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Development of an artificial meniscus using polyvinyl alcohol-hydrogel for early return to, and continuance of, athletic life in sportspersons with severe meniscus injury. I: mechanical evaluation

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Abstract

The importance of knee meniscus function is now recognized, and the treatment of meniscus injury has been changing from resection to repair. However, depending on the type of injury, meniscectomy sometimes cannot be avoided. The young athlete might undergo meniscectomy in order to return to sports life as early as possible. However, in such a knee, it is important to anticipate the future problem of degenerative change or osteoarthrosis. In consideration of the prognosis and circumstances in such patients, we have developed an artificial meniscus using polyvinyl alcohol-hydrogel (PVA-H) and performed mechanical tests for compression and stress–relaxation. We found that the human meniscus has unique viscoelastic properties and a high water content. PVA-H showed viscoelastic behaviour similar to that of human meniscus in mechanical tests. These results suggest that an artificial meniscus using PVA-H with a high water content can compensate for meniscal function and might be clinically applicable.

Keywords: Polyvinyl alcohol-hydrogel; Meniscectomy; Artificial meniscus; Osteoarthritis; Biocompatibility

1. Introduction

Meniscectomy of the knee is most commonly performed for injuries resulting from traffic accidents or sports. Recent experimental studies on knee meniscus function have shown an important role for the meniscus in relaxing and dispersing impact stress during loading and in stabilizing the joint lubrication mechanism [1–3]. There have also been many clinical reports on articular degeneration in patients who have undergone meniscectomy [4–7]. Thus, the treatment method for meniscus injury has changed from meniscectomy to repair. In particular, for peripheral meniscal tears where circulation is present, repair is the preferred surgical option. Sometimes, however, depending on the type of meniscus injury, meniscectomy cannot be avoided. For such cases, experimental and clinical studies have provided several approaches to the reconstruction of meniscus function, such as allograft meniscal transplantation [8,9], meniscal tissue regeneration using an artificial biomaterial [10–12] and implant replacement [13,14]. Each method has problems and cannot be used clinically.

Most patients with meniscus injury are active young sports players, for whom there is a strong incentive to avoid long-term immobilization, rehabilitation or major surgery so that they may continue their sporting activities. We may assume that the transplantation of regenerated meniscus induced from autograft by tissue engineering will become the most effective therapy in the future. But even if this method does become established, in some cases the patient will not be able to undergo this operation immediately. For these patients, an effective ‘salvage’ treatment may be direct meniscus replacement with a biomaterial that does not cause immune reactions, thus allowing the earliest possible return to athletic life while preventing a delayed arthrosis. We have developed an artificial meniscus using polyvinyl alcohol-hydrogel (PVA-H), which has been studied in our laboratory as an artificial cartilage, and

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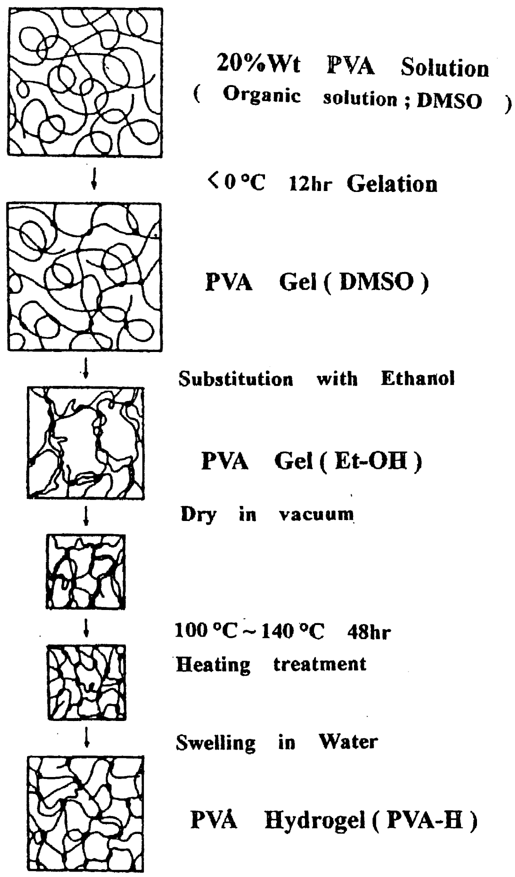

Fig. 1. The manufacturing process of PVA-H.

we have now performed some mechanical experiments in relation to its clinical application.

