Finite Element Analysis of Anterior Cruiciate Ligaments

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***Abstract*-Experimentally it is very difficult to find out response of ACL, because of composite nature of ligament. Previously many techniques have been developed by various researchers in order to study the response of ACL at different parameters such as by considering weight of human body, vivo testing etc. Experimental techniques are unable to perform on different parameters and also very costly due to preservation of original human ACL. Therefore, Finite Element Analysis has emerged as a viable approach for ligament analysis.**

This work presents Finite Element modelling and analysis of ACL ligament using high end software tools. Non-Linear static analysis is applied to predict the strength of ACL by considering flexion, tension and torsion, before and after increasing the volume of ligament. In every case the stress-strain relationships and load-deformation relationships shows the strength of ACL. 3D scan image of original ligament is used for analysis purpose. In each increased volume and normal ligament cases, analysis has to be done by considering flexion, torsion and tension parameters.

Keywords-Anterior Cruiciate Ligament, Mechanical Properties of ACL, Viscoelastic properties, Finite Element Analysis of ACl,

I. INTRODUCTION

A. The anterior cruciate ligament (ACL) is important for knee stabilization. Unfortunately, it is also the most commonly injured intra-articular ligament. Due to poor vascularisation, the ACL has inferior healing capability and is usually replaced after significant damage has occurred. Currently available replacements have a host of limitations.

B. The ACL controls anterior movement of the tibia and inhibits extreme ranges of tibial rotation. The majority of authorities believe that the ACL consists of 2 major bundles, the posterolateral bundle (PL) and the anteromedial bundle (AM). The AM bundle is 33 mm and is 18 mm for the PL bundle. The overall width of the ACL in cadavers ranged from 7 to 17 mm, with the average being 11 mm. The ACL is a dense, highly organized, cable-like tissue composed of collagens (types I, III, and V), elastin, proteoglycans, water, and cells. The human ACL has an average length of 27–32 mm and Average ACL cross-sectional area is 36 and 47 mm2 for women and men, respectively. The ACL is composed of type I collagen fibers.

1.1 Mechanical Properties Of ACL:

Ligaments are composite, anisotropic structures exhibiting non-linear time and history- dependent viscoelastic properties. Ligaments display triphasic behaviour when exposed to strain. First there is a region where the ligament exhibits a low amount of stress per unit strain, this is called the non-linear or toe region. This region is followed by an area noted for its increase in stress per unit strain, called the linear region. The last region displays a slight decrease in stress per unit strain and marks the failure of the ligament; this is the yield and failure region. The presence of this unique behaviour is due to the components of the ligament and their arrangement in the tissue. When force is first applied to the tissue it is transferred to the collagen fibrils. This results in lateral contraction of fibrils, the release of water, and the straightening of the crimp pattern in the collagen fibrils. Once the crimp pattern is straightened, the force is applied directly to the collagen molecules. The collagen triple helix is stretched and interfibrillar slippage occurs between cross links. This results in an increase in stress per unit strain. Finally, the collagen fibers in the ligament fail by defibrillation causing a decrease in stress per unit strain and tissue failure.

II. METHADOLOGY

Finite element analysis carried out by using Ansys 14.5.

2.1Modelling:

The acquisition of the accurate geometry of the ligaments and possibly the bones is fundamental requirement for the construction of the three-dimensional F.E models of the ligament. Laser scanning and medical imaging is the primary techniques that can be used for this purpose. Laser scanning can be very accurate but cannot differentiate between the ligament of interest and surrounding bone and soft tissue structures. It can only digitize geometry that is visible directly from the laser source. Both magnetic resonance imaging (MRI) and computer tomography (CT) can be used to acquire ligament geometry.MRI can provide detailed images of soft tissue structure. When compared CT with MRI, CT yields superior spatial resolution and better signal to noise ratio.

Extraction of the geometry of ligaments from CT or MRI data is performing by first segmenting the boundary of the structure. Once the ligament of interest is segmented in the 3D image dataset, polygonal surface may be generated by either lacing together stacks of closed bounded contours or by performing is surface extraction.

