Finite Element Analysis of the Effects of Length Increment on the Performance Characteristics of a Ligament

[1]Ashish A. Deshmukh, [2]Dr. S.G. Taji, [3]H. S. Bawiskar

[1]Shree Ramchandra College of Engineering, Lonikand, Pune, India
[2]MIT Academy of Engineering, Alandi, Pune, India
[3]Shree Ramchandra College of Engineering, Lonikand, Pune, India

***Abstract*-- With ability of analyzing fibers, FEA (Finite Element Analysis) has moved into the domain of Medical implants and their simulations. Recently we have acquired the capability of creating ligaments, the fibrous tissues which connect the bones, and give strength and control over motion. Hence we are in position of replacing damaged ones with more effect artificial ones. The Anterior cruciate ligament (ACL) is an important ligament for knee stabilization. Sadly, it is also the most commonly injured ligament in case of knee injuries. Using FEA software, 3-dimensional finite element modeling and analysis of the ligament is possible. The objective is to use Finite Element Analysis (FEA) and conduct a series of trial runs and try to simulate ligament in normal body operations of tension, flexion and torsion, then to understand how increment of length affects the performance of the ligament in the above considerations.**

Index Terms -- Artificial ligaments, Increment of length, Non-Linear FEA

I. INTRODUCTION

Biomechanics, one of the applications of engineering principles, to study forces and motions of biological systems As Biomechanics relate to sports medicine, these studies are designed to determine the direction and magnitude of forces and moments of various tissues in and around a diarthrodial joint, and also to measure the corresponding joint kinematics.

A. *Knee anatomy*

I. Bones

The knee is essentially made up of four bones. The femur (the thigh bone), which is the large bone in your thigh, attaches by ligaments to your tibia (the shin bone). Just below and next to the tibia is the fibula running parallel to the tibia. The patella, (kneecap), slides on the knee joint as the knee bends. Also there are number of ligaments, cartilages and muscles which strengthen and support the knee.

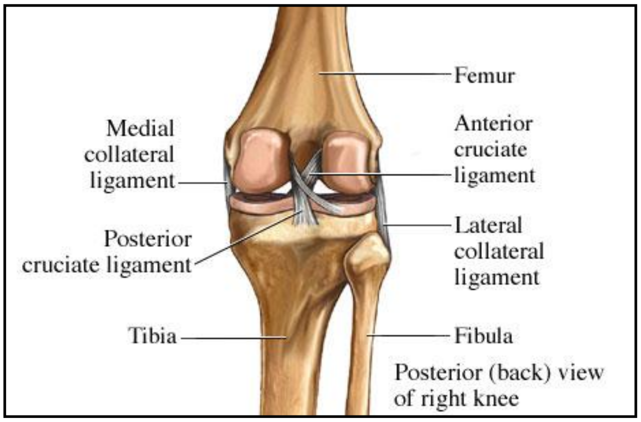

Fig.1 .Knee anatomy

II. Ligament

The knee can be thought of as basically having four ligaments holding it in place, one on each side, to stop the bones sliding sideways, and two crossing are over & in the middle to stop the bones sliding forwards and backwards.

i. *Lateral collateral ligament* – runs along the outer part of the knee preventing bending outwards.
ii. *Medial collateral ligament* – runs along the inner part of the knee preventing bending inwards.
iii. *Anterior cruciate ligament* – is one of a pair of ligaments in the centre of the knee joint that form a cross, and this is where the name "cruciate" comes from. It prevents the tibia sliding forwards in front of the femur, also provides rotational stability to the knee.
iv. *Posterior cruciate ligament* - works in conjunction with the ACL, preventing the tibia sliding backwards under the femur.

The knee ligaments make sure that the weight that is transmitted through the knee joint is cantered within the joint minimizing the amount of wear and tear on the cartilage inside the knee. Each ligament name matches its attachment point on the tibia.

B. *Introduction to Ligament*

I. Anterior cruciate ligament

The anterior cruciate ligament is important for knee stabilization. Sadly, it is also the most commonly injured intra-articular ligament. The anterior cruciate ligament controls anterior movement of the tibia and inhibits extreme ranges of tibial rotation. Due to poor vascularization, it has inferior healing capability and is usually replaced after significant damage has occurred. Presently available replacements have a host of limitations.

