Influence of Flexing Load Position on the Loading of Cruciate Ligaments at the Knee—A Graphics-Based Analysis

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Abstract Injuries of the cruciate ligaments of the knee, particularly the anterior cruciate ligament (ACL), is a common problem in young athletes. Therefore, identification of high-risk factors that lead to injury of the knee ligaments is required to avoid loading or protecting the ligaments from injury or during rehabilitation. In the present study, mechanics of the knee was analyzed for the influence of external flexing load positions on loading of the cruciate ligaments in the sagittal plane during 0° to 120° flexion. Experimental data was taken from literature. Mechanical equilibrium of the tibia was considered due to four types of forces, namely, a force in the patellar tendon, a ligament force, a tibio-femoral joint contact force, and an external flexing load applied distally on the tibia. The analysis suggests that during the muscle exercise at the knee, loading of the cruciate ligaments depends on flexion angle as well as on the position of external load on the tibia. Far distal placements of flexing loads on the tibia can stretch the ACL significantly at low flexion angles. The PCL is stretched during mid-to-high flexion range for all positions of the external flexing loads on the tibia. However, during the mid-flexion range, the effects of placement are modest. Therefore, rehabilitation exercises requiring protection of the ligaments need to pay attention to the position of external flexing load on the tibia as well as flexion angle at which the exercise is performed.

Keywords Ligament injuries · ACL rehabilitation · Ligament mechanics

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1 Introduction

Injuries of the cruciate ligaments of the knee, particularly the anterior cruciate ligament (ACL), is a common problem in young athletes. Studies suggest that the ACL injured patients are at a high risk of developing osteoarthritis 10–15 years after injury, irrespective of treatment [1, 10]. Therefore, identification of high-risk factors that lead to injury of the knee ligaments is required to avoid loading or protecting the ligaments from injury or during rehabilitation. Previous studies have identified positions of the external loads on the tibia that have the potential of loading either the anterior or the posterior cruciate ligament (ACL or PCL) [5, 11]. In the present study, mechanics of the knee was analyzed for the influence of flexing load positions on loading of the cruciate ligaments in the sagittal plane during 0° to 120° flexion. The analysis is based on considerations of mechanical equilibrium of the joint with external loads balanced by forces and moments developed in the internal structures like, tendons and ligaments as well as bone-to-bone joint contact force.

2 The Knee in the Sagittal Plane

Figure 1a gives a simplified representation of the knee in the sagittal plane with main load bearing structures as the two cruciate ligaments, muscle tendons and the bones. Straight lines were used to show the net forces in the respective tendons or ligaments. Other soft tissues, like articular cartilage or the menisci were not taken into consideration. Also, the collateral ligaments were not included in the analysis as they are shown to have minimal contributions in the sagittal plane [6, 7].

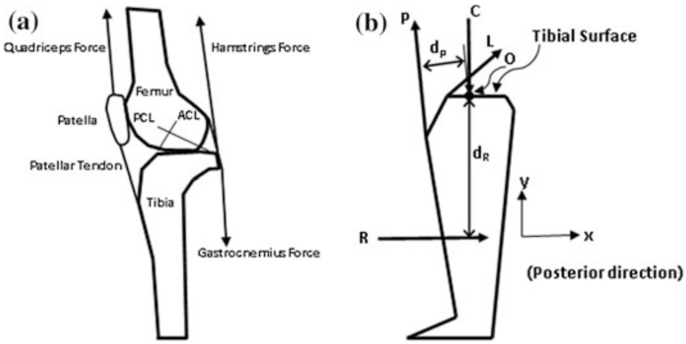

Fig. 1 Major load-bearing structures of the knee in the sagittal plane. **a** Outlines of the femoral and tibial bones and the patella are shown. *Straight lines* represent the net forces in the ligaments and muscle tendons. **b** Equilibrium of the lower leg during simulated quadriceps muscle exercise. External flexing load (R) is balanced by internal forces P, C and L. (‘L’ represents either the ACL or the PCL forces)

3 Equilibrium of the Joint During a Simulated Quadriceps Contraction

Figure 1b shows the lower leg in equilibrium during a simulated quadriceps muscle contraction which resists flexion due to an externally applied load on the leg. There are four types of forces involved, namely an external load, muscle force transmitted to the tibia through patellar tendon, a ligament force and a joint contact force. Each of these forces is described below.