FEA mesh model with femur surface and attached ACL ligament. The femur surface is the upper part of knee joint which is considered for the data acquisition and segmentation and geometry construction. The ligament is inserted in the femur part. It is an approximate geometry, where the midsection cross-sectional area is smaller than that of the insertion. A typical ACL is comprised of bundle of collagen fibre, but the model used here is solid model with anisotropic material properties.

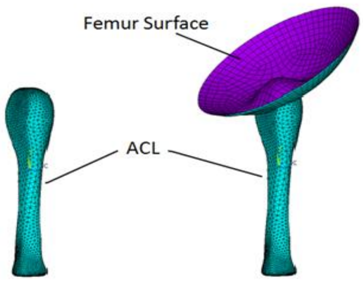
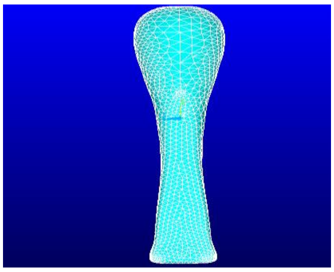


Fig. 2.1.1 FEA meshed model of ligament



2.1.1 Material Properties

The material properties used are visoelastic and anisotropic properties.

2.1.2 Viscoelasticity

The shape of the stress-strain curve depends on the material itself and the test condition. However when the loads are applied and removed slowly, certain features of the stress-strain curves are similar for all structure materials. For example if the load is sufficiently small, the relation between stress and strain is linearly elastic. The material that behaves in a plastic manner does not retain to a unstrained state after the load is released. If after the load removal material response continues to change with time its response is said to be Viscoelastic or Viscoplastic. Upon removal of load, The stress-strain response of viscoelastic material follows a path (AB) that is different from the loading path. But in time after complete unloading the material will return to an unstrained state (along BO).

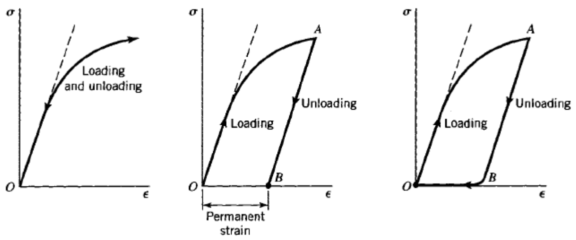


Figure (5.4) Nonlinear elastic, Plastic and Viscoelastic response

2.1.3 Viscoelastic implementation in Ansys

Viscoelastic material could be modelled by different rheological models. One of the basic rheological models for modeling viscoelasticity was proposed by James Clerk Maxwell in 1867. This model includes elastic and viscous property of material and linear ideally viscous Newtonian damper and linear ideally elastic Hookian spring in series.

As Maxwell model has the problem of giving zero stress at time infinity at relaxation test, a general Maxwell model proposed to solve the problem for viscoelastic material. It takes into account that relaxation does not occur at a single time. As viscoelastic material behaviour can be divided into large and small deformation.

$$\sigma = \int_0^t 2G(t-\tau)\frac{de}{d\tau}d\tau + I\int_0^t K(t-\tau)\frac{d\Delta}{d\tau}d\tau$$

Where σ Cauchy's stress e and Δ are deviatory and volumetric part of strain. G (t) and K(t) are Shear and Bulk modulus of function, t and τ are current and past time. I is identity matrix. Prony series was then proposed by the following formula relating shear modulus and bulk modulus over the time.

$$G = G_0\left[\alpha_\infty^G + \sum_{i=1}^{n_G}\alpha_i^G\, exp\left(\frac{-t}{\tau_G^i}\right)\right]$$

$$K = K_0\left[\alpha_\infty^K + \sum_{i=1}^{n_K}\alpha_i^K\, exp\left(\frac{-t}{\tau_K^i}\right)\right]$$

There are two viscoelastic material models present in Ansys. TB EVISC is associated with VISCO 8x element and is meant for hyperelastic behaviour. A relatively newly implementation is input via TB, PRONY which uses prony series. The shift function is independently input via TB, SHIFT.