II. Anterior cruciate ligament mechanical properties

Ligaments are composite, anisotropic structures exhibiting non-linear time and history- dependent viscoelastic properties. Ligaments display triphasic behavior when exposed to strain. First region is where the ligament exhibits a low amount of stress per unit strain, known as the non-linear or toe region. This region is followed by the linear region, an area noted for its increase in stress per unit strain. 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 behavior is due to the components of the ligament and their arrangement in the tissue. When force is applied to the tissue it is transferred to the collagen fibrils resulting in lateral contraction of fibrils, the release of water, and the straightening of the crimp pattern in the collagen fibrils. As soon the crimp pattern is straightened, the force is applied directly to the collagen molecules, stretching collagen triple helix and inter-fibrillar slippage occurs between cross links. The result of this is 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.

III. Ligament failure

Injuries to the ligament are very common. It has been estimated that the incidence could be happen at 2/1000 people per year in the general population and much higher rate for those involved in sports activity. Ninety percent of knee ligament injuries involve the anterior cruciate ligament and the medial collateral ligament. The results of ligament injuries can be devastating. Frequently surgery is required but outcomes are variable. Further post-surgical rehabilitation could require an extend absence from work or athletic competition. Basic science and clinical studies have revealed that a ruptured medial collateral ligament can heal spontaneously. On the other hand, mid-substance tears of the anterior cruciate ligament and posterior cruciate ligament would not heal spontaneously and surgical reconstruction using a replacement graft is often required.

II. OBJECTIVES

1. To study the ligaments and their properties for the study of optimization.
2. To study various ligament failures.
3. The objective of the project is to analyze the ligament for tension, and torsion.
4. Study of stress and strain in the ligament and their relationship with respect to increased load.
5. The effect of the same with different length ligaments.
6. To increase length of ligament if possible.

III. GEOMETRY ACQUISITION

The acquisition of the accurate geometry of the ligaments and possibly the bones is fundamental requirement for the construction of the three-dimensional Finite element models of the ligament. Both magnetic resonance imaging and computer tomography can be used to acquire ligament geometry. Magnetic resonance imaging can provide detailed images of soft tissue structure. When compared, computer tomography yields superior spatial resolution and better signal to noise ratio. Extraction of the geometry of ligaments from computer tomography or magnetic resonance imaging data is performed 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 Iso-surface extraction.