3.1 External Load (R)

The external flexing load (R) acts on the tibia parallel to the tibial surface and a known distance below the joint line in the posterior direction. In practice, the external loads on the leg may arise due to gravity, ground reaction or other sources during activity like a reaction force when a player hits a ball with his leg.

3.2 Muscle Force

A force in the patellar tendon (P) due to a pull exerted by the quadriceps muscle contraction and transmitted to the tibia via the quadriceps tendon, patella and the patellar tendon. The force P has an extending effect at the joint and can also translate the lower bone or tibia relative to the upper bone or femur. The orientation of P changes with flexion, directed more anteriorly near extension and more posteriorly in high flexion. The orientation of P is also influenced by the tibial translation, for example, an anterior translation of the tibia would decrease the anterior component of P near extension or increase the posterior component of P in high flexion.

3.3 Ligament Force (L)

The ligaments (ACL or PCL) exert forces on the tibia when stretched due to relative translation or distraction of the two bones. An anterior translation of the tibia relative to the femur stretches the ACL, while a posterior translation stretches the PCL. The angle of ACL with the tibial articular surface decreases with increasing flexion [3] or with increasing anterior translation of tibia [5]. The angle of PCL with the posterior direction first decreases from low-to-mid flexion range and then increases from mid-to-high flexion range [3]. A posterior translation of tibia results in reduced inclination of the PCL with tibial articular surface.

3.4 Joint Contact Force (C)

A compressive contact force (C) exists between the femoral and tibial bones at the joint. As the healthy joints are known to have nearly zero friction [9], the contact force acts normal to the surfaces at their contact. Also, in normal healthy joints, articular surfaces and menisci (not considered for this analysis) help in reducing stresses by increasing the area of contact [2].

3.5 Kinematics

At full extension or 0° flexion, the long axes of the tibial and femoral bones are parallel. With flexion, the angle between the two axes increases to a maximum of about 140°. Any change in the flexion angle results in changed orientations and/or locations of the internal joint forces.

3.6 Conditions of Equilibrium

Equation (1) gives the condition for equilibrium of moment; Eqs. (2) and (3) give the conditions for equilibrium of forces in the anterior-posterior and proximal-distal directions, respectively.

With reference to Fig. 1, the flexing moment generated by R about the knee is balanced mainly by an extending moment provided by P due to a pull from the quadriceps muscles transmitted to the tibia through patella. As the patellar tendon is located much closer to the joint center of rotation than the external loads, the moment arm available to P is normally much smaller than that available to R. As a consequence, the force P is much bigger than R, as given by Eq. (1).

Forces parallel to the tibial articular surface have translational effect. Any unbalanced horizontal force in Fig. 1b would translate the tibia relative to the femur. As a consequence, the ligaments would stretch and resist the translation with a force (L). When excessive, such translations have the potential of overstretching the ligament fibers, possibly resulting in injury to the involved ligament.

Forces perpendicular to the tibial surface either push the bones into each other or distract them. The joint contact force (C) resists interpenetration of the bones while ligamentous structures resist distraction of the bones.

$$P * d_P + R * d_R = 0 \quad (1)$$

$$P * \cos(\phi_P) + R * \cos(\phi_R) + L * \cos(\phi_L) = 0 \quad (2)$$

$$P * \sin(\phi_P) + L * \sin(\phi_L) + C * \sin(\phi_C) = 0 \quad (3)$$

where,

R, P, L and C are the forces as defined earlier in this section.

ϕ is the angle with the positive x-axis for a force given by its respective subscript.

'd' is the moment arm from the tibio-femoral contact point (point O in Fig. 1b) for a force given by its respective subscript.

By definition, $\phi_R = 0°$.

4 Factors that Influence the Loading of Cruciate Ligaments

During a simulated quadriceps exercise, the effects of position of external flexing load on tibia and the orientation of patellar tendon are analyzed below in terms of their influence on the loading of cruciate ligaments. The situations that would load or unload each of the cruciate ligaments are described below and also illustrated in Figs. 2 and 3.