2.1.4 Anisotropic Hyper elastic implementation in Ansys

When dealing with the nonlinear material response it is customary to separate volumetric and deviatoric behaviour. The well known relationship with elastic modulus E and Poisson's ratio μ is given,

$$K = \frac{E}{3(1-2\mu)}, G = \frac{E}{2(1+\mu)}$$

For viscoelastic materials the time dependent response is characterized by separated volumetric and deviatoric terms. Prony series use relative module to describe stress relaxation.

Viscoelastic constitutive models allow users to analyze the time-dependent relaxation or creep behavior of material, including glass, polymers, and solid rocket propellants, to name a few. one may view viscoelastic materials as containing an elastic and viscous component, similar to spring and dashpot in series. An anisotropic hyperelastic material model is used with viscoelasticity for the ACL simulation. Anisotropic hyperelasticity is a potential based function with parameters to define the volumetric part, the isochoric part, and the material directions. The exponential strain energy potential is used for characterizing the isochoric part. The strain energy potential for anisotropic hyperelasticity is given by:

$$W = W_V(J) + W_d(\bar{C}, A\times A, B\times B)$$

Where:

J=Determinant of the elastic deformation gradient

$\bar{C}$=Cauchy Green tensor

A, B=Constitutive material directions

The volumetric strain energy is given by

$$W_V(J) = \frac{1}{d}(J-1)^2$$

The exponential-function-based strain energy potential is given by:

$$W_d(\bar{C}, A\times A, B\times B) = \sum_{i=1}^{3} a_i(\bar{I}_1-3)^i + \sum_{j=1}^{3} b_j(\bar{I}_2-3)^j + \frac{c_1}{2c_2}\{exp[c_2(I_4-1)^2]-1\} + \frac{e_1}{2e_2}\{exp[e_2(I_6-1)^2]-1\}$$

The constants a1, c1 and c2 are taken from Pena, et al. and compressibility parameter d is considered to be small.

Anisotropic Hyperelastic Material Properties	
a_1	1.5 MPa
C_1	4.39056 MPa
C_2	12.1093
d	0.001 MPa-1
Viscoelastic Material Properties	
α_1^G	0.3
τ_1^G	0.3 sec
α_2^G	0.4
τ_2^G	0.9 sec

Table 2.2.3 Material Properties

2.1.5 Element Description

Solid 187 have been used in order to mesh the Ligament model. It is higher order 3-D, 10 node element. It has quadratic displacement behaviour and it is well suited for modelling irregular meshes. The element is defined by 10 nodes having 3 degree of freedom at each node: translation in nodal x, y, and z direction. The element has plasticity, hyperelasticity, large deflection, and large strain capabilities. It also has mixed formulation capability for simulating deformation of nearly incompressible elastoplastic material, and fully incompressible hyperelastic material.

2.1.6 Boundary condition

1) Normal flexion

The below figure shows the boundary conditions for normal flexion analysis where upper part is fixed and the tensile load is applied on the bottom part of ligament.

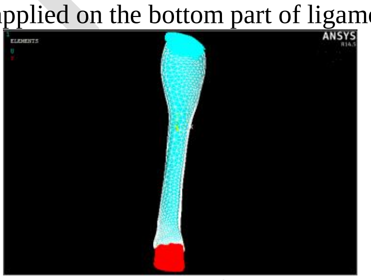


Figure (5.7) Normal flexion load

2) 45 degree flexion

The below figure shows the condition for 45 degree flexion analysis. The upper part is kept fixed and the lower part has given load at an angle of 45.

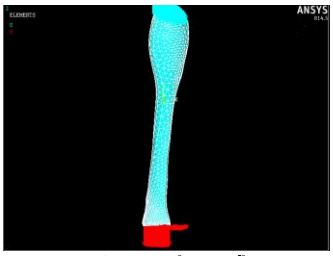


Figure (5.8) 45 degree flexion

3) Twist Load

The below figure shows the condition for the twist analysis where same upper part is fixed while lower part has given twist effect by coupling the force from the centre of the ligament to produce twist effect

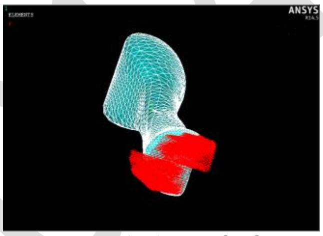


Figure (5.9) Twist load

2.2 Finite Element Analysis:

Following assumptions are made while analysis are as follow;

1) The ligament is fully developed without rupture. The cad model obtained from scanning is perfect modelling without any discontinuity.

