Guest Editorial

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Meniscal Scaffolds in the Clinics: Present and Future Trends

Ricardo Bastos[1,2,3], Renato Andrade[2,3,4], Hélder Pereira[5,6,7,8], J. Miguel Oliveira[5,6], Rui L. Reis[5,6], Scott Rodeo[9,10,11,12,13], João Espregueira-Mendes[2,3,5,6,14]

Abstract

Despite the high incidence, meniscal lesions still remain a clinical challenge due to its limited regenerative ability. In the last two decades, the development of scaffolding strategies has revolutionized meniscus treatment possibilities. Along with these new developments, the orthopaedic community has embraced the campaign "preserve the meniscus". In this sense, acellular or cellularized scaffolds have emerged as a potential solution to treat irreparable meniscal lesions. Herein, it are overviewed the up-to-date acellular meniscal scaffolds used in the clinics, indications and discussed their outcomes.

Keywords: Meniscal scaffolds; Meniscal implants; Meniscal substitutes;

Introduction

The menisci have been described as a two-edge shaped semilunar discs of fibrocartilaginous tissue, found at the medial and lateral compartment of the tibiofemoral joint (1, 2). They play a fundamental role in many aspects of knee function, including articular congruency and stability, load distribution, shock absorption as well as a role in joint lubrication and proprioception (3). Many of these functions are achieved through the ability to transmit and distribute load over the tibial plateaus. The medial and lateral menisci can transmit from 50% up to 70% of the load when the knee is in extension, and up to 85% at 90 degrees of knee flexion (4). Removal of the medial meniscus can result in a 50% to 70% reduction in femoral condyle cartilage contact area and a 100% increase in contact stress (5). Total lateral meniscectomy causes a 40% to 50% decrease in cartilage contact area and increases contact stress in the lateral compartment up to 200% to 300% of normal. Furthermore, even just partial removal of the meniscus does alter joint loading, particularly when two thirds of the posterior horn is excised (6). Despite the importance of the meniscus structure and the need for its preservation, meniscal lesions are the most common surgically treated knee pathology, and their annual incidence can be estimated at 60-70 per 100,000 knees, with 850,000 meniscal procedures performed yearly only in the United States (7) and 400,000 in Europe (8).

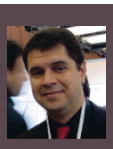
For several years, the meniscus function was not fully understood. Recent pre-clinical and clinical evidences support the idea that the preservation of the meniscus structure is of outmost importance (9, 10). Thus, tissue engineering approaches have gain great attention as promise to regenerate different tissues and organs, including meniscus tissue (11-15). It has provided a fundamental understanding and technology that have permitted the development of scaffolds derived from biological tissues and synthetic materials, and there is currently a large amount of active, ongoing research into meniscus scaffolds (16-18). The meniscus scaffolds have been mainly limited to the treatment of meniscus partial repair once it requires an undamaged meniscal rim and enough tissue at the anterior and posterior horns to allow the fixation of the scaffold to the remaining meniscal tissues.

Types of Scaffolds

Scaffold biomechanical structure must have adequate material properties to allow tissue regeneration, while protecting the newly-forming tissue from excessive stresses. Their

[1]Universidade Federal Fluminense, Nireói, Rio de Janeiro, Brazil.
[2]Clínica do Dragão, Espregueira-Mendes Sports Centre - FIFA Medical Centre of Excellence, Porto, Portugal.
[3]Dom Henrique Research Centre, Porto, Portugal.
[4]Faculty of Sports, University of Porto, Porto, Portugal.
[5]3B's Research Group – Biomaterials, Biodegradables and Biomimetics, University of Minho, Headquarters of the European Institute of Excellence on Tissue Engineering and Regenerative Medicine, AvePark- Parque de Ciência e Tecnologia, 4805-017 Barco, Guimarães, Portugal.
[6] - ICVS/3B's – PT Government Associated Laboratory, Braga/Guimarães, Portugal.
[7] - Orthopaedic Department, Centro Hospitalar Póvoa de Varzim - Vila do Conde, Póvoa de Varzim, Portugal.
[8] - Ripoll y De Prado Sports Clinic FIFA Medical Centre of Excellence, Murcia-Madrid, Spain.
[9] - Co-Chief Emeritus, Sports Medicine and Shoulder Service, Hospital for Special Surgery, New York, USA.
[10] - Co-Director, Tissue Engineering, Regeneration, and Repair Program, New York, USA.
[11] - Orthopaedic Surgery, Weill Medical College of Cornell University, New York, USA.
[12] - Attending Orthopaedic Surgeon, Hospital for Special Surgery, New York, USA.
[13] - Head Team Physician, New York Giants Football, New York, USA.
[14] - Orthopaedics Department of Minho University, Minho, Portugal.