2. Materials and methods

2.1. Materials

PVA-H, the material used for the artificial meniscus, has been studied extensively [15–19]. Its excellent biocompatibility [20] and mechanical properties have been confirmed. In addition, adjusting the water content in the gel production process can provide viscoelastic characteristics similar to those of human soft tissues.

There have been many studies on the various mechanical characteristics of human menisci [1–3]. Taking the results of these studies into consideration, we selected PVA-H with a degree of polymerization of 17 500 (the maximum that can be synthesized in our laboratory) to improve abrasion resistance.

The PVA-H specimens were produced as follows. PVA was completely dissolved with an organic solvent (dimethyl sulphoxide) and water by heating and agitation under a nitrogen:air current, and a 20 wt.% solution was obtained. This solution was left at a low temperature (4 °C) for more than 12 h for the crystallization and cross-linking of PVA molecules to occur. The obtained gel was immersed in alcohol for more than 24 h for substitution of the inorganic substrate. It was then vacuum-dried, heated to 100–140 °C for 48 h for annealing, and left in water to adjust the water content by swelling again. These processes are shown in Fig. 1.

The various PVA-H thus obtained (water content: 20, 45, 60 and 90%; degree of polymerization, 17 500) were in the form of cylindrical rods, which were cut up as samples for mechanical tests and stored in physiological saline.

2.2. Methods

Tests were performed to evaluate the mechanical characteristics of PVA-H with different water content as a potential material for artificial meniscus implants. In order to compare the PVA-H with human meniscus, specimens were also prepared from menisci that had been surgically resected from patients (aged 35–60 years) who had been injured in road traffic accidents.

Compression and stress–relaxation tests were performed by electrohydraulic autography (S-100 Shimadzu Corporation, Japan). Because PVA-H tends to dry out, the measurements were made in physiological saline. Human menisci were also measured in the saline medium as shown in Fig. 2.

For mechanical tests, cubic samples ($5\times5\times5$ mm^3) were cut from the PVA-H rods. Five to 10 samples were prepared under the same conditions. Samples from the human menisci were also cut into cubes ($5\times5\times5$ mm^3). Human meniscus has an anisotropic arrangement of fibres, which can cause errors in measurement.

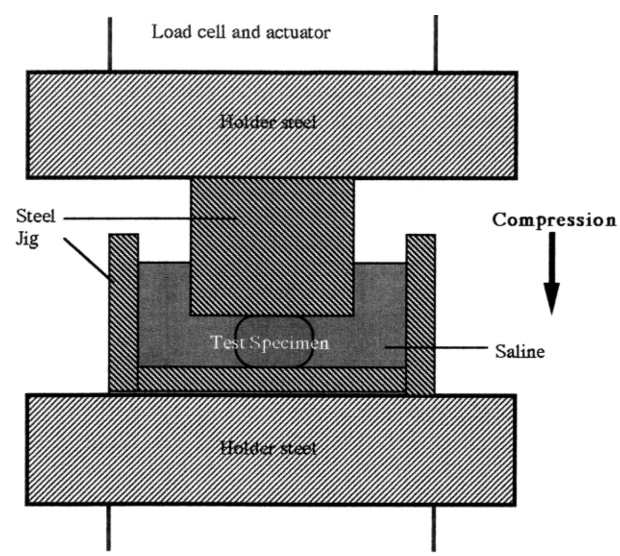

Fig. 2. Diagram of the apparatus for mechanical testing in saline. In this test, the steel holder-transmitted load cell of the autography machine moved at 5 mm/min and the stress and strain values of PVA-H and meniscus specimens were measured.

Therefore, test samples were collected from as many sites and directions as possible, and the number of samples was increased to 10–15 for each measurement condition.

2.2.1. Compression test

Compression tests were performed in water at a crosshead speed of 5 mm/min. Stress–strain curves were recorded from the PVA-H samples and human meniscus samples by autography and their viscoelastic behaviour was observed. For the modulus of elasticity, the tangent in the early-phase strain on stress–strain curves was measured. However, for yield stress, since PVA-H has high viscosity and does not fracture, a definite yield point as is observed in metals cannot be determined. Therefore, with a gradually increasing load on the sample, a compression test consisting of loading and unloading was repeatedly performed. As shown in Fig. 3a, the load at which PVA-H deformation remained, even without loading after releasing, was defined as the yield point.

