LIGAMENTOUS KNEE JOINT - EFFECT OF LAXATION AND PARTIAL RUPTURE

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ABSTRACT

The effect of cruciate ligament injuries on the dynamic response of the human knee joint is presented. This effect is considered as a change of the ligament force coefficient from it's original value to a reduced value. This change may represent the partial rupture of the ligament, or a degree of laxation. The results for both cruciate ligaments show that the load is shared between the anterior and posterior cruciate ligaments in a certain manner consistent with the anatomy of the human knee joint. The effect of cruciate ligament laxation may be a qualitative measure of injuries by applying a small pulsating load on the tibia and compare the change of flexion angle with the time after injury with that for the same person before injury. This may help to estimate whether the anterior cruciate or the posterior one is injured.

NOMENCLATURE

A	The amplitude of the external dynamic load (N)
$f_1(x)$	A function representing the equation of the femoral articulating surface.
$f_2(x')$	A function representing the equation of the tibial articulating surface.
I_z	Moment of inertia of leg (Nms^2).
M	The mass of the leg (kg).
M_e	The external moment (Nm).
n_1	The unit normal to the femoral surface.
N	The contact force.
$_c$	The position vector of the contact point.
$_0$	The position vector of the origin of the coordinate system (x',y') relative to the coordinate system (x,y).
	The time elapsed from the start of motion (s).
	The load duration (s).
y	The coordinate system relative to the tibia.
,y'	The coordinate system relative to the femur.
	The distance between the coordinate systems in x direction (m).
	The distance between the coordinate systems in y direction (m).
	The angle of rotation between the two coordinate systems.
$_l$	The unit vector along the ligament m.
	The coefficient of friction between the tibial and femoral articulating surfaces.
$_c$	The position vector of the contact point in the coordinate system x',y'.
$_m$	The position vector of the articulating attachment point of the m ligament relative to the femur.

INTRODUCTION

The most important field of biomechanics is helping physicians to get the right diagnosis. Hence, the study of dynamic models is essential in the presence of some diseases or joint damage. The study of these models may help in the estimation of forces and moments applied to the human body during certain motion and their effects. These models may help physicians to have an engineering comprehension for the stages of field injuries. If these injuries are related to the knee joint, the physical fitness of the cruciate ligaments has to be checked. This is due to the important function of the cruciate ligaments [1]. The posterior cruciate ligament prevents forward sliding of the femur, particularly when the knee is flexed, while the anterior one prevents backward sliding of the femur and hyperextension of the knee and limits medial rotation of the femur when the foot is on the ground.

R. Crowninshield et al. [2], based their model upon mathematical calculation and, in vivo, measurements of ligament length patterns. This model was accounted for geometry, characteristic of motion, and the material properties of the knee. They pointed out that the stability of the knee joint is resulted from the ligamentous structure of the knee and this does not include the effect of muscular activity. To simplify their model, the relation between ligament force and ligament strain was assumed to be in a linear form. The relative effect of a given ligament was investigated by eliminating the element in the model and comparing this to actual tests where the ligament is transacted. This comparison -in some cases- showed a great difference between theoretical and experimental results. Neither external dynamic loads nor body weight were considered. The effect of contact conditions, friction, non-linearity of ligamentous stress-strain relationship, articulating surface equations, external moments, the effect of partial rupture, were absent as well.

L.K. Dorius et al. [3], presented an analytical investigation for the dynamic response of the leg torsion for cases of snow ski injuries. The results indicated that ankle, knee and tibial injuries exhibit dynamic behaviour. It also helped athletes to take a good binding to eliminate ski injuries. In the event of knee joint, several useful information were obtained. J. Mansour et al. [4], constructed a device to determine the moment acting on the knee joint when all muscles crossing it are relaxed (passive elastic moment). T. Fukubayashi et al. [5], tested the anterior - posterior motion of normal cadaver knees from zero to 90 degrees of flexion using special apparatus which applies a dynamic load on knee joint.

In the present work, the two- dimensional dynamic model of the tibiofemoral joint [6], is used to study the effect of partial rupture of cruciate ligaments on the other ligaments or contact forces. This may help in diagnosis by comparing the response before and after injury.

ON THE ANATOMY OF THE HUMAN KNEE JOINT.

The human knee joint consists of two joints, the tibiofemoral joint, and the pattellofemoral joint. The ligamentous structure is connecting the tibia with the femur as a local controller, independent of the central nervous system [7].