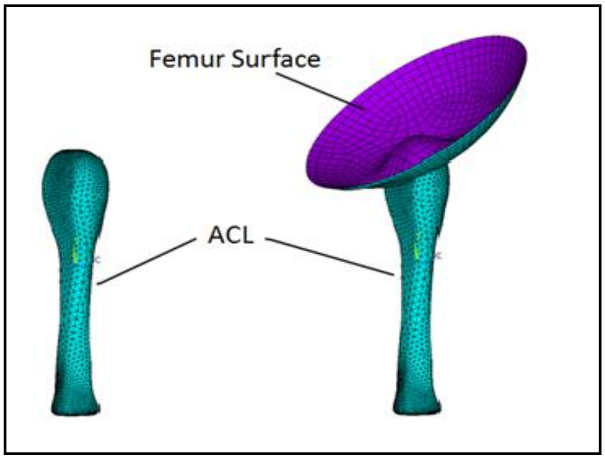

Fig.2 FEA meshed model of ligament

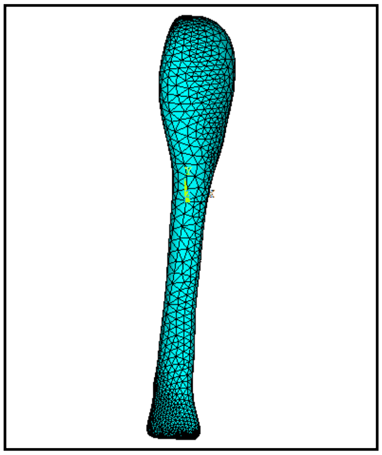

Fig.3 ACL Ligament meshed model

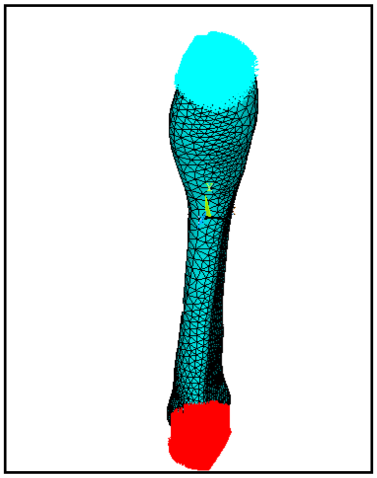

Fig.4 Axial loading condition

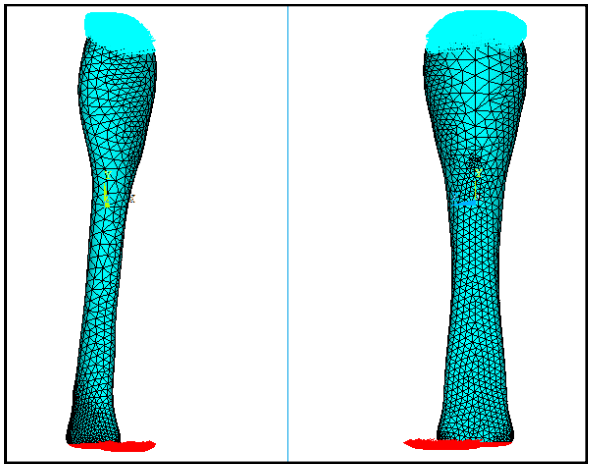

Fig.5 Bending in +X direction and +Z direction

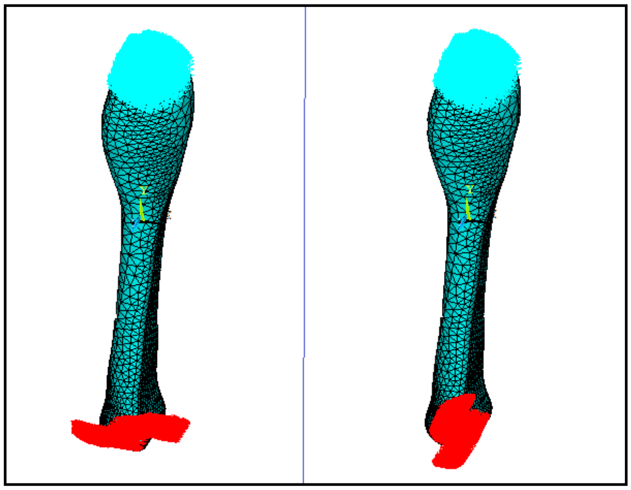

Fig.6 Twisting along X direction and Z direction

Table 1 Material Properties

Anisotropic Hyperelastic		Viscoelastic	
a_1	1.5 MPa	α_1^G	0.3
C_1	4.39056 MPa	τ_1^G	0.3 sec
C_2	12.1093	α_2^G	0.4
D	0.001 MPa^{-1}	τ_2^G	0.9 sec

