Analyzing the Patellar Tendon Force During Quadriceps Muscle Exercise

Ahmed Imran, *Member, IAENG*

***Abstract*—The mechanics of the knee was analyzed in the sagittal plane to study the role of patellar tendon as influenced by the placement of external flexing loads on the tibia and by translation of the tibial bone 7mm anterior to the femoral bone during the flexion range 0–120^o. Anatomical parameters and measurements for orientations and moment arms of the patellar tendon during the flexion range were taken from experiments on cadaver knees available in the literature.**

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, 7mm anterior translation of the tibia relative to the femur resulted in significantly reduced anterior component of the net shear force for all flexion positions and all placements of loads distal to the joint line. This has relevance to ACL-deficient knees where large tibial translations may be necessary to compensate for the deficiency.

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.

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

I. Introduction

THE patellar tendon transmits forces of the quadriceps muscles through the knee extensor mechanism to the tibia [1]. 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) [1]. The relative translation of the bones tends to stretch the cruciate ligaments in the sagittal plane. Overstretching can lead to the ligament injuries.

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 [2–9].

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 [2–9]. 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 [2]. The tendon orients anteriorly in extension and posteriorly in high flexion, with an overall variation of nearly 20^o during 0–120^o flexion [2].

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) [1]. 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) [1]. 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 [1, 10, 11].

The purpose of this study is to analyze the patellar tendon force as influenced by the placement of external flexing loads on the tibia and by the relative translations of the tibial and femoral bones in the sagittal plane in several flexion positions of the knee.

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 'M_R' cm below the joint line (or tibial articular surface) and acting parallel to the line.

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

Manuscript received on 10 December, 2013; revised on 20 February 2014. 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).

moment arms available to the ligaments through most of the flexion range are relatively much smaller, 1 cm or less [2]. Also, the frictional effect between the bones in the natural intact joint, being negligible [12], was ignored.

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

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 [2]. 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 [2]. 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. The orientations of the patellar tendon force were measured also after anterior translation of the tibia relative to the femur (ATT).

Table 1: Average values for the orientations and moment arms of the patellar tendon during flexion of the knee as estimated from ref. [2].

Flexion Angle (Degrees)	Moment Arm (cm)	Orientation (Degrees)	
		Without ATT	With ATT=7mm
0	4.1	103.2	95.8
20	4.6	102.8	93.6
40	4.7	97.9	89.1
60	4.2	93	83.7
80	4	86.9	78.9
100	3.9	85	76.1
120	3.6	82.8	76.7

Using the moment arms 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 were performed during 0–120^o flexion and repeated with different positions of R below the tibial surface with, M_R=20 and 40 cm.

The calculations were also performed with 7mm ATT in order to analyze the possible effects on the shear forces that might require contributions from the ACL.

III. Results

Fig. 2 shows the P / R ratio calculated during flexion with M_R=20 and 40 cm with ATT=7mm as well as without ATT.

Fig. 3 shows the T / R ratio calculated during flexion with M_R=20 and 40 cm with ATT=7mm as well as without ATT.

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. The effect of ATT was to reduce the angle of P at all flexion positions of the joint. The reduction in angle was about 10^o at full extension and 6^o at 120^o flexion, varying nearly linearly. The P/R ratio increased due to ATT. The increase was more when the load was placed 40 cm compared to that when the load was placed 20 cm distally.

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 both positions of R below the tibial surface. The T/R ratio became positive with increasing flexion. Further, 7mm ATT result in positive values of T/R for all flexion positions, suggesting that no anteriorly directed shear force acted on the tibia, suggesting sufficiently compensatory position for the ACL-deficiency.
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 0-10^o, while for M_R=40 cm, the ratio was negative for flexion less than 40^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 [13–15], 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 patellar tendon force during flexion. The influence of distal positions of the external flexing loads on the tibia and the influence of anterior translation of the tibia relative to the femur were analyzed in several flexion positions of the knee. 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, anterior translation of the tibia relative to the femur resulted in significantly reduced anterior component of the net shear force, which has relevance to ACL deficient knees where large tibial translations may be necessary to partially compensate for the ACL-deficiency.

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.

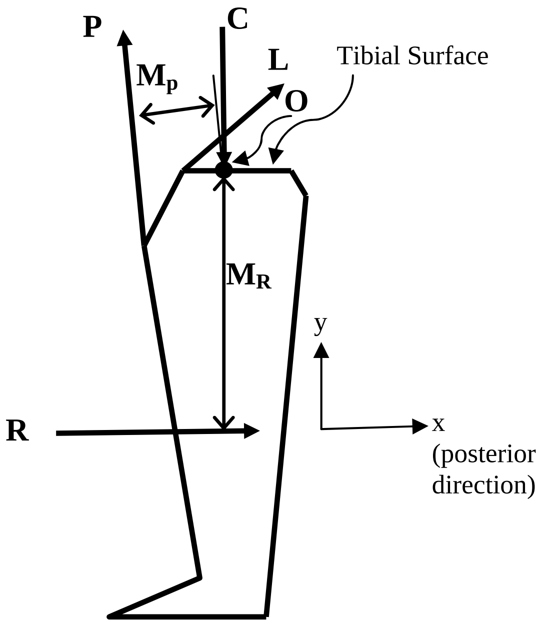

Fig. 1. The Flexing moment due to the external load (R) on the tibia is balanced by an extending moment provided by the patellar tendon force (P). The external force is balanced by the internal forces P, L and C.