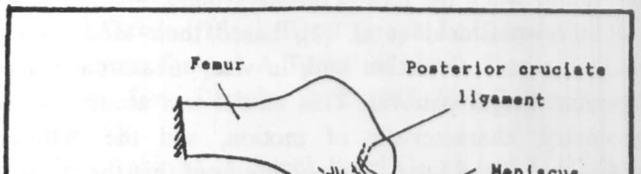

Figure 1. The ligamentous structure of the human knee joint.

Figure (1), shows the position of cruciate ligaments a the collateral ligaments. From this figure, one can reali that the cruciate ligaments are the primary restrain against large anterior and posterior displacement of th tibia [8]. So, if the cruciate ligaments are laxed or partial ruptured the control of the leg motion or even stability o motion will be greatly affected. Then, the problem o cruciate ligament injuries is the problem of the leg motio control, and the defective cruciate ligament may cause sort of disability.

MATHEMATICAL MODEL

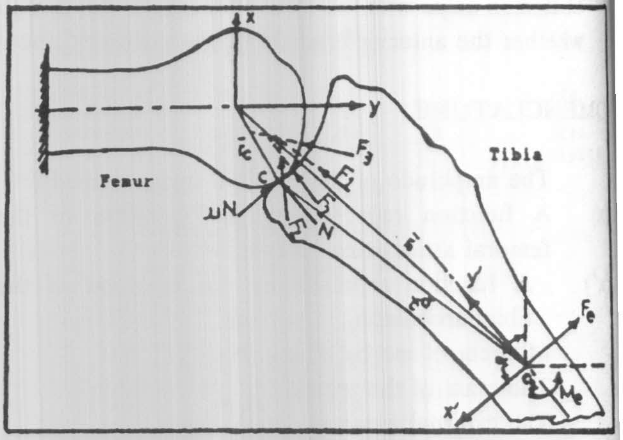

Figure 2. The two dimensional representation of the ligamentous knee joint.

Figure (2), represents the forces acting on a moving tibi for two dimensional model of the knee joint. Th procedure to solve for the dynamic model can be outline as follows:

1- Study the geometric compatibility of the articulatin surfaces of the tibia and femur.

2- The major four ligaments are only considered. Thes are :

the lateral collateral ligament (LC), the media collateral ligament (MC), the anterior cruciat ligament (AC) and the posterior cruciate ligamen (PC).

These ligaments are treated as non- linear springs.

3- The equations of motion governing the forced motio of the tibia with respect to the femur are written.

The above mentioned procedure is presented in detai elsewhere [6], and summarized here for convenience. The two geometric compatibility equations

$$\{r_c\} = \{r_o\} + [T]\{\rho'_c\} \tag{1}$$

where [T] is a transformation matrix. The contact condition

$$\tan\alpha = \frac{\left[\left(\frac{df_1}{dx}\right)_{x=x_c} - \left(\frac{df_2}{dx'}\right)_{x'=x'_c}\right]}{\left[1 + \left(\frac{df_1}{dx}\right)_{x=x_c} * \left(\frac{df_2}{dx'}\right)_{x'=x'_c}\right]} \tag{2}$$

And the three equations of motion

$$(F_e)_x + \gamma N(\bar{n}_1)_x + \delta\mu N(\bar{n}_1)_y + \sum_{m=1}^{4} F_m(\bar{\lambda}_m)_x = M\ddot{X}_0 \tag{3}$$

$$(F_e)_y + \gamma N(\bar{n}_1)_y + \delta\mu N(\bar{n}_1)_x + \sum_{m=1}^{4} F_m(\bar{\lambda}_m)_y = M\ddot{y}_o \tag{4}$$

$$M_e + (T\rho'_c)(\gamma N\bar{n}_1) + (T^{-1}\rho'_c)(\delta\mu N\bar{n}_1) + \sum_{m=1}^{4} (T\rho'_m)(F_m\bar{\lambda}_m)_x = I_z\ddot{\alpha} \tag{5}$$

where $\delta = \pm\gamma = \pm 1$

The external force (Fe) is suggested to have the form of exponentially sinusoidal pulse of duration t_o, and amplitude A:

$$F_e(t) = Ae^{4.73(t/t_o)^2}\sin(\pi t/t_o)$$

The above mentioned equations were solved numerically using Gauss elimination method after approximating the time derivatives by Newmark difference formulae.