IV. RESULTS AND DISCUSSIONS

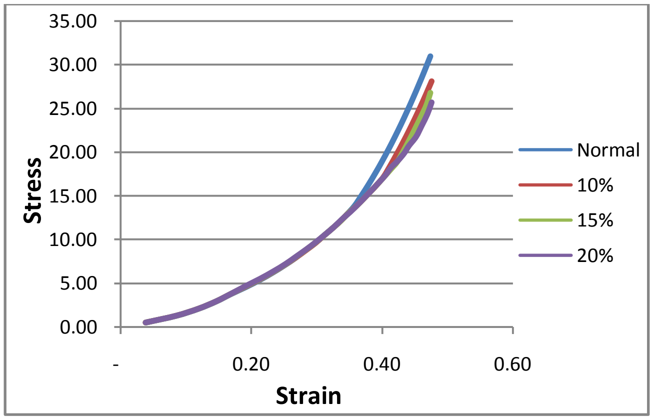

Fig.7 Stress vs. strain relation considering all cases under normal tension

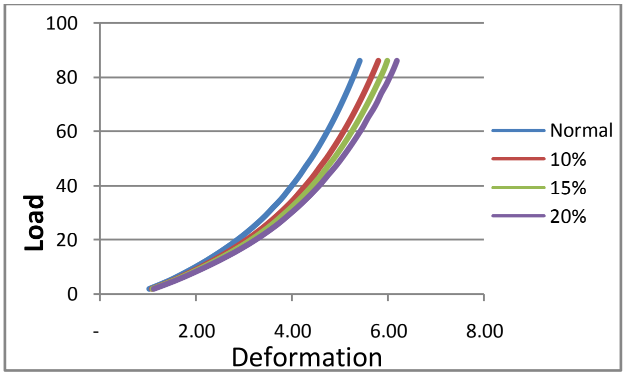

Fig.8 Load vs. deformation relation considering all cases under normal tension

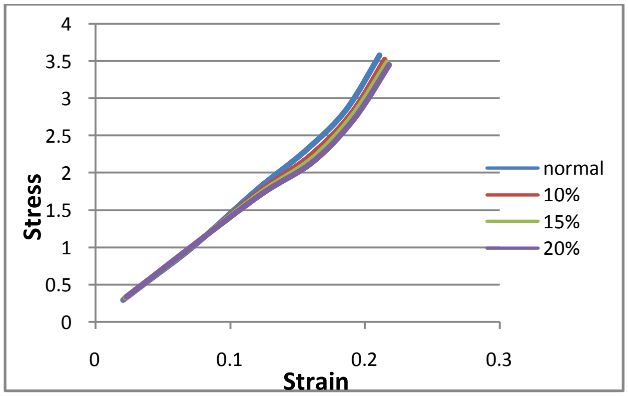

Fig.9 Stress vs. strain relation considering all cases under +X direction Bending

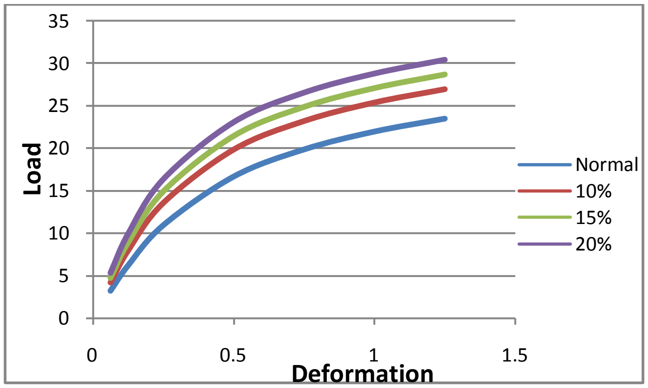

Fig.10 Load vs. deformation relation considering all cases under +X Bending

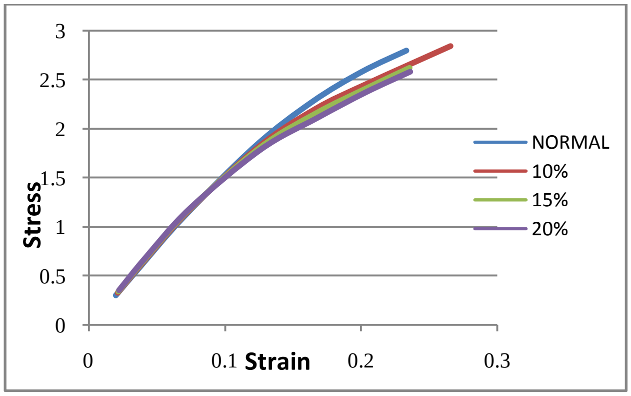

Fig.11 Stress vs. strain relation considering all cases under -X direction Bending

