

Investigation of Anterior Cruciate Ligament of the Knee with Relevance to Surgical Reconstruction—A Planar Mathematical Analysis



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Abstract Anterior Cruciate Ligament of the knee is injured quite often while performing strenuous activities like in sports. Due to poor healing characteristics, surgical reconstruction of the ligament is used to restore the joint function. However, many significant percentage of the patients are unable to return to their pre-injury levels of activity. In addition, more complications of the joint can result in repeated surgeries. Several clinical and experimental reports suggest the need for further investigations in order to gain insight in the behavior of the reconstructed ligament and related outcome. The present study used mathematical modelling to simulate the knee function in the sagittal plane when the ligaments are intact. The ligaments were separated into fiber bundles similar to those reported in the literature. Such simulations could be used to investigate effects of different tunnel positions during the ligament reconstruction. Knee motion during 0° – 120° flexion and an anterior laxity test at different joint positions were simulated. The outcome of the model simulations suggest that anterior fibers of the ligament contribute significantly throughout the knee flexion in resisting anterior forces on the tibia. In comparison, the posterior fibers contribute in near extremes of motion only. The results of model simulations corroborated with experimental observations from literature and have clinical relevance.

Keywords ACL injuries · ACL mechanics · Double bundle ACL reconstruction · Femoral tunnel in ACL reconstruction · Knee joint mechanics · Reconstruction of ACL

1 Introduction

Anterior Cruciate Ligament (ACL) of the knee is injured quite often while performing strenuous activities like in sports. This is more common in young athletes. Treatment of such injuries often involves surgical reconstruction of the ligament with the goal

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S.-I. Ao et al. (eds.), *Transactions on Engineering Technologies*,

https://doi.org/10.1007/978-981-15-8273-8_4

of restoring stability and kinematics of the joint. Another goal is to restrict further long-term risks of complications like osteoarthritic changes, chondral or meniscal damage that often occur subsequent to the ligament injury [1–5]. Clinical reports on long-term outcomes of treatment give somewhat satisfactory results, however, a significant number of patients, about one-third, still remain problematic and report complications with difficulty in returning to their earlier level of activity [1, 5]. The reported outcome shows a wide variety of outcomes. For example, one study recorded less than 50% cases of athletes who were treated with reconstruction returned to their activities of pre-injury level [5]. In contrast, another clinical report recorded that 94% of patients from the surgery even after five years of follow-up continued to report knee instability [6]. Such observations suggest that there is a need for further investigations in order to gain insight in the behavior of the reconstructed ligament and related outcome.

The two cruciate ligaments, namely, anterior cruciate ligament or ACL and posterior cruciate ligaments or PCL are considered to be the main stabilizers of the knee joint in the sagittal plane [7–10]. ACL provides the main restraint to anterior movement of the lower tibial bone relative to the upper femoral bone. PCL provides the main restraint to posterior movement of the tibia relative to the femur.

Anatomical and histological studies of the ACL have classified the ligament into two distinct functional bundles of fibers with separate areas of clearly marked insertions on the femur and tibia [11–17]. These observations follow two approaches for surgical reconstruction—one treating the whole ligament as a single bundle while the other treating the ligaments as a combination of two distinct bundles [11–17].

Recent surgical approaches of reconstruction have given importance to the two bundles of fibers and have accordingly tried to restore the ligament with its original anatomy. However, surgical reconstruction with two bundles has also sometimes resulted in unexpected outcome where the joint produced abnormal instability and kinematics [2–5].

A clinical study of 90 patients with a 10-year follow-up showed fewer graft failures [2]. About one third of this group of patients had double bundle reconstruction of the ACL. The study also reported that 66% patients developed osteoarthritis of the knee with most severe 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, 14]. Steckel et al. [16] used radiographs to evaluate anteromedial (AM) and posterolateral (PL) bundles of the ACL. The researchers observed that beyond 90° flexion, centers of these fiber bundles become more horizontal. 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. [14] analyzed the role of ACL fibers in resisting tibial displacement in cadaver knees. They reported major role for the AM and PL bundles of ACL in resisting anterior tibial displacement relative to femur.