CASE STUDY

The ligament force coefficient is not constant for all human knees, so a comparison between unlimited values of results can be done. Here the effect of change in ligament force coefficient is studied as a percentage of the original healthy value. This change takes place due to the laxation or partial rupture of the cruciate ligaments. The change of ligament force coefficient here is studied only for the cruciate ligaments because the collateral ligaments has a slight effect on joint laxity which probably would not be clinically detectable [9].

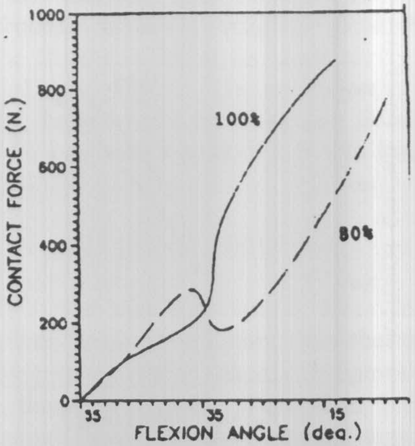

Figure 3. The effect of anterior cruciate ligament force coefficient on the contact force.

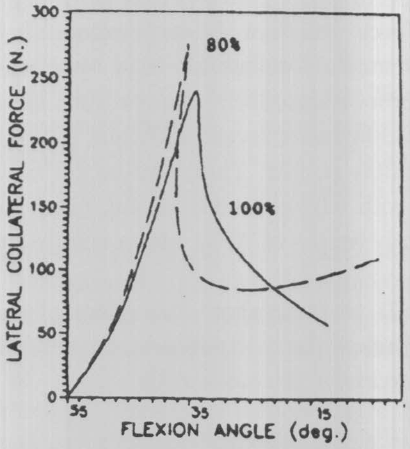

Figure 4. The effect of anterior crutiate ligament force coefficient on the lateral collateral ligament force.

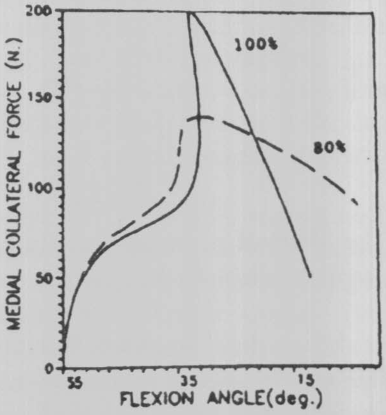

Figure 5. The effect of anterior crutiate ligament force coefficient on the medial collateral ligament force.

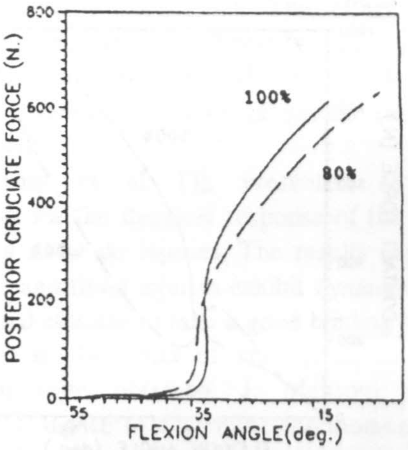

Figure 6. The effect of anterior crutiate ligament force coefficient on the posterior crutiate ligament force.

Figures (3) to (6), show the effect of change in anterior cruciate force coefficient on contact force, lateral collateral, medial collateral, and posterior cruciate ligament forces respectively. These results are achieved by using a laxed ligament force coefficient as a percentage of that for healthy people. These curves are based on 60 N peak load with 0.05 second duration, tibial length of 420 mm and body weight of 70 kg with a coefficient of friction of 0.01 .

Figures (7) to (10), show the effect of the posterior cruciate ligament force coefficient on contact force and ligament forces for the same data.

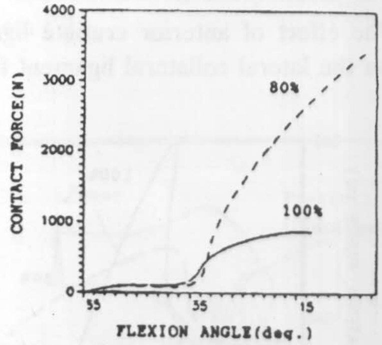

Figure 7. The effect of posterior cruciate ligament force coefficient on the contact force.

The effect of cruciate ligaments laxation or partial rupture on the antro-posterior rotation of the leg is shown as the change of flexion angle with time for healthy and laxed ligaments.