Address of Correspondence:
Dr. João Espregueira-Mendes; Via Futebol Clube do Porto - F. C. Porto Stadium, Porto, Portugal; +351 220 100 100; Email: espregueira@dhresearchcentre.com.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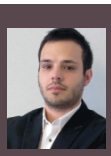
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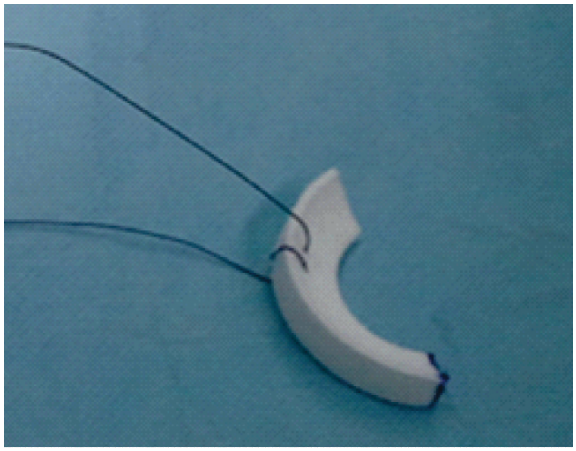

Figure 1: Meniscal scaffold (Actifit®), tailored by the surgeon to address the characteristics of each individual meniscus defect

Table 1: Indications and contraindication of meniscal scaffolding

Indications	Contraindications
Age between 16 and 50 years old.	Uncorrected ligamentous instability.
Skeletally mature male or female.	Uncorrected axial malalignment (deformity greater than 5°).
Acute or chronic irreparable medial or lateral meniscal tear or partial meniscal loss (>25%).	Body mass index > 35
The synthetic meniscus substitute is not intended for the treatment of total meniscus defect. Ideally, the defect length should be limited to 5-6 cm.	Full-thickness loss of articular cartilage with exposed bone - International Cartilage Repair Society (ICRS) classification > 3
Intact meniscal rim and enough tissue in the anterior and posterior horns to allow the scaffold fixation.	Meniscal root lesions
Aligned knee joint (favorable axis of less than 5°).	Evidence of osteonecrosis of the involved knee
	Systemic or local infection
	Inflammatory arthritis or autoimmune diseases

absorption must be sufficiently gradual, allowing appropriate cell migration, formation of new vessels, and matrix synthesis in order to create meniscal-like tissue (19, 20). At the same time, the scaffold and its degradation products should not damage the articular surface or invoke a foreign body reaction. An important step in the preparation of acellular meniscal scaffolds is the ability of mimicking the architectural and geometric complexity of the native tissue (20, 21). In this sense, it is crucial to further understand the menisci anatomy, biology, ultrastructure and biomechanical function to enhance the success of the meniscal substitution (1, 13).

Two scaffolds are currently in clinical use. Collagen Meniscus Implant (CMI, Ivy Sports Medicine GmbH, Germany) – First published in 1997, CMI is a type-I collagen (isolated and purified from bovine Achilles tendon) scaffold (22) to which glycosaminoglycans are added. It has a meniscus-like shape, is implantable arthroscopically, and it is biocompatible and biodegradable. It has a microscopic porous structure that allows cellular ingrowth, induces differentiation and proliferation of fibrocartilaginous cells, leading to the creation of a meniscus-like tissue, concomitant with gradual resorption of the scaffold. Nevertheless, collagen scaffolds are fragile during the implant procedure, and have shown a decrease in size on follow-up magnetic resonance image (MRI) and arthroscopic second look follow-up.

The second type of scaffold is Actifit® (Orteq, United Kingdom) that has been developed to overcome the perceived limitations of CMI related to difficulties in tissue handling with respect to suturing during implantation (Figure 1). Actifit® is composed of a slowly degrading polymer with polycaprolactone and urethane segments (23). Its structure seems to have better mechanical properties and is more resistant to sutures and loads as compared to CMI. The scaffold is 80% porous; the remaining 20% are made of a polymer with a low absorption rate. Degradation starts with hydrolysis of polycaprolactone segments, which lasts up to five years; the polyurethane segments are removed by macrophages and giants cells or integrated into surrounding tissues (24, 25).

