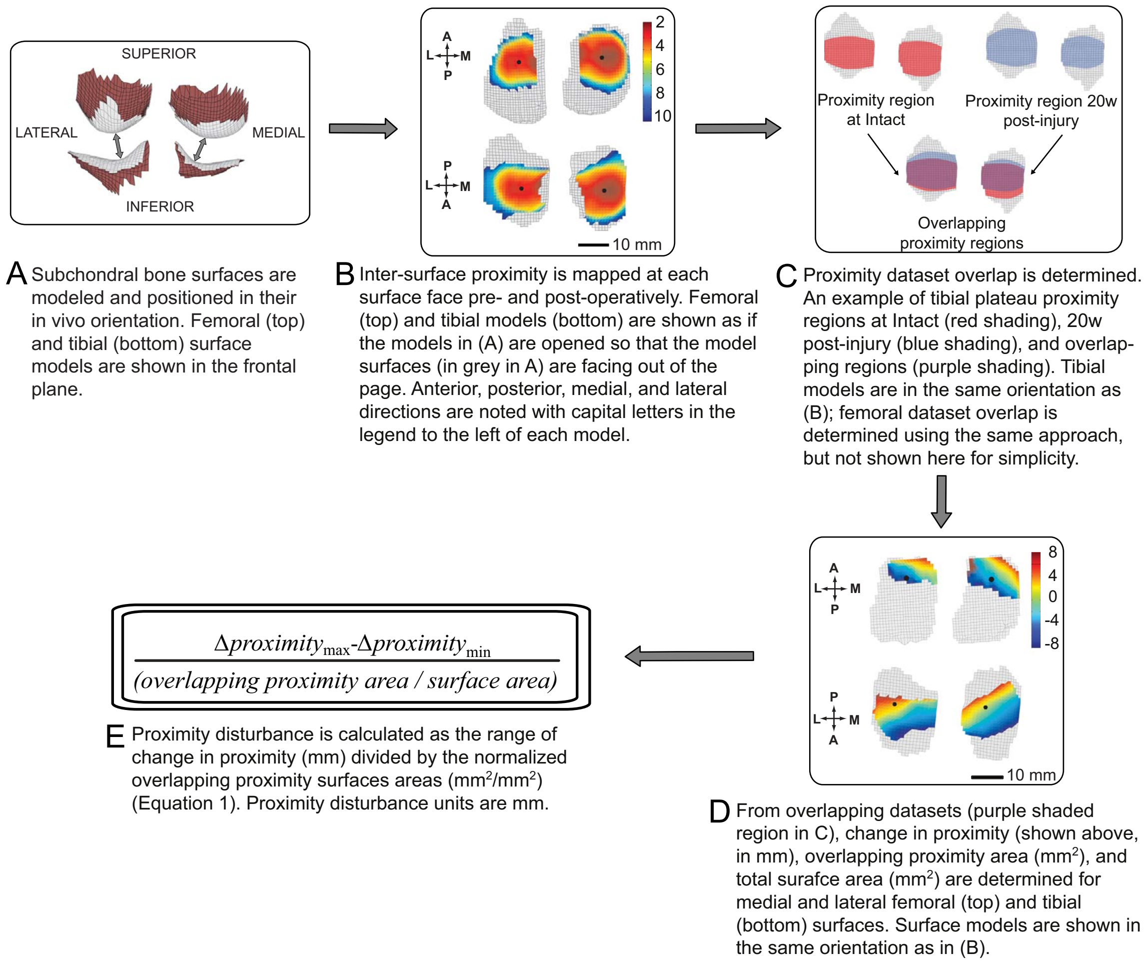

Fig. 1. Overview of each step in the Proximity Disturbance calculation. Black dots in the surface plots shown in (**B**) and (**D**) indicate locations of weighted centroids used to approximate regions of tibiofemoral proximity. Colour bar values are in mm and indicate the relative separation between tibiofemoral surfaces in (**B**) and the change in proximity in (**D**). Figure from Beveridge et al. (2014), with permission.

injury (Tapper et al., 2008; Tashman et al., 2004). More recently, the term "surface interactions" has been adopted to describe the dynamic motion and alignment of tibiofemoral surfaces, and are believed to play a critical role in PTOA pathogenesis (Andriacchi et al., 2009). Our group recently introduced a measure of dynamic tibiofemoral alignment in a sheep model of combined ACL and MCL transection. We termed the surface interaction "proximity disturbance" because it captures the change in distance between opposing tibiofemoral surfaces across a region of near proximity (Beveridge et al., 2014). That is, injury resulted in some tibiofemoral regions moving much closer together, and other regions moving farther apart. The greater this spread in change in proximity over a smaller contact area common to both intact and post-injury time points, the larger the proximity disturbance value (Fig. 1). Thus proximity disturbance is a combined measure that quantifies changes in the complex tibiofemoral surface alignment, and is related to contact location and the individual's unique tibiofemoral surface geometry. Importantly, we showed that the severity of cartilage damage 20 weeks post-ACL/MCL transection in a sheep model is associated with larger proximity disturbance values. At the time, we hypothesized that proximity disturbance may reflect the loading environment of the joint, and could be related to the redistribution of contact stresses within the joint. Because the menisci play a key role in modulating contact stress, meniscal loads may be particularly sensitive to changes in dynamic tibiofemoral surface alignment.

Quantifying how abnormal dynamic tibiofemoral surface alignment affects the load bearing function of menisci would be a first step towards establishing a means to identify and monitor the presence of mechanisms believed to contribute to PTOA initiation in vivo. Using a sheep model of ACL deficiency, we tested the hypothesis that increased in vivo meniscal loads correlate with greater proximity disturbance values.

2. Methods

2.1. *In vivo kinematics*

Four skeletally mature female Suffolk-cross sheep were halter broken and trained to walk on a treadmill at a standardized speed of 0.9 m/s. Sheep were exercised at least thrice weekly, which consisted of 40 min of over ground and treadmill walking. Four weeks prior to kinematic measurement, modified fracture plates (Zimmer, Warsaw, IN, USA) were surgically affixed to the distolateral aspect of the hind right femur, and the proximolateral aspect of the hind right tibia to accommodate a custom removable plate-post assembly (Tapper et al., 2004). At the time of kinematic collection, the rigid removable posts were secured to the implanted facture plates, and an instrumented spatial linkage (ISL) was mounted to the posts. The ISL consists of six rotational encoders, providing 6-DOF to its motion (accuracy = 0.3°/0.3 mm), and has been described in detail previously (Rosvold et al., 2015). Using the ISL, in vivo kinematics were recorded prior to surgical intervention (Intact), and longitudinally at 4 and 20 weeks (w) post-operatively. At each kinematic session, approximately 200 strides were collected. Surgical intervention consisted of arthroscopic transection of the hind right ACL, also described in detail previously (Atarod et al., 2014a). Following the final 20-week in vivo kinematics measurement, animals were euthanized via intravenous injection