4.1 Proximal—Distal Position of the External Flexing Load

Distal placement of flexing load on the tibia results in an increased moment arm available to R, thus, flexing moment about the joint center of rotation is also increased. The balancing effect in the form of an extending moment is provided

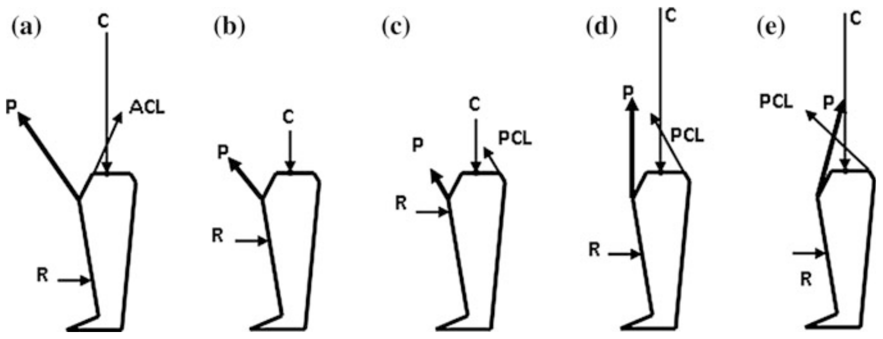

Fig. 2 Diagrammatic representation of the factors that influence the loading of cruciate ligaments at the knee. The *lines* showing the respective forces in each illustration are in proportion to their magnitudes as calculated using Eqs. (1–3). **a** Anterior component of P is greater than R, the joint equilibrium requires a force in the ACL. **b** Anterior component of P equals to R, the joint equilibrium does not require any ligament force. **c** Anterior component of P is smaller than R, the joint equilibrium requires a force in the PCL. **d** P is perpendicular to the tibial surface, the joint equilibrium requires a force in the PCL. **e** P is directed posteriorly, the joint equilibrium requires a force in the PCL

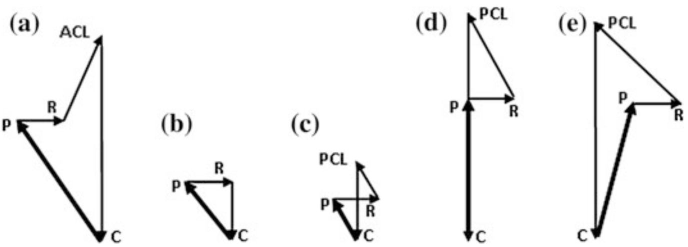

Fig. 3 Equilibrium of forces acting on the lower leg shown graphically corresponding to the five different situations illustrated in Fig. 2. ACL force is required in (**a**), while PCL force is required in (**c**–**e**). No ligament force is required in (**b**)

mainly by quadriceps muscle force through the patellar tendon. However, in comparison to the external load, the patellar tendon force is located closer to the joint center with a much smaller moment arm. As a consequence, the force P required for equilibrium of moment is much larger than the force R. As given by Eq. (1), the force ratio, P/R is inversely proportional to the ratio of their moment arms, d_R/d_P.

4.2 Orientation of the Patellar Tendon

The patellar tendon, therefore, the force P is shown to have an anterior direction in the flexion range from 0° to nearly 70°, and posterior direction for higher flexion angles [4, 8].

A force in the ACL would be required if P has an anterior component that is greater than R, as illustrated in Fig. 2a. A force in the PCL would be required if P has an anterior component that is smaller than R, or if P is not directed anteriorly, as illustrated in Fig. 2c–e. No ligament force would be required if the anterior component of P exactly balances the posterior R (Fig. 2b).

Figure 3 graphically shows the equilibrium of forces at the knee for five different situations leading to loading or unloading of the cruciate ligaments during quadriceps exercise. The force estimates follow Eqs. 1–3.

4.3 Shear Force on the Tibia

Shear force (T) on the tibia is defined here as the sum of the components of P and R that are parallel to the tibial surface. Using Eq. (2) without the ligament force, the equation for T is as given by Eq. 4.

$$T = P * \cos(\phi_P) + R * \cos(\phi_R) \tag{4}$$

where, the meaning of the symbols is same as defined earlier.

