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Prediction of ACL and PCL loads during isokinetic knee exercises using experimental tests and musculoskeletal simulations

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Abstract

Aim of the study is to investigate the tension acting on the anterior cruciate ligament, ACL, and posterior cruciate ligament, PCL, during the knee isokinetic flexion-extension in a not-invasive way. Two different approaches were used: a numerical approach using OpenSim and an analytical approach. After having calculated the shear acting on the tibial plateau, it was possible to evaluate the tension at cruciates. After comparing the results with other studies in literature, the numerical approach resulted more correct than the analytical in flexion, whereas the analytical approach gave better results in extension. Results of the present work can suggest development directions for the ACL & PCL loads prediction from numerical muscololoskeletal models as well as indications of clinical relevance in isokinetik training or rehabilitation.

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Keywords: "Isokinetik, muscoloskeletal, EMG, ACL, PCL;"

1.Introduction

The knee is one of the most complex joints of the human body and quite often affected by ligament injuries occurring during sport activities: isokinetic exercise are widely used during rehabilitation programs. In this study, the knee biomechanics during isokinetic flexion-extension was investigated in order to evaluate joint loads and tensions at cruciate ligaments with a non-invasive approach in order to predict possible overloads caused by a wrong execution of the movement. In literature, many studies about knee flexion-extension can be found: Yamaguchi et al. [9], Herzog et al. [4] investigated in particular the line of action and the moment arm of the most important muscles and ligaments acting during the movement and they suggested an analytical schematization of the femur-patella joint. D'Lima et al. [2] focused on implantable devices, which allow measuring contact forces on tibia and femur during daily life activities; Beynnon et al. [1] examined the tension at the anterior cruciate ligament by means of differential transducer embedded directly to the central part of the ligament. The results of these previous studies, were used in this thesis in order to introduce an analytical model useful to obtain the tension at the anterior and posterior cruciate ligaments: the benefit of the model is its versatility for the study of flexion extension in the sagittal plane. In addition, the results were compared with those deriving from numerical simulations obtained by the OpenSim software. A first validation of the results was done by using electromyography; after that, the results were compared with previous studies in literature.

2.Material and Methods

The knee flexion-extension was investigated in isokinetic conditions by using a Technogym isokinetic machine, REV 7000, as shown in fig.1. In this study six male healthy subjects, with no trauma at the knee, were involved after signing an informed

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consent form. Each subject was asked to perform at least five consecutive cycles of flexion-extension, at his maximum effort, with the right leg moving at 60°/s, 120°/s, 180°/s and 240°/s, within the range of 25-95° of flexion angle as measured by the machine arm, with a complete rest between the exercises. After that, isometric tests were performed at 95°, 70°, 55°, 40° and 25°, with a complete rest between the exercises, in order to evaluate the Maximum Voluntary Contraction of investigated muscles: 5 seconds of maximum contraction in extension, 10 seconds of relax, 5 seconds of maximum contraction in flexion. Fig.1.b shows how the exercises were performed: the right femur was strapped to the machine by using a specific padded device; torso, pelvis and left leg could be considered in a fixed position too.
To reconstruct the spatial movement (kinematics), an optoelectronic system (BTS Engineering) was used (fig.1.a). Six coaxial cameras compose this system (50 Hz sampling rate, 0.5 mm spatial resolution), with infrared led lamps illuminating 20 reflective markers; the markers were applied to the skin of the subject and on the arm of the machine.

a) b)

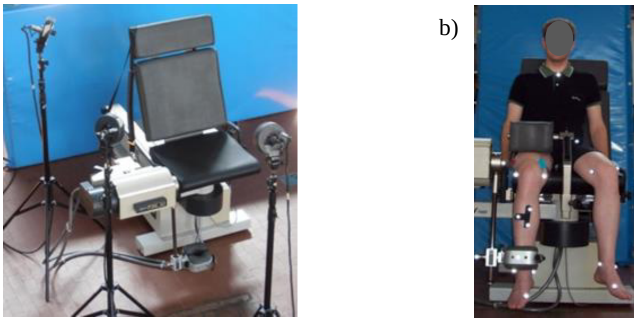

Fig.1. a) Technogym REV 7000 and BTS optoelectronic system (only three cameras are shown); b) Markerset, electrodes and testing conditions.

