Relating Knee Laxity with Strain in the Anterior Cruciate Ligament

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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. Therefore, there is a need for better understanding of the knee. In the present study, anterior laxity of the knee resulting from anterior tibial translation is related to strain developed in the fibres of the ACL while the joint is flexed.**

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. 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. For selected values of anterior tibial translation, strain in different fibres of the ACL was calculated.

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. Fibres of the ACL slackened or stretched differently depending on their relative insertions that altered due to changes in flexion angle and tibial translation. The anterior fibre showed increased levels of strain with flexion for each value of tibial translation. The intermediate and posterior fibre stretched at low and high flexion positions depending on the applied tibial translation and flexion angle.

Anterior bundle of the ACL stretched increasingly with flexion and with anterior tibial translation. The posterior bundle stretched 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, ACL strain.**

I. Introduction

CLINICAL experience suggests that the anterior cruciate ligament (ACL) of the knee is frequently damaged while performing strenuous activities such as in sports. There are an estimated 200,000 injuries related to the ACL annually in the United States alone, over half of which result in a complete ACL rupture [1]. Other studies in the literature suggests 100000–200000 sports-related ACL injuries per year in the USA alone [2]. Further, Arden *et al* [3] 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 [4]. This suggests that more understanding of the knee ligaments is 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 [5–8]. While the ACL restricts anterior translation, the 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 [9]. 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 [5–7, 10] or using mathematical modelling [11]. Also, investigators have analyzed patterns of geometric changes in the ligament fibre bundles during flexion [6, 7, 12, 13]. The ACL shows a complex functional behavior mainly resulting from variations in geometry and in material properties of different fibre bundles. Such changes have influence on the knee joint mechanics [5–8, 10–14].

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 strain in different fibres of the ACL resulting from altered anterior – posterior positions of the knee applied passively at several flexion positions of the joint.

II. Methods

A mathematical model of the knee in sagittal plane was used similar to those reported in reference [11]. A brief description of the model is as follows. The cruciate ligaments were represented as non-linear elastic fibers. Collateral ligaments of the knee were not considered as their

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contribution towards anterior-posterior stability is minimal [15]. Passive motion of the knee was defined in the absence of muscle forces or external loads such that selected fibres in the cruciate ligaments maintained nearly constant lengths during 0–120^o flexion [11, 16, 17]. An anterior laxity test, similar to Lachman test or Drawer test [9], was simulated during flexion at 15^o 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 [16–20]. The model calculations for the anterior laxity test were compared with results from similar experiments on cadaver knees available in literature [10]. The comparison helped in validating the model calculations with independent experiment.

For further analysis of how the ACL strains varied with tibial translation, anterior tibial translation (ATT) of 3.4, 4 and 5 mm were applied on the model knee and corresponding strains in selected fibres of the ACL were calculated for each flexion position of the knee.

III. Results

Table 1 gives values of anterior translation resulting from 130N anterior force applied on the tibia during 0–120^o flexion at 15^o interval. Model calculations are compared with experimental measurements on cadaver knees [10].

Figure 1 gives model calculations during 0–120^o flexion for strains in the anterior (a), intermediate (b) and posterior (c) fibres of the ACL as ATT of 3.4, 4 and 5 mm were applied.

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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* [10] 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^o flexion and then decreased non-linearly in higher flexion.

Strains in the ligament fibers:

Fig. 1 shows model calculations for strains in the anterior, middle and posterior fibres of the ACL resulting from anterior tibial translation during flexion. The anterior fibre showed increased levels of strain with flexion for each applied ATT. The intermediate fibre stretched at low and high flexion angles depending on the applied ATT. The posterior fibre stretched only at 0 and 120^o for any value of ATT. As shown, the intermediate and posterior fibres remained slack for most of the flexion range, suggesting their limited contribution in the mid-flexion range.

Table 1. Comparison between model calculations and experimental measurements (extracted from Lo *et al*. [10]). 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 10] 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	--

All the ligament fibres stretched at 0 and 120^o flexion for all values of ATT except that the intermediate fibre remained slack at 120^o with ATT =3.4 mm. Further, Fig. 1 (b) and (c) also suggest that near the extremes of motion, the strain developed in the posterior fibre was more than that in the intermediate fibre.

Lengths of most of the ligament fibres are shown to change significantly during flexion [12, 13, 21]. Anterior translation of the tibia stretched anterior fibres for all flexion positions for any value of applied ATT. The intermediate and posterior fibres showed stretch or slackness depending on the applied ATT as well as the flexion position of the joint. These patterns of fibre strains appear due to relative translations of the tibial and femoral bones as well as due to rotations of areas of fibre attachments on the femur.