2) The cad model is meshed with the higher order solid element (solid 187).

3) The load acting on ligament is only in one direction. Other forces are neglected.

4) Material behaviour is same like ligament.

5) Volume of the model is increase by the percentage over all dimensions.

2.2.1 Nonlinear Static Analysis

Nonlinear static analysis is performed under axial loading, bending and twist. Large deflection effects are included in this analysis. Because the purpose of this problem is to show the anisotropic, hyperelastic, and viscoelastic behaviour of the ACL ligament, a simplified model is used. The problem focuses on the ACL part only. Instead of using complex model of ligament and femur only ligament is consider for analysis, remaining part is replace by the boundary conditions.

The femur part is kept fix and constrained with all degree of freedom the load is applied on the tibia part to perform analysis. The knee joint is work under flexion; extension and rotation therefore show the behaviour of ACL under flexion, extension and rotation.

2.3.1) Flexion Analysis

The Femur part is fixed and normal load is applied on the tibia side. Four cases are considered for the analysis. The result is captured as an image for the first condition. The following images show the deformation, von misses stress, and elastic strain for the normal flexion analysis.

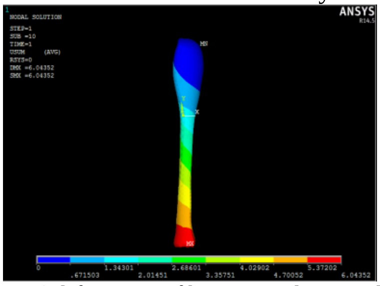


Figure (2.3.1) deformation of ligament under normal flexion

In the above picture the deformation shows at the tibia side where the forces are applied.

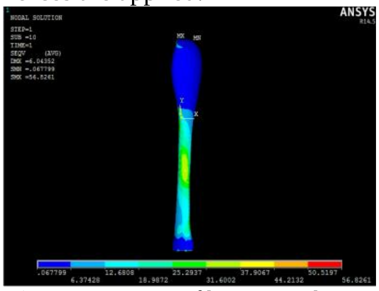


Figure (2.3.2) Von mises stress of ligament under normal flexion

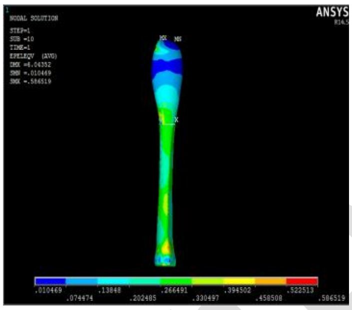


Figure (2.3.3) Elastic strain of ligament under normal flexion

2.4) 45 Degree Flexion analysis

The Femur part is fixed and 45 degree load is applied on the tibia side. four cases are considered for the analysis.