In addition, other studies analyzed strains developed in the fibers of the ACL. Observations from such studies also support distinct role for the ACL fibers. Again, the AM bundle was found to be the primary restraint for anterior translation of tibia relative to femur. Further, the PL bundle bundle was found to provide contributions near the extremes of joint motion in the sagittal plane [17–19].

The aim of the present work is to study forces in distinct bundles of the ACL during a simulated laxity test which is similar to an anterior drawer test conducted at a fixed position of the joint. For this purpose, a sagittal plane mathematical model of the knee is used. The model ligaments were formed with bundles of elastic fibers having distinct insertions on their respective bones. Joint motion and the laxity test are simulated at several flexion positions of the joint.

2 Methods

Quantitative analysis of the ACL function required a model of the knee to simulate the joint kinematics and a laxity test at several flexion positions. The joint kinematics in the sagittal plane was simulated mathematically and the effects of laxity test similar to anterior drawer test were superimposed at selected positions.

The model parameters comprised 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. The model parameters were taken from anatomical studies reported in the literature [20–27].

The knee mechanics is described with four major ligaments—two cruciate ligaments and two collateral ligaments. A representation of non-linear elastic fibers was used for each ligament. The fibers resisted stretching and remained slack under compression. Further, consistent with the anatomical literature, the collateral ligaments had insignificant contribution in the sagittal plane mechanics of the joint.

2.1 Kinematics of the Knee During Flexion

The knee joint motion in the sagittal plane was simulated for 0–120° flexion. The knee kinematics in the absence of external loads or muscle action was defined as passive motion that required selected fibers in the cruciate ligaments to maintain isometric lengths as the bones rotated and moved relative to each other [25]. This modelled the joint kinematics in the unloaded state [26]. Resulting from relative rotations and translations of the bones, insertions of the ligaments on the respective bones also changed their relative positions. The mathematical model of the knee with intact ligaments and resulting joint kinematics was developed based on previously reported studies [20–28].

2.2 *Simulated Anterior Laxity Test*

During a laxity test like the Drawer test at a fixed joint position, the tibia is pulled anterior to the femur and resulting translation is recorded corresponding to a known applied force [29–32]. This effect was simulated by superimposing additional relative translation at insertion points of the ligament fibers. Such tests are conducted to estimate integrity of the ligaments [29].

During the model simulation of the laxity test, A flexing moment and an anterior force were applied on the tibia. As a result, the tibia translated and stretched the ACL fibers until equilibrium. In the model, joint angle and magnitude of the anterior force could be selected and resulting anterior translation of tibia (ATT) calculated. In addition, the model also allowed application of a predetermined value for ATT and calculation of associated forces in different fiber bundles of the ACL.

2.3 *Distribution of Forces in Different Areas of the Ligament Attachments*

The ACL was modelled as a combination of two bundles of fibers as reported in the literature. The anterior bundle represented the anteromedial fibers and the posterior bundle represented the posterolateral bundles of the ACL [7–9, 11–14]. Fibers in each bundle sequentially stretched or slackened during motion or due to the tibial translation relative to femur.

In the model simulation of the laxity test, the tibia was translated 8 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.

3 Results and Analysis

3.1 *Simulated Anterior Laxity Test*

Table 1 gives a comparison of model calculations with experimental measurements. ATT calculations and measurements correspond to laxity test with 90 N anterior force on the tibia while the joint angle remained fixed at selected positions.

The experimental measurements with mean values and standard deviation were reported by Kondo et al. [15]. The model used a similar simulation with 90 N force.