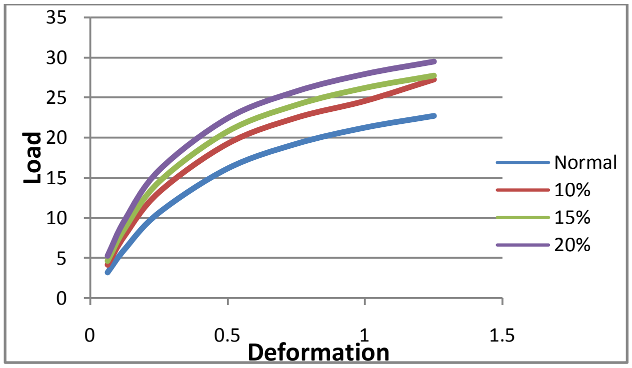

Fig.12 Load vs. deformation relation considering all cases under -X Bending

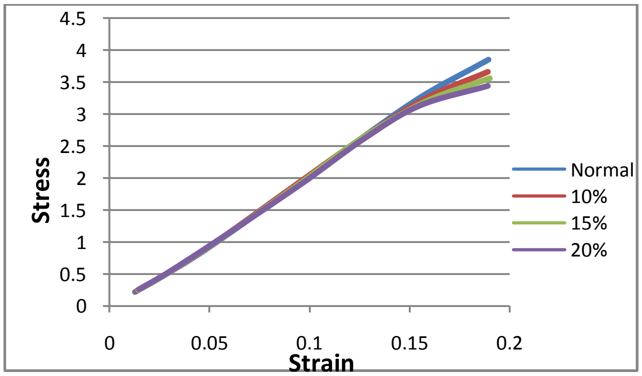

Fig.13 Stress vs. strain relation considering all cases under +Z direction bending

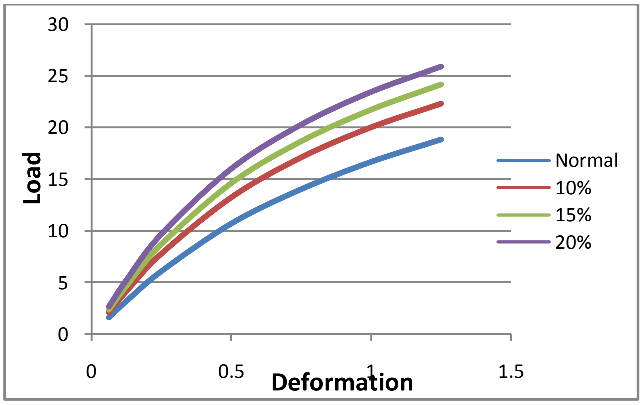

Fig.14 Load vs. deformation relation considering all cases under +Z bending

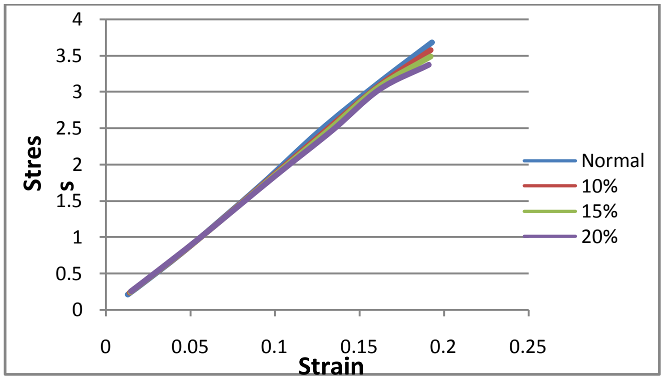

Fig.15 Stress vs. strain relation considering all cases under -Z direction bending

