Analyzing the Anterior Knee Laxity During Passive Flexion

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***Abstract*—Anterior-posterior knee laxity in the sagittal plane indicates the functional state of cruciate ligaments. Particularly, the anterior cruciate ligament or ACL is damaged frequently during strenuous activities like in sports. Following injury and treatment, not only a significant percentage of patients are not able to return to their pre-injury level activity, but also they continue to have knee related complications in medium to long term period. Therefore, there is a need for better understanding of the knee. In the present study, anterior laxity of the knee that is related to the function of the ACL, is analyzed during passive flexion of the joint.**

The knee was modelled in the sagittal plane using anatomical data and material properties to represent the joint structures mathematically and simulate the joint motion during 0–120^o flexion while no muscle force or external load was applied. The ACL was represented as bundles of non-linear elastic fibers. A laxity test with 130N anteriorly directed external force on the tibia was simulated at several flexion angles.

The results from model calculations showed agreement with experimental observations from literature. 130N anterior force translated the tibia anterior to the femur non-linearly throughout the flexion range. Due to the applied force, fibers of the ACL slackened or stretched differently depending on their location of insertion as well as on flexion angle. For example, the most anterior fiber stretched at all flexion positions while the most posterior fiber stretched at low or high flexion. Anterior bundle of the ACL contributed significantly in resisting the external force while the posterior bundle contributed mainly near extension or in high flexion. The analysis has relevance to ACL-reconstruction and ACL rehabilitation.

***Index Terms*— knee biomechanics, anterior cruciate ligament injury, ACL reconstruction, ACL rehabilitation, knee laxity.**

I. Introduction

ANTERIOR – Posterior laxity of the knee in the sagittal plane is considered as an indicator of integrity of the cruciate ligaments. These ligaments are considered as the main stabilizers of the joint in the sagittal plane [1–4]. Anterior cruciate ligament (ACL) restricts anterior translation and posterior cruciate ligament (PCL) restricts posterior translation of the lower bone, or tibia, relative to the upper bone, or femur. Passive laxity tests in the absence of muscle forces measure relative translations of the bones at fixed flexion positions of the joint [5]. Such tests are conducted to estimate integrity of the ligaments. For example, an increased laxity in the anterior direction, normally compared with the laxity of contralateral knee, may indicate damage to the ACL.

Contributions of the knee ligaments in stabilizing the intact or replaced joint have been studied using *in vitro* experiments on cadaver knees [1–3, 6] or using mathematical modelling [7]. Also, investigators have analyzed patterns of geometric changes in the ligament fiber bundles during flexion [2, 3, 8, 9]. The ACL shows a complex functional behavior mainly resulting from variations in geometry and in material properties of different fiber bundles. Such changes have influence on the knee joint mechanics [1–4, 6–10].

Clinical experience suggests that the ACL is frequently damaged while performing strenuous activities such as in sports. Recent literature suggests 100000–200000 sports-related ACL injuries per year in the USA alone [11]. Further, Arden *et al* [12] reported that less than 50% of athletes with ACL reconstruction were able to return to their pre-injury level activity. Interestingly, another clinical study showed that 94% of patients from ligament surgery continued to have knee instability even after a five-year follow-up [13]. This suggests that more understanding of the knee ligaments is needed in order to improve outcome.

Therefore, more investigations are needed in order to understand the role of ACL in knee mechanics as well as in order to understand the mechanics of ACL injury. Further, there is a need to determine appropriate requirements for ligament reconstruction and rehabilitation.

The purpose of the present study is to analyze the passive anterior knee laxity during flexion motion of the joint in terms of strains in various fibers of the ACL and in terms of contributions of selected fiber bundles within the ligament.