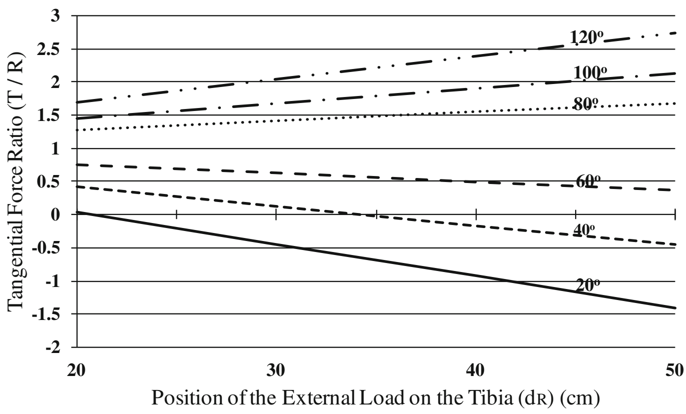

Fig. 4 Tangential force ratio (T/R) plotted against increasing values of the moment arm d_R for different flexion angles of the knee. Negative is anterior

As explained in the sections above, for balancing the shear force, a negative value of T would require a force in the ACL and a positive value of T would require a force in the PCL. Using Eq. (1), the ratio P/R can be calculated in terms of moment arms of the respective forces. Further, utilizing experimental measurements from Herzog and Read [3] for moment arms and orientations of the patellar tendon during flexion, the values of T are calculated per unit of R for known positions and orientations of the external load. Figure 4 shows the force ratio T/R plotted for increasing values of 'd_R' while ϕ_R = 0°. The ratios are plotted for flexion angle = 20, 40, 60, 80, 100 and 120°. The following important observations can be made from the plot:

- At 20° flexion, the T/R ratio is negative, requiring ACL force, for $d_R > 20.5$ cm.
- At 40° flexion, the T/R ratio is negative, requiring ACL force, for $d_R > 34$ cm.
- At all other flexion positions shown, the T/R ratio is positive, requiring a force in the PCL.
- For all flexion positions, the magnitude of shear force increases with increasing values of d_R.
- At low as well as at high flexion angles, the force ratio increases relatively sharply as the distance d_R increases. In the mid-flexion range, the increase in the shear force due to an increase in d_R is relatively modest.

5 Conclusions

Based on the model results, analysis suggests that during the muscle exercise at the knee, loading of the cruciate ligaments depends on flexion angle as well as on the position of external load on the tibia.

Far distal placements of flexing loads on the tibia can stretch the ACL significantly at low flexion angles. The PCL is stretched during mid-to-high flexion range for all positions of the external flexing loads on tibia. However, during the mid-flexion range, such effects of variation in placement are relatively modest.

Therefore, rehabilitation exercises requiring protection of the ligaments need to pay attention to the position of external flexing load on the tibia as well as the flexion angle at which the exercise is performed.

References

1. Gillquist J and Messner K (1999) Anterior cruciate ligament reconstruction and the long-term incidence of gonarthrosis. Sports Med. 27: 143–56.
2. Goodfellow J and O'Connor J (1978) The mechanics of the knee and prosthesis design. J Bone Jt Surg. Br. 60(B): 358–369.
3. Herzog W and Read LJ (1993) Lines of action and moment arms of the major force-carrying structures crossing the human knee joint. J Anatomy 182: 213–230.
4. Imran A, Huss R, Holstein H and O'Connor J (2000) The variation in the orientations and moment arms of the knee extensor and flexor muscle tendons with increasing muscle force: a mathematical analysis. J Engineering in Medicine 214(H): 277–286.
5. Imran A and O'Connor J (1998) Control of knee stability after ACL injury or repair: interaction between hamstrings contraction and tibial translation. Clin Biomech. 13(3): 153–62.
6. Masouros SD, Bull A and Amis (2010) Biomechanics of the knee joint. Orthopaedics and Trauma. 24(2): 84–91.
7. Mommersteeg T, Blankevoort L, Huiskes R, Kooloos J and Kauer J (1996) Characterization of the mechanical behavior of human knee ligaments: a numerical-experimental approach. J Biomechanics 29(2): 151–160.
8. O'Connor J, Shercliff T, Biden E and Goodfellow J (1989) The geometry of the knee in the sagittal plane. J Engineering in Medicine 203 (H4): 223–233.
9. Unsworth A, Dowson D and Wright V (1975) Some new evidence on human joint lubrication. Ann. Rheum. Dis. 34: 277–285.
10. von Porat A, Roos EM and Roos H (2004) High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. Ann Rheum Dis. 63: 269–73.
11. Zavatsky AB and O'Connor J (1993) Ligament forces at the knee during isometric quadriceps contractions. J Engineering in Medicine 207(H1): 7–18.