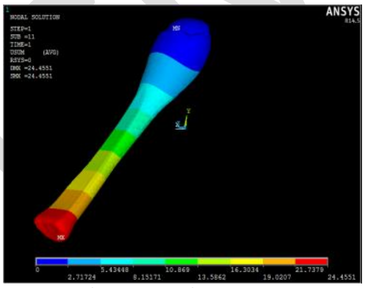


Figure (2.4.1.) Deformation of ligament under 450 flexion

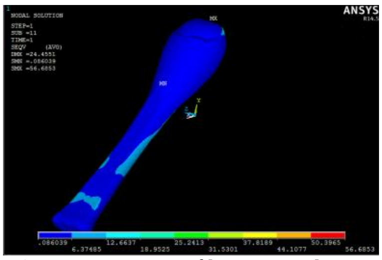


Figure (2.4.2) Von mises stress of ligament under 450 flexion

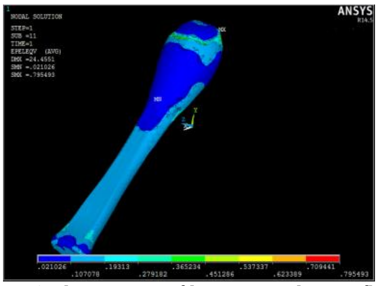
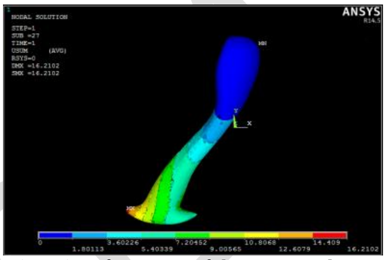


Figure (2.4.3) Elastic strain of ligament under 450 flexion

2.5) Twist analysis

The Femur part is fixed and torsion load is applied on the tibia side. Four cases are considered for the analysis.



Figure(2.5.1) Deformation of ligament under twist

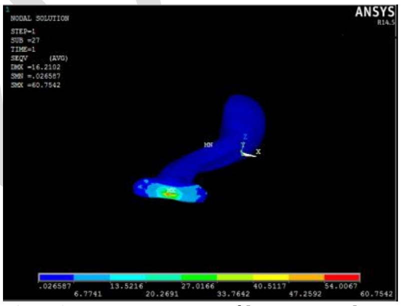


Figure (2.5.2) Von mises stress of ligament under twist

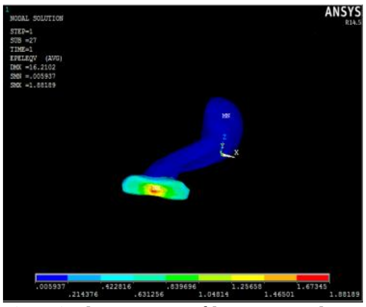


Figure (2.5.3) Elastic strain of ligament under twist

III. RESULT AND DISCUSSION

After solving all the cases for flexion and rotation for ligament, the stress-strain relationships has studied for the behaviour of ligament. 90 analysis has been done on Ansys for all cases of acl. Because the ACL transmits tensile forces experimental studies of this tissue are generally performed in uniaxial tension.

IV. RESULTS

The Load, Von mises stress, and Elastic strain are calculated for different loading condition. Four models are considered for the analysis. The result shows 2%, 3%, and 4% analysis results followed by normal ligament.

Flexion Analysis:

The below graph shows the Stress -Strain relationship for the normal ligament. The graph shows nonlinearity curve for some loading condition and after 45-50 N the curve showing linear line which shows triphasic behaviour.

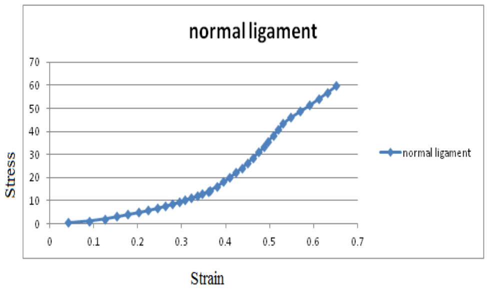


Figure (3.1.1.1) stress vs. strain relation of ligament under normal flexion

The below figure shows the effect of normal ligament and the percentage increased volume ligament for the same loading condition. Colour graph clearly shows the difference between each ligament values.

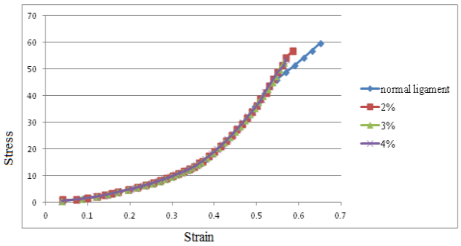


Figure (3.1.1.2) stress vs. strain relation considering all cases under normal flexion

