TIBIAL RESTRAINT INFLUENCES CRUCIATE LIGAMENT FORCES IN THE KNEE JOINT UNDER EXTENSOR/FLEXOR MOMENTS

INTRODUCTION: To counterbalance the moments of quadriceps/hamstrings forces while preserving the joint flexion at a desired level, in vitro investigations usually restrain the tibial A-P translation at a distance away from the joint level. Such constraint, however apart from flexor/extensor moments, introduces artefact A-P shear forces on the joint that could in turn influence joint kinematics and forces in cruciate ligaments. Using a 3D nonlinear finite element model of the entire knee joint, this study aims to investigate the effect of the manner in which the joint is constrained (with or without restraining forces) on joint mechanics and cruciate ligament forces under 205.5N hamstrings and/or 411N quadriceps forces. This study also deals with the effect of tibial restraining location on the risk of injury to cruciate ligaments or their grafts under muscle activations during the knee joint flexion/extension rehabilitation exercises.

METHODS: The finite element model of the knee joint consists of tibia, femur, and patella plus their articular cartilage layers, menisci, six major ligaments, patellar tendon, quadriceps muscle force vectors (3 distinct components; vastus lateralis, rectus femoris-vastus intermedius medialis, vastus medialis obliquus) and hamstrings muscle force vectors (3 distinct components; biceps femoris, semimembranosus, sartorius-gracilis-semimembranosis) (Fig. 1). The relative magnitude/direction of muscle components are based on data in the literature. Ligaments are uniaxial elements with different prestrains and nonlinear properties (no compression). For stable and unconstrained boundary conditions, the femur is fixed while the tibia and patella are left completely free.

Following the application of ligament pre-strains and hamstrings (F\text{bF}=205.5N) and/or quadriceps (F\text{qF}=411N) forces, the tibia is incrementally subjected to rotations from 0° to 90° under constant muscle preloads. Since the joint flexion angle is prescribed, the required joint moment under muscle activation patterns is calculated at each step of the analysis. To investigate the effect of tibial constraint on results, additional cases are studied with the joint constrained by a perpendicular tibia, femur, and patella plus their articular cartilage layers, menisci, six ligaments or their grafts under muscle activations during the knee joint flexion(extension rehabilitation exercises. Proper consideration of these forces (artefact or not) is essential in precise assessment of data accuracy and in subsequent comparison of results of various investigations. Rehabilitation exercises following ACL or PCL reconstructions should also account for the effect of the lever arm on cruciate ligament forces in order to reduce the risk on the ligament grafts at post-operation periods. Near joint placement of the resistance is recommended as it tends to decrease forces in ACL grafts in extension exercises at small flexion angles and in PCL grafts in flexion exercises at larger flexion angles.

DISCUSSION: The manner in which the tibia is constrained at a fixed flexion angle has an important effect on A-P translations and, hence, ACL/PCL forces. This is due to artefact shear forces generated at the tibial restraint location at 20cm or 30cm distal to the joint level (i.e., lever arm) as compared with (reference) cases constrained by a pure moment with no shear force. In isolated quadriceps loading, these artefact forces resulted in posterior tibial translations which significantly diminished ACL forces but increased PCL forces. In contrast, under hamstrings activation, restraining forces reversed direction causing tibial anterior translations that diminished PCL forces while increasing ACL forces. The relative extent of foregoing changes depends on the magnitude of restraining forces that in turn alter as a function of muscle activity/coactivity levels and lever arm. The presence of these shear forces are, however, justified if extension/flexion exercises against a resistant force is considered. Proper consideration of these forces (artefact or not) is essential in precise assessment of data accuracy and in subsequent comparison of results of various investigations. Rehabilitation exercises following ACL or PCL reconstructions should also account for the effect of the lever arm on cruciate ligament forces in order to reduce the risk on the ligament grafts at post-operation periods. Near joint placement of the resistance is recommended as it tends to decrease forces in ACL grafts in extension exercises at small flexion angles and in PCL grafts in flexion exercises at larger flexion angles.

Quadriceps activation alone substantially increased ACL forces (and risk of injury to the ligament or its graft) at smaller flexion angles while decreasing PCL forces at larger flexion angles. Hamstrings muscles, in contrast, diminished ACL forces but increased PCL forces. In contrast, under quadriceps activation alone, ACL forces increased while PCL forces decreased in presence of hamstrings co-activation to 66N and -22N at 0° and 90°, respectively for 0° and 90° joint angles. These forces considerably increased throughout flexion up to 90°. In contrast to ACL force, PCL forces were kept substantially diminished throughout flexion up to 90°. In contrast to ACL force, PCL forces were kept substantially diminished ACL forces but increased PCL forces. In contrast, under hamstrings activation, restraining forces reversed direction causing tibial anterior translations that diminished PCL forces while increasing ACL forces. The relative extent of foregoing changes depends on the magnitude of restraining forces that in turn alter as a function of muscle activity/coactivity levels and lever arm. The presence of these shear forces are, however, justified if extension/flexion exercises against a resistant force is considered. Proper consideration of these forces (artefact or not) is essential in precise assessment of data accuracy and in subsequent comparison of results of various investigations. Rehabilitation exercises following ACL or PCL reconstructions should also account for the effect of the lever arm on cruciate ligament forces in order to reduce the risk on the ligament grafts at post-operation periods. Near joint placement of the resistance is recommended as it tends to decrease forces in ACL grafts in extension exercises at small flexion angles and in PCL grafts in flexion exercises at larger flexion angles.

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RESULTS: At full extension, the anterior tibial translation under isolated F\text{qF}=411N reversed direction to become posterior when F\text{bF}=205.5N was added or acted alone. This yielded large forces in the ACL under F\text{bF} that diminished in presence of F\text{qF} (Fig. 2). The ACL force diminished throughout flexion up to 90°. In contrast to ACL force, PCL force increased under F\text{bF} and throughout flexion (Fig. 3). Tibial restraining forces under F\text{bF} reached 82N and 23N (+ve in posterior direction) when located at 20cm and 56N and 16N when at 30cm, respectively for 0° and 90° joint angles. These forces considerably decreased in presence of hamstrings co-activation to 66N and -22N at 20cm and to 45N and -15N at 30cm, and further to -21N and -45N at 20cm and to -13N and -30N at 30cm when under F\text{bF} alone, respectively for 0° and 90° joint angles. By altering tibial translations, the restraining forces substantially diminished ACL force. On the other hand, they increased PCL force at 90° under F\text{bF} but decreased it under the combined muscle loading and F\text{qF} alone (Figs. 2 and 3).

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