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Analyzing the Role of Patellar Tendon Force During Flexion of the Knee

Ahmed Imran, *Member, IAENG*

***Abstract*—The mechanics of the knee was analyzed in the sagittal plane to study the role of patellar tendon in resisting a flexing load and in translating the tibia anterior or posterior to the femur. The effect of load placement at different positions distal to the tibial surface was analyzed during the flexion range 0–120^o. Data for orientation and moment arm of the patellar tendon during the flexion range was taken from experiments on cadaver knees available in the literature.**

The results and analysis suggest that during quadriceps strengthening exercises distal placement of flexing loads on the tibia, in comparison to more proximal placements, results in larger muscle forces. However, such loads are also associated with larger translations of the tibia relative to the femur, thus, loading the cruciate ligaments. Particularly, the anterior cruciate ligament is predisposed to loading due to load placements far distal on the tibia in the low–to–mid flexion range. Therefore, rehabilitation exercises requiring protection of the ligament need attention for the position of external flexing load on the tibia as well as the flexion angle at which the exercise is performed.

***Index Terms*— knee biomechanics, rehabilitation of the anterior cruciate ligament, quadriceps contraction, knee moment arms, tibial translation.**

I. Introduction

SEVERAL investigators have estimated moment arms and orientations of the patellar tendon at the knee using theoretical or experimental approach for the intact or replaced knee [1–5]. The tendon transmits forces of the quadriceps muscles through the knee extensor mechanism to the tibia [6]. The tendon force provides extending moment at the knee as well as force components that can translate the lower bone (or tibia) relative to the upper bone (or femur) [6].

During the knee flexion, moment arm available to the patellar tendon force varies due to changing location and orientation of the tendon as well as due to changing location of the point from which the moment arm is measured, such as, the tibio-femoral contact point or the joint centre of rotation [1–6]. The moment arm of the tendon normally remains small and varies non-linearly from more than 4 cm in extension to less than 4 cm in high flexion [1]. The tendon orients anteriorly in extension and posteriorly in high flexion, with an overall variation of nearly 20^o during 0–120^o flexion [1].

In early–to–mid flexion range, the patellar tendon force has a component parallel to the tibial surface directed anteriorly, which can pull the tibia anterior to the femur, thus, stretching the anterior cruciate ligament (ACL) [6]. In mid–to–high flexion range, the patellar tendon force has a component parallel to the tibial surface directed posteriorly, which can pull the tibia posterior to the femur, thus, stretching the posterior cruciate ligament (PCL) [6]. These anterior or posterior force components of the tendon can be large in certain strenuous activities and could lead to serious consequences for the subject as the knee ligaments, particularly the ACL, are injured frequently during situations involving large tibial translations [6–8].

The purpose of this study is to analyze the role of the patellar tendon in several flexion positions of the knee in terms of its ability to resist an external flexing moment and its ability to translate the tibia relative to the femur, thus, loading the cruciate ligaments.

II. Methods

Mechanics of the knee was analyzed in the sagittal plane during 0–120^o flexion of the joint. With reference to Fig. 1, mechanical equilibrium of the joint was considered due to four types of forces, namely, a force in the patellar tendon (P), a ligament force (L), a tibio-femoral joint contact force (C) applied by the femur normal to the tibial surface and a flexing load (R) applied externally on the tibia acting parallel to the tibial surface.

The anatomical posterior direction was defined along the positive x-axis. Also, the tibial surface was taken to be flat and parallel to the x-axis.

Equilibrium of moment was given by (1); equilibrium of forces parallel to the tibial surface was given by (2) and equilibrium of forces perpendicular to the tibial surface was given by (3).

In (1), the rotational contribution of the ligament force, due to either the ACL or the PCL, was ignored because the moment arms available to the ligaments through most of the flexion range are relatively much smaller, 1 cm or less [1]. Also, the frictional effect between the bones in the natural intact joint, being negligible [9], was ignored.