The results of simulation and experimental show similar trends. With the flexion angle increasing from 0° to 110°, ATT first increased till about the mid range and then

Table 1 ATT calculations from the model knee are compared with in vitro measurements on 14 cadaver knees resulting from anterior laxity test with 90 N force [15]

Flexion angle (°)	ATT (mm)	
	Model calculations	Experiment [15] 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)

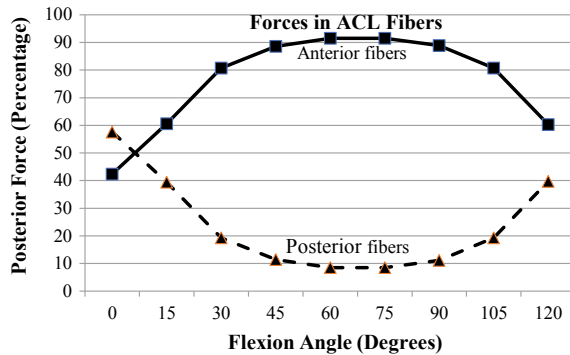
decreased in high flexion. The values calculated at each position remained within the range of those measured.

Near extension, the fibers of ACL are less slack and more ready to stretch but oriented more perpendicular to the anterior direction resulting in less ATT when 90 N force 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 to the 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 ligament fibers over 0°–120° flexion range. Contributions of the anterior and posterior bundles of the ACL given as a percentage of total anterior force applied to translate the tibia 8 mm anterior to the femur at each simulated flexion position.

Fig. 1 Posterior force developed in the ligament is given over 0°–120° flexion. Forces in each of the anterior and posterior bundles of the ACL are given in terms of percentage of total anterior force on the tibia that resulted in 8 mm ATT simulation



At low flexion, both the fiber bundles contributed significantly in resisting the external force. With increase in flexion angle, contribution of the posterior bundle decreased sharply and that of the anterior bundle increased till about 45° . The anterior bundle resisted the external force fully in the mid range of the joint motion. Beyond 90° , the posterior fibers stretched again and provided their contribution.

Kawaguchi et al. [14] also reported similar patterns in their in vitro experimental observations using 8 cadaver knees to analyze load bearing function of the ACL fibers in resisting tibial displacement. In the study, attachments of ACL fibers on the femur were cut sequentially and translating force were measured for 6 mm ATT.

The investigators reported that the anteromedial bundle of the ACL contributed 66–84% of the total resistance during 0 – 90° flexion. In comparison, the posterolateral bundle contributed nearly 16–9%. They also measured the torques required for internal or external rotation of the bones and found no significant effect of cutting of the ACL fibers, This later observation confirmed that the main function of the ACL is in resisting ATT.

4 Conclusions and Future Work

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 restraint provided by different fiber bundles in the ACL depends two important factors, namely, flexion position of the joint and overall magnitude of ATT. This is because of each of the flexion position and the ATT result in changed orientations of the ACL fibers.

Further, the joint flexion and the ATT also influenced relative contributions of the anterior and posterior bundles of the ligament.. 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.

Changes in attachment positions of the ligament fibers and resulting effects form further extension of this investigation.

5 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, the model as well as experimental observations suggest that the intact ACL permitted less translation of the bones near the extremes of motion than in

the mid flexion range. This may indicate that rehabilitation exercises or activities involving extreme positions of the joint may prove to be more demanding on an anatomically reconstructed graft. The analysis has relevance to ACL-reconstruction and ACL rehabilitation.

Acknowledgements The author would like to thank College of Engineering and Information Technology at Ajman University, UAE for financial and research support provided during the development of this work.

