MOTION ANALYSIS AND MATHEMATICAL MODELING OF THE FORCES IN THE ADULT RABBIT KNEE JOINT DURING HOPPING

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INTRODUCTION

The rabbit is commonly used as an animal model to study the development of osteoarthritis in the knee joint. Experiments have included ACL resections accompanied by medial meniscectomy [1], or tibial osteotomy [2] to induce alterations in joint loading or stability. Although these studies often induce osteoarthritic changes, it is difficult to attribute these changes to mechanical factors without a better understanding of the normal biomechanics of the rabbit knee joint. For example, little is known about the relative magnitude and duration of ACL loading during typical activities, or the distribution of medial and lateral joint contact forces, both likely to be critical in development of osteoarthritis. There have been very few quantitative analyses of gait in the rabbit, with work by Mansour et al. [1] being one of the more detailed investigations. However, this analysis was limited to kinematic observations, and not combined with kinetic data that would make modeling of joint contact forces possible.

The purpose of this preliminary study was to investigate the normal hopping gait of the rabbit and use measurements of the intersegmental forces and moments to estimate the joint contact force distribution across the tibial plateaus. A mathematical model introduced by Harrington [3] was adapted for use in the rabbit.

METHODS

Motion Analysis

Knee kinematics and kinetics were determined *in vivo*, in a skeletally mature male New Zealand White rabbit (3.6 kg) with data collected on several days over a two-week period. The rabbit was trained to hop within a Plexiglas track for kinematic analysis using an Optotrak 3020 Motion Analysis System (Northern Digital, Inc.). To prevent soft tissue motion artifact, three infrared emitting diodes (IREDs) were mounted on disks attached to implanted intra-cortical pins in the tibia and femur of the rabbit. Following surgical procedures approved by the University of Rochester UCAR committee, threaded Steinmann pins (1.9 mm diameter) were inserted with a cordless orthopaedic drill (Stryker Inst.) into the cortices of the right femur and tibia. Pins were oriented perpendicular to the lateral surface of each bone and driven through the lateral cortex until they pierced the medial cortex. Stainless steel nuts were tightened against the bone surface to prevent migration of the pins. An additional set of three IREDs was placed on a holder strapped around the foot.

Kinetic data were obtained with a piezoelectric force plate (Kistler Instrument Corp.). Kinematic and kinetic data were collected simultaneously with sampling rates of 300 Hz and 60 Hz, respectively. A video camera operating at 30 frames/sec was also employed to film the rabbit while hopping. Coupling of the videotape and the kinetic data allowed for isolation of data for only hind limb contact. Sixty-five trials were analyzed and five selected for further modeling based on consistency of gait patterns, adequate collection of kinematic data, and ability to clearly identify hind limb contact.

Image-based Anatomy

Rabbit knee anatomic data were based on measurements obtained from magnetic resonance images (1.5 T clinical imaging unit, GE Medical Systems, Milwaukee WI). Using a phased array receiver coil, axial MR images of an intact cadaveric rabbit knee joint were acquired at a single flexion angle (Proton Density Sequence, TR = 2000, TE = 20, FOV = 6 cm x 6 cm, 0.9 mm Thickness, 0.3 mm Spacing, 256 x 192 Matrix). Area centroids of each muscle and ligament cross-section were determined from multiple slices, and were transformed from the MR global coordinate system to a local anatomic coordinate system for the tibia, which was defined by identification of bony landmarks. Individual muscle and ligament moment arms and lines of action were calculated in both the frontal and sagittal planes relative to the origin of the tibia coordinate system.

Modeling

The right hind leg was modeled as a rigid link system, comprised of the femur, tibia and the foot. Assuming the linear and angular accelerations to be negligible, the intersegmental forces and moments at the knee were calculated throughout the stance phase of the hop. A statically determinate model, adapted from Harrington [3], was used to predict muscle, ligament and tibiofemoral joint contact forces during hopping (Figure 1). In addition to both medial and lateral resultant joint contact forces, the model included cruciate and collateral ligaments as well as the quadriceps, hamstrings and gastrocnemius muscle groups. The muscle, ligament and joint contact forces were calculated by balancing their actions with the external intersegmental forces and moments. Thus, only a flexor or extensor group is active depending on the sagittal plane moment, neglecting co-contraction. The hamstrings muscle group (biceps femoris, semitendinosus, semimembranosus), served as flexors, if needed, during the first 20% of stance, while the gastrocnemius (medial and lateral heads) fired during the last 80% of stance. Resultant force lines of action and moment arms for the included muscle groups were based on PCSA-weighted averages of the MR-based anatomic data for each individual muscle [4].

