Thermographic and microscopic evaluation of LARS knee ligament tearing

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Abstract
Damage to knee articular ligaments causes important functional problems and adversely affects particularly the stability of the knee joint. Several methods were developed in order to repair damage to the anterior cruciate ligament (ACL), which employ autografts, allografts, as well as synthetic ligaments. One such synthetic scaffold, the ligament advanced reinforcement system (LARS) synthetic ligament is made of non-absorbing polyethylene terephthalate fibers whose structure allow tissue ingrowths in the intra-articular part, improving the stability of the joint. The LARS ligament is nowadays widely used in modern knee surgery in the Europe, Canada, China or Japan. This paper evaluates LARS ligament from two perspectives. The first regards a study done by the Orthopedics Clinic I, Timisoara, Romania, which compared results obtained by employing two techniques of ACL repair – the Bone-Tendon-Bone (BTB) or LARS arthroscopic, intra-articular techniques. This study found that patients treated with the BTB technique presented with an IKDC score of 45.82±1.44 units preoperative, with increasing values in the first nine months after each implant post-surgical ligament restoration, reaching an average value of 75.92±2.88 units postoperative. Patients treated with the LARS technique presented with an IKDC score of 43.64±1.11 units preoperative, and a score of 77.32±2.71 units postoperative. The second perspective describes the thermographic and microscopic analysis of an artificial knee ligament tearing or loosening. The objective of the study was to obtain information regarding the design of artificial ligaments in order to expand their lifespan and avoid complications such as recurring synovitis, osteoarthritis and trauma of the knee joint. Thermographic data has shown that tearing begins from the inside out, thus improving the inner design of the ligament would probably enhance its durability. An optical microscope was employed to obtain images of structural damage in the inner layers, for use in further analysis of the tears. In conclusion, the LARS artificial ligament, like the BTB technique, displays both advantages and disadvantages. It is important to understand that these two options of ACL lesion repair are not competing. LARS could, in addition to its use in primary ACL ruptures, be utilized in revisions of autologous graft rupture post primary ACL repair.

Keywords: LARS, knee, thermography, microscopy, synovitis.

Introduction
Damage to knee articular ligaments causes important functional problems and adversely affects particularly the stability of the knee joint. The normal articular mechanics are disturbed, resulting in the destruction of articular surfaces and eventually leading to the necessity of an arthroplasty within a 12-year period. It is thus necessary to surgically repair broken ligaments in order to prevent this degradation [1]. This has been done using different methods, which employ autografts, allografts, as well as synthetic ligaments like the ligament advanced reinforcement system (LARS) [2, 3].

LARS is a synthetic scaffold that is used to augment the repaired native soft tissue. It is an internal fixator, which allows ingrowth of tissue in the intra-articular part, so it is permeable to the healing process [4].

The scaffold uses a design that mimics the native anatomic ligament fibers: intra-articular longitudinal fibers resist fatigue and allow fibroblastic ingrowth, whilst extra-articular woven fibers provide strength and resistance to elongation. LARS requires no tissue harvesting and it will not lead to further loss of proprioception, as compared to other procedures of ACL reconstruction [5].

Naturally, the technique relies on both the feasibility and the ability to repair the native torn ligament. The LARS ligaments were developed and used initially by the French, but recently there has seen a surge in use in Australian elite athlete patients. About 100 000 LARS ligaments have been used around the world over the past 20 years, with increasingly satisfactory results [6, 7]. Nowadays, LARS is used in many countries across Europe, such as Austria, Italy, France, or Romania, but also in countries such as Canada, China, Japan, or Australia [8]. It has certain advantages as it may allow quicker rehabilitation time since the patient’s own tissues are spared of surgical trauma. LARS is suitable in patients fulfilling specific criteria, including a relatively recent injury and availability of a suitable native ligament stump to repair [6]. LARS grafts are designed to be used in relatively recent injuries, or where there is a partial tear of the ligaments, or where a
usable stump of the old ruptured ligament is present. The functionality is to provide a scaffold in the form of LARS, which will allow the native tissue to heal in an appropriate fashion. The remaining stump of the torn ligament is repaired at the same sitting [9].

LARS was designed to reproduce the structure and function of the ligament it replaces. Its fibers present no free intra-articular friction and eliminate the appearance of free microparticles that could cause chronic synovitis. In addition, the synthetic ligament structure allows fibroblast multiplication along the fibers, providing a scaffold and promoting healing [10, 11]. The base polyester structure of LARS ligaments is esterified and free intra-articular fibers absorb deformations due to flexion-extension and torsion. Thus, the fibers resist high-traction from 2500 N for 60 fibers up to 4600 N for 100 fibers and even to 5600 N for 120 fibers. Regarding torsion, LARS shows no signs of damage even after 10 million cycles [12, 13].

