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Ligament and meniscus loading in the ovine stifle joint during normal gait

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ABSTRACT

Background: The ovine stifle joint is an ideal preclinical model to study knee joint biomechanics. Knowledge of the ovine ligamentous and meniscal loading during normal gait is currently limited.
Methods: The *in vivo* kinematics of the ovine stifle joint (N = 4) were measured during "normal" gait using a highly accurate instrumented spatial linkage (ISL, 0.3 ± 0.2 mm). These motions were reproduced *in vitro* using a unique robotic testing platform and the loads carried by the anterior/posterior cruciate ligaments (ACL/PCL), medial/lateral collateral ligaments (MCL/LCL), and medial/lateral menisci (MM/LM) during gait were determined.
Results: Considerable inter-subject variability in tissue loads was observed. The load in the ACL was near zero at hoof-strike (0% gait) and reached a peak (100 to 300 N) during early-stance (~10% gait). The PCL reached a peak load (200 to 500 N) just after hoof-strike (~5% gait) and was mostly unloaded throughout the remainder of stance. Load in the MCL was substantially lower than the cruciate ligaments, reaching a maximum of 50 to 100 N near the beginning of stance. The LCL carried a negligible amount of load through the entire gait cycle. There was also a major contribution of the MM and LM to load transfer from the femur to the tibia during normal gait. The total meniscal load reached a maximum average between 350 and 550 N during gait.
Conclusion: Knowledge of joint function during normal motion is essential for understanding normal and pathologic joint states. The considerable variability in the magnitudes and patterns of tissue loads among animals simulates clinical variability in humans.
Level of evidence: III.

1. Introduction

The knee is a complex mechanobiologic joint operating in full six degree of freedom (6-DOF). Understanding how different structures in the knee joint function during normal motion is critical in assessing intact joint biomechanics as well as pathological changes that result in joint degeneration and osteoarthritis (OA) [1].

Previous methods used to determine ligament loading during normal motion include both direct *in vivo* measurements, simulated *in vitro* loading, and numerical modeling [2]. Numerical methods rely on accurate kinematic data coupled to the relevant anatomic geometry. Typically, these methods use an optimization scheme to solve for ligament, muscle, and contact loads from kinematics and ground reaction forces [3]. These methods are susceptible to the accuracy of the input data and the reliability of the objective function used. Additionally, ligament loads are assumed to be correlated to inter-insertional distances. Direct methods tend to be highly invasive and therefore may impact the reliability of the data. Further challenges with implantable sensors are calibration, location, accuracy, and reliability [2].

Increasingly, industrial robots are being used to study the response of ligaments to applied loads and motions [4–11]. The method by Berns et al. [12] and Woo et al. [5,9] uses a hybrid force control methodology to find a 5-DOF path of least resistance along prescribed flexion angles. Loads can be applied along defined anatomic directions and the resulting kinematics measured. As a different approach, Boguszewski et al. [13] used kinematic data from a sheep and applied it to a swine joint to determine anterior knee force. To date no investigations are reported using "joint specific" *in vivo* kinematic data to determine the ligament loads.

The sheep has proven to be a promising model for studying joints and the development of OA. Following injury, the sheep stifle joint develops OA, though at an accelerated rate compared to humans [14]. We have previously examined the kinematics of the ovine stifle joint

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during normal gait and their changes after injury [14–17]. To further this model, knowledge of tissue loads during normal motion is essential for understanding normal/pathologic joint states.

The increased prevalence of OA following meniscectomy infers that these structures play an important role in joint mechanics [18]. The load carried by the menisci in elderly humans was suggested to be 45% of the total load, when 1000 N was transmitted across the knee joint *in vitro* [19]. Walker et al. examined the contact and load-bearing areas in the knee joint under non-loaded and loaded (150 kg) conditions *in vitro*. Under no load, they observed that contact occurred primarily on the menisci. Under loading, the lateral meniscus carried most of the load on the lateral side, while on the medial side the load was shared by the meniscus and the cartilage [20]. Recently, Nesbit et al. [21] examined the force contributions in the ovine knee of individual structures to the overall joint force, using "an average" *in vivo* ovine gait motion, and demonstrated a major role of the medial meniscus during stance. To the authors' knowledge, no studies have been performed to measure the loading of the medial meniscus (MM) and lateral meniscus (LM) during normal gait using "joint specific" *in vivo* kinematics.

The main objective of the present study was to use a highly accurate ISL to first measure the 6-DOF *in vivo* kinematics of the ovine stifle joint during normal gait, and second in combination with a novel robotic testing platform [22] to determine the ligamentous (ACL, PCL, MCL, LCL) and meniscal (MM and LM) loading during normal gait.