Indications - Contraindications

When considering meniscal scaffolding, the surgeon should take into account several individual aspects, such as the patient's age and weight, status of meniscal degeneration or concomitant conditions (such as axial malalignment and ligamentous insufficiency) (26). In this sense, several indications and contraindications have been developed as summarized in Table 1.

Preoperative Preparation

The preoperative imaging preparation usually involves radiography, MRI and, in some special cases, an arthro-computed tomography (arthro-CT). The radiographic imaging studies usually include bilateral comparison of weight-bearing radiographs (antero-posterior, lateral, Schuss or Rosenberg views). The MRI is usually performed to assess the cartilaginous structures status, quantify the meniscal damage, as well as the presence of bone marrow edema and/or meniscal extrusion (Figure 2). The arthro-CT scan may complement the MRI studies by assessing the meniscal volume and chondral damage (26).

The imaging studies should be complemented with a comprehensive clinical examination of the knee. Special attention should be given to the knee ligament stability, as this has several implications in the meniscal surgery. In addition, diagnostic arthroscopy (Figure 3) may be performed to further assess the meniscal status and decide upon the best technique (26).

Surgical Technique

The procedure can be performed arthroscopically using the two standard anteromedial and anterolateral portals. The

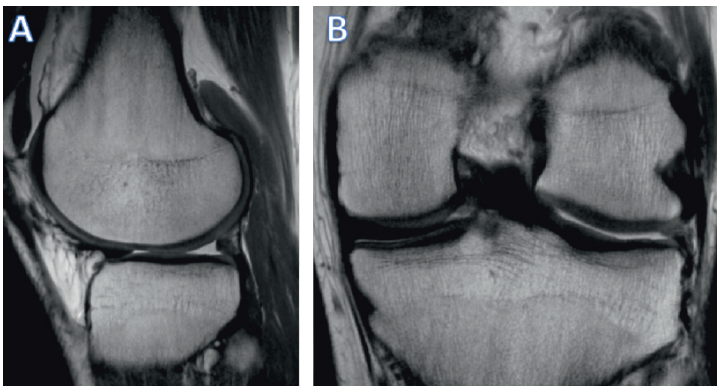

Figure 2: MRI scans of a buckled handle tear of the lateral meniscus. A) Sagittal MRI view of the right knee joint showing degenerative changes on the posterior part of the lateral meniscus; B) Coronal MRI view of the right knee joint degenerative changes of the lateral meniscus (on the right).

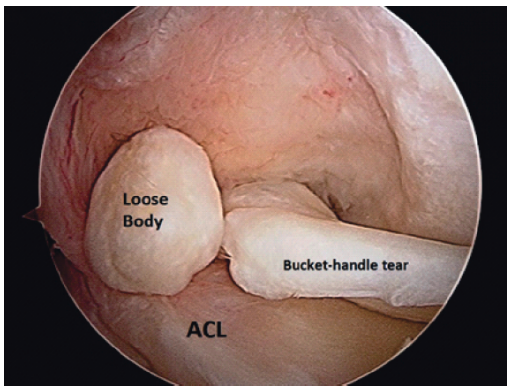

Figure 3: Arthroscopic diagnosis of a meniscal tear. Arthroscopy revealed an intact anterior cruciate ligament (ACL), an intraarticular loose body and a bucket-handle meniscal tear.

portals should be enlarged for an easier passage of the scaffold. The native remaining meniscus is thoroughly evaluated, and any torn or degenerative tissue is removed in order to leave a healthy and uniform meniscal rim, ensuring that the resulting defect site extends into the vascularized red-on-red or red-on-white zone of the meniscus. The meniscal rim is punctured in order to create vascular access channels. Gentle rasping of the synovial lining may further stimulate meniscal integration and tissue ingrowth. The exact size of the defect is measure with a flexible rod loaded in a rigid cannula starting at the posterior end of the lesion. The scaffold is measured and trimmed to the correct size on the sterile field of the operating environment (10% larger than in situ measurement to compensate for the shrinkage caused by suturing of the sponge-like material and to assure a snug optimal fit into the prepared defect). In order to achieve a perfect fit of the scaffold with the native meniscus at the anterior junction, the anterior side should be cut at an oblique angle of 30°-45°.