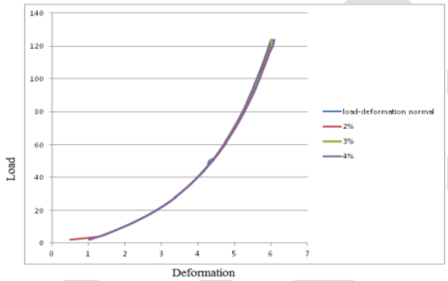


Figure (3.1.1.3) Load vs. Deformation relation considering all cases under normal flexion

45 Degree Flexion Analysis:

The Load, Von mises stress , and Elastic strain are calculated for different loading condition. Four models are considered for the analysis. The result shows 2%, 3%, and 4% analysis results followed by normal ligament

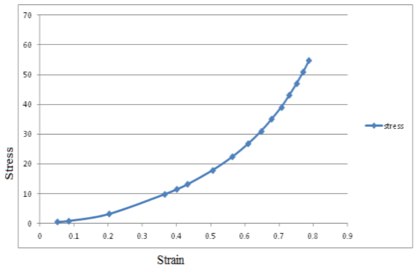


Figure (3.1.2.1) stress vs. strain relation of ligament under 450 flexion

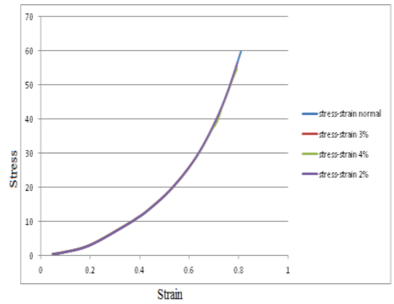


Figure (3.1.2.2) stress v/s strain relation considering all cases under 450 flexion

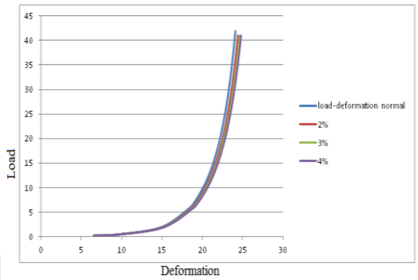


Figure (3.1.2.3) load v/s deformation relation considering all cases under 450 flexion.

Twist analysis:

The Load, Von mises stress , and Elastic strain are calculated for different loading condition. Four models are considered for the analysis. The result shows 2%, 3%, and 4% analysis results followed by normal ligament.

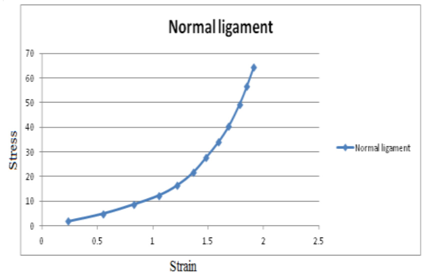


Figure (3.1.3.1) stress v/s strain relation of ligament under Twist

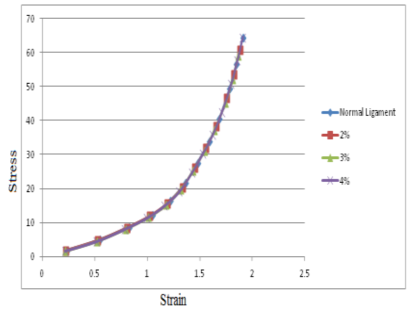


Figure (3.1.3.2) stress v/s strain relation considering all cases under Twist

V. DISCUSSION

The output obtained from model analysis is stress-strain and load-deformation. There are four results are obtained from each particular case. In order to obtained performance of ligament comparison of normal ligament with the percentage increased volume ligament carried out. Our aim is to achieve increase in performance of the ligament by increasing the volume of ligament.

1) In the model (fig.no.2.3.1, 2.4.1) the peak stress in the ACL ligament are seen in the middle. This area could be susceptible to injury when the loading condition is normal.

2) ACL can be injured or torn in a number of different ways. Some of the common ways are flexion and internal rotation of femur and tibia. During knee flexion increase in von mises stresses occurs near to the minimum cross sectional area. The stress in the ligament increases with the increase in internal rotation.

3) As the volume of the ligament increases the strain in the ligament decreases with the fewer amounts. The stress-strain curve shows nonlinearity within starting. So in order to increase performance volume increase will not be efficient.