2. Materials and methods

2.1. Motion capture in vivo

Four skeletally mature (N = 4) female Suffolk-cross sheep (weight 78.1 ± 5.4 kg) were used. Special modified surgical fracture plates were implanted onto the femur and tibia of the right hind limb, and the animals were allowed to heal, as previously described in [15,16]. Ground reaction forces from force plate data were compared from before the surgery to four weeks after plate implantation to ensure that the animal was using the limb normally [15,16]. Just prior to collection of the kinematic data, incisions were made on both the femur and tibia, and posts were attached to the fracture plates. A highly accurate ISL (0.3 ± 0.2 mm) [22] was attached to these posts. The test subject walked on a standard treadmill at 0.9 m/s (two miles per hour) and the ISL angle sensor readings recorded (400 Hz). Data were collected for a minimum of 200 strides for each animal. All animal surgeries and testing were approved by the University of Calgary Animal Care Committee and comply with the guidelines of the Canadian Council on Animal Care.

Following kinematic collection, the animal was euthanized and the limb stored overnight (four degrees Celsius). All surrounding tissues were subsequently removed from the joint, sparing the ACL, PCL, MCL, LCL, and menisci. A coordinate measuring machine, CMM (FaroArm Platinum, Faro Technologies, Lake Mary, FL, USA; accuracy 0.025 mm) was used to create anatomically relevant coordinate systems on the femur and tibia. From the 200 strides recorded for each animal, 20 consecutive representative strides were chosen based on their average variation from the mean stride. These strides generally fell within ±1 standard deviation of the 6-DOF motion while still containing enough variation to provide insightful data.

2.2. Motion reproduction in vitro

Using bone cement (PMMA) and custom pots, the joint was mounted on a parallel robotic test platform (R-2000, PRSCo, Hampton, NH, USA; 0.05 mm accuracy), again with the ISL remaining on the bones as placed previously *in vivo*. The tibia was fixed rigidly to a tibial fixture system,

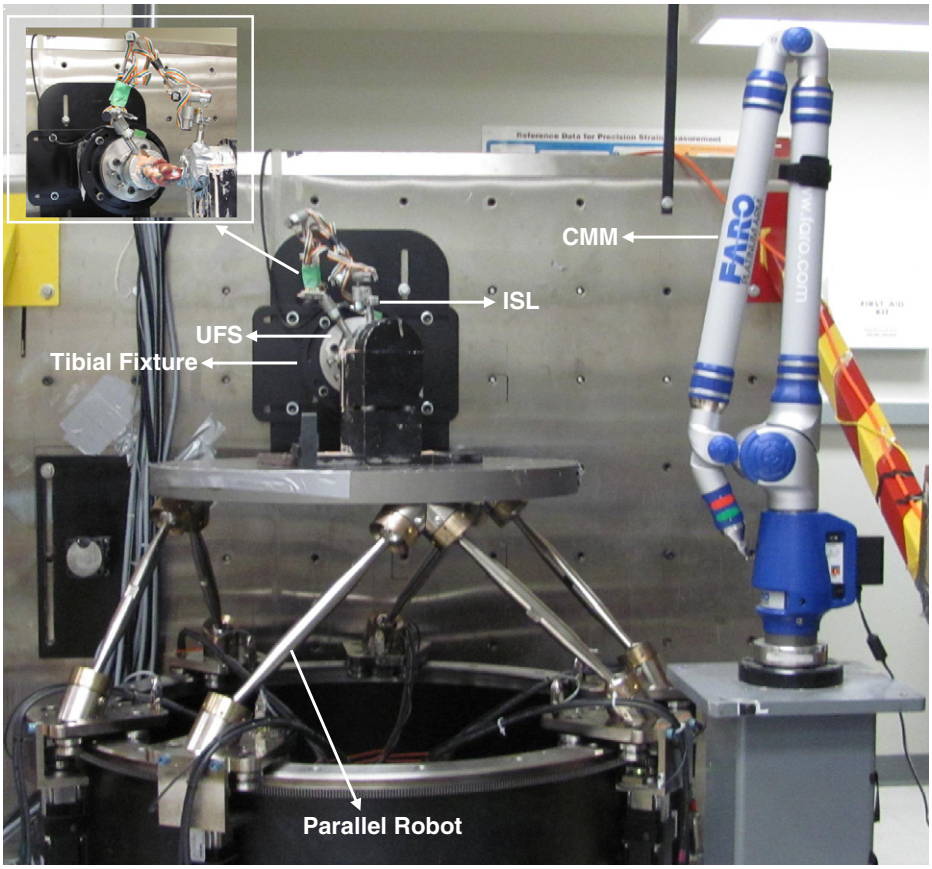

Fig. 1. The 6-DOF unique robotic testing platform (adapted from [22]). The ovine stifle joint kinematics recorded *in vivo* using the instrumented spatial linkage (ISL) is then reproduced *in vitro* using the parallel robot. Using the universal force-moment sensor (UFS) and application of the principle of superposition, the ligamentous and meniscal loading during gait is estimated.