The implant is inserted into the defect (Figure 4). Standard arthroscopic meniscal suturing techniques may be utilized for scaffold stabilization. The authors prefer "all-inside" vertical stitches placed every 4 to 5 mm to suture the scaffold along the periphery. The anterior and posterior scaffold extremities are fixed to the native remnant with horizontal stitches.

Concomitant Surgeries

Since other associated deficiencies (such as axial malalignment or ligamentous instability) may lead to poorer outcomes following meniscal surgery, these should be address in combination with the meniscal substitution (27).

Anterior cruciate ligament insufficiency, if not addressed, may result in residual laxity, which may lead to an unfavorable meniscal healing environment. In this sense, ACL reconstruction has been performed along with the meniscal substitution in up to 67% of the patients (28-30). When performing concomitant ACL reconstruction, the meniscal bed should be firstly prepared and then the tibial and femoral tunnels may be drilled. After the tunnels are drilled, the ACL graft is passed through the tunnels and fixed at the femoral site, as the meniscal scaffold is inserted and sutured.

Subsequently, the ACL graft is fixed at the tibial site with 20° of knee flexion (31).

When uncorrected axial knee malalignments are found, these should be concomitantly or previously corrected. In a varus malalignment situation, a high tibial osteotomy may be performed to correct the malalignment. Special attention must be directed to the tibial slope and proper release of the medial collateral ligament should be performed. In valgus malalignments, if the deformity does not involve the tibial bone, osteotomy is done on the femoral side to avoid joint line obliquity (27).

Rehabilitation protocol

Patients are required to undergo a conservative rehabilitation program similar to that for a meniscal allograft. Special attention is required when the meniscal scaffold is implanted with concomitant ACL reconstruction or realignment osteotomy. In these cases, a rehabilitation program should be tailored to comply with the concomitant procedures postoperative particularities (26, 27). General guidelines for the rehabilitation program are presented in Table 3.

Clinical Studies

Although the literature contains clinical studies (33-35) that support the use of meniscal scaffold implantation for the treatment of irreparable meniscal tears, the quality of the studies is generally low, with lack of randomized trials and long-term follow-up to confirm clinical benefit and the most appropriate indications. Furthermore, long-term follow-up studies are required to verify the protective effect on the damaged joint compartment exerted by meniscal scaffold implantation.

A recent systematic literature review (35) analyzed results and indications for the treatment of meniscal loss. There has been an increase in publications regarding this topic recently, and the authors concluded that both CMI and Actifit seem to be safe and positive results have been shown for both scaffolds.

Bulgheroni et al. (36) evaluated the safety and effectiveness of the polyurethane

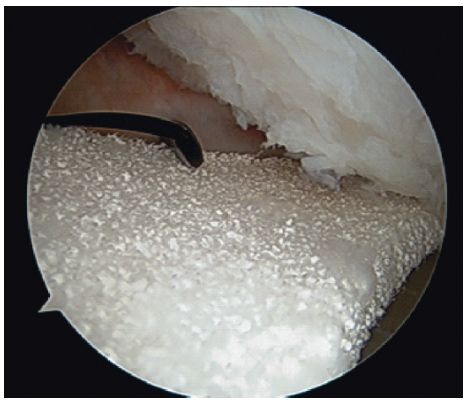

Figure 4: Arthroscopic features of a medial meniscal implant (Actifit®).

meniscal scaffold through clinical examination, MRI and arthroscopic second look, over a minimum two-year follow-up and showed no adverse reactions to the implant. The implant showed clear, hyperintense signal, sometimes irregular, and the chondral surface was preserved in all cases. At arthroscopic second look at 12 and 24 months, the scaffold was found to have an irregular morphology and to be slightly reduced in size.

Zafagnini et al. (37), in a 10-year follow-up study, compared the medial collagen meniscus implant versus partial medial meniscectomy. The CMI group showed significantly lower visual analog scale scores for pain and higher objective International Knee Documentation Committee and Tegner index scores. Radiographic evaluation showed significantly less medial joint space narrowing in the CMI group compared to partial medial meniscectomy. No significant differences between groups were reported regarding Lysholm and Yulish scores.