Figure (11), shows the effect of cruciate ligaments laxation at a very small peak load of 2N with a l duration of 0.08 seconds for a change in force coeffic equal to 50% of healthy subject for a body weight o kg and coefficient of 0.02 .

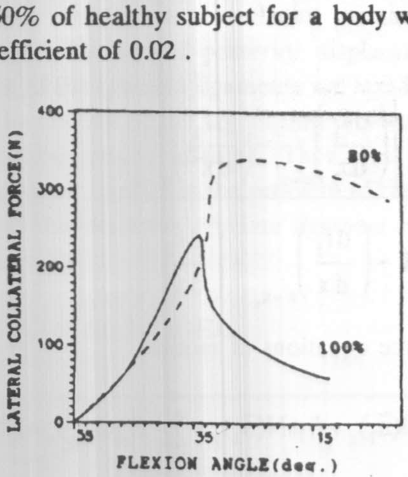

Figure 8. The effect of posterior cruciate ligament f coefficient on the lateral collateral ligament froce.

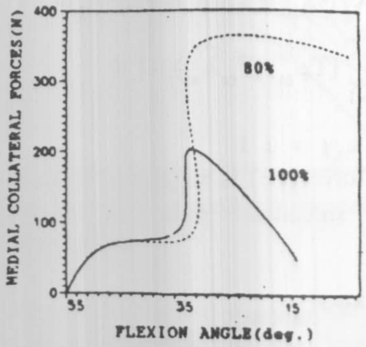

Figure 9. The effect of posterior cruciate ligament f coefficient on the medial collateral ligament force.

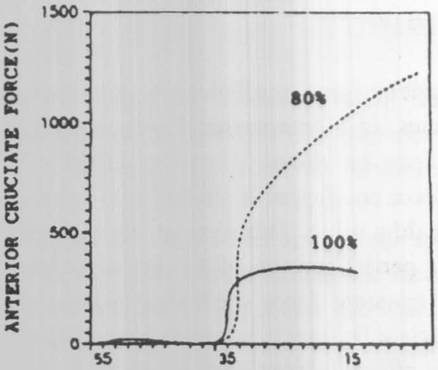

Figure 10. The effect of posterior cruciate ligament f coeffuicient on the anterior cruciate ligament force.

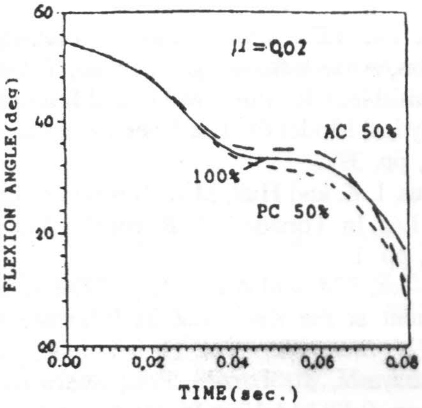

Figure 11. The effect of posterior and anterior cruciate laxation on the leg motion.

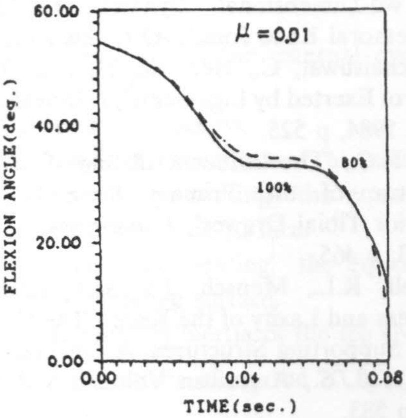

Figure 12. The effect of anterior cruciate laxation on leg motion.

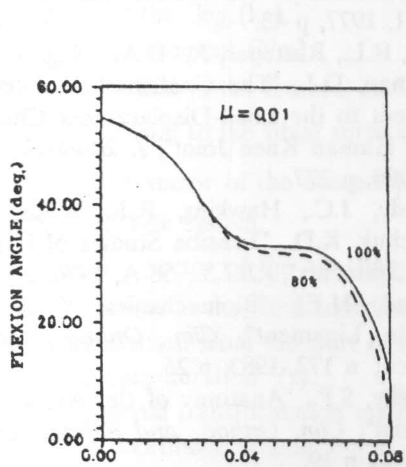

Figure 13. The effect of posterior cruciate laxation on leg motion

Figures (12) and (13) are plotted for anterior and posterior cruciate ligament laxation respectively. The change in the force coefficient for these curves is limited to 80% of healthy ligaments. The coefficient of friction is equal to 0.01, body weight of 70 kg and tibial length of 420 mm, and a load with a peak of 2 N with load duration of 0.05 second.