The thermography technique was also used as part of this study. It is a non-invasive, infrared imaging tool that is currently used to evaluate various pathologies and medical processes such as: vascular, breast and neurology imaging, rheumatology and orthopedics evaluation, forensic, surgery, and full body screening. In infrared imaging, a specialized camera creates images using the infrared radiation emitted by a body [14–17].

The aim of this overall study was to present our experience in reconstructing ACL ruptures using LARS ligaments as well as other techniques, such as BTB, and also to describe the development at tearing or loosening of a LARS synthetic knee ligament using thermographic evaluation in order to obtain indications for the future design of significantly improved artificial ligaments.

Materials and Methods

A retrospective study was conducted on a group of 370 patients across seven years, from 2006–2013. Of those 370 patients, 243 were male while 127 were female, all between 16 and 38-year-old.

All ACL lesions in this study were due to sports traumas. The BTB technique was employed in 250 cases while the LARS technique was used in 120 cases (Figure 1). The data are summarized in Table 1 below.

Table 1 – Summary view of demographics and techniques applied in this study

<table>
<thead>
<tr>
<th>No. of patients</th>
<th>Technique applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>243</td>
<td>127</td>
</tr>
</tbody>
</table>

BTB: Bone-tendon-bone; LARS: Ligament advanced reinforcement system.

For BTB cases, the neoligament was harvested off of the patellar ligament according to the Kenneth–Jones technique. Synthetic 100-fiber LARS ligament was used in both primary ACL repairs as well as in the majority of revision cases. In all cases, LARS and BTB ones, the same intra-articular insertion technique was used.

The indications of LARS synthetic ligament usage are the following: acute lesions (less than 3-week-old), young and active patients, subacute or chronic lesions in the presence of a suitable ligament stump or in interstitial or synovial lesions, revisions of ACL secondary rupture, which were previously repaired using other techniques. In case of chronic lesions, the usage of a synthetic isolated ligament is permitted according to the following criteria: senior patients desiring moderate physical activity, performance athletes requiring a quick recovery and return to peak physical activity. In young patients, when there is no usable ACL stump, the repair is attempted using autologous reinforced reconstruction.

All patients were evaluated at the pre- and post-operative stages using a KT 1000 Arthrometer, which measures knee instability (Figure 2). Knee function was assessed using the International Knee Documentation Committee (IKDC) score and Lysholm Score. Physical activity levels were measured using the Tegner Activity Scale.

Rehabilitation was performed using specific protocols, allowing for full load on the second day postoperative. Physical activity such as performance sport was allowed after 6–8 months in BTB cases and after six weeks in LARS cases.

The thermography tearing experiments were performed using partial LARS knee ligaments obtained from the Department of Orthopedics, County General Hospital, Timișoara, Romania, as seen in Figure 3. First, one sample was torn using a Walter–Bai AG LFV-10 kN tensile testing machine, running with a speed of 2 mm per minute at the Laboratory of Mechanics and Materials Strength, Politehnica University of Timisoara. The entire process was visualized with a FLIR A40M thermographic camera. Figure 4 shows a thermographic image at the moment when the ligament reached maximum temperature during tearing. The thermographic parameter values were: 0.86 material emissivity, 0.2 m distance between sample and camera, 25.5°C initial ligament temperature, 26.3°C air temperature, 50% air humidity and the color mode of the thermogram used was IRON. Finally, after preparation, the samples were visualized with the MSZ5000 A. Kruss Optronic microscope at different magnifications.

Results

This study found that patients treated with the BTB technique presented with an IKDC score of 45.82±1.14 units preoperative, with increasing values in the first nine months after each implant post-surgical ligament restoration, reaching an average value of 75.92±2.88 units postoperative. Patients treated with the LARS technique presented with an IKDC score of 43.64±1.11 units preoperative, and a score of 77.32±2.71 units postoperative.

Furthermore, there were no infections documented, and there was excellent stability of the knee four weeks postoperative, as evidenced by Arthrometer readings. There was one revision case after LARS usage in the primary repair, and a 200-fiber LARS ligament was used on the same tunnel. Next, 100-fiber LARS ligaments were used in 11 patients for ACL rupture revision where the primary rupture was repaired using a different primary graft. There was a case of synthetic ligament loosening due to a more anterior placement of the tibial tunnel. This case occurred one-year post-
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operative and was solved by re-achieving tension in the ligament and immobilizing it with a larger screw.

Results at the five-year follow-up mark were excellent. A second-look arthroscopy was performed in 30% of the cases to investigate other lesions (meniscus, cartilage lesions) and good neo-ligament integration and fibroblast colonization was observed.