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

$$P \times M_P + R \times M_R = 0 \quad (1)$$
$$P \times \cos(\theta_P) + R \times \cos(\theta_R) + L \times \cos(\theta_L) = 0 \quad (2)$$
$$P \times \sin(\theta_P) + L \times \sin(\theta_L) + C \times \sin(\theta_C) = 0 \quad (3)$$

Where,
R, P, L and C are the forces as defined earlier in this section.
θ is the angle with positive x-axis for a force given by its respective subscript. By definition, $\theta_R = 0^o$.
M is the moment arm from the tibio-femoral contact point (point O in Fig. 1) for a force given by its respective subscript.

The data used in this study was based on the experimental measurements of Herzog and Read [1]. Table 1 gives average values for orientations and moment arms estimated from the data given for six cadaver knees recorded at several positions during the knee flexion [1]. In the experiment, similar to the present study, the orientation of the patellar tendon was taken with the posterior direction and the moment arm was taken about the tibio-femoral contact point.

Table 1: Average values for the orientations and moment arms of the patellar tendon during flexion of the knee were estimated from ref. [1].

Flexion Angle (Degrees)	Orientation (Degrees)	Moment Arm (cm)
0	103.2	4.1
20	102.8	4.6
40	97.9	4.7
60	93	4.2
80	86.9	4
100	85	3.9
120	82.8	3.6

Using the moment arm data from table 1, values of patellar tendon force per unit external load (P / R) were calculated based on (1).

In (2), the ligament force L would arise due to stretching of the ACL if the tibia translated anteriorly (negative x-direction in Fig. 1) or due to the PCL if the tibia translated posteriorly. The net tangential force (T) responsible for the tibial translation, was calculated per unit R as $[P \times \cos(\theta_P) + R \times \cos((\theta_R)]$. The values for θ_P were obtained from table 1, while $\theta_R = 0^o$ was taken by definition.

The calculations described in the above two paragraphs were performed during 0–120^o flexion and repeated with different positions of R below the tibial surface with, M_R=20, 30, 40 and 50 cm.

III. Results

Fig. 2 shows the P / R ratio calculated during flexion with M_R=20, 30, 40 and 50 cm.

Fig. 3 shows the T / R ratio calculated during flexion with M_R=20, 30, 40 and 50 cm.

IV. Analysis

The Role of the Patellar Tendon in Resisting a Flexing Moment:

With reference to table 1, the moment arm available to the patellar tendon was around 4 cm near extension, increased with flexion angle until around 40^o to an average value of 4.7 cm and then decreased in higher flexion to remain below 4 cm after 80^o flexion. In comparison, the moment arm of the external load could be around 40 cm or more during normal activities. As a consequence, the force P would be much larger than R and it would vary with the position of R below the tibial surface as suggested by (1) and demonstrated by the calculations in Fig 2. With increase in M_R, P/R ratio in Fig. 2 increased uniformly throughout the flexion range. During quadriceps strengthening exercises, distal placement of R may be required for the muscle exercises to be effective. However, such distal placements could have detrimental effects on the ACL loading as suggested by the analysis given below.

The Role of the Patellar Tendon in Translating the Tibia Anterior or Posterior to the Femur:

With reference to Fig. 3, the T/R ratio was negative in early flexion for all positions of R below the tibial surface. The T/R ratio became positive with increasing flexion. This suggests that the tibia would translate initially anteriorly and then posteriorly during flexion depending on the position of R. Accordingly, the ACL would be stretched for negative values and PCL would be stretched for positive values of T/R. Neither ligament would stretch for T/R=0.
For external loads placed far distal to the tibial surface, the flexion range with negative values for T/R was increased, *e.g.*, for M_R=20 cm, T/R was negative for the flexion range 0-15^o, while for M_R=50 cm, this flexion range was increased to 0-54^o. This observation suggests that the quadriceps exercises performed with the external load placed far distal to the tibial surface could stretch the ACL up to nearly the mid flexion range. Further, since most of the normal activities, like walking, jogging, stair climbing, involve low–to–mid flexion range at the most [10–12], anterior translation of the tibia and, thus, loading of the ACL would be expected during such activities.