To evaluate the exercises in terms of muscular activation, surface electrodes were used. The right limb muscles analyzed in this study were Rectus Femoris, Vastus Lateralis and Vastus Medialis as extensors, Biceps Femoris Caput Longus among flexors. Electromyographic signal was synchronized to the BTS motion capture system using a pocket EMG BTS, a device that allows collecting the signal and sending the information to the optoelectronic system.

3.Data analysis

The trajectory of the markers placed on the skin of the subject was used to obtain the spatial movements of the right limbs. The markers trajectory was first reconstructed using a model within the BTS software Smart Tracker (Fig.2.a) and then interpolated using a protocol created within the BTS software Smart Analyzer. Kinetic data were obtained considering the torque curve measured at the servomotor of the machine: using the markers placed on the arm slider used for the flexion-extension tests, it was possible to obtain the instantaneous lever arm of the force acting on the tibia, as shown in Fig.2.b.

a) b)

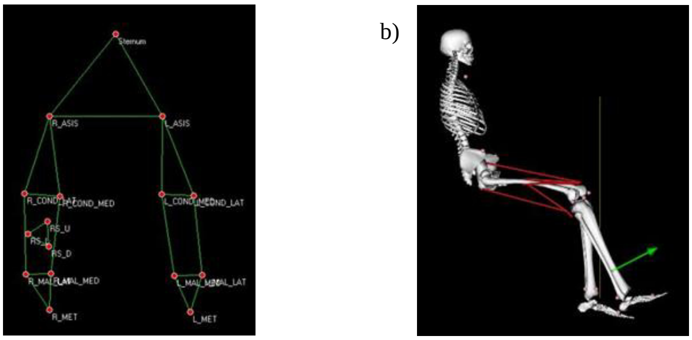

Fig.2. a) Tracker model used in kinematics analysis; b) Example of application of the external force acting on the tibia in flexion with gait2392 Opensim numerical model (biceps femoris and quadriceps are shown).

The electromyographic signals were rectified, integrated with a moving window of 200 ms, lowpass filtered at 6 Hz and normalized to the maximum signal recorded during the isometric tests or the isokinetic tests.
The movement was simulated using the software OpenSim and kinematic and kinetic data recorded in each test: in particular, gait2392 (Fig.2.b) was adopted, presenting 23 DOF and 92 muscles in the lower part of the body. The simulations were conducted following the usual OpenSim steps. Scaling the model, in terms of mass and muscles (the relation suggested by Lee et

al. [6] was used for the muscles); Inverse Kinematics, which allowed to obtain the angular coordinates of the bodies and the joints. Inverse Dynamics, from which it was possible to evaluate the net-moment at the knee joint; Static Optimization and Joint Reaction analysis, from which it was possible to obtain respectively the muscular forces (or muscular activation) and the reactions forces at the knee joint.
A first validation of the results obtained by the OpenSim software was performed in terms of muscular activation by comparing the muscular activation predicted by the software with the electromyographic signal; the comparison was done by considering the Error Indexes adopted in a previous study by Petrone et al. [8]:

Error between numerical (OSIM) and experimental (EMG) in terms of maximum values (Peak):

$$\text{Peak error [\%]} = \frac{\text{Peak}_{\text{EMG}} - \text{Peak}_{\text{OSIM}}}{\text{Peak}_{\text{EMG}}} \cdot 100$$

Error between numerical (OSIM) and experimental (EMG) in terms of synchronism of the instant at which the maximum occurs (Peak_Time), normalized to the period of a cycle T:

$$\text{Time error [\%]} = \frac{\text{Peak\_Time}_{\text{EMG}} - \text{Peak\_Time}_{\text{OSIM}}}{\text{T}} \cdot 100$$

Error between numerical (OSIM) and experimental (EMG) in terms of area under the signal (Area):

$$\text{Area error [\%]} = \frac{\text{Area}_{\text{EMG}} - \text{Area}_{\text{OSIM}}}{\text{Area}_{\text{EMG}}} \cdot 100$$

