Force Distribution in Femoral Attachment of Anterior Cruciate Ligament During Drawer Test – A Planar Model Analysis

Ahmed Imran, *Member, IAENG*

***Abstract*—Injuries of anterior cruciate ligament of the knee are common, particularly in young athletes. A procedure to restore the joint function involves ligament reconstruction. A significant percentage of the patients report unsatisfactory outcome and inability to return to previous levels of activity. Further complications of the joint and repeated surgeries are also reported. Clinical and experimental studies suggest that a better understanding of the ligament and knowledge of its reconstruction requirements are needed for improved outcome.**

The present study used a planar mathematical model of the knee with intact ligaments and anatomical articular surfaces to analyze contributions of different fiber bundles in the ligament with distinct areas of attachment on the femoral bone in search of appropriate positions of femoral tunnel during ligament reconstruction. Knee motion during 0–120° flexion and an anterior drawer test at different joint positions were simulated.

The model analysis showed that the ACL fibers attached anteriorly on the femoral bone contributed significantly throughout the knee motion and resisted anterior loads on the tibia at all flexion positions, while the fibers attached posteriorly on the femoral bone contributed during 0 – 45° and above 90° flexion. The results agreed with experimental observations and have clinical relevance.

***Index Terms*— Injuries of the Anterior Cruciate Ligament; ACL reconstruction; Double bundle reconstruction of ACL; femoral tunnel position in ACL reconstruction; Knee joint mechanics.**

I. INTRODUCTION

INJURIES of Anterior Cruciate Ligament (ACL) of the knee are common especially among young athletes. The ligament is frequently damaged while performing strenuous activities such as those in sports. Such injuries are often treated with surgical reconstruction of the ligament with an aim to restore joint stability and kinematics as well to contain subsequent long-term risk of complications like osteoarthritic changes, chondral or meniscal damage [1–5]. Though long-term satisfactory outcomes have been reported, about one-third patients remain unsatisfied with difficulty in returning to previous level of activity [1, 5]. One clinical study reported that less than 50% of athletes with ACL reconstruction were able to return to their pre-injury level activity [5]. Interestingly, another clinical study showed that 94% of patients from ligament surgery continued to have knee instability even after a five-year follow-up [6]. This suggests that more understanding of the knee ligaments and reconstruction characteristics are needed in order to improve outcome. The anterior and posterior cruciate ligaments or ACL and PCL, respectively, are considered as the main stabilizers of the joint in the sagittal plane [7–10]. While the ACL restricts anterior translation, the PCL restricts posterior translation of the lower bone, or tibia, relative to the upper bone, or femur.

Common understanding of the ACL through anatomic and histologic studies suggests two functional bundles of ligament fibers with distinct attachments on the femoral and tibial bones [11–14]. Accordingly, recent surgical techniques of ACL reconstruction emphasize importance of double bundle approach to restore original anatomy of the ligament. However, studies of the reconstruction outcome have shown that sometimes such joints produced abnormal instability and kinematics [2–5].

A comparative clinical study with 10-year follow-up results involving 90 patients with about a third of them having double bundle ACL reconstruction experienced significantly fewer graft failures [2]. The study also reported that 66% patients developed osteoarthritis of the knee with most sever changes in the patients who had the longest delay from the primary injury to ACL reconstruction and in the patients who underwent partial meniscal resection at the time of ACL reconstruction [2]. Other clinical studies further suggest that exact attachment of femoral site of the reconstructed graft critically influences the surgical outcome [3, 4, 11]. In a radiographic evaluation of femoral insertions of anterormedial (AM) and posterolateral (PL) bundles of ACL, Steckel *et al* [13] concluded that the centers of the AM and PL bundles become horizontally aligned when the knee is flexed beyond 90°. The investigators, hence, suggested that the degree of knee flexion should be taken into account for femoral tunnel placement and for describing tunnel positioning

Kawaguchi *et al* [11] used cadaveric knees to analyze the role of fibers in the femoral attachment of the anterior cruciate ligament in resisting tibial displacement. From several areas of attachment explored, they found that the anteromedial and posterolateral bundles of the ACL attached to the femur provided major contributions towards resisting tibial displacement.

Further, studies involving patterns of fiber strains in bundles of ACL fibers suggest that the anteromedial bundle

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A. Imran is with the Department of Biomedical Engineering, Ajman University, Ajman, U.A.E. (phone: +971-50-2850131; fax: 971-6-7438888; e-mail: a.imran@ajman.ac.ae or ai_imran@yahoo.com).

of ACL is the primary restraint against anterior tibial translation and the posterolateral bundle provides contributions near full extension or in high flexion [14–16].