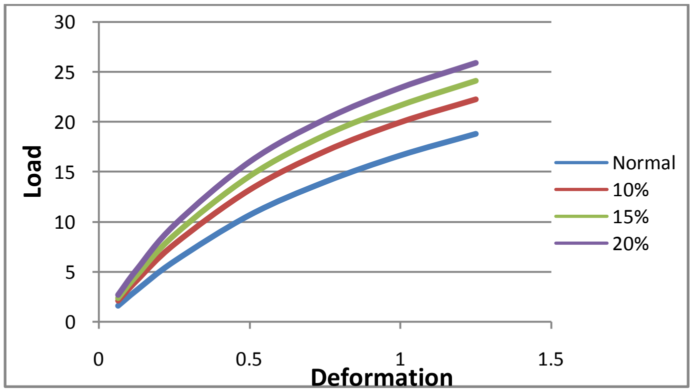

Fig.16 Load vs. deformation relation considering all cases under -Z bending

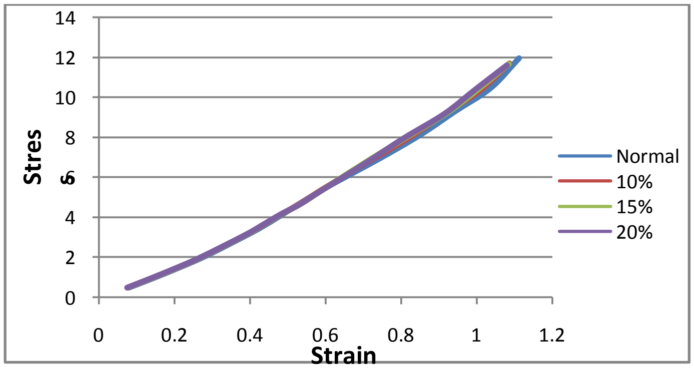

Fig.17 Stress vs. strain relation considering all cases under X direction Shear

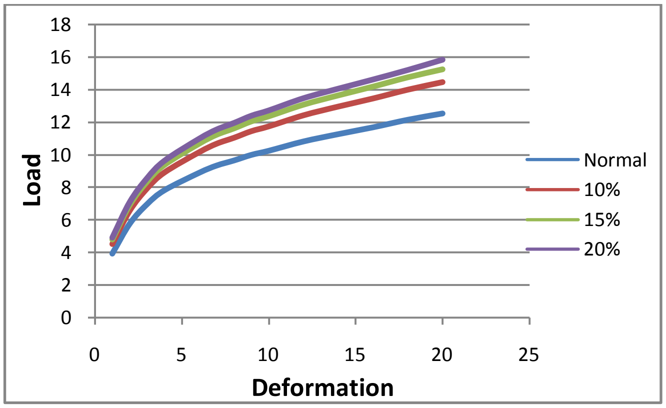

Fig.18 Load vs. deformation relation considering all cases under X direction twisting

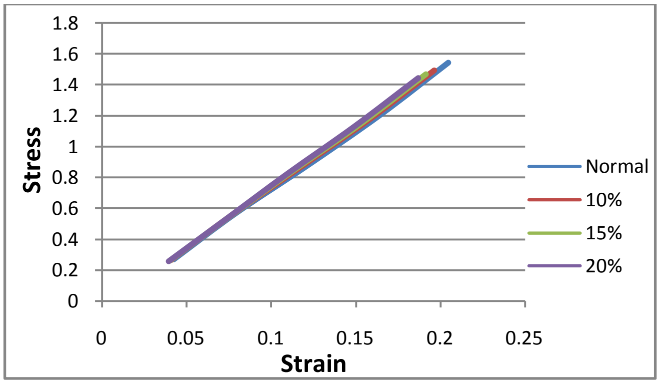

Fig.19 Stress vs. strain relation considering all cases under Z direction twisting

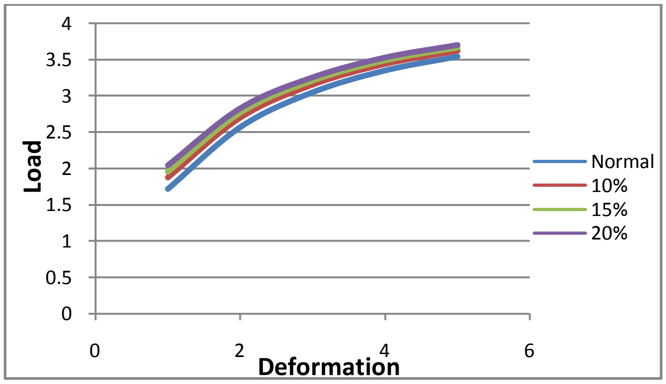

Fig.20 Load vs. deformation relation considering all cases under Z direction twisting

The output obtained from model analysis is stress-strain and load-deformation. In order to obtained performance of ligament comparison of normal ligament with the percentage increased volume ligament carried out. Aim is to achieve increase in performance of the ligament by increasing the Length of ligament

1) In the model the peak stress in the anterior cruciate ligament are seen in the middle. Suggesting middle area could be susceptible to injury when the loading conditions are normal.
2) Some of the common ways of ACL being injured or torn are flexion and internal rotation of femur and tibia. 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 length 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 length increase will not be efficient.
4) Load - Deformation relation for the normal Tension and Torsion analysis is same for all the ligaments. Therefore increase in length does not effect on the deformation of the ligament.