V. Conclusion

The mechanics of the knee was analyzed in the sagittal plane to study the role of patellar tendon in resisting a flexing load and in translating the tibia anterior or posterior to the femur. The analysis suggests that the force in the patellar tendon varies directly with the distance of the external flexing load placed distal to the tibial surface. This effect is uniform throughout the joint flexion range. Further, depending on the position of the flexing load on the tibia, in the low-to-mid flexion range the tibia translates anterior to the femur, while in the mid-to-high flexion range the tibia translates posterior to the femur.

Two critical factors that may require special attention to protect the ACL during rehabilitation exercises are the flexion angle and the position of the flexing load below the tibial surface.

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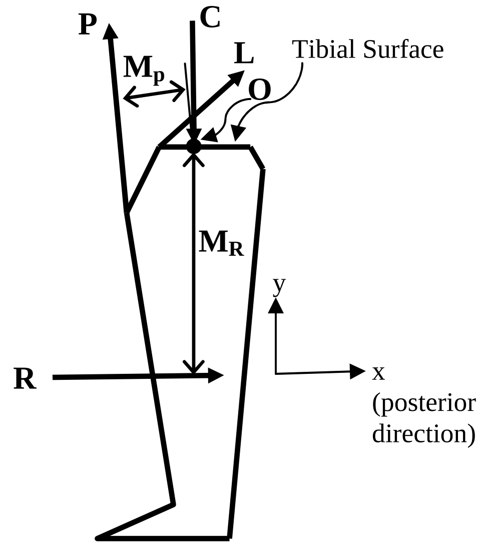

Fig. 1. The Flexing moment due to the external load (R) on the tibia is balanced by an extending moment provided by the patellar tendon force (P). The external force is balanced by the internal forces P, L and C.

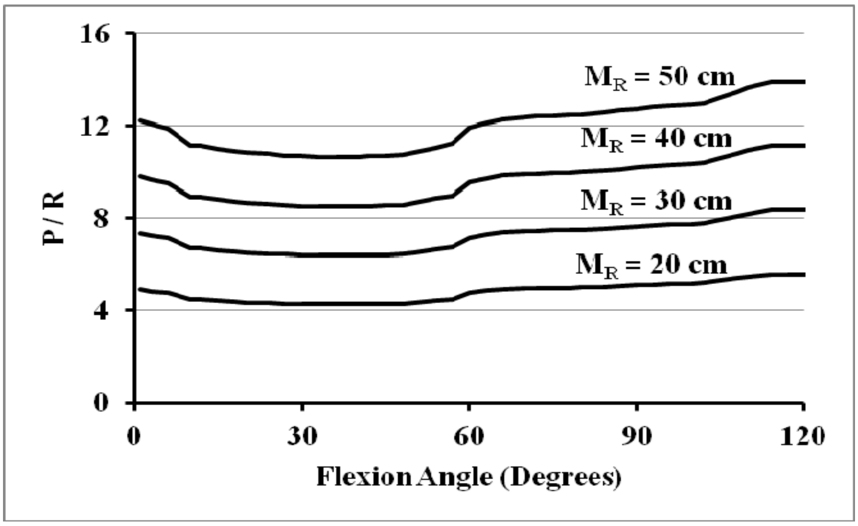

Fig. 2. The patellar tendon force per unit of the external load (P/R) plotted during 0–120^o flexion for values of M_R = 20, 30, 40 and 50 cm.

