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Variation in patellofemoral kinematics due to changes in quadriceps loading configuration during in vitro testing ☆

Sami Shalhoub [a], Lorin P. Maletsky [a,b,*]

[a] University of Kansas, Bioengineering Graduate Program, Lawrence, KS, United States
[b] University of Kansas, Department of Mechanical Engineering, Lawrence, KS 66045, United States

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ABSTRACT

This study investigated changes in patellofemoral (PF) kinematics for different loading configurations of the quadriceps muscle: single line of action (SL), physiological-based multiple lines of action (ML), weak vastus medialis (WVM), and weak vastus lateralis (WVL). Fourteen cadaveric knees were flexed from 15° to 120° knee flexion using a loading rig with the ability to load different heads of the quadriceps and hamstring muscles in their anatomical orientation. PF rotation in the sagittal plane) and medial lateral translation were significantly different ($p<0.05$) for SL and ML, with maximum differences of 2.8° and 0.9 mm at 15° and 45° knee flexion, respectively. Compared to the ML, the WVM induced an average lateral shift of 1.5 mm and an abduction rotation of 0.8°, whereas a 0.9 mm medial shift and 0.6° adduction rotation was seen when simulating a WVL. The difference in the sagittal plane resultant force orientation of 26° between SL and ML was the major contributor to the change in PF rotation in the sagittal plane, while the difference in the frontal plane resultant force orientation of both the WVM and WVL from the ML (17° medial and 8° lateral, respectively) were the primary reasons for the change in PF frontal plane rotation and medial lateral translation. The two PF kinematic were significantly different from the ML for WVM and WVL ($p<0.05$). The results suggest that quadriceps muscle loading configuration can have a large influence on PF kinematics during full extension but less in deeper flexion. Therefore, using quadriceps single line loading for simulating activities with low flexion angles might not be sufficient to accurately replicate the physiological condition.

1. Introduction

The quadriceps is the sole muscle group that crosses the patellofemoral (PF) joint, making it the primary contributor of the knee extensor mechanism. PF joint disorders such as lateral patellar compression syndrome and anterior knee pain can occur frequently in the general population. These disorders have a substantial effect on one's ability to perform activities like walking, climbing, kneeling, and other activities of daily living (Fairbank et al., 1984; MacIntyre et al., 2006; Thomee et al., 1999). Multiple factors contribute to PF joint disorders, with the leading cause being muscle weakness of the quadriceps, specifically the vastus medialis (Amis et al., 2006; Ostermeier et al., 2007; Thomee et al., 1999; Zavatsky et al., 2004). In vitro testing has been used to measure PF kinematics, contact area, and the effect of muscle weakness on the knee. In addition, it is common to test total knee replacement (TKR) designs in vitro to evaluate their performance relative to the natural knee and previous prostheses and to ensure a safe transition into clinical application. Therefore it is important that the muscle loading configuration, used in these in vitro testing, replicates the in vivo physiological loading conditions to obtain meaningful PF kinematics that can be related to clinical findings for the natural and prosthetic knee for both normal and pathological conditions. To replicate in vivo physiological loading, one must consider the line of action of each muscle, the percent contribution of these muscles, the change in the muscle force during the simulation, and the total force that needs to be applied. Many dynamic knee simulators are quadriceps driven and only load the rectus femoris (RF) and vastus intermedius (VI) along a single axis parallel to the long axis of the femur (Hashemi et al., 2007; MacWilliams et al., 1999; Maletsky and Hillberry, 2005). The exclusion of the other heads of the quadriceps could affect PF kinematics since the vastus medialis (VM) and the vastus lateralis (VL) insert into the superomedial and superolateral edges of the patella, respectively, creating a sheet that surrounds and stabilizes the patella in the femoral groove (Farahmand et al., 1998a). In

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* Corresponding author at: University of Kansas, Department of Mechanical Engineering, 1530W 15th St, Learned Hall, Room 3138, Lawrence, KS 66045, United States. Tel.: +1 785 864 2985; fax: +1 785 864 5152.
E-mail address: maletsky@ku.edu (L.P. Maletsky).

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addition, the VM and the VL fibers in the sagittal plane have a posterior orientation relative to the axis of the femur which, when loaded, creates a force that drives the patella into contact with the femoral groove (Farahmand et al., 1998a; Wickiewicz et al., 1984). The exclusion of these loads that are not along the axis of the femur, in the single line of action simulation could decrease patella stability and lead to changes in the PF kinematics.

Understanding the effects of different extensor mechanism loading configurations on knee joint kinematics is important to analyzing the in vitro testing results and correlating it to clinical findings. The primary study objective was to compare the PF kinematics using a single line of action quadriceps load with a more physiologically based distributed loading. A secondary objective was to measure the effect on PF kinematics with limited medial and lateral vasti loading during dynamic knee simulations, simulating weakness of these muscle groups.

2. Materials and methods

2.1. Muscle loading rig

A muscle loading rig (MLR) was developed to load the individual hamstrings and quadriceps in their anatomical directions. The MLR consisted of a mounting frame for the knee with the femur rigidly attached to the machine in an inverted position and the tibia free to move (Fig. 1). To maintain the correct physiological orientation of the quadriceps and the hamstrings, eye bolts and pulleys were used to redirect the loading cables. Loading the muscles was accomplished by using either static weights or a motor attached to the muscle tendon. The inverted position of the knee in the MLR results in a deep flexed position when the muscles are unloaded.