The parameters above were evaluated for each subject on the mean curve among the second, third and fourth cycle in flexion or extension, normalized to cycle duration. After that, parameters calculated for each subject were successively averaged over the six subjects to obtain peak, time and area errors as mean values and standard deviation.
A second investigation was carried out in terms of loads acting on the tibia, in particular by considering the shear load acting on the tibial plateau and after resolving the shear load into the ACL and PCL loads. The Numerical results obtained from OpenSim were compared to those deriving from a bidimensional Analytical model developed by the authors (Fig.3). This model adopted the same overall dimensions and inertial properties (mass and moment of inertia of each segment) of the gait2392_model; in particular, both the Numerical gait2392_model and the Analytical model adopted the knee schematization proposed by Yamaguchi et al. [9], which introduces different lever-arms of the two tendons of the extensors muscles attached to the patella.

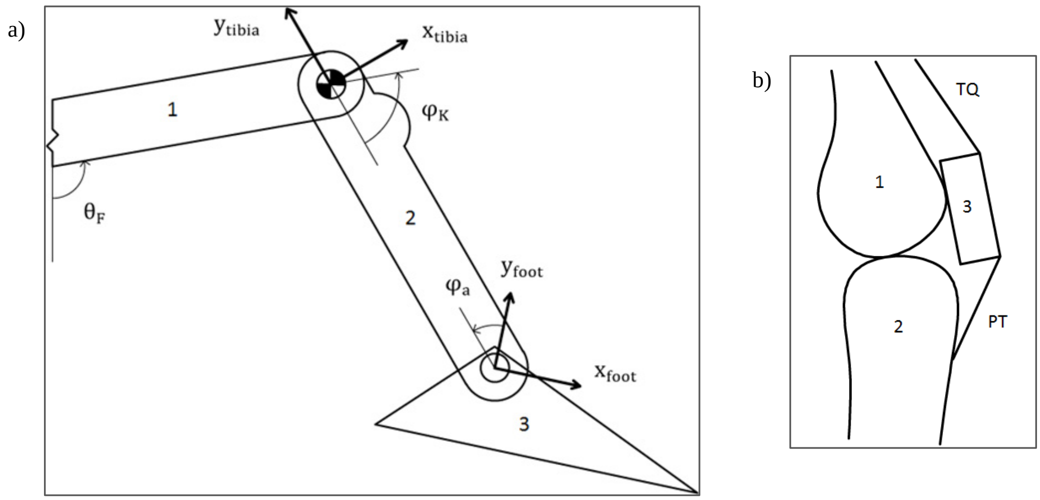

Fig.3. a) Analytical model used in the analysis.1: femur; 2: tibia; 3: foot; θ_F, φ_k , φ_a: kinematics angles; x_{tibia}, y_{tibia}, x_{foot}, y_{foot}: reference axis
b) Schematic Representation of the knee deriving from Yamaguchi's study, [9]. 1:femur;
2:tibia; 3:patella; TQ: tendon of quadriceps; PT: patellar tendon.

Kinematic and kinetic input data used to simulate the movement in the analytical solution were the same used for OpenSim numerical solution. Muscular forces were evaluated using the Herzog's formulation (Herzog et al. [3]): lever-arm and line of action of the major muscles acting during the movement were expressed as a function of the knee flexion angle measured in the local reference system embedded to tibia shown in Fig.3.a. The relation suggested by Nigg et al. [7], based on the muscle PCSA normalization, was used to solve the load sharing problem among the different muscles involved in the movement. Once the muscular forces were estimated, it was possible to obtain the instantaneous reaction loads acting on the tibia by imposing its equilibrium. Eventually, after focusing on the shear load applied to the tibial plateau, the force at ACL and PCL were calculated assuming the line of action suggested by Herzog et al. [4] again and resolving the polygon of forces acting on the tibial plateau, with the sign convention reported in Fig.6. Due to the fact that the force at the cruciate ligaments is not calculated in the gait2392_model, in order to compare the results, the shear on tibia evaluated by OpenSim software was used to resolve forces at the cruciate ligaments as described above by using the Herzog's approach. The results of analytical and numerical solutions were expressed as mean and standard deviation of the three collected cycles and normalized to the maximum value of the knee torque, in order to compare them among subjects of different absolute strength. After that, the mean results of all subjects were calculated.