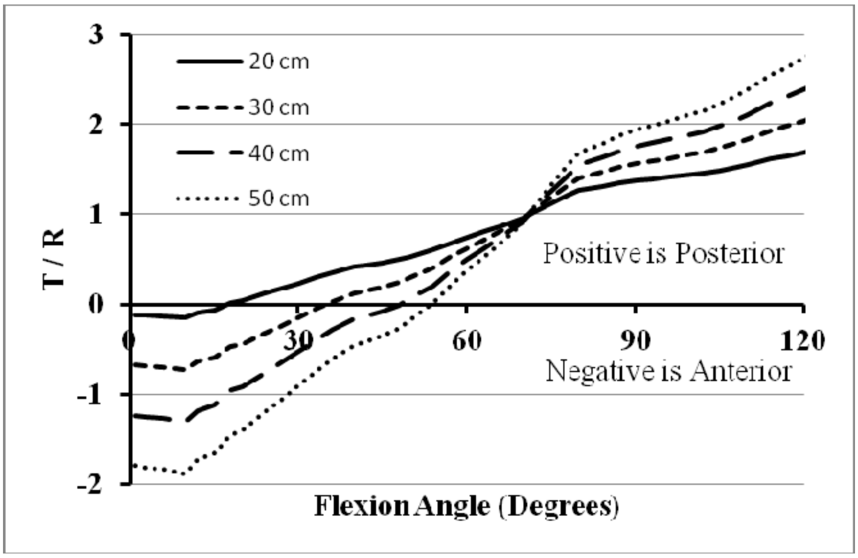

Fig. 3. The net tangential force arising due to the patellar tendon force and the external load was calculated as T / R during 0–120^o flexion for values of M_R = 20, 30, 40 and 50 cm.

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References

[1] W. Herzog and L. J. Read, “Lines of action and moment arms of the major force-carrying structures crossing the human knee joint,” *J. Anatomy*, vol. 182, pp. 213–230, 1993.

[2] J. L. Krevolin, M. G. Pandy and J. C. Pearce, "Moment arm of the patellar tendon in the human knee,” *J Biomechanics*, vol. 37, no. 5, pp. 785–8, 2004.

[3] D. T. O’Brien, N. D. Reeves, V. Baltzopoulos, D. A. Jones and C. N. Maganaris, “Moment arms of the knee extensor mechanism in children and adults,” *J. Anatomy*, vol. 215, pp. 198–205, 2009.

[4] R. Stagni, S. Fantozzi, F. Catani and A. Leardini, "Can Patellar Tendon Angle reveal sagittal kinematics in total knee arthroplasty?” *Knee Surg. Sports Traum. Arthrosc*. vol. 18, no. 7, pp. 949–54, 2010.

[5] D. E. Tsaopoulos, V. Baltzopoulos, P. J. Richards and C. N. Maganaris, "In vivo changes in the human patellar tendon moment arm length with different modes and intensities of muscle contraction,” *J Biomechanics*, vol. 40, no. 15, pp. 3325–332 2007.

[6] S. D. Masouros, A. M. J. Bull and A. Amis, “Biomechanics of the knee joint,” *Orthopaedics and Trauma*, vol. 24, no. 2, pp. 84–91, 2010.

[7] T. Mommersteeg, L. Blankevoort, R. Huiskes, J. Kooloos and J. Kauer, “Characterization of the mechanical behavior of human knee ligaments: a numerical-experimental approach,” *J Biomechanics*, vol. 29, no. 2, pp. 151–160, 1996.

[8] D. Klass, A. P. Toms, R. Greenwood and P. Hopgood, “MR imaging of acute anterior cruciate ligament injuries,” *The Knee*, vol. 14, pp. 339–347, 2007.

[9] A. Unsworth, D. Dowson and V. Wright, “Some new evidence on human joint lubrication,” *Ann. Rheum. Dis.*, vol. 34, pp. 277–285, 1975.

[10] K. J. Deluzio, U. P. Wyss, P. Zee, P. A. Costigan and C. Sorbie, “Principal component models of knee kinematics and kinetics: Normal vs. pathological gait patterns,” *Human Movement Science*, vol. 16, pp. 201–217, 1997.

[11] J. J. Collins and J. O'Connor, “Muscle-Ligament Interactions at the Knee during Walking,” *Proc IMechE Part H: J Engineering in Medicine*, vol. 205, pp. 11–18, 1991.

[12] K. Nakhaee, F. Farahmand and H. Salarieh, “Studying the effect of kinematical pattern on the mechanical performance of paraplegic gait with reciprocating orthosis,” *Proc IMechE Part H: J Engineering in Medicine*, vol. 226, no. 8, pp. 600–611, 2012.

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