2.2. Testing protocol

Fourteen fresh frozen cadaveric knees (age: 67 ± 14 years; BMI: 23.8 ± 4.4) were thawed at room temperature and dissected. The femur and tibia were sectioned 22.5 cm proximal and 17.5 cm distal to the epicondylar axis and potted in aluminum fixtures with bone cement. All the soft tissue within 10 cm of the joint line was left intact. Except for the muscle bodies of the quadriceps and hamstrings, all soft tissue and musculature beyond 10 cm from the joint line were completely removed. Individual heads of the quadriceps (VM, VL, RF, and VI) and the hamstrings (biceps femoris and semimembranosus) were identified, separated, and clamped individually using a piece of cloth and metal clamps. The knees were mounted onto the MLR and the muscle orientations were adjusted based on the orientation reported by Farahmand et al. (1998a). The kinematics of each bone was recorded using an Optotrak 3020 motion capture system (Northern Digital, ON). The Optotrak can measure changes in rotation and translation up to 0.04° and 0.03 mm, respectively (Maletsky et al., 2007). Anatomical landmarks on the femur and patella were digitized to describe the kinematics using an open chain three-axis orthogonal coordinate system adapted to the PF joint (Bull et al., 2002). Patellar medial–lateral translation and rotation in the frontal plane were defined as patellar shift and rotation respectively with lateral rotation considered as the distal pole moving laterally with respect to the proximal pole. Patellar medial–lateral tilt was defined as the rotation about the longitudinal axis of the patella while patellar flexion was defined as the rotation in the sagittal plane (Amis et al., 2006; Bull et al., 2002).

Manual and motor protocols were used to achieve the objectives of this study. The knee was continuously moved through flexion–extension cycles, against the flexion action of the hamstring and gravity. This was achieved by applying an extension moment at the distal end of the tibia for the manual protocol or through the motor attached to RF and VI in the motor protocol. The knee flexion and extension rates were approximately 10° per second for both the motor and the manual simulation. Eight knees were tested using the manual protocol, and eight knees were tested using the motor protocol. Two specimens were tested using both manual and motor protocols. For the manual protocol, a total load of 175 N was applied to the quadriceps based on previous studies for both the single line and multiple line configuration using static weight (Amis et al., 2006; Farahmand et al., 1998b; Sakai et al., 2000). Four different loading configurations were tested:

(1) Normal manual manipulation (NMa): physiological based loading with each head of the quadriceps loaded with a percentage of the total load based on the muscle mean physiological cross sectional area (Farahmand et al., 1998a; Wickiewicz et al., 1984).
(2) Single line manual manipulation (SMa): single line of action loading simulation with the total load applied through the RF and VI only.
(3) Weak vastus medialis (WVM): simulating the extreme case of weakness in the VM while keeping minimal tension on the muscle.
(4) Weak vastus lateralis (WVL): simulating the extreme case of weakness in the VL while keeping minimal tension on the muscle.

The percentage of the total load applied to the individual muscles of the quadriceps for each configuration is presented in Table 1.

For the motor simulations, a Nema 34 stepper motor (Danahar Automation, Wood Dale, IL) was attached to the RF and VI clamp. A 1300 N load cell (Transducer Technique, Temecula, CA) was connected in-line with the motor to measure the load applied by the RF and VI. The knee was flexed between 15° and 120° knee flexion for two different simulations: (1) no loads on the VM and the VL (SMo), and (2) the VM and the VL statically loaded, similarly to the manual manipulation, with 30 N and 75 N, respectively (NMo). Each knee was flexed-extended three times for each of the loading configurations in both protocols. Patellofemoral and tibiofemoral kinematics were recorded at 100 Hz during both flexion and extension. A total load of 175 N was split equally between the semimembranosus and the biceps femoris to simulate approximately 30% of the specimen bodyweight (MacWilliams et al., 1999). The load on the hamstrings was also used to counteract the 175 N applied by the quadriceps and provide a flexion moment during both manual and motor simulations.

2.3. Data analysis

The NMo and the NMa cycles were set as the base PF kinematics for motor and manual simulations. An excursion (deviation from the base cycle kinematics) was calculated for each cycle (SMa, WVM, and WVL for the manual, SMo for the motor) relative to their respective physiological based cycle. The means and standard deviations were calculated for both protocols separately and a one way ANOVA was

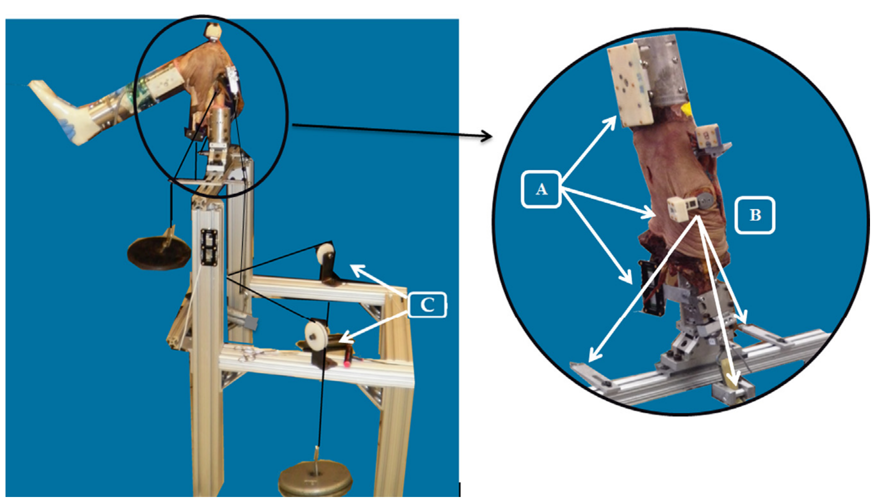

Fig. 1. The muscle loading rig with the femur rigidly attached to the MLR in an inverted position with: (A) motion tracking array, (B) arrows showing the line of action of the individual muscles of the quadriceps (from left to right: VL, RF&VI, and VM), and (C) pulleys to redirect the load of the hamstrings.