Table 2 determining the % Error by comparing Experimental and FEA results

Experimental		FEA		%Error
Force	Deformation	Force	Deformation	
2	1.14038	2	1.023060	10.2877
20	2.98673	20	2.850390	4.5648
50	4.39056	50	4.397490	-0.1578
80	5.29076	80	5.271170	0.3702

Taking average of all the above %Error

$$\frac{10.2877 + 4.5648 + -0.1578 + 0.3702}{4} = 3.7662$$

So the average % Error value is 3.7662 %.

Thus from above comparison, we have achieved approximately more than 95 % accuracy for the normal flexion analysis.

V. CONCLUSIONS

As the study shows, a ligament model can be analyzed for such conditions. Numbers of analysis are performed 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 tension, and twisting loading the stress level matches with the normal at very small load comparatively the increased length conditions.

While Comparing Experimental results with the FEA analysis results of the ligament we have achieved approximately more than 95 % accuracy for the normal flexion analysis. That is the % Error is within 5% which is appreciable.

Stress values reduces with the increasing length of ligament and minimizing deformation and strain in all cases.The increase in length 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 length, the cost of the ligament will be very high when compared with the respected stress-strain effect. By increasing the length of the ligament it is seen that performance of the ligament remains same. Therefore the increase in length will not improve the load carrying capacity effectively.

VI. REFERENCES

[1] Kiapour Ata M., Kaul Vikas, Kaipour Ali, Quatman Carmen E., Wordman Samuel C., Hewett Timonthy, Goel Vijay K., “The effect of ligament model technique on knee joint kinematics, a finite element study”. Applied Mathematics, 2013, 4, 91-97

[2] Hosseini Ali, Gill Thomas J, Li Guan. “Estimation of vivo ACL force changes in response to increase weight bearing.”Journal of Biomechanical Engineering Copyright © 2011 by ASME May 2011, Vol. 133 / 051004-1

[3] Pena E., Calvo B., Martinez M.A., Doblare M. “An unisotropicvisco-hyperrelastic model for ligament at finite strains. Formulation and computational aspects”. International journal of solid and structure 44(2007),760–778.

[4] XieFeng, Yang Liu, Guo Lin, Dai Gang. “A study on constructional nonlinear finite element model and stress distribution analysis of anterior cruciate ligament”. Journal of Biomechanical Engineering Copyright © 2009 by ASME DECEMBER 2009, Vol. 131 / 121007-1

[5] Weiss A. Jeffrey, Gardiner John C, Ellis Benjamin J, Lujan Trevor J, Pahtak Nikhil S. “Three dimensional finite element modeling of ligaments: Technical aspectsMedical Engineering & Physics 27(2005), 845–861.

[6] Savio L. –Y. Woo, Steven D. Abramowitch, Robert Kilger, Rui Liang “Biomechanics of knee ligaments: injury, healing, an repair” Journal of biomechanics 39(2006), 1-20.

[7] HirokawaShunji, Tsuruno Reiji. “Three-dimensional deformation and stress distribution in an analytical/computational model of anterior cruciate ligament” Journal of biomechanics 33 (2000) 1069-1077

[8] Kevin B. Shelburne, Marcus G. Pandy, Frank C. Anderson, Michael R. Torry “ Pattern of anterior cruciate ligament force in normal walking” Journal of biomechanics 37(2004), 797-805.

[9] G. Limbert, M. Taylor, J. Middleton “Three-dimensional finite element modeling of the human ACL: simulation of passive knee flexion with a stressed and stress-free ACL” Journal of biomechanics 37(2004), 1723-1731.

[10] Song Yuhana, Debeski Richard E., MuashlVolkar, Thomas Maribeth, Savio L-Y. Woo “A three dimensional finite element model of the human anterior cruciate ligament: a computational analysis with experimental validation.”Journal of Biomechanics 37(2004), 383–390.

[11] Bowman Jr. Karl F. Sekiya John K, “Anatomy and Biomechanics of the posterior cruciate ligament and other ligaments of the knee.” Journal of biomechanics (2009),126-134

[12] Joseph W. Freeman and Albert L. Kwansa “Recent Advancements in Ligament Tissue Engineering: The Use of Various Techniques and Materials for ACL Repair” Recent Patents on Biomedical Engineering 2008, 1, 18-23

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