DISCUSSION AND CONCLUSIONS

Figure (3) shows that the contact force for a laxed anterior cruciate ligament is higher than that for healthy one till 35 degree of flexion, then it becomes lower for angles less than 35 degrees. The same behaviour is recorded through figures (4) to (6) for the same effect on ligament forces. These results mean that the effect of the laxation value of the anterior cruciate ligament is more significant during flexion angles above 35 degree and below this value its effect as a load carrier decreases.

Figure (7) shows the dramatic increase of contact force when the posterior cruciate ligament is injured. This increase begins through the region under 38 degrees of flexion and continues through a wider range of motion. The effect of posterior cruciate laxation on ligament forces has the same effect on contact force, which is shown in Figures (8) to (10).

Comparing figures (4) to (6) with figures (8) to (10), it is clear that the ligament forces are affected by the change of cruciate ligaments force coefficient generally. The results also obtained show that for small flexion angles, the effect of posterior cruciate ligament stiffness is significant. However, for higher flexion angles the anterior cruciate ligament is more effective. This is accepted according to anatomy and function of each of the cruciate ligaments [1]. Not only the anatomical point of view accepts these results, but also the experimental results reported by R.L. Piziali et al. [10]. They concluded that, the cruciate ligaments are important in antro-posterior, medial- lateral and rotary motion, as well as hyperextension and hyperflexion. Also, they found that the forward and backward sliding of the tibia on the femur are controlled by the anterior and posterior cruciate ligaments, respectively [11].

Referring to figures (11) to (13), one can realize that the change of flexion angle with time after impact is slightly affected by the reduction of the cruciate ligaments force coefficient during high flexion angles. The deviation between the curve of healthy subjects and that of the case of laxed cruciate ligament is not sensible till a flexion angle of about 34 - 38 degrees. After that, it is easy to recognize that during most of the period considered the laxed anterior cruciate ligament curve is above the healthy one, and the curve of laxed posterior cruciate ligament is under the healthy curve. Before the end of loading time, the curve of the injured anterior cruciate ligament decreases sharply intersecting the curve of the posterior cruciate ligament. This means that both ligaments are responsible for the stability of the joint. This result is confirmed by the fact that the cruciate ligaments were found to carry almost the entire antro-posterior load [11].

The results show that the effect of posterior cruciate injuries is more influential than that for the anterior. This agrees with the fact that "the posterior cruciate ligament is significantly stronger than the tibial and anterior cruciate ligament" [12].

It may be also concluded from figure (12) that not only the posterior cruciate ligament but also the anterior one affects the motion of the tibia through the range of motion. This is accepted since the anterior cruciate ligament is a necessary structure to the stability of the knee joint [13]. The contribution of the anterior cruciate ligament force coefficient on the tibial motion during almost the whole period of time is due to the fact that at any position of the knee, a portion of the anterior cruciate ligament remains under tension and functional [14].

Finally, these results may help in constructing a device which enable physicians to have a good diagnosis for cruciate ligament injuries without surgery. To have such diagnosis, there has to be a relation between, change of flexion angle with time for the same patient before injury to compare it with the same relation after injury. This may be impractical for any person to have such a relation. But for athletes, it is important for them and in the same time easy to apply this test on their knees.

This test is simple and will not take more than few seconds, so the diagnosis will be so fast after injury which has a great importance. That is because it is well known that the ligaments tend to be shortened after rupture and if the treatment is delayed, the player may loose his previous control on his leg. Many famous players were retired because of the cruciate ligament injuries and spend long time before discovering these injuries. So, if this device is available, the disability due to cruciate ligament injuries will be decreased.

The procedures of this test are:

1- Set the patient in a standard position corresponding to 54.7 degree of flexion.
2- Apply a standard load at a fixed position on his leg .
3- The leg is fastened to a lever connected to fixed disc with variable resistance, then the motion of the leg change the electric current passing through the potentiometer.
4- This relation with time is recorded or plotted.
5- If the player is injured, these steps have to be repeated to have a relation which will be compared with pre-injury relation.
6- The results shown in figure (11) will give the diagnosis.

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