Strains in anterior and posterior bundles of the ACL:

These patterns of fibre strains show general agreement 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 [19].

V. Conclusion

Model calculations during a simulated knee laxity test showed reasonable agreement with experimental measurements from literature. The analysis suggests that strain in the ACL fibres is influenced by flexion position and anterior tibial translation, which is used as a measure of anterior knee laxity. 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 strain depending on flexion angle and tibial translation. The anterior bundle stretched at all positions, while the posterior bundle stretched mainly near extension or in high flexion. The analysis has relevance to ACL-reconstruction and ACL rehabilitation.

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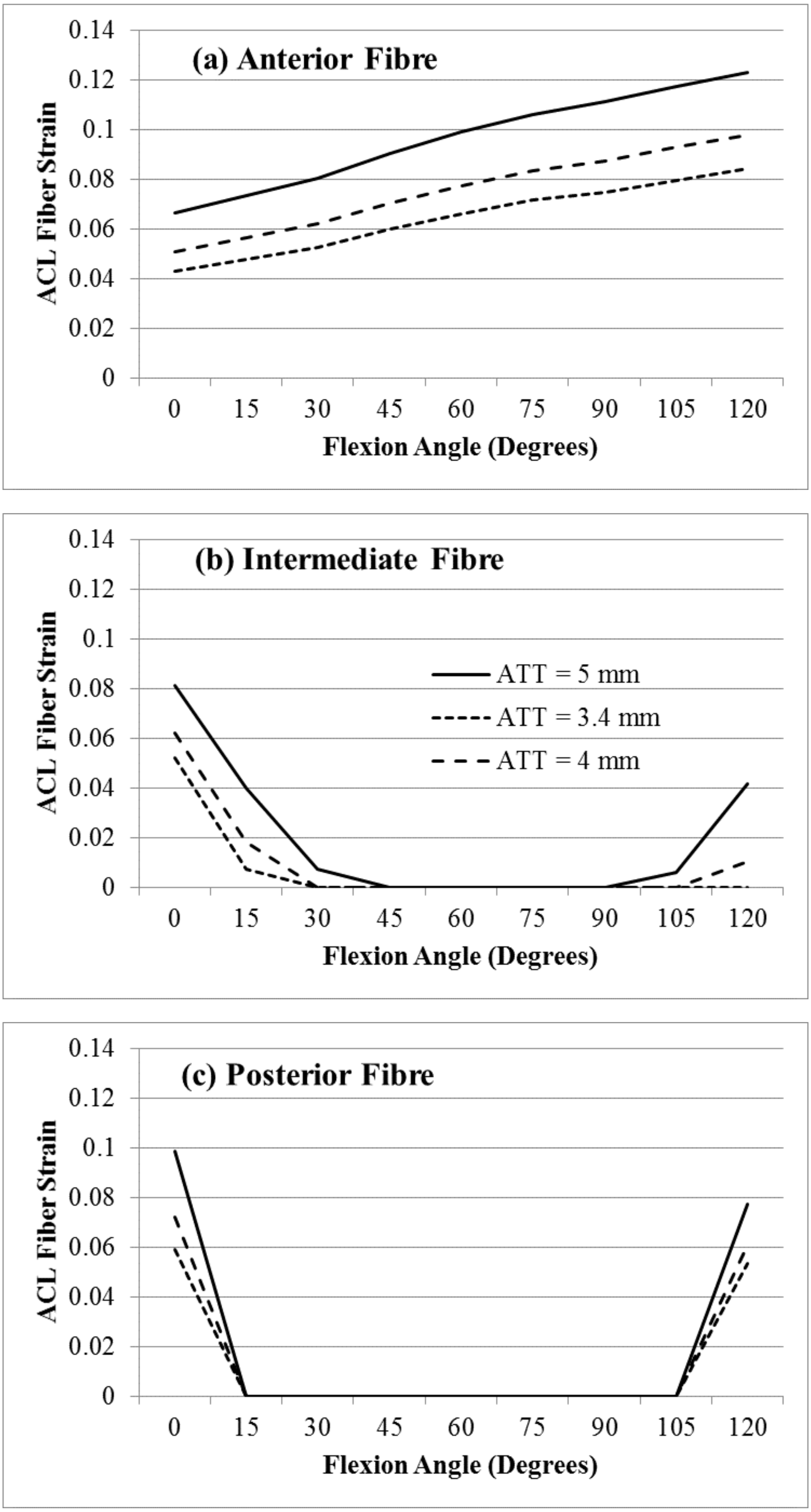

Fig. 1. Strain in the (a) anterior, (b) intermediate and (c) posterior fibres of the ACL resulting , respectively,from ATT 3.4, 4, and 5mm during 0–120^o flexion.

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