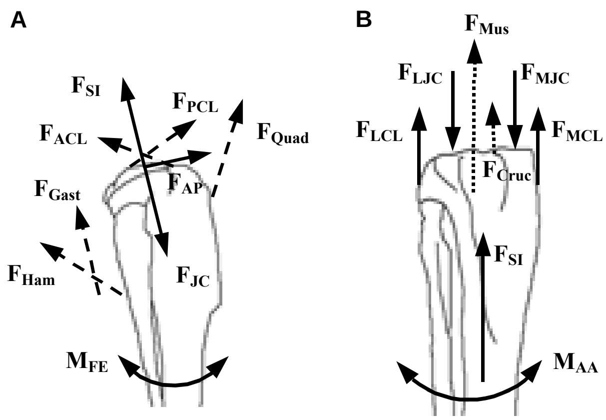

Figure 1. Sagittal (A) and frontal (B) plane free body diagrams of rabbit proximal tibia

RESULTS

Results of the motion analysis demonstrate our ability to collect accurate kinetic data for a rabbit using equipment in a clinical motion analysis laboratory. By combining the data from the force plate and videotape, we were able to select five trials that exhibited a distinctive timing pattern for further analysis (Figure 2). In all trials, the front limbs experienced a larger vertical ground reaction force than the hind limbs, with right and left hind legs evenly and simultaneously loaded.

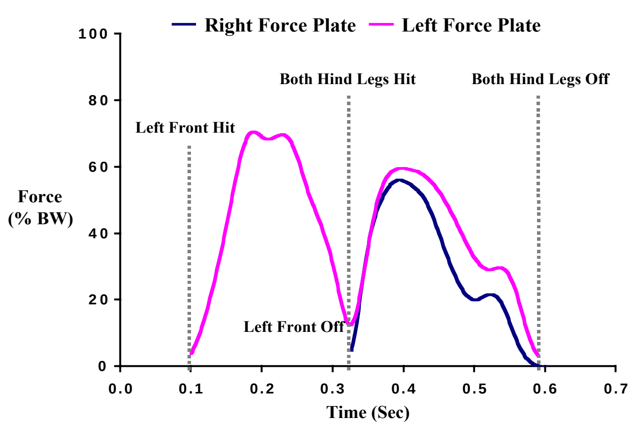

Figure 2. Vertical ground reaction forces during hopping

The mathematical model predicted that approximately 80% of the total load is concentrated on the medial compartment of the knee joint (Table 1). However, due to differences in foot placement, some trials (not shown) exhibit large lateral joint contact forces. This change in kinematics results in a large variation in knee adduction moment, and subsequently the distribution of tibiofemoral joint contact forces.

Table 1. External forces and moments and internal muscle, ligament and joint contact forces. Values are averages of peak values during the stance phase of five hopping trials.

	Mean	SD
Intersegmental Forces (% BW) and Moments (N*mm)		
Anterior Force	2.4	1.1
Posterior Force	5.7	0.3
Axial Force	41.4	8.2
Adduction Moment	429.0	230.4
Flexion Moment	214.3	109.7
Extension Moment	424.8	333.9
Muscle and Ligament Forces (% BW)		
Quadriceps	120.4	94.6
Hamstrings	18.4	9.7
Gastrocnemius	23.5	22.1
Anterior Cruciate Ligament	68.6	55.3
Posterior Cruciate Ligament	30.4	17.0
Tibiofemoral Joint Contact Forces (% BW)		
Medial Joint Contact Force	190.1	81.3
Lateral Joint Contact Force	41.3	34.3

DISCUSSION

Although the rabbit is a commonly used animal model for studies of bone growth and osteoarthritis, knee joint loads during typical activities have not been quantified. This study presents an estimation of tibiofemoral joint contact forces throughout the complete stance phase of hopping, rather than a static analysis of a single point in time.

Similar to normal human gait [5], the dependence on medial compartmental loading for equilibrium is important, and is directly related to the external adduction moment. Furthermore, the relative magnitudes of the intersegmental moments and joint contact forces are similar to those measured in the human during normal walking.

Despite collecting numerous trials over a two-week period, our study is limited by the use of only one rabbit, and consideration of a single gait pattern. Furthermore, our current model, similar to previous models, is limited by the absence of muscular co-contraction. Therefore, our muscle, ligament and joint contact forces represent the minimal contributions required to maintain equilibrium. In spite of these limitations, our current study provides preliminary data upon which qualitative comparisons to both human gait and experimental alterations in joint loading and stability may be made.

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