References

1. K.L.P. Monaghan, H. Salem, K.E. Ross, E. Secrist, M.C. Ciccotti, F. Tjoumakaris, M.G. Ciccotti, K.B. Freedman, Long-term outcomes in anterior cruciate ligament reconstruction—a systematic review of patellar tendon versus hamstring autografts. *Orthop. J. Sports Med.* **5**(6), 1–9 (2017)
2. S. Jarvela, T. Kiekara, P. Suomalainen, T. Jarvela, Double-bundle versus single-bundle anterior cruciate ligament reconstruction: a prospective randomized study with 10-year results. *Am. J. Sports Med.* **45**(11), 2578–2585 (2017)
3. S. Irarrázaval, A. Masferrer-Pino, M. Ibañez, T.M.A. Shehata, M. Naharro, J.C. Monllau, Does anatomic single-bundle ACL reconstruction using hamstring autograft produce anterolateral meniscal root tearing? *J. Exp. Orthop.* **4**(17), 1–5 (2017)
4. V.S. Alfonso, J.C. Monllau, Acute anterior cruciate ligament tear surgery: repair vs reconstruction—when? in *The ACL-Deficient Knee: A Problem Solving Approach* (Springer, Berlin, 2013), pp. 203–310
5. C.L. Arden, N.F. Taylor, J.A. Feller, E.K. Webster, Return to sport outcome at 2 to 7 years after anterior cruciate ligament reconstruction surgery. *Am. J. Sports Med.* **40**, 41–48 (2012)
6. M.M. Murray, S.D. Martin, T.L. Marti, M. Spector, Histological changes in the human anterior cruciate ligament after rupture. *J. Bone Joint Surg.* **82-A**(10), 1387–1397 (2000)
7. S. Amiri, T. Derek, V. Cooke, U.P. Wyss, A multiple-bundle model to characterize the mechanical behavior of the cruciate ligaments. *Knee* **18**(1), 34–41 (2011)
8. M. Mommersteeg, L. Blankevoort, R. Huijskes, J. Kooloos, J. Kauer, Characterisation of the mechanical behavior of human knee ligaments: a numerical-experimental approach. *J. Biomechanics* **29**(2), 151–160 (1996)
9. A. Amis, G. Dawkins, Functional anatomy of the anterior cruciate ligament–fibre bundle actions related to ligament replacement and injuries. *J. Bone Jt. Surg. (Br)* **73-B**, 260–267 (1991)
10. D. Butler, M. Kay, D. Stouffer, Comparison of material properties in fascicle-bone units from human patellar tendon and knee ligaments. *J. Biomech.* **19**(6), 425–432 (1986)
11. M.R. Carmont, S. Scheffler, T. Spalding, J. Brown, P.M. Sutton, Anatomical single bundle anterior cruciate ligament reconstruction. *Curr. Rev. Musculoskelet Med.* **4**, 65–72 (2011)
12. P.B. Jorge, D. Escudeiro, N.R. Severino, C. Santili, R.L. Cury, A.D. Junior, L.G.B. Guglielmetti, Positioning of the femoral tunnel in anterior cruciate ligament reconstruction: functional anatomical reconstruction. *BMJ Open Sport Exerc. Med.* **4**(1) (2018). <https://bmjopensem.bmj.com/content/4/1/e000420>. Last accessed on 15 May 2020
13. A. Imran, Force distribution in femoral attachment of anterior cruciate ligament during drawer test—a planar model analysis. *Lecture Notes in Engineering and Computer Science: Proceedings of The World Congress on Engineering 2019*, 3–5 July, 2019, London, U.K., pp. 418–421
14. Y. Kawaguchi, E. Kondo, R. Takeda, K. Akita, K. Yasuda, A.A. Amis, The role of fibers in the femoral attachment of the anterior cruciate ligament in resisting tibial displacement. *J. Arthroscopic Relat. Surg.* **31**(3), 435–444 (2015)