II. Methods

A mathematical model of the knee in sagittal plane was used with the cruciate ligaments represented as non-linear elastic fibers, similar to those reported in reference [7]. Collateral ligaments of the knee were not considered in this study as their contribution towards anterior-posterior stability is minimal [14]. Passive motion of the knee was defined in the absence of muscle forces or external loads such that selected fibers in the cruciate ligaments maintained nearly constant

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lengths during 0–120° flexion [7, 15, 16]. An anterior laxity test, similar to Lachman test or Drawer test [5], was simulated during flexion at 15° interval. In the simulation, a known anterior force (130N) was applied on the tibia while maintaining the flexion angle fixed. As a result of the applied force, the tibia translated anterior to the femur and stretched the ACL. The magnitude of translation gave the anterior laxity at that flexion angle. Anatomical parameters and material properties of the ligaments were estimated from the literature [15–19]. The model calculations for the anterior laxity test were compared with results from similar experiments on cadaver knees available in literature[6]. Further, ACL is shown to have two distinct functional bundles of fibers, classified as antero-medial and postero-lateral bundles [2, 10, 19]. Accordingly, the model analysis in the sagittal plane was performed on two sets of ligament fibers, namely, anterior and posterior fiber bundles.

III. Results

Table 1 gives values of anterior translation resulting from 130N anterior force applied on the tibia during 0–120° flexion at 15° interval. Model calculations are compared with experimental measurements on cadaver knees [6].

Figure 1 gives model calculations for strains in the anterior, middle and posterior fibers of the ACL resulting from 130 N anterior laxity test during 0–120° flexion.

Figure 2 gives model calculations for percent contributions from the anterior and posterior bundles of the ACL fibers resulting from 130N anterior laxity test during 0–120° flexion.

IV. Analysis

Comparison with experiment:

From table 1, the model results for simulated test with 130N anterior force on tibia show values of tibial translations very similar to those reported by Lo *et al* [6] from *in vitro* experiments conducted on 6 cadaver knees. At each flexion position, the model calculations for tibial translation are close to the experimental mean values and are within the reported standard deviation. The tibial translation or the anterior laxity first increased from 0 to 45° flexion and then decreased non-linearly in higher flexion.

Strains in the ligament fibers:

Figure 1 shows model calculations for strains in the anterior, middle and posterior fibers of the ACL resulting from anterior tibial translation due to 130 N anterior force on the tibia. The anterior fiber stretched at all flexion positions while the intermediate fiber stretched at 0, 15 and 120° and the posterior fiber stretched only at 0 and 120°. As shown, the intermediate and posterior fibers remained slack for most of the flexion range, suggesting their limited contribution to resisting the 130 N anterior force. It may be important to point out the observation that at 0° flexion the calculated strain was highest for the posterior fiber and lowest for the anterior fiber, while at 120°, the calculated strain was highest for the anterior fiber and lowest for the middle fiber.

Table 1. Comparison between model calculations and experimental measurements (extracted from Lo *et al*. [6]). Tibial translation due to 130N anterior laxity test is given for different flexion positions of the joint.

Flexion angle (Degrees)	Tibial Translation (mm)	
	Model Calculations	Experiment [reference 6] Mean (Std. Dev.)
0	3.7	4.1 (0.6)
15	5.7	6.4 (1.3)
30	6.4	7.5 (1.8)
45	6.5	7.9 (2.2)
60	6.3	7.4 (2.2)
75	6.1	6.5 (2.1)
90	5.8	6.2 (1.9)
105	5.4	--
120	4.5	--

Lengths of most of the ligament fibers are shown to change significantly during flexion [8, 9, 20]. All ligament fibers, except for the anterior one, remained slack for most of the flexion range during passive motion. Anterior translation of the tibia reduced slackness and stretched anterior and intermediate fibers for most of the flexion range. These patterns of fiber length changes or of variations in fiber strains appear due to relative translations of the tibial and femoral bones as well as due to rotations of areas of fiber attachments on the femur.

Contributions of anterior and posterior bundles of the ACL:

As shown by figure 2, in order to resist 130N anterior force on the tibia, anterior bundle of the ACL provided more than 90% contribution for most of the flexion positions. At 0, 15 and 120° flexion, the posterior bundle contributed, respectively, 55%, 21% and 14%. At all other flexion positions, contribution from the posterior bundle remained less than 10%. These patterns agree with anatomical observations suggesting that the anteromedial bundle of ACL is the primary restraint against anterior tibial translation and the posterolateral bundle provides contributions near full extension [18].