Another long-term study compared outcomes of CMI versus partial meniscectomy in patients with concomitant ACL reconstruction. The authors concluded that patients with chronic meniscal tears treated with medial CMI reported lower levels of post-operative pain compared to meniscectomy, while acute lesions treated with CMI showed less knee laxity at follow-up (38). The CMI when performed in the acute setting showed no additional benefits when compared to partial medial meniscectomy alone (28).

Zafagnini et al. (39), in a multi-center study, evaluated the clinical outcomes of 43 patients after lateral CMI implantation. They reported improvement of all clinical scores from baseline to follow-up evaluations. At the final follow-up, 58% of the patients reported activity levels comparable to their pre-injury values, with 95% patient reported satisfaction. A higher body mass index, the presence of concomitant procedures, and a chronic injury pattern were identified as potential negative prognostic factors.

As far as concomitant open-wedge high tibial osteotomies is concerned, Gelber et al. (40) found no short-term additional benefit when compared to partial meniscectomy and meniscal scaffolding.

Table 2: General rehabilitation guidelines, adapted from .

Feature	Guideline
Brace	Full extension brace is recommended for the first 4-6 weeks. The brace should be removed 3-4 times a day to perform self-assisted passive range of motion exercises.
Weight bearing	Non-weight bearing for the first 4 postoperative weeks. After the first 4 weeks, partial weight bearing with gradual increase of loading up to 100% load at 8-9 weeks after surgery (initiated in stages, increasing 10 kg/week for patients weighing <60 kg and 15 kg/week for patients weighing >60 to 90 kg).
Range of motion	Immediate range of motion is allowed, with flexion limited to 60-70° of flexion in the first 4 weeks. Range of motion should be limited to 90° of flexion the first 6 weeks.
Patellar mobilization	Supervised or instructed patellar mobilizations (3 times a day).
Active exercises	At the 8th week, the patient may start more active exercises, such as cycling, swimming, and active range of motion exercises (strengthening).
	Cycling and pool: increase up to 5 minutes daily to a maximum of 45 minutes, within the tolerance threshold.
	Pearl: The water should be deep enough that the foot does not touch the bottom of the pool.
Return to sports	Contact or impact sports should not be allowed before 6-7 months after the surgery.

Final Remarks and Future Directions

The menisci are known to be heterogeneous complex structures with segmental variations according to their anatomy, biology and function. The proper understanding on the different types of meniscal injuries (both traumatic and degenerative) and their pathophysiology and pathomechanics will assist the clinician in identifying the correct indications and contraindication for each type of lesion, preserving the meniscus whenever possible. The clinical application of meniscal scaffolds is limited to CMI and Actifit. In order to successfully implant these meniscus scaffolds, it is required an intact meniscal rim and sufficient meniscal tissue at the anterior and posterior meniscus horns to

attach the scaffold. When in case of axial malalignments and/or ligament insufficiencies, these must be correct prior or during the scaffold implantation.

The rehabilitation protocol should be tailored to address each patient's individual characteristics, respect the chronobiology of the scaffold tissue integration and the progression within phases should be goal-based.

Novel meniscal scaffolds have been developed for addressing total meniscus reconstruction with a functional meniscus replacement, mimicking the biology and mechanical properties of the native meniscus. These novel scaffolds may further protect the articular cartilage surface of the knee joint from the extensive damage after a total meniscectomy. A second generation of implants pre-cultured in vitro allows cell adhesion and extracellular matrix production and then are implanted into the meniscal defects which will probably follow as cell seeding as has been demonstrated to improve the mechanical properties and histological results.

In the future, it may be possible to improve tissue formation in the meniscal scaffold using autologous cells (e.g., stem cells) and/or growth factors (e.g., platelet-rich plasma). This strategy may augment the tissue regeneration and improve clinical results. The use of mesenchymal stem cells may also enhance a greater promotion of intrinsic meniscal healing capacity. In addition, nanotechnology and gene therapy have emerged as potential options and have showed great potential for the treatment of meniscal lesions, however its translation into the clinical setting may take a few more years. Biofabrication of patient-specific meniscal scaffolds with a 3D printer from the advanced segmentation of menisci knee MRI datasets has been showing promising results in the laboratory setting. This novel technique will allow tailoring the meniscal scaffold to the patient-specific native characteristics of the knee.

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