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Study of the Effect of Cyclic Stress on the Mechanical Properties of Braided Anterior Cruciate Ligament (ACL)

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Abstract

In the present, the design of ACL is attracting more attention. In this work, three different braided artificial ligaments were manufactured and tested under a cyclic stress to simulate the actual normal conditions. Knee simulator tester was designed to simulate the actual knee movement during the application of load on ACL. A comparison between three different braided artificial ligaments was analyzed after subjecting the ligament to 50,000 cycles using the designed knee tester, and compered with the results obtained on tension-tension fatigue tester. The tensile properties of the samples, after applying cyclic loading, were tested to study the effect of ACL structure design.

Keywords: ACL; Repeated cyclic stress; Braided structures; Biomedical textile; Tensile properties

Introduction

The anterior cruciate ligament (ACL) is one of the important ligaments in the knee which is vital for stability and kinematics [1]. It is also the most commonly injured ligament of the knee and due to its poor healing potential, severe damage warrants surgical intervention including complete replacement. The knee is one of the most complex joints in the human body. Being a hinge joint it is structured to perform two principle actions, flexion (bending) and extension (straightening) [2]. The knee is comprised of the bottom end of the Femur (thigh) and the upper end of the Tibia (shin) and the Patella (knee cap). The construction of the knee joint which is comprised of three bones (femur, patella and tibia), Cartilage protects and cushions the ends of the long bones; it functions to reduce the effect of concussion and friction between these bones [3]. Muscle, tendons and ligaments hold these bones in apposition stabilize the joint and render it freely moveable. Biomechanics is the application of engineering principles to the study of forces and motions of biologic systems [4]. Biomechanical studies are designed to determine the magnitude and direction of forces and moments of various tissues in and around a joint, as well as to measure the corresponding joint kinematics. This information can then be used by clinicians for the assessment of function of a normal or an injured joint and for planning the appropriate course of treatment. The movement of the knee joint is governed by its ligaments, other supporting soft tissue structures, and the geometric constraints of the articular surfaces. The knee is capable of movement in six degrees of freedom three rotations and three translations. The description of knee motion can be accomplished by relating movement to three principle axes the TIBIA shaft axis, the epicondylar axis, and the anteroposterior axis, which is perpendicular to the other axes.

The simplest solution to regain the stability of torn ACL would be to find a biocompatible strong rope-like structure to replace the torn ACL [5]. Cyclic loading affected ACL by exposing to cycles of tension, bending, and torsion stresses which affect mechanical properties of the ACL with the time. Saber Marzougui [6-8] and others described the fatigue behavior of braided artificial ligaments, they had constructed a device that gives stresses to the braided manufactured ligament like stresses affected the natural ACL. Different materials were used in manufacturing several braided designs such as, biaxial, triaxial and core-braided deign [6]. Ideal repeated stress cycle for Tension fatigue is applied on different ACL testing. If the mean stress is equal to zero, the cycle is completely reversed, where in some practical applications the stress cycles are typically random [9].

In this work, knee simulator tester was developed and three different braided structures were designed in order to be used as ACL. The results of the mechanical properties of ACL subjected to 50000 cycles and tested on fatigue tester and knee simulator tester were discussed.

Material and Methods

Material

Yarn specifications: Textured polyester yarn of count 33.3 tex and tenacity 36 cN/tex was used for the manufacturing braided samples of ACL. Figure 1 shows the stress-strain curve of the used textured polyester yarn.

Sample manufacturing: Three different braided designs for ACL reconstruction were manufacturing by the braiding machine as shown in Figure 2.

- Flat biaxial braided ACL,
- Three-zone braided ACL, in which a middle zone has a loose structure made by increasing the braid pitch,
- Double-band braided ACL made from the same flat biaxial braid and folded by a way to give the design of the required braided ACL.

Braiding machine of 9 carriers was used for the manufacturing the samples. The settings of the machine are chosen to get a braiding angle of 38°. Referring to Three-zone braided ACL, in which a middle zone with a loose structure was created through the increase of the braid

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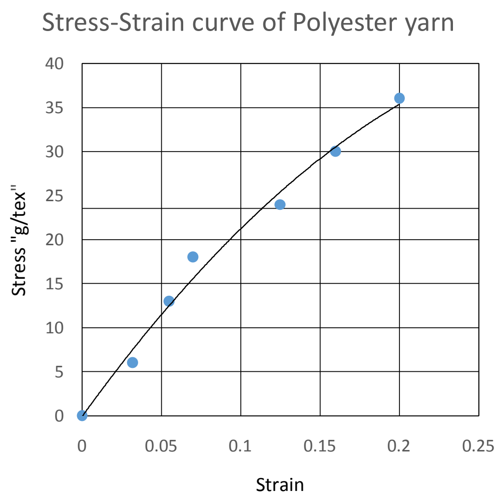

Figure 1: Stress-strain curve of the polyester yarn.