The graph in Figure 5 was obtained after processing thermographic data. The graph displays two temperature peaks in the tearing process. This shows that there is a two-step ligament rupture. The first peak (A) corresponds to a first tear of the ligament that cannot be visualized with the naked eye. This was because the inner structure of the ligament gave in first. The second peak (B) illustrates the final tear. The normal inner structure of the ligament can be seen in Figure 6. A second sample was tested in order to observe if it behaves as the previous, and the two peaks were once again obtained. To further analyze the tear and the structure of the ligament, two other samples were torn until they showed the A peak. Immediately after the A peak was registered, the experiment was stopped in order to avoid the total tear of the specimen. Thus, two samples with an intact outer layer, and damaged inner layers, were obtained. The two samples were opened up by cutting the outer layer of fabric longitudinally to expose the inner structure. Figures 7–12 illustrate the different structural defects found in the fabric. The first layer was adversely modified as the fabric strings did not fully return to their initial position in the structure (Figure 7). In the inner layer, damage ranging from individual fiber ruptures, to full bundle ruptures, was seen.

Figure 1 – ACL repaired with LARS.
Figure 2 – KT 1000 Arthrometer.
Figure 3 – Partial LARS knee ligament used in the experiment.
Figure 4 – Infrared image of the tearing process at the highest temperature measured.
Figure 5 – Temperature variation of the tearing process.
Figure 6 – Transversal view of the LARS knee ligament structure, before tearing, 0.8× magnification.
Figure 7 – Exterior view of specimen with distorted fibers (after elongation until peak A), 0.8× magnification.
Figure 8 – Microscopic image of damage to the inner layer with 1.5× magnification.
Several authors that reported on ACL repairs in the literature were used as a basis for comparison in this study. Maharis reports on a total of 512 cases of ACL lesion repairs with good results and four complications of secondary rupture because of misplaced tunnel over the period 1997–2003. Papadopoulos reports on 155 cases with good results achieved using LARS, compared to BTB or gracilis-semitendinous-semimembranous graft techniques between January 1996–December 2003, similar to what Pinčzewski and Wipfler obtained [18–20]. Huang presented 81 cases over a period of four years with good results [9]. Laboureau, inventor of LARS, presented thousands of cases of ligaments applied with good results and very good developing and patenting his own surgical techniques for each type of ligament [21].

The casuistry and results of our study are similar to those present in the literature. Good overall results with complete recovery and socio-professional reintegration were achieved in all patients. This includes athletes. There was a single complication of “loosening” due to an excessively anterior placement of the tibial tunnel. The results show that using a LARS ligament dramatically improves the function outcome and patients display higher knee stability, leading to an early return to high physical activity levels. We consider this technique to be a facile and timely solution for ACL reconstruction with a faster recovery period compared to other techniques. It is, in our opinion, a very good solution for athletes and sport professionals due to its resistance, reliability and stability, and the short rehabilitation period. It is also important to note that there is no need to harvest a ligament in order to complete the procedure. However, several less favorable outcomes could occur, including weakening of the donor joint, a longer recuperation time, or the existence of anatomical material that is not reusable in case of failure.

Numerous synthetic ligaments have been developed over the past ten years, mostly consisting of polyesters. The biocompatibility of this material has been well documented as of several decades ago and it has been long used as a suturing thread, and, in more recent years, for vascular prostheses [7]. Still there is a need for further research in order to prolong the lifespan of artificial ligaments and to avoid re-implantation. Re-implantation determines complications such as synovitis due to debris and tear of tissue [8, 11, 12, 22]. Also, the onset of early osteoarthritis can occur due to the trauma that the knee joint has to suffer at re-implantation [23, 24].

These results show that in order to obtain a higher reliability, and thus a greater lifespan of artificial ligaments, further research is needed to improve the inner structure of the LARS knee ligament. Varying the structures of both the inner and the exterior layers could provide a higher tensile strength. Also, inserting a secondary material and thus creating a composite, could enhance the tensile properties of the ligaments. Still this is not always possible, nor optimal, as along with tensile strength, a ligament has to possess a specific flexibility and elasticity and of course great biocompatibility. This equilibrium is not easily achieved.

During the last 20 years, the lifespan of artificial ligaments has increased significantly. Now, the goal to achieve a lifelong artificial ligament is within our grasp. Thus, any research that brings new indications about what and how to improve the current generation of artificial ligaments is of great importance.

Further progress can be achieved by investigating the issue of how to select the right fiber from both the mechanical and biological point of view. This can be achieved by learning more about the anatomy and physiology of the natural ligaments to mimic their structure, and by defining precise surgical procedures adapted to synthetic fiber and the complicated role it needs to fulfill.

The LARS artificial ligament, like the BTB technique, displays both advantages and disadvantages. It is important to understand that these two options of ACL lesion repair are not competing. LARS could, in addition to its use in primary ACL ruptures, be utilized in revisions of autologous graft rupture post primary ACL repair. Using thermo-graphic evaluation, this study demonstrated that synthetic LARS ligaments tear in two steps, starting from the inside out. A first step in improving the LARS knee ligament
and in avoiding all the complications that appear due to re-implantation might be to change the design of the inner structure of the artificial ligament in order for it to gain a higher mechanical resistance. Still, the sensitive equilibrium between biocompatibility, tensile strength and flexibility of an artificial ligament is not easy to achieve and must sometime force a compromise in design.

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