15. E. Kondo, A.M. Merican, K. Yasuda, A.A. Amis, Biomechanical analysis of knee laxity with isolated anteromedial or posterolateral bundle deficient anterior cruciate ligament. *J. Arthroscopic Relat. Surg.* **30**(3), 335–343 (2014)
16. H. Steckel, V. Musahl, F.H. Fu, The femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: a radiographic evaluation. *Knee Surg. Sports Traumatol. Arthrosc.* **18**, 52–55 (2010)
17. A. Imran, Relating knee laxity with strain in the anterior cruciate ligament. *Lecture Notes in Engineering and Computer Science: Proceedings of The World Congress on Engineering 2017*, 5–7 July, 2017, London, UK, pp. 1037–1042 (2017)
18. A. Imran, Analyzing anterior knee laxity with isolated fiber bundles of anterior cruciate ligament, *Lecture Notes in Engineering and Computer Science: Proceedings of the World Congress on Engineering 2016*, 29 June–1 July 2016, London, UK, pp. 869–872 (2016)
19. W. Petersen, T. Zantop, Anatomy of the anterior cruciate ligament with regard to its two bundles. *Clin. Orthop. Relat. Res.* **454**, 35–47 (2007)
20. V.B. Duthon, C. Barea, S. Abrassart, J.H. Fasel, D. Fritschy, J. Ménétrey, Anatomy of the anterior cruciate ligament. *Knee Surg. Sports Traumatol. Arthrosc.* **14**(3), 204–213 (2006)
21. A. Imran, J.J. O'Connor, Control of knee stability after acl injury or repair: interaction between hamstrings contraction and tibial translation. *Clin. Biomech.* **13**(3), 153–162 (1998)
22. A. Race, A. Amis, The mechanical properties of the two bundles of the human posterior cruciate ligament. *J. Biomech.* **27**(1), 13–24 (1994)
23. A.B. Zavatsky, The functional architecture of human knee ligaments. Ph.D. thesis, University of Oxford, 1993
24. A. Zavatsky, J. O'Connor, A model of human knee ligaments in the sagittal plane: Part 1. Response to passive flexion. *J. Eng. Med.* **206**(H), 125–134 (1992)
25. J.J. O'Connor, T.L. Shercliff, E. Biden, J.W. Goodfellow, The geometry of the knee in the sagittal plane. *Proc. Inst. Mech. Eng. (Part H) J. Eng. Med.* **203**, 223–233 (1989)
26. A. Imran, Modelling and simulation in orthopedic biomechanics-applications and limitations, in *Computational and Experimental Biomedical Sciences: Methods and Applications* ed. by J. M Tavares, R.M. Jorge (Springer, Berlin, 2015)
27. A. Watanabe, A. Kanamori, K. Ikeda, N. Ochiai, Histological evaluation and comparison of the anteromedial and posterolateral bundle of the human anterior cruciate ligament of the osteoarthritic knee joint. *Knee* **18**(1), 47–50 (2011)
28. T.W. Lu, J.J. O'Connor, Fiber recruitment and shape changes of knee ligaments during motion: as revealed by a computer graphics based model. *Proc. Inst. Mech. Eng. (Part H) J. Eng. Med.* **210**, 71–79 (1996)
29. J. Kupper, B. Loitz-Ramage, D. Corr, D. Hart, J. Ronsky, Measuring knee joint laxity: a review of applicable models and the need for new approaches to minimize variability. *Clin. Biomech.* **22**, 1–13 (2007)
30. A. Imran, Sagittal plane knee laxity after ligament retaining unconstrained arthroplasty: a mathematical analysis. *J. Mech. Med. Biol.* **12**(2), 1–11 (2012)
31. A. Imran, Influence of flexing load position on the loading of cruciate ligaments at the knee—a graphics-based analysis, in *Computational and Experimental Biomedical Sciences: Methods and Applications*, ed. by J.M Tavares, R.M. Jorge (Springer, Berlin, 2015)
32. A. Imran, Computer graphics based analysis of loading patterns in the anterior cruciate ligament of the human knee, in *Advances in Intelligent Systems and Computing*, ed. by K. Arai et al. (Springer Nature, Berlin, 2019), pp. 1–6. (https://doi.org/10.1007/978-3-030-01177-2_98)