Figure 2: Different braided ACL types produced; flat (top), three-zone (middle) and double-band (bottom) ACL.

pitch in the middle zone for the designed length, and then continues to the previous regime.

Fatigue tester

Standard fatigue tester was used to study the designed samples under repeated cyclic stress. Figure 3 shows the main parts of tester.

The stress applied on the sample each cycle is illustrated in Figure 4.

The value of alternating stress

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{\max} - \sigma_{\min}}{2} \qquad (1)$$

Mean stress

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \qquad (2)$$

In order to evaluate the mechanical properties of the designed ACL when subjected to tension-tension cyclic loading of 50000 cycles, the sample is exposed to pre-tension of 10 N.

σ_m - jamming stress of the ACL textile structure 10 N , σ_{max}=400 N. The values of σ_{max} and σ_{min} were chosen from the real values measured on the ACL [10].

Knee simulator cyclic loading tester

The knee joint is not a simple hinge joint but rather a complex joint that provides set of translations and rotations [11]. It is a modified-hinge joint that exhibits 6 degrees of motion during dynamic activities. These 6 degrees of motion may be characterized as 3 rotations (flexion and extension, external and internal rotation, versus and valgus angulation) and 3 translations (anterior and posterior glide, medial and lateral shift, compression and distraction). Figure 5 shows the six degrees of freedom of the knee joint motion.

The forces on the ACL in the actual conditions are very complicated. For that purpose knee motion simulator was designed using a real shape of a knee, instead of simulating the forces acting on the ACL [7] apart of the real situation of the ACL inside the knee. The movement of the knee joint is governed by its ligaments, other supporting soft tissue structures, and the geometric constraints of the articular surfaces. The

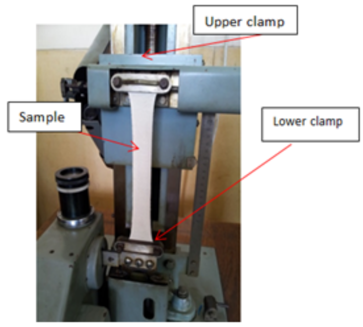

Figure 3: Fatigue tester.

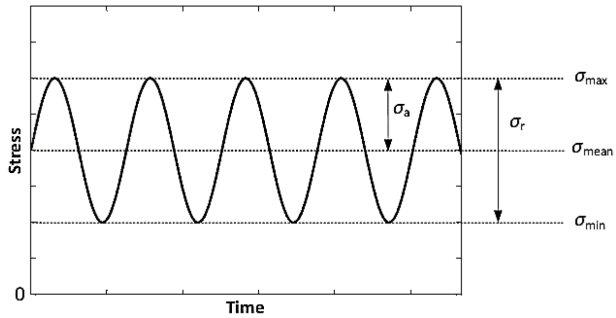

Figure 4: Applied cyclic sample loading on fatigue tester.

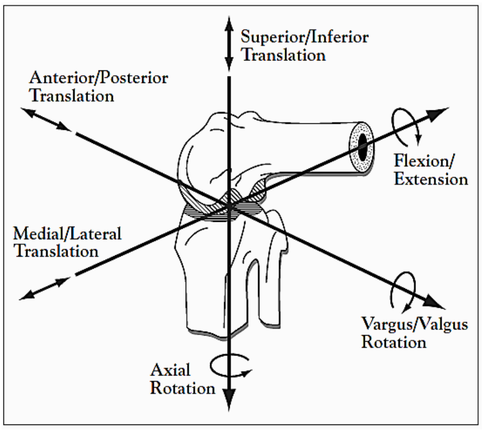

Figure 5: Six degrees of freedom of the knee joint [10].

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knee is capable of movement in six degrees of freedom three rotations and three translations [4,11]. The description of knee motion when ALC is fixed can be accomplished by relating movement to three principle axes the tibia shaft axis, the epicondylar axis, and the anteroposterior axis, which is perpendicular to the other axes as shown in Figure 6.

A developed simulator tester shown in Figure 7 was used to give simulating movements as the actual knee motion and by installing a PVC artificial knee with the same actual knee dimensions, as shown in Figure 8. Space linkage mechanism was developed to insure simulation of the movement of the actual knee during the movement of the femur relative to the tibia. The mechanism can change the twisting of the tibia relative to the femur and allowing the tibia to swing over the femur during the one cycle. The produced ACL braided ligament was inserted into the artificial knee in the same way made in ligament replacement in the accurate position and same inclination angles in both tibia and femur bones. That gives simulating cyclic motions which produces fatigue forces on the used ligament identical to the actual knee motion.

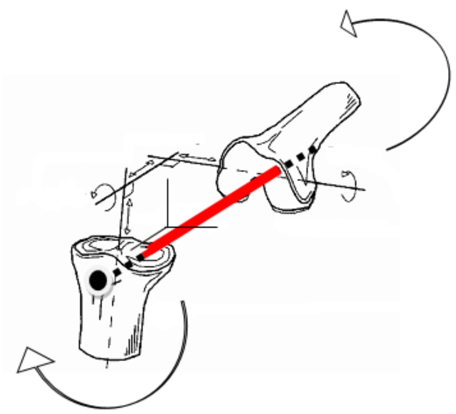

Figure 6: ACL under six degrees of motion of the human knee joint.

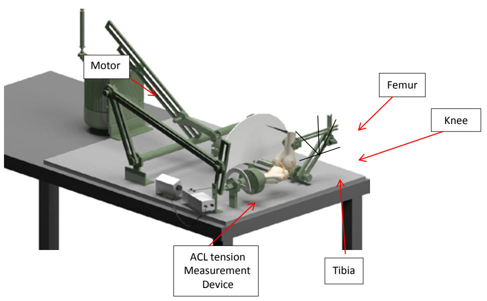

Figure 7: Linkage mechanism of the developed knee simulator tester.

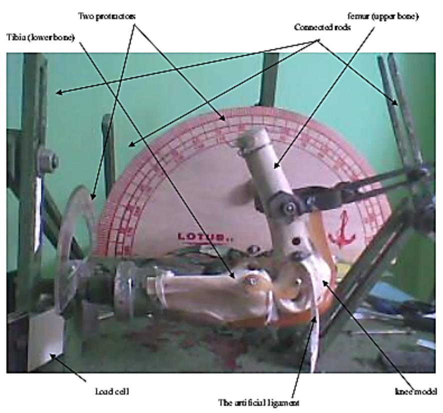

Figure 8: Knee simulator tester.

Testing methods

Testing procedure on the simulator tester: The ACL sample was fixed at one end and the tension was applied on the other end and recorded. The twisting angle of tibia relative to the femur where both were in horizontal position was adjusted, and then the running of the testing simulator will swing the femur for an angle 100°. The number of the cycles is chosen according to the conditions of the test.

Tensile strength of ACL: The ACL where tested to determine the change of the tensile strength of the ACL. Testing of samples was carried out according to ASTM D-751 [11]. Suitable pre-tension was applied according to each sample weight to insure that the sample reaches jamming condition before starting the test.

Results and Discussion

Forces acting on the ACL during normal service

In the case of ACL which is fixed in both femur and tibia is presented by space vector joining them together. During their motion ACL will be subjected to bending moment, torsional moment as well as tension force due to the movement of the knee joint in different positions, since the contact point between femur and tibia is sliding backward and forward. The load applied on ACL during the movement of the knee is illustrated in Figure 9.

The tension force acting on the ACL will be increased on bending of the knee as well as the twisting of the ACL depending on the trajectory of point A and B, as illustrated in Figure 9. Created tension force T (T_x ,T_y ,T_z) and moments M (M_x ,M_y ,M_z), hence the ACL made of textile structure is generally of low bending stiffness, the effect of the moments will not reflect on the increase of the ACL tension. Another force F represents the friction between the ACL and the bone during the movement of the knee joint. The change of both femur and tibia position will vary the value of the tension according to the nature of the motion which can be analyzed into flexion motion and twisting motion

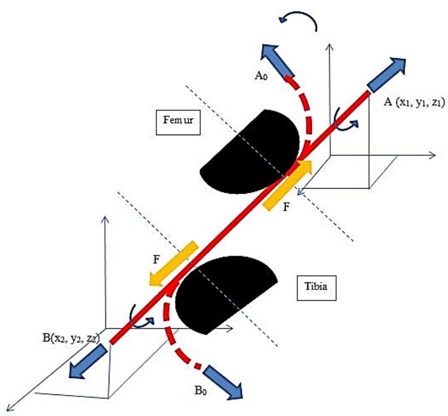

Figure 9: Simplified analysis of the forces acting on the ACL.

the previous measurement of the tension of ACL in this two motions separately [9] is given in Figure 10.

As the flexion angle "Θ" creases from zero to 100º, the tension force acting on the braided ACL increases too. When changing the direction of flexing, the value of the tension force acting on ACL is less than at the same angle of flexion due to the change of the friction force between ACL and the bone of the joint. If the tibia is twisted with angle "β " relatively to femur, the value of the tension will change as shown in Figure 11.

During the application of the cyclic motion on femur by the simulator, the ACL was subjected to; cyclic tension, torsion and bending stresses, and friction at the surface of the ACL that comprise the cyclic movement effect on the ACL

Effect of the cyclic loading on the ACL

Three different types of braided samples were designed and manufactured on the same braiding machine using the same types of yarn. The tensile properties of the three designed samples are given in Table 1.

Results of testing the ACL braided samples after 50,000 cycles working on the developed fatigue simulator apparatus are shown in Table 2.

Tension force and bending moment affecting the braided ACL are increasing with the increase of flexion angle of the knee, while torsion moment is produced inside the braided ACL due to the inclination of the ligament axe on the knee axe (normal position of the ACL inside the knee). Effect of the cyclic load on ACL mechanical properties are given in Figures 12-14.

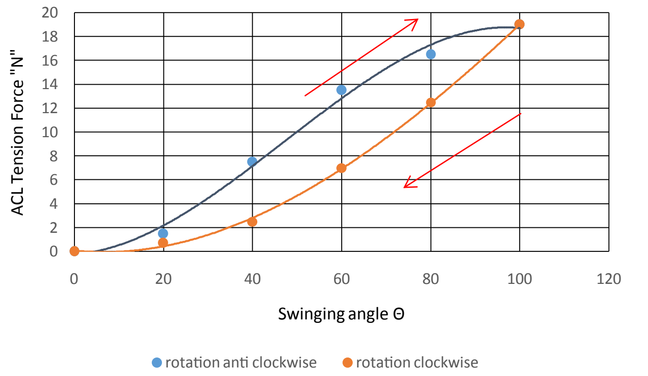

Figure 10: Tension force versus flexion angle.

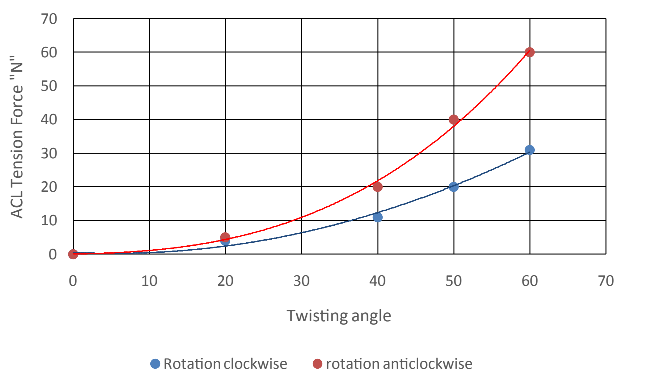

Figure 11: Tension force versus twist angle "β".

Braid type	Braid mechanical properties				
	Breaking load (N)	Max. stress (cN/tex)	Max. strain	Linear stiffness (N/mm)	Young's Modulus cN/tex
Flat	800	29	0.50	37.5	68.1
Three-zone	800	29	0.46	38.1	68.1
Double-band	1100	20	0.42	56	38.4

Table 1: Mechanical properties of the manufactured samples.

Braid type	Braid mechanical properties after applying 50,000 cycles				
	Breaking load (N)	Max. stress (g/tex)	Max. strain	Linear stiffness (N/mm)	Young's Modulus cN/tex
Flat	324	11.7	0.40	24	27.7
Three-zone	245	9	0.21	30	51.4
Double-band	470	8.5	0.29	55	27

Table 2: Mechanical properties of the different ACL braided types after 50000 cycles.

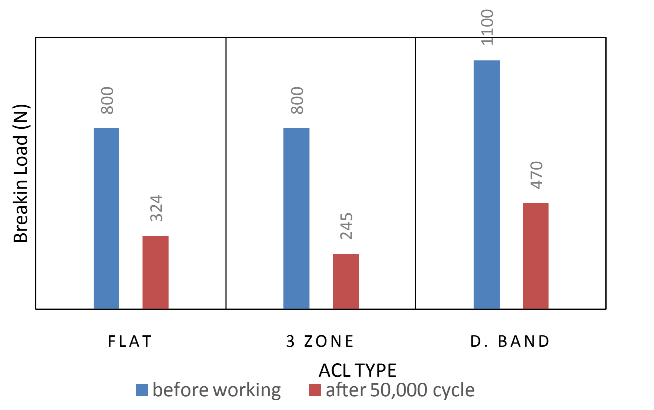

Figure 12: Fatigue effect on the three types braided ligament breaking load.

As shown in Figure 12, cyclic loading affects the breaking load of the three types of braided ligaments. It reduces the breaking load around (57-70) % of its value after 50,000 cycles of working. Double-band ligament type gives the best result before and after working due to its special design which increases the value of the breaking load and gives the lowest percentage of breaking load reduction after working. Figure 12 shows that, as cyclic loading affects greatly the breaking load of the braided ligaments, it subsequently affects the tenacity of the braids by the same reduction percentages.

As shown in Figure 13, cyclic loading affects also the breaking strain of the three types of braided ligaments. It reduces the maximum strain by around (20-54) % of its value after 50,000 cycles of working. Low values of strain are suitable for artificial ligaments, which can be achieved by the three-zone and double-band braided ligaments.

As shown in Figure 14, cyclic loading affects the linear stiffness of the braided ligaments. It reduces the linear stiffness (the slope of the load-elongation curve) by around (2-36) % of its value after 50,000 cycles of working. Double-band ligament type gives the best result before and after working due to its special design which gives the best value of the linear stiffness and the lowest percentage of reduction after working. The double band gives the best results due to the low value of tension on ACL material.

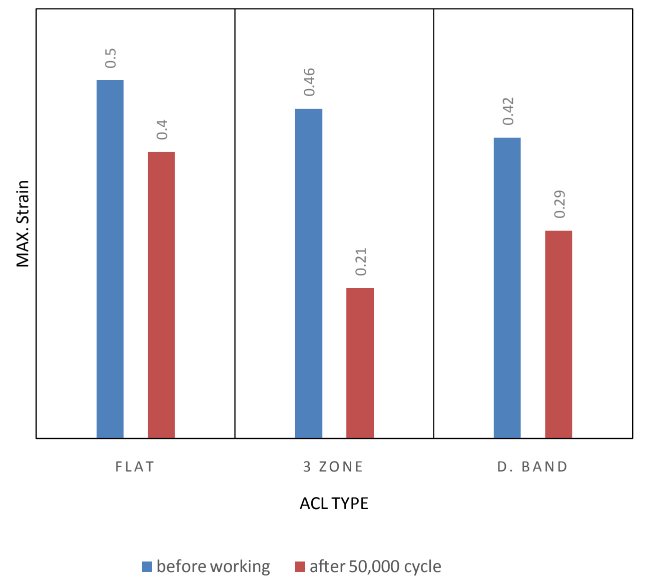

Figure 13: Cyclic loadingeffect on the three types braided ligament maximum strain.

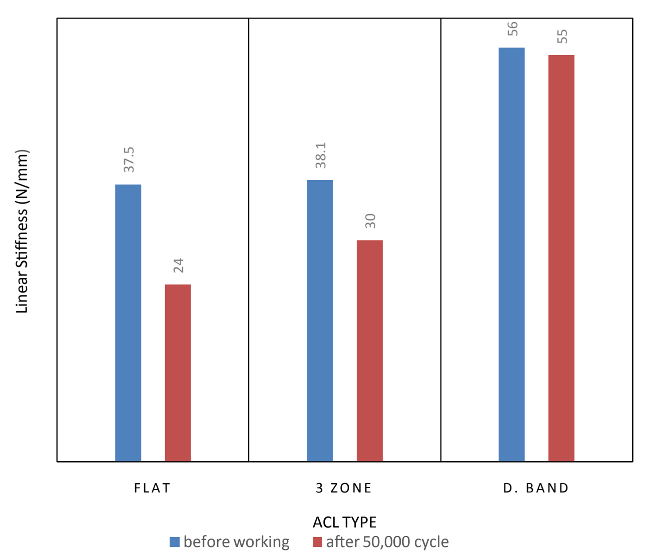

Figure 14: Cyclic loading effect on the three types braided ligament linear stiffness.

After 50,000 cycles of the extension and flexion of the artificial knee acting by the cyclic loading tester, an abrasion effect was noticed especially on the sample of three-zone braided ACL, as shown in Figure 15. This noticeable effect of abrasion is due to the braid special design which has a wider part that affected greatly when it became in contact with the movable parts of the knee causing surface abrasion on ACL. Whereas, the other designs of braided ACL were not affected obviously with abrasion. That makes the double-band design of braided ACL the referable one which can be used in ACL reconstruction with its high mechanical properties and high resistance for cyclic loading and abrasion.

When the ACL subjected to tension-tension cyclic loading on Fatigue tester, Figure 3, the reduction in the ACL strength was found to be less. The difference is due to the effect of the other forces on the ACL braid when used in knee simulator. Figure 16 illustrates the comparison of the strength elongation in two cases. The reduction of strength of ACL after subjection to 50000 cycles in the case of tension-tension cyclic loading only was by 4% while when tested on the knee simulator was by 25%. This fact indicates that the ACL structures should be tested on real knee simulator tester in order to predict the behavior of the ACL material and design.

The fatigue sensitivity coefficient according to normalized S-N curve

$$\frac{\sigma_f}{\sigma_b} = 1 - a\log N \quad (3)$$

Where;

σ_f is the breaking load after N cycles, σ_b is the breaking load, a is slope of S-N

The experimental results the value of the constant is found to be;

For double band (a=0.122) for 3 –zone (a=0.148) and for flat (a=0.127) which indicates the advantages of using the double band.

Conclusion

The developed knee simulating tester insures actual movement, simulates walking movement which included all types off stresses affecting the ligament inside the knee, such as; tension, bending and torsion stresses, while the axial fatigue tester simulates one type of

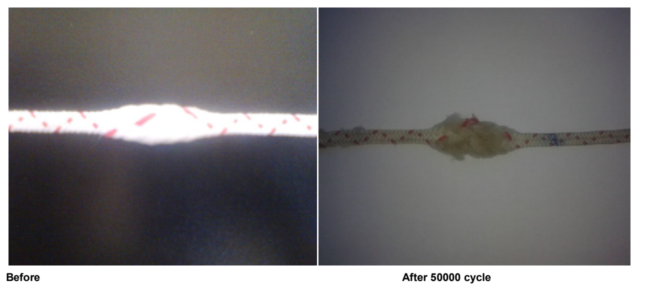

Figure 15: Braided samples before andafter working on knee simulator tester.

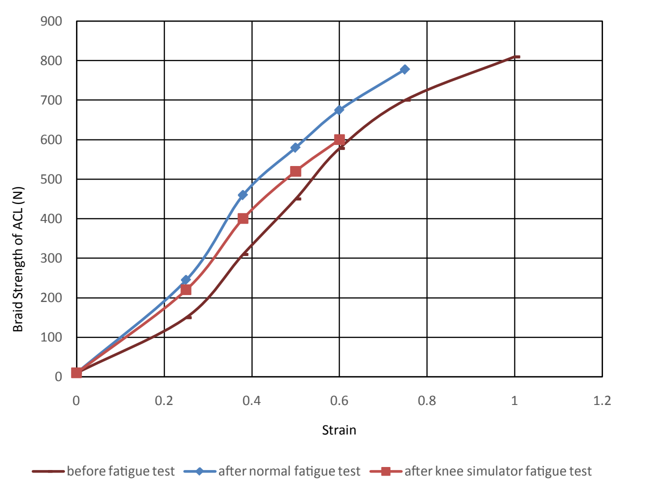

Figure 16: Strength strain curve of ACL before and after the applying of the cyclic loading of 50000 cycles.

stresses (tensile stress) on the tested sample. So, the developed apparatus insure real simulation for the actual forces acting on the ACL inside the knee and is recommended for the tests of knee ligaments. Three different types of braided ACL were tested to find out the most suitable design which can resist more the effect of cyclic loading. Testing of mechanical properties of samples before and after application of 50000 cycles was done and results showed that all mechanical properties of braided ligaments such as breaking load, maximum stress, maximum strain and linear stiffness are negatively affected in different percentages. The double-band braided ligament is the most suitable design that gives the lower loss of mechanical properties after simulates walking cycles.

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