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Tibiofemoral joint contact forces and knee kinematics during squatting

Stacey M. Smith [a,*], Robert A. Cockburn [a], Andrea Hemmerich [b], Rebecca M. Li [a], Urs P. Wyss [a]

[a] Department of Mechanical and Materials Engineering, McLaughlin Hall, Queen's University, Kingston, ON K7L 3N6, Canada
[b] Department of Human Biology, University of Cape Town, Cape Town, South Africa

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Abstract

Axial tibiofemoral joint contact forces were non-invasively determined for two high range of motion (high flexion) squatting activities. An electromagnetic motion tracking system and a non-conductive force platform were used to collect kinematic and kinetic data. An innovative scaling method was used to model subject-specific muscle group moment arms. One subject attained a peak axial tibiofemoral joint contact force of 49.7 N/kg during squatting at 149.9° knee flexion. Average joint angles and average axial joint contact forces were calculated for each of the activities in order to facilitate a comparison with stair climbing data. Compared to stair climbing, the maximum average joint contact forces during the squatting activities occurred at significantly higher flexion angles ($p < 0.05$.) The relative simplicity of the method makes it useful for application to large subject groups from diverse regions. The results of this study can be applied to the diagnosis and treatment of pathologies, and to the development of high range of motion (ROM) knee replacements.

Keywords: High flexion; Knee kinematics; Knee kinetics; Tibiofemoral joint; Joint contact forces

1. Introduction

1.1. High flexion activities of daily living and joint disease

Joint disease, such as osteoarthritis, can hinder activities of daily living (ADL), especially high range of motion (ROM) tasks. Published data regarding kinematics and kinetics of high ROM activities is limited [1]. In North America, high ROM activities may include gardening, floor sitting, yoga, and some golf tasks [2]. In Asia and the Middle East, a large knee ROM is required for praying and daily floor level tasks, such as toileting, washing, and family meals [3].

Knowledge of healthy knee kinematics and kinetics is valuable for identifying possible causes of joint disease and developing or improving treatment options, including partial and total knee arthroplasty (TKA). Kinematic and kinetic data are presented in this study for a small, healthy, North American subject group. The data collection and processing techniques can be clinically applied in diagnosing or monitoring joint disease, and for pre- and post-operative evaluation. Wright and Maher [4] stated that "the usefulness of preclinical testing (of implants) depends on how well the test simulates the clinical situation." They identified "knowing the magnitudes and direction of joint forces to simulate a worst case scenario" as a major challenge to designing such preclinical test protocols [4]. In this study, axial tibiofemoral joint contact forces are predicted during full flexion squatting, and can be used for high flexion prosthesis development during finite element analysis or preclinical fatigue and joint simulator testing.

1.2. Tibiofemoral joint contact force

The tibiofemoral joint contact force is the force exerted on the articulating surfaces of the tibia and femur. It includes

* Corresponding author. Tel.: +1 613 533 3060; fax: +1 613 533 6489.
E-mail address: smiths@me.queensu.ca (S.M. Smith).

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the effect of the net joint reaction force and the forces exerted by the muscles crossing the knee joint. Taylor et al. [5] found that while the net reaction forces at the knee were only approximately one times body weight, joint contact forces were several times body weight, emphasizing the importance of the muscle forces in joint loading.

The objective of this study was to non-invasively determine joint contact forces during squatting, using a model based on measured kinematics, anthropometrics, and ground reaction forces, and calculated kinetics. The model was a combination of previously published models [6,7] with new features appropriate to high flexion activities and the equipment used. These high flexion tibiofemoral joint contact forces were compared to those for stair climbing, which requires a smaller ROM than the high ROM activities studied.

The tibiofemoral contact force model used in this study focuses on the axial joint contact force acting on the tibia, which is useful for compressive testing of TKA components. The method, although based on previous literature, has the following advantages and innovative features: it applies an innovative scaling method to determine subject-specific quadriceps and hamstrings moment arm magnitudes over a high range of flexion. The method is non-invasive and uses direct measurements from the subject as much as possible. Therefore, there are few assumptions about the subject having average anthropometric measurements. Both sagittal and frontal plane muscle force contributions are included.