4.Results

The results of the comparison of muscular activation evaluated by using electromyography and OpenSim at 60°/s, 120°/s, 180°/s and 240°/s, considering all six subjects, are shown in Fig.4. As it is possible to see, the error related to the synchronism (Fig.4.b) presents the lowest values, usually positive (OpenSim peak occurs earlier than experimental EMG), and with a decreasing trend with increasing angular velocity (maximum value: 24.3±14.1% for Vastus Medialis at 60°/s). Errors related to the Peak value (Fig.4.a) and the Area under the curve (Fig.4.c) are higher. The area error is always positive (the activation calculated by the software is lower than experimental one) and it tends to increase slowly with the increase of velocity, showing a maximum value of 45.4±4,3% for Vastus Medialis at 240°/s. A clear trend for the error based on the peak values can't be found in Fig. 4.a: however, a maximum error of 29.1±7,3% for Vastus Medialis at 60°/s was found, with Biceps Femoris showing typically negative values.

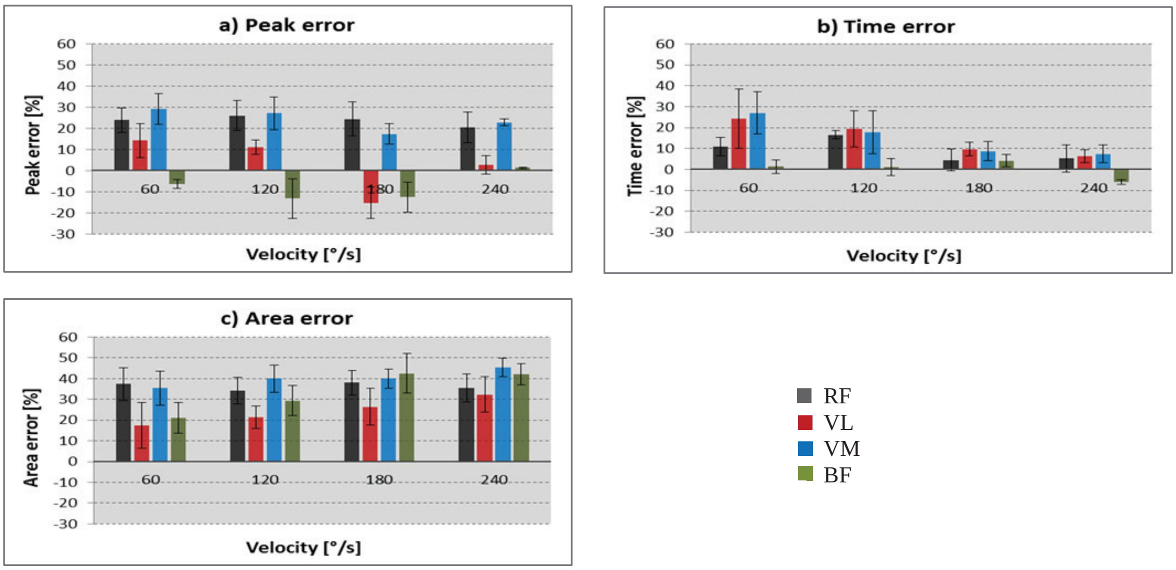

Fig.4. Results of the comparison in terms of muscular activation evaluated experimentally and numerically at different speeds. a) Peak error; b) Time error; c) Area error. (n=6)

Comparisons between Analytical and Numerical results at the tibial plateau are based on the real knee flexion angle (13.72±4,35° to 92.41±3.71°) as evaluated by OpenSim IK, which is different from the range measured by the machine loading arm because of the small misalignment between the knee joint and the joint of the machine.