V. Conclusion

Model calculations during a simulated knee laxity test showed reasonable agreement with experimental measurements from literature. The analysis suggests that during flexion motion of the knee, anterior laxity is significantly influenced by positions and orientations of the ACL fibers. Anterior and posterior bundles of the ACL provide significantly different contributions towards resisting anterior forces on the tibia during knee motion. The contribution of each bundle depends on flexion angle. The anterior bundle resists forces at all flexion positions, while the posterior bundle resists forces mainly near extension or in high flexion. The analysis has relevance to ACL-reconstruction and ACL rehabilitation.

ISBN: 978-988-14047-0-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

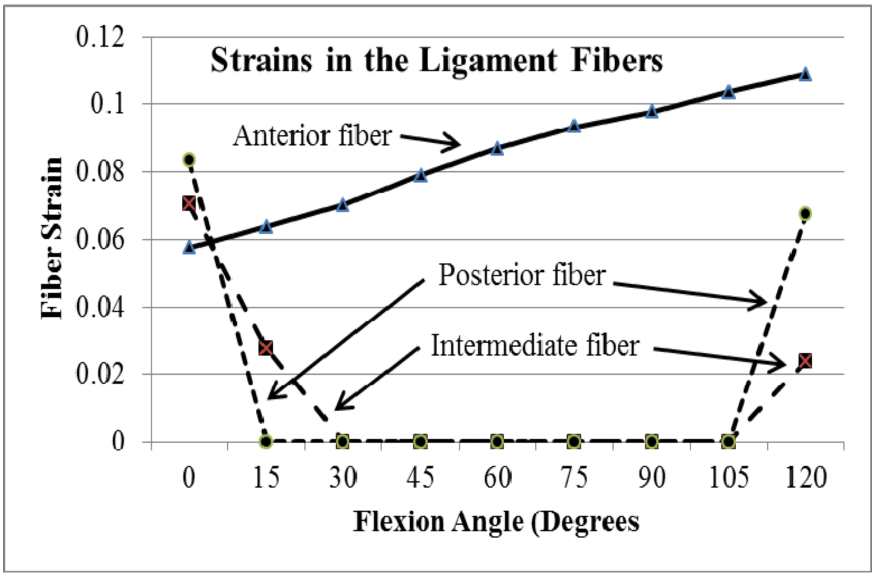

Fig. 1. Strains in the anterior, middle and posterior fibers of the ACL as a result of 130 N anterior laxity test during 0–120º flexion.

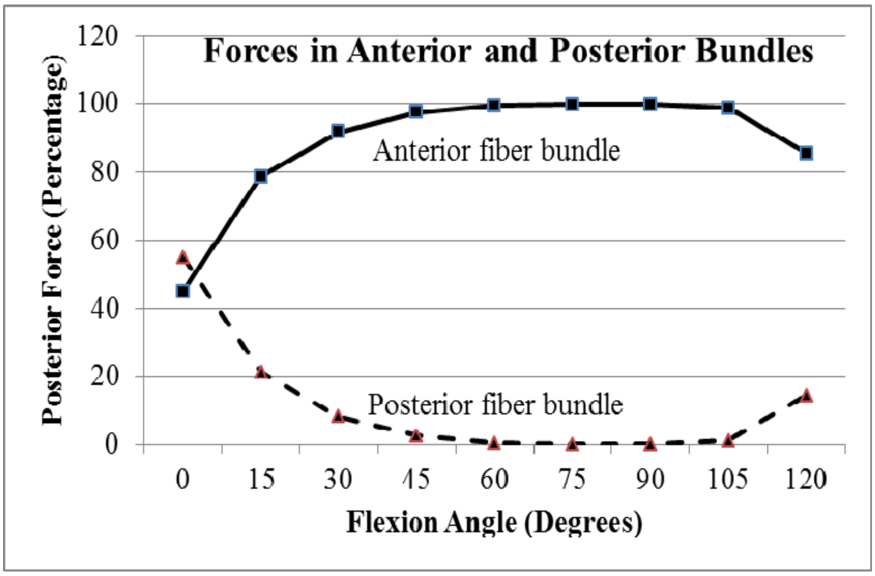

Fig. 2. Contributions of the anterior and posterior bundles of the ACL are shown as percentage of total posterior resisting force in the ligament resulting from 130N anterior laxity test simulated during 0–120º flexion.

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ISBN: 978-988-14047-0-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

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