Knee Closed-Kinetic-Chain Squat Exercises Generate High Cartilage Contact Stresses and Low Ligament Forces

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INTRODUCTION

Effective non-operative and post-operative managements of knee joint disorders demand appropriate rehabilitation programs to restore joint near-normal function while conditioning quadriceps and hamstrings muscles. Excessive stresses in cartilage/menisci and forces in ligaments should, however, be avoided in order not to exacerbate joint condition especially after an injury or reconstruction. Selection of an optimal exercise program depends on a sound knowledge of joint biomechanics in various exercise configurations. Athletic trainings stand also to benefit from improved understandings of joint response. The open-kinetic-chain (OKC) exercises isolate specific muscle groups for strengthening and evaluation purposes; leg-extension recruits quadriceps whereas leg-flexion activates hamstrings. In contrast, closed-kinetic-chain (CKC) exercises in squat and leg press generate a large reaction force at foot (i.e., weight bearing) and involve multi-joints coordination working on both quadriceps and hamstrings muscles. The OKC and CKC exercises, hence, cause distinct muscle activities, ligament forces and articular contact stresses. In the absence of earlier detailed model studies and in continuation of our OKC simulations, this work aimed to employ a validated 3D knee joint model to compute biomechanics of the entire joint in CKC squats at different flexion angles and femur/tibia orientations with and without load in hands and hamstrings coactivity. Joint response is also compared between OKC and CKC exercises.

METHODS

The 3D nonlinear finite element model consists of bony structures (tibia, femur, and patella), articular cartilage layers, menisci, six principal ligaments (collaterals LCL/MCL, cruciates ACL/PCL, and medial/lateral patellofemoral ligaments), patellar tendon PT, quadriceps muscles (divided into three components; vastus lateralis/rectus femoris-vastus intermidus medialis/vastus medialis obliqus) and hamstrings muscles (divided also into three components; biceps femoris/sartorius-gracilis-semitendinosus/semimembranosus). Magnitude and direction of forces in muscle components are based on literature. For unconstrained boundary conditions, the femur is fixed while the tibia and patella are left free except in flexion that is prescribed. Ligaments are modeled by uniaxial elements with different prestrains and nonlinear properties (no compression). Cartilage layers are isotropic elastic whereas menisci are composite with collagen fibrils in radial/circumferential directions. After the application of ligament pre-strains, the tibia is flexed at an interval of 10° from 20° to 90°. Reaction force of 303.3 N (half of 61.9 kg weight) is applied at foot at a sagittal lever arm generating moments reported in female subjects during squatting (Fig. 1). At each flexion angle, quadriceps forces are then sought that counterbalance these moments. Nonlinear analyses are performed using ABAQUS 6.7 program.

In the reference case a with identical femoral and tibial orientations, vertical reaction force of 303.3 N at foot generates moments increasing from 14.59 Nm at 20° to 59.4 Nm at 90°. Idealized pure moment loading (case b) is also considered. In case c, greater reaction force of 453.3 N (i.e., 300 N in hands) at the same lever arms is applied at 20° and 90°. The role of 10% coactivity in hamstrings (178 N) is investigated in case d at 20° and 50°. Finally at 90° and under the same moments as in case a, tibial and femoral orientations are altered from 45°-45° to either 60°-30° (case e) or to 75°-15° with 400 N load added in hands (case f).

RESULTS

Total force in quadriceps muscles substantially increase with flexion and joint moment reaching peak of 5560 N in case c (Fig. 2). They also increase with loads in hands and hamstrings coactivity. Same trends are computed for PT force where it increases with flexion to 1575 N in case a and 2312 N in case c. The ratio of PT force to quadriceps force diminishes in all cases from ~0.95 to 0.40 as joint flexes from 20° to 90°. The effective lever arm estimated as the ratio of joint moment to PT force diminishes with joint flexion from 51.7 mm to 38.7 mm (case a).

Small ACL forces (<46 N, except in pure moment case b that reaches 141 N at 60°) are computed that disappear at flexions >50°. PCL (<20 N) as well as MCL (<50 N) and LCL (<35 N) forces remain also small. TF contact force increases markedly with flexion from 598 N at 20° to 1689 N at 90° in case a and peak of 2507 N (>4 times body weight) at 90° in case c. Similarly, PF contact forces increase substantially with flexion reaching peak force of 5677 N (>9 times body weight) in case c at 90°. Similar to contact areas, the average/peak TF contact pressures significantly increase with flexion in all cases reaching maximum at 90° of 2.2/10.9 MPa and 2.86/12.1 MPa in cases a and c, respectively. Similarly, average/peak PF contact pressures increase with flexion reaching maximum at 90° of 8.7/14.4 MPa and 11.1/18.99 MPa, respectively in cases a and c (Fig. 3).

DISCUSSION

Predictions are in agreement with results of earlier model and experimental studies. The drop in extensor lever arm with flexion indicates that quadriceps, in contrast to hamstrings, are much more efficient in resisting moments at smaller flexion angles. Estimation of small ACL/PCL forces in various CKC exercises with and without loads in hands advocate the use of squat exercises at all joint angles and external loads in post-ligament injury and reconstruction periods. In contrast, however, large contact stresses, especially at the PF joint, that approach the cartilage failure threshold in compression calls for care in avoiding squats at greater flexion angles, joint moments and load in hands. In comparison and based on our earlier results, use of OKC flexion exercises in post-PCL reconstruction/injury period is supported only at near full extension positions with small resistant forces while use of OKC extension exercises in post-ACL reconstruction/injury periods should be avoided at near full extension and large resistant forces. Current results are helpful in comprehensive evaluation and design of exercise regimens allowing for effective exercise therapies and trainings involving minimal risk to various components.

ACKNOWELEDGEMENT

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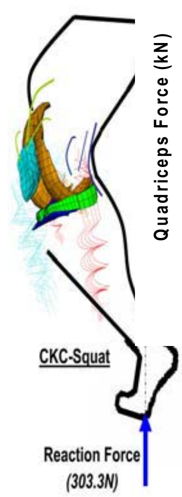

Fig. 1

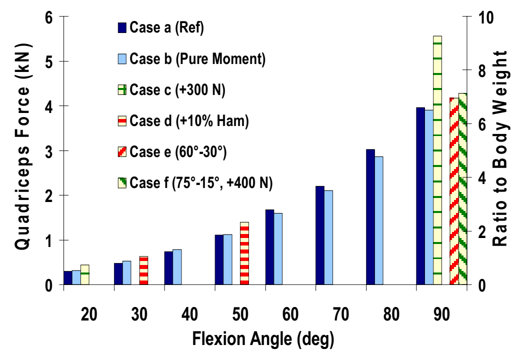

Fig. 2

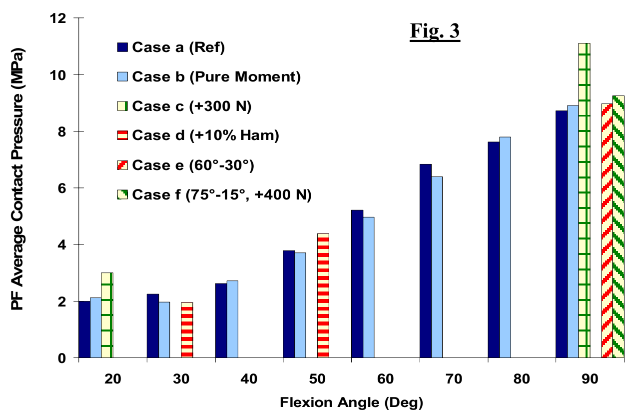

Fig. 3