The aim of the present study is to analyze distribution of forces in the femoral attachment of the ACL during an anterior drawer test conducted at different flexion positions of the joint. For this purpose, a planar mathematical model of the knee is used with intact ligaments that are represented as bundles of elastic fibers. Joint motion and anterior drawer test are simulated at several flexion positions.

II. Methods

A planar mathematical model of the knee was used that allowed simulation of the knee kinematics and anterior drawer test in the sagittal plane. Anatomical shapes of tibial and femoral bones, shapes and positions of articular surfaces, points of attachment of the joint ligaments and material properties of ligaments utilized in the model were based on previous anatomical studies taken from literature [17–24].

Four major ligaments of the knee, namely, anterior and posterior cruciate ligaments and lateral and medial collateral ligaments were represent as bundles of elastic fibers that developed resistance when stretched and buckled when slack. It may be noted here that based on anatomical studies [8, 11], the lateral and medial collateral ligaments were assumed to have insignificant contribution towards resisting anterior-posterior relative movements of the bones in the sagittal plane.

2.1. Kinematics of the knee during flexion

The knee joint motion was simulated in the sagittal plane during 0–120^o flexion. It is shown that in the absence of muscle forces or external loads, the bones rotate and slide relative to each other such that selected fibers in the cruciate ligaments maintain nearly fixed length that is neither stretched nor slack [22]. This feature was used in the model to determine the joint kinematics in the unloaded state [23]. As a consequence of relative rotations and translations of the bones during motion, the attachments of the ligaments also changed their relative positions accordingly. The model of the intact knee with ligaments and joint kinematics were developed based on previously reported studies [17–25].

2.2. Simulated anterior drawer test

Additional relative translations of the bones with all attachment points were superimposed at selected flexion positions in order to simulate anterior drawer test that requires translation of the tibia anterior to the femur while the joint angle is maintained [26–29]. Such tests are conducted to estimate integrity of the ligaments. For example, an increased displacement in the anterior direction, normally compared with the displacement of contralateral knee, may indicate damage to the ACL [26].

During a simulated anterior drawer tests, the joint angle was held fixed with a flexing moment and an anterior force applied on the tibia translated the bone anteriorly resulting in stretched fibers of the ACL that resisted the movement through posteriorly directed forces in the stretched fibers.

Table 1: Comparison between model calculations and experimental measurements [12]. ATT due to 90N anterior laxity test.

Flexion angle (Degrees)	ATT (mm)	
	Model Calculations	Experiment [12] Mean (Std. Dev.)
0	2.6	1.8 (1.3)
30	5	4.0 (1.3)
60	5	3.8 (2.2)
90	4	3.0 (1.4)
110	3.7	2.9 (1.7)

The model allowed application of a fixed magnitude of anterior force, for example, 90N and determine the resulting anterior tibial translation (ATT) with forces developed in different fiber bundles of the ACL. Alternatively, the model also allowed application of a predetermined ATT with calculations of resulting forces in different fiber bundles of the ACL.

2.3. Distribution of forces in different areas of the ligament attachments

The model ACL was divided into two distinct bundles of fibers representing anteromedial and posterolateral bundles as reported in the literature [7, 8, 9, 11]. Each bundle of the ligament composed of several fibers that allowed effect of sequentially stretching or slackening during motion or due to the tibial translation relative to femur. Material properties for each bundle were taken from literature [20].

During a simulated anterior drawer test, the tibia was translated 6 mm anterior to its position achieved at each flexion angle during motion. As a result of the applied external force, the tibia translated anterior or posterior to its resting position recruiting ligament fibers progressively until the external force was balanced by the forces generated in the stretched segments of the involved ligaments. Corresponding to the altered positions, posterior force developed in each of the anterior and posterior bundles was calculated at each selected flexion angle.

III. Results and Analysis

3.1. Simulated anterior drawer test

Table 1 gives values of ATT resulting from 90N anterior force applied on the tibia for different flexion positions of the joint. Model calculations are compared with experimental measurements on 14 cadaver knees shown as mean values with standard deviation as reported by Kondo *et al* [12].

The model calculations show trends similar to those from experiment. ATT was minimum at full extension or 0^o flexion and high at 30^o and 60^o. The values of ATT decreased in high flexion at 90^o and 110^o.

Possible explanation for these observations is as follows: two main causes that contribute to this pattern of ATT over the flexion range are variations in slackness and orientation of the ACL fibers. Near extension, the fibers are less slack and more ready to stretch but oriented more perpendicular to the anterior direction resulting in less ATT when 90N force

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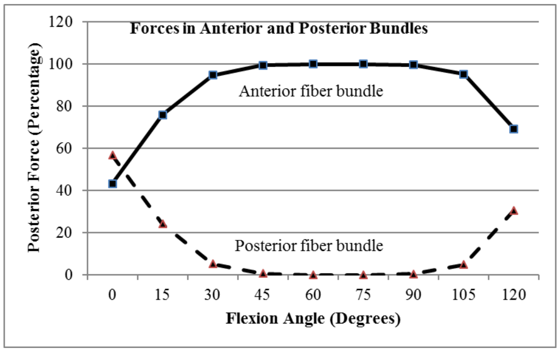

Fig. 1: Contributions of the anterior and posterior bundles of the ACL are shown as percentage of total force resulting from 6 mm ATT during the simulated test over 0–120^o flexion.

is applied. In comparison, the fibers become slack in the mid flexion range and application of anterior forces translates them anteriorly, thus, stretching the ligament fibers sequentially that helps in developing progressive resistance in the ligament.

Finally, in high flexion, the ligament fibers are oriented with reduced inclination with anteroposterior direction, thus, providing a larger posterior component to balance the external anterior force.

3.2. Distribution of forces in anterior and posterior bundles of the ACL

Figure 1 shows posterior forces developed in the anterior and posterior bundles of the ACL fibers given as a percentage of total external force applied to translate the tibia 6 mm anterior to the femur at different flexion positions during 0–120^o range.

At extension, or 0^o degree flexion, both the fiber bundles contributed significantly in resisting the external force. As the flexion angle increased, contribution of the posterior bundle decreased sharply till about 45^o. In the mid flexion range the external force was fully resisted by the anterior bundle of the ACL. Again, for angles greater than 90^o, contribution of the posterior bundle increased.

These patterns of contributions due to anterior and posterior fiber bundles are supported by experimental observations from literature. Kawagachi *et al* [11] studied 8 cadaver knees to analyse load bearing function of fibers in the femoral attachment of the ACL in resisting tibial displacement. Femoral attachment of the ACL was divided into several areas and the fibers were cut sequentially and resulting changes in translating force were measured corresponding to 6 mm ATT or corresponding to internal or external rotations.

The measurements suggested that the anteromedial bundle of the ACL provided 66% to 84% of the total resistance during 0^o to 90^o flexion, while the posterolateral bundle contributed nearly 16% to 9% resistance in this flexion range. The torques required for internal or external rotation were not affected significantly due to the cutting of the ACL fibers, confirming that the main function of the ACL is in resisting ATT.

Calculations based on the joint model corroborate the experimental observations in the literature and emphasize the clinical relevance of appropriate tunnel positioning in ACL reconstruction such that the selected femoral areas have significance on load bearing. Further, as anteromedial bundle of the ACL is also associated with maintaining near isometry during flexion [7, 8, 9, 11], this position is affected less due stretching or slackening effects during the joint motion

IV. Conclusion

The model calculations showed general agreement with experiments on cadaver knees reported in separate studies in relation with patterns of anterior tibial translations and contributions of anteromedial and posterolateral bundles of ACL with distinct attachments on bones.

The analysis suggests that resistance in the ACL fibers is influenced by flexion position and anterior tibial translation. This is because of altered positions and orientations of the ACL fibers due to changes in flexion angle or tibial translation.

Anterior and posterior bundles of the ACL show significantly different patterns of resistance depending on flexion angle and tibial translation. The anterior bundle resisted anterior forces on the tibia at all positions, while the posterior bundle stretched mainly near extension or in high flexion positions.

V. Clinical Relevance

Position of attachment of the ACL graft during the ligament reconstruction critically determines the surgical outcome and ability of the patient to return to earlier levels of activity. The present analysis suggests that anteromedial bundles of the ACL in the intact knee contribute significantly towards resisting anterior forces on the tibia.
Further, analyses suggest that the intact ACL allows more translation in the mid flexion range than near extension or in high flexion, suggesting that rehabilitation exercises or activities involving extreme positions of the joint may prove to be more demanding on the reconstructed graft. The analysis has relevance to ACL-reconstruction and ACL rehabilitation

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