2. Methods

2.1. Subjects

Nine subjects, three male and six female, provided informed consent to participate in this IRB-approved study. The average age, mass, and height of the subject group were 53.9 years (±5.4 years), 75.9 kg (±15.6 kg), and 1.68 m (±0.08 m), respectively. Subjects were Canadian, living a Western lifestyle, and over 40 years of age with no history of joint disease or pain. Subjects completed questionnaires about their ability to perform activities and the frequency with which those activities were performed.

2.2. Equipment and data collection

The set-up involved a six-degree-of-freedom electromagnetic tracking system (Fastrak®; Polhemus, Colchester, VT, USA), a non-conductive force plate (BP400600NC; AMTI, Watertown, MA, USA) and a wooden platform with railing. The protocol described by Hemmerich et al. was followed [3]. The Fastrak® system allowed for the study of a much higher joint ROM than would be permitted using X-ray or MRI equipment. Unlike opto-electric systems, the Fastrak® does not require a receiver-to-emitter line of sight that might be obstructed during high ROM activities. Receivers were securely fixed to the subject's sacrum, right foot, shank and thigh so that they would not interfere with the subject's motion. All activities were performed with the subject's right foot only on the force plate. The wooden platform was built 50 cm high to minimize electromagnetic distortion from the steel-reinforced floor.

With the foot, shank, and thigh receivers fixed to the subject's right leg, a stylus attached to the fourth receiver was used to digitize bony landmarks while the subject was standing. A seated reference position was digitized, in addition to Hemmerich et al.'s protocol [3]. The patellar apex, centre of the posterior aspect lateral femoral condyle, tibial tuberosity, and fibular head were digitized while the subject was seated with the knee positioned at approximately 90° flexion. A flexion angle of 90° was used because it was near mid-range on the cadaver moment arm curves used for scaling, discussed in Section 2.5. These landmarks were used to calculate the angle of the patellar tendon relative to the long axis of the shank, the quadriceps moment arm, and the hamstrings moment arm in the seated position. After digitizing bony landmarks in the seated and standing reference positions, the stylus was removed and the receiver was attached to the sacrum. The protocol continued as described by Hemmerich et al. with the subject performing the two squatting activities [3].

Subjects were asked to perform two different squatting activities as shown in Fig. 1: squatting with heels off the floor (the ''squatting heels up'' activity), and squatting with heels on the floor (the ''squatting heels down'' activity.) As a subject squatted, the centre of gravity remained approximately over the feet. At no time did the subject's knees or shank make contact with the ground. These activities were meant to simulate common ADL, such as tying shoelaces and gardening.

Subjects were asked to lower themselves into position with the aid of gravity, remain in the lowered ''rest position'' for a few seconds, and then raise themselves out of position against gravity. The rest positions are shown in Fig. 1. Subjects could choose to use the railing on the platform for support if they felt unstable during the motion. The subjects were videotaped performing the activities, in order to help with interpretation of results.

2.3. Segment-fixed coordinate systems and kinematics

Segment-fixed coordinate systems (CS) were defined for the foot, shank, thigh, and trunk in order to define floating axis angles [8]. Only the shank and thigh CS are described here since only these axes were used to define knee angles. The origin of the thigh CS was the mid-point of the medial and lateral femoral epicondyles. The direction of the z-axis was defined from the origin to a point 2 cm distal of the midpoint between the symphysis pubis and the A.S.I.S. The frontal plane was defined by the z-axis and the transepicondylar line. The y-axis was defined by a normal to the frontal plane, and the x-axis was defined by the cross product of the y- and z-axes. The origin of the shank CS was the mid-point between the lateral and medial malleoli. The z-axis was directed from this origin to the mid-point between the lateral and medial tibial condyles. The y-axis was defined as the cross product of the z-axis and the line joining the tibial condyles. The x-axis was again defined as the cross product of the y- and z-axes. Three-dimensional knee joint angles were calculated from these segment-fixed axes as described by Hemmerich et al. [3], following the joint coordinate system convention [8].

2.4. Components of the axial tibiofemoral contact force

In each data frame, the axial tibiofemoral joint contact force acting on the tibia was comprised of the axial (distal-proximal) component of the following forces: