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Production of Novel Textile-Based Artificial Anterior Cruciate Ligament

Original Scientific Article

Received 03-2016 • Accepted 04-2016

Abstract

The aim of this research was to produce artificial anterior cruciate ligaments (ACL) using the weaving (plain and leno) and braiding techniques, and to compare the mechanical and fatigue life properties of these ligaments with the natural ACL. For this purpose, tubular fabric structures were produced on braiding and weaving machines from polyester and Vectran yarns. To turn these structures into ligaments, the core of the tubes were filled with straight yarns. The mechanical properties of the resulted ligaments were tested before and after a fatigue test. The results showed that all produced ligaments provide enough tensile strength and breaking elongation when they were compared with the natural ACL mechanical properties. After the fatigue test, the tensile strength of ligaments did not decline substantially. Regarding the tensile strength, the leno weaving structure has the most similar properties to the natural ACL. The leno weaving ligament made from Vectran has one-third of the strain percentage of the natural ACL.

Keywords: Leno weaving, braiding, narrow weaving, artificial ligament

1 Introduction

A ligament is a band of tough, flexible fibrous tissue that connects bones in the body to other bones and keeps these structures stable. The human body has 900 ligaments, of which 10 are located in the knee joint. The anterior cruciate ligament (ACL) is one of the four major knee ligaments, which provide stability of the knee joint by controlling excessive knee motion. In other words, ACL restricts both the horizontal translation (anterior-posterior and medial lateral translation) and relative rotation (varus-valgus and internal-external rotation) between femur and tibia (Figure 1) [1‒3]. ACL might be subjected to overloading during heavy physical activities and sports, resulting in a sprain or tear of the ligament. An ACL tear is a very common sports injury. The injury rates are higher for women. The tearing happens during a rapid change in direction when moving, slowing down when running, landing after a jump or receiving an abrupt force to the knee. ACL has a poor healing ability, since it is enveloped by synovial fluid and lacks significant vascularization. In consequence, its treatment frequently requires surgical procedures. According to Legnani et al. [4], this reconstruction operation is performed to 100,000 patients per year in the USA, 3,000 per year in Sweden.

There are some options for a surgical treatment including auto grafts, allografts and artificial grafts. In the auto grafting operations, patient's own tissues (most commonly the middle third of the patella tendon and hamstring tendons) are used for the treatment. Auto grafts provide good results; however, they do not eliminate some risks like morbidity secondary knee pain, patellar tendonitis and fracture or hamstring tendon weakness. In allograft operations, cadaveric tissue coming from a tissue bank (human or animal tendons) is used. There are numerous risks at allograft due to limited

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DOI: 10.14502/Tekstilec2016.59.121-125

donor tissue sources, disease transmission and tissue rejection [5]. In artificial grafts, a natural ACL is mimicked by the structures made from synthetic fibres. Artificial ligaments are used to replace the ruptured ACL, to support tissue growth, to take applied loads until the new tissue grows and to shorten the healing period. Today, despite some disadvantages such as synovitis, a synthetic biocompatible material based artificial ligaments such as Carbon, Gore-Tex, Dacron, Leeds-Keio, Kennedy LAD (ligament augmentation devices), Stryker, Ligastic-Ligapro and LARS (ligament advanced reconstruction system) are implanted to injured ACL patients [4–6].

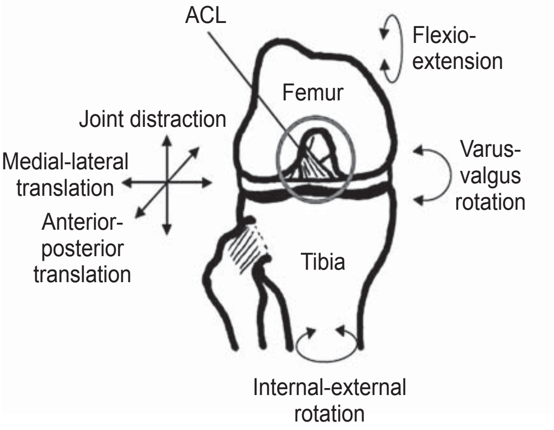

Figure 1: Six degrees of knee motion [3]

The aim of this research was to produce artificial anterior cruciate ligaments (ACL) using the weaving and braiding techniques, and to compare the mechanical properties of these ligaments with the natural ACL before and after a fatigue test.

2 Experimental

As test materials, artificial ACL were produced from high tenacity filament polyester (1100/192 dtex) and Vectran (220 dtex) staple yarns. To mimic the natural ACL, tubular structures were produced on an automatic sampling loom: Model SL8900s, Kus narrow weaving machine (similar to Jakob Muller needle loom) and 48 carriers circular braiding machine. The samples woven on an automatic sampling loom had a leno weave structure and the samples woven on a narrow weaving machine had a plain weave structure. The leno weaving and braiding structures were chosen to provide resistance against abrupt and directional forces. Following the production of tubular fabrics, core parts of these fabrics were filled with straight polyester and Vectran yarns to construct artificial ligaments. The objective of this bicomponent structure was to increase tenacity against high forces and facilitate cell adhesion on the surface when it is implanted. Table 1 summarises the production methods and components of ligaments.

The mechanical properties of ligament samples were measured on a ZWICK Z10 test machine. The test samples were conditioned in a standard atmosphere for minimum 24 hours. Tensile tests were conducted by using a constant speed gradient dynamometer at the speed of 10 mm/min [3] with test length of 40 mm [3], and tenacity and breaking elongation values were recorded.

To simulate the actual wear condition, the textile woven based artificial ligaments were subjected to a fatigue test using a dynamic fatigue tester which is very similar to the one developed by Marzougui et al. and Jedda et al. [7, 3]. This fatigue tester generates cyclic movements, i.e. bending, twisting and traction, synchronously to mimic the knee motion during the walking. These deformations are performed in a saline medium at 37 ± 0.5 °C [8, 3] to simulate the synovial liquid in the knee joint. In our test, to analyse the creep properties and to predict the lifetime of the ligament, a fatigue test was performed at 1.66 Hz, which is the actual knee motion frequency during the walking [9, 3]. The motion angles were 60° and 15° [7, 3]. Since flexion is related to the inclination angle of the tunnel from the Tibial plateau for artificial ligaments, they are subjected to the deviation angle 60° at the flexion test [3]. The bending angle chosen for our study was thus 60°. After 50,000 ± 100 of fatigue cycles, the tensile properties of ligament samples were measured again and compared with the untreated samples.

3 Results and Discussion

The mechanical properties of the resultant artificial ligaments, e.g. tenacity and breaking elongation, were revealed through the mechanical tests and the results were compared with the natural anterior cruciate ligament (Figure 2).

Table 1: Produced artificial ligaments and their component properties

Ligament Number (Samples)	Construction	Core yarn	Core yarn count [dtex]	Shell yarn	Shell yarn count [dtex]
1	Narrow weaving	PET filament	1100/30	PET filament	1100
2	Narrow weaving	Vectran staple fibres	220/150	PET filament	1100
3	Braiding	PET filament	1100/30	PET filament	1100
4	Braiding	Vectran staple fibres	220/150	PET filament	1100
5	Leno weaving	Vectran staple fibres	220/150	Vectran staple fibres	220
6	Leno weaving	PET filament	220/150	Vectran staple fibres	1100

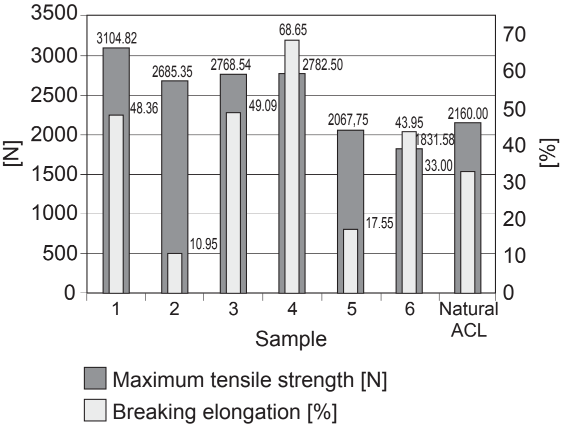

Figure 2: Mechanical properties for novel artificial ACL and natural ACL [2]

Figure 2 shows that the material and textile structure play an active role in tensile strength and breaking elongation. When considering the fact that the maximum tensile strength of the natural ACL of a middle-aged man is approximately 2,160 N, it is clear that almost all produced ligaments provided sufficient tensile strength. Only sample 6 had slightly lower tensile strength compared to the natural ACL. As for the elongation at break, the narrow woven ligament made of PET and filled Vectran yarn (sample 5) had the lowest elongation value. It is likely that the Vectran core restricted elongation. As expected, the braided samples had the highest elongation values (samples 3–4), since braiding provides a more flexible textile structure. Technically, when the force is applied to a circular braiding structure along the longitudinal axis, yarns slip easily and the braiding angle increases, since the yarns of the braided structure are crossed diagonally. The braiding diameter consequently decreases and the braid length increases.

The leno structure has weft and warp yarns like a conventional weaving structure. However, in leno weave, yarns are locked in place by crossing two or more warp yarns over each other, interlacing with one or more weft yarns. When the force is applied on the leno structure longitudinally, warp yarns start to squeeze weft yarns, cutting them eventually. Low tensile strength can be associated with the ligaments with the leno structure.

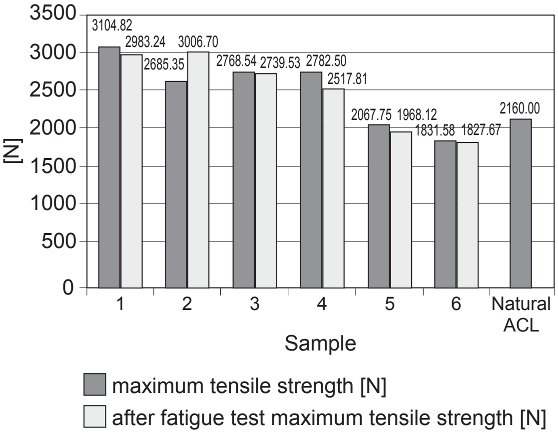

Figure 3: Tensile strength of ligaments before and after fatigue test (50,000 cycles)

After 50,000 ± 100 dynamic fatigue cycles, the tensile properties of ligament samples were measured again and compared with the untreated samples.

Figure 3 compares the tensile properties of ligaments before and after the fatigue test. The results showed that the textile structure influenced the fatigue properties of ligaments. In general, as expected, tenacity of ligaments decreased after the fatigue test. Only in sample 2, there was a slight increase in tensile strength, but this was more likely due to an experimental error. Apart from sample 2, all ligaments showed similar fatigue properties. Their tensile strengths did not decrease substantially.

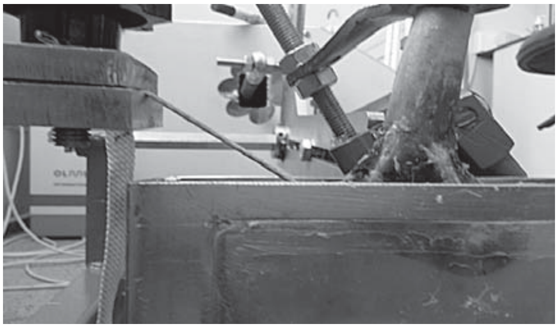

Figure 4: Dynamic cyclic fatigue tester

Especially the tensile strength of the braided ligament made from PET (sample 6) was approximately the same before and after the fatigue test. In terms of tensile strength, the leno weave structure (samples 5 and 6) caused the closest tenacity value compared to the natural ACL and among other ligaments, sample 6 showed the highest fatigue resistance against cyclic motion.

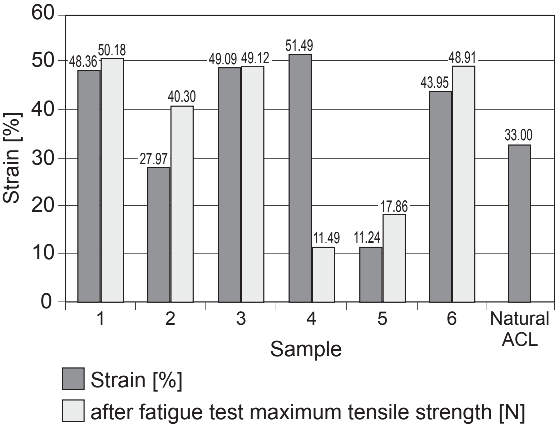

Figure 5: Maximum tensile strain of unfatigued ligaments and fatigued ligaments (50,000 cycles)

Figure 5 shows the maximum tensile strain of ligaments before and after the fatigue test. Samples 3 and 4 had the highest elongation percentage, which might be related to the braid structures of samples 3 and 4 having more flexibility than the others. The breaking strain of the leno ligament made from Vectran (sample 5) equalled one third of that of a natural ACL before the fatigue test, while after the fatigue test, it equalled one half of that of a natural ACL.

Nevertheless, it is expected that breaking strain would be lower after the fatigue test as due to permanent deformation, the breaking strain values of samples 1 and 3 remained the same. It can be said that samples 1 and 3 had higher resistance against the fatigue cyclic motions (bending twist, traction etc). Comparing the strain percentage, it can be seen that the leno weaving ligaments made from Vectran have the lowest strain value. All ligaments, except for number 4, had similar elongation properties with a natural ACL. It seems that there was a slight decrease in the strain value after the fatigue cycles for sample 4, but since this might be related to an experimental error, the tests will be repeated.

It was expected that the value of the breaking strain of all ligaments would decrease after the fatigue tests when they were compared with virgin ligaments. The reason for obtaining opposite results is that the tests were performed in saline media at 37 °C.

4 Conclusion

The aim of this research was to produce artificial anterior cruciate ligaments (ACL) using the weaving and braiding techniques, and to compare the mechanical properties and fatigue behaviour of these ligaments with the natural ACL. The results showed that almost all produced artificial ligaments had higher strength values than the natural ACL. With regard to the elongation at break, the resultant ligaments had either higher values or lower values compared to the natural ACL. The tensile strength values of the ligaments did not change after the fatigue test. The closest value was obtained through the leno weave ligament made from Vectran compared to the natural ACL. In addition, this ligament showed higher resistance against dynamic fatigue behaviour. In conclusion, some encouraging results were obtained with this study. However, to determine the fatigue lifetime of ligaments, the number of test cycles should be increased.

References

1. ARNOCZKY, Steven Paul. Anatomy of the anterior cruciate ligament. Clinical Orthopaedics and Related Research, 1983, 172, 19‑25, doi: 10.1097/00003086-198301000-00006.
2. ALTMAN, Gregory H., HORAN, Rebecca L., LU, Helen H., MOREAU, Jodie, MARTIN, Ivan, RICHMOND, John C., KAPLAN, David L. Silk matrix for tissue engineered anterior cruciate ligaments. Biomaterials, 2002, 23(20), 4331‑4141, doi: 10.1016/S0142-9612(02)00156-4.
3. MARZOUGUI, S., KILANI, L., ABDESSALEM, Ben S., SAKLI, F. Dynamic fatigue of braided textile ligaments. Arabian Journal for Science and Engineering, 2014, 39(3), 2205–2214, doi: 10.1007/s13369-013-0777-9.
4. LEGNANI, Claudio, VENTURA, Alberto, TERZAGHI, Clara, BORGO, Enrico, ALBISETTI, Walter. Anterior cruciate ligament reconstruction with synthetic grafts. A review of literature. International Orthopedics, 2010, 34(4), 465‑471, doi: 10.1007/s00264-010-0963-2.
5. Ligaments and ligamentoplasties. Edited by L'Hocine YAHIA. Berlin, Heidelberg : Springer, 1997.
6. MASCARENHAS, Randy, MacDONALD, Peter B. Anterior cruciate ligament reconstruction: A look at prosthetics – past, present and possible future. McGill Journal of Medicine, 2008, 11(1), 29‑37.
7. JEDDA, H., ABESSALEM, S. BEN, SAKLI, F. The effect of cyclic loading on the mechanical properties of the artificial ligament. The Journal of The Textile Institute, 2011, 102(4), 332‑342, doi: 10.1080/00405001003771218.
8. DROUIN, Gilbert, MASSON, Martin, YAHIA, L'Hocine. In vitro fatigue testing of prosthetic ligaments: A new concept. Bio-Medical Materials and Engineering, 1991, 1(3), 159‑165, doi: 10.3233/BME-1991-1304.
9. PACHI, Aikaterini, JI, Tianjian. Frequency and velocity of people walking. The Structural Engineer, 2005, 83(3), 36‑40.