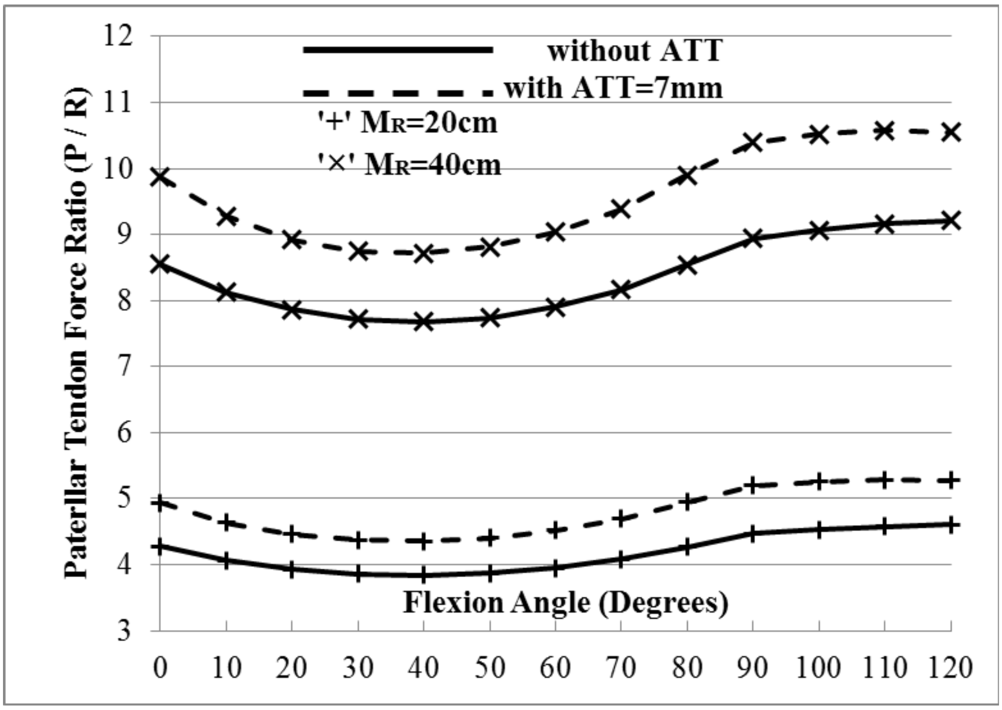

Fig. 2. The patellar tendon force per unit of the external load (P/R) plotted during 0–120° flexion for values of M_R = 20 and 40 cm with and without tibial translation.

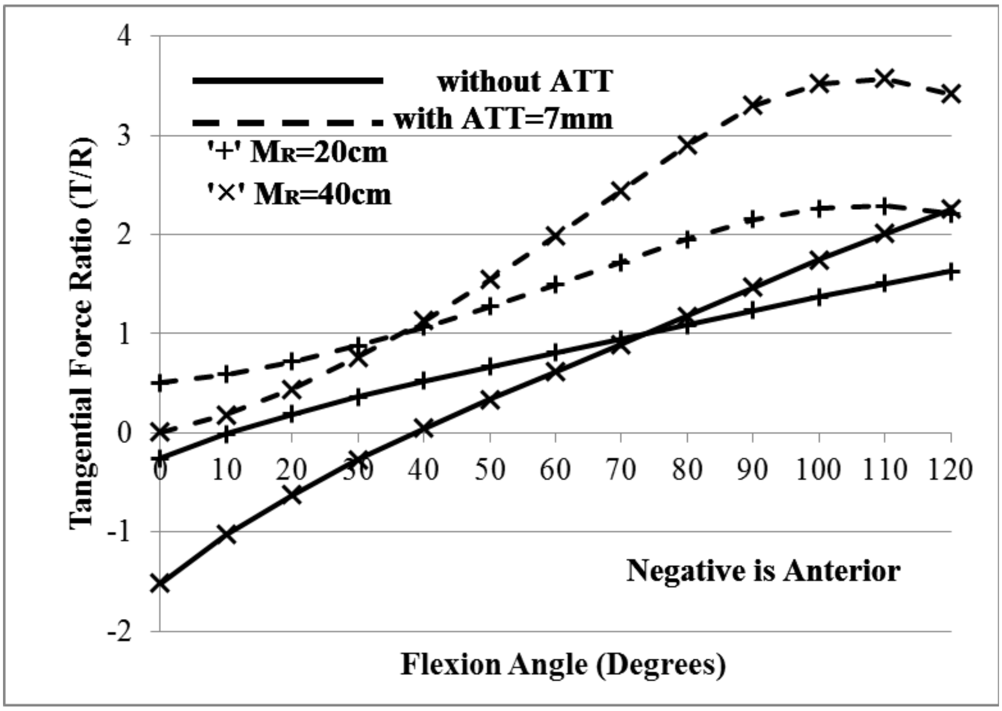

Fig. 3. The net tangential force arising due to the patellar tendon force and the external load was calculated as T / R during 0–120^{o} flexion for values of M_R = 20 and 40 cm with and without tibial translation.

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