4) Load - Deformation relation for the normal flexion analysis is same for all the ligaments. Therefore increase in volume does not effect on the deformation of the ligament. In the case of 45 degree flexion analysis the deformation is increasing slightly.

5) For the 45 degree analysis the tibia side rotates and the femur remains fixed. During flexion an increase in von mises stresses occurs near the minimum cross sectional area of the ACL. The femoral and tibial insertion zones are not consider, as this model emphasis only the ACL part behaviour irrespective of insertion zones. If one also considers the insertion part, more accurate stresses near the femoral insertion zone can be expected.

VI. CONCLUSION

As the study shows, a ligament model can be analyzed for such conditions. The results clearly shows the effect of stress - strain relation when the loads are applied on the increased volume ligament. For the normal flexion near 35 analyses are done with increased loading conditions and the graph for normal ligament showing triphasic behavior. The study of this project is to understand the ligament behavior and the same result were obtained to conclude the result. For the 45 degree flexion the stress level matches with the normal flexion at very small load comparatively. There is a chance of ligament failure if the load is act on the knee while lower leg is at 45 degree.

Stress values reduced with the increasing volume of ligament and minimize deformation and strain in all the three cases.The increase in volume of the ligament can increase the load carrying capacity of the body but the effect on the stress-strain shows less improvement compare with the normal values. To increase the ligament volume, the cost of the ligament will be very high when compared with the respected stress-strain effect. By increasing the volume of the ligament it is seen that performance of the ligament remains same. Therefore the increase in volume will not improve the load carrying capacity effectively.

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I feel happiness in forwarding this paper as an image of my research work.

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REFERENCES

[1] Kiapour Ata M., Kaul Vikas, Kiapour Ali, Quatman Carmen E., Wordeman Samuel C., Hewett Timonthy, Goel Vijay K.,"The effect of ligament modeling technique on knee joint kinematics. a finite element study". applied mathematics 2013.

[2] Hosseini Ali, Gill Thomas J, Li Guan."Estimation of vivo ACL force changes in responce to increase weight bearing."

[3] Dai Boyi, Yu Bing."Estimating ACL force from lower extremity kinematics and kinetics".

[4] Pena E., Calvo B., Martinez M.A., Doblare M. "An unisotropic visco-hyperelastic model for ligaments at finite strains. formulation and computational aspects". International journal of solid and structure 44(2007).

[5] Xie Feng, Yang Liu, Guo Lin, Dai Gang."A study on constructionl nonlinear finite element model and stress distribution analysis of anterior cruciate ligament".

[6] Song Yuhana, Debeski Richard E., Musahi Volkar, Thomas Maribeth, Woo L-Y."A three dimensional finite element model of the human anterior cruciate ligament: a computational analysis with experimental validation." Journal of biomechanics 2004.

[7] Weiss A. Jeffrey, Gardiner John C, Ellis Benjamin J, Lujan Trevor J, Phatak Nikhil S."Three dimensional finite element modeling of ligaments: Technical aspects." medical engineering and physics 2005.

[8] Woo Savio L-Y, Abramowitch Steven D., Kilger Robert, Liang Rui,"Biomechanics of knee ligaments: Injury, healing and repair". journal of biomechanics 39 -2006.

[9] Hirakawa Shunji, Reiji Tsuruno "Three dimensional deformation and stress distribution in an analytical / computational model of the anterior cruciate ligament". journal of biomechanics 33 (2000) 1069-1077.

[10] Kevin B. Shelburne, Margus G. Pandy, Frank C. Anderson "Pattern of Anterior cruciate ligament in normal walking". journal of biomechanics 37(2004) 797-805.

[11] Limbert G., Taylor M., Middleton J., "Three dimensional finite element modelling of the human ACL simulation of passive knee flexion with a stress and stress free ACL". journal of biomechanics 37(2004) 1723-1731.

[12] Bowman Jr, Karl F, Sekiya John K,"Anatomy and biomechanics of the posterior cruciate ligament and other ligaments of the knee."126-134. 2009

[13] ANSYS, ANSYS User's Manual Version 14.5, ANSYS Inc, 2013