Regarding the tension at ACL and PCL, the profile is of the average curve of the 6 subjects is shown as an example in Fig.5 at 60°/s, within the range 13°÷94°, due to the scatter of results; these findings can be extended to other three velocities. In Extension (Fig.5.a), the shear load applied to the tibial plateau evaluated by OpenSim resulted to point forward (positive) in all range of motion; on the other hand, the shear evaluated by the analytical model points backward (negative) between 37° and 13° of knee flexion angle, while it points forward (positive) in the early portion of the extension movement. Consequently, in Fig.5.b it appears that the PCL is always in tension by using the numerical results; on the contrary, by considering the results of the analytical model, the ACL is strained from 37° flexion to full extension, and it remains unstrained in the other portion of the extension movement, in which the PCL is loaded instead.

In knee flexion, Fig.5.c shows that the required shear load at the tibial plateau points forward in all range of motion, both after considering the numerical and the analytical results; the shear evaluated by the analytical model is higher than the numerical one.

Consequently, only the PCL is strained for both models during flexion (Fig.5.d).

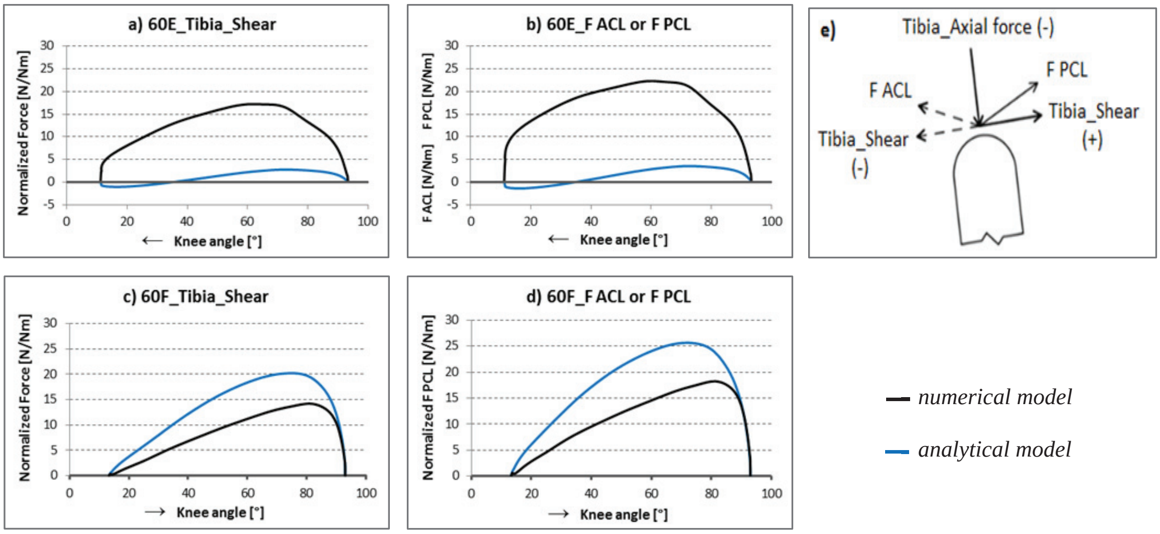

Fig.5. Knee loads at 60°/s from Numerical and Analytical solutions. a) Shear on Tibial Plateau (Tibia_Shear) in extension. b) Tension on ACL or PCL in extension, normalized to maximum knee torque. c) Shear on Tibial Plateau in flexion. d) Tension on ACL or PCL in flexion, normalized to maximum knee torque. e) Notation: shear positive if the force points forward. Tension at cruciates: shear positive, PCL strained. Shear negative: ACL strained.)

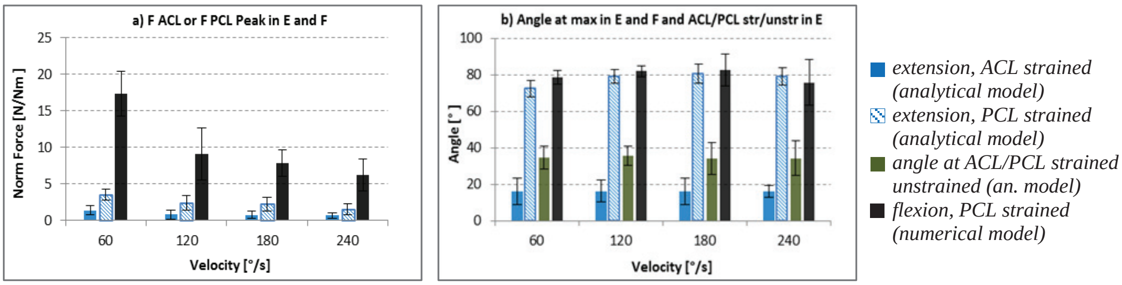

Fig.6. a) Peak force on ACL and PCL at different velocities in Extension and Flexion, normalized to maximum knee Torque; b) angle at which the maximum force at ACL and PCL is reached in extension and flexion and angle at which the ACL becomes unstrained in extension (analytical model) at different velocities. Analytical and numerical results.

The results obtained at the other velocities are consistent with the results at 60°/s and give an insight about the overall trend. Fig.6 synthetizes the results at different velocities of peak force at the cruciate ligaments (Fig.6.a), angles at which the maximum force occurs and angles at which the ACL becomes unstrained with the analytical approach in extension (Fig.6.b). For the reasons described below, in extension only the results deriving from the analytical model are taken into account; in flexion those of the numerical model. The peak force decreases with the increasing velocity; it is higher in flexion with respect to extension. The maximum is 1.41±0.65 N/Nm for ACL in extension at 60 °/s; 17.32±3.11 N/Nm for PCL in flexion at 60°/s. The angle at which the maximum occurs and the angle at which the ACL becomes unstrained in extension are instead quite constant: in extension the maximum for ACL is reached at 16.26±5.93°, for PCL at 77.84±5.12° and the angle at which ACL becomes unstrained is 34.75±8.73°; in flexion the maximum occurs at 79.78±8.13°.

5.Discussion

The present work intended to extend the method developed in a previous pilot set of tests [8] and to go deeper in the analysis of the knee joint structures, involving cruciate ligaments.

Regarding muscular activation, the higher value of area under the signal measured experimentally can be related to some kind of co-activation, which was not associated to an increase of torque and was not simulated by the software. However, because the maximum Area error between electromyography and OpenSim resulted to be 45.4±4.3% for vastus medialis at 240°/s, it is

reasonable to say that the gait2392_model is able to give significant results in the evaluation of muscular forces for the present exercise. These finding are in line with the previous study done by Petrone et al. [8].
In terms of tension at cruciate ligaments in extension, the results obtained by the analytical model are in good agreement with those obtained by Kaufmann et al. [5] and Beynonn et al. [1]; as a matter of fact, in these previous studies it was demonstrated that during the knee flexion-extension, in extension the ACL is strained only in the last phase of the movement. For this reason, the gait2392_model can't be used to evaluate the tension at cruciates in extension, or it requires a more sophisticated model of the knee passive structures. In flexion, the tension curves obtained both from the numerical and the analytical approaches are consistent with those deriving from Kaufmann's study [5]. Because of the good correspondance between electromyography and muscular activation evaluated numerically, it is reasonable to assume that gait2392_model is more reliable than analytical one in producing loads to predict cruciate tension in knee flexion.

6.Conclusions

Aim of the study was to predict the cruciate ligaments loads during the knee isokinetic flexion-extension. A numerical approach and an analytical approach sharing the same kinematic and kinetic recorded data were obtained. By comparing the results with those in literature, it appears that the results of the numerical approach should be used mainly in flexion, in which the maximum load condition is reached at 60°/s and the angle at which this maximum occurs is quite constant with increasing velocity. In extension, the results of the analytical model are more reliable and suggest that the maximum force occurs at 60°/s at an angle that is quite constant with an increasing velocity; moreover the angle at which the ACL starts straining is quite constant too. In terms of clinical relevance, it can be stated that the range of extension between 0° and 35° motion should be avoided in order to avoid to strain the ACL, in particular for subjects after ACL reconstruction during rehabilitation.

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