2.2.2. Stress–relaxation test

To compare viscosity between the PVA-H and human meniscus samples, pressure (0.8 MPa) was applied to the samples in water to induce a particular strain. The time-related decreasing stress was recorded by autography and the stress–relaxation curves obtained.

3. Results

3.1. Compression test

Fig. 3b and c shows typical stress–strain curves and yield stress values for the PVA-H and human menisci. The stress–strain curves of the PVA-H showed more definite elastic deformation in samples with a higher water content. However, with increasing water content, viscosity increased and the modulus of elasticity decreased. The samples of human menisci had a modulus of elasticity even lower than that of the PVA-H containing 90% water, and the most marked viscous behaviour. Yield stress was higher in materials with a lower water content.

3.2. Stress–relaxation test

Fig. 4 shows the results of stress–relaxation tests. PVA-H with a high water content tended to show more marked stress–relaxation. The human menisci showed the most acute stress–relaxation.

In both compression and stress–relaxation test, PVA-H samples with a water content of 90% showed viscoelastic behaviour similar to that of the human meniscal samples.

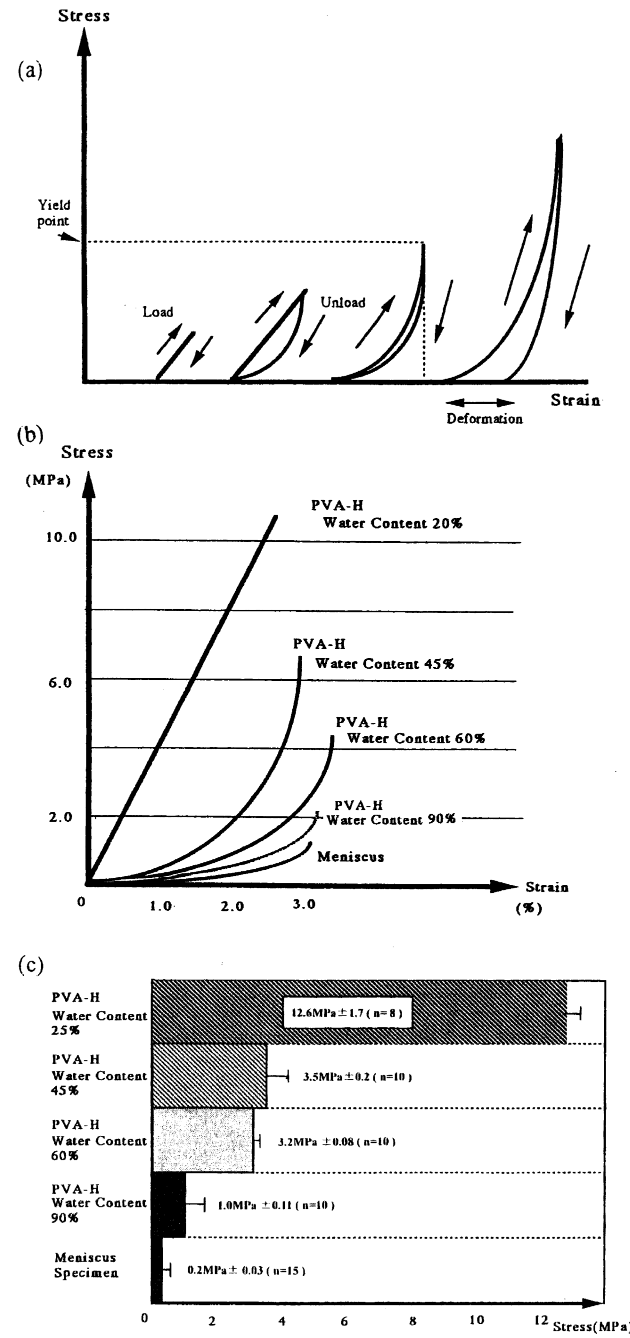

Fig. 3. (a) Measurement of yield point in stress–strain curves of this compression test. (b) Typical stress–strain curves of PVA-H samples and natural meniscus specimens (compression test). (c) Comparison of the yield stress of PVA-H and meniscus specimens.

4. Discussion

Since the first experimental study on the degeneration of the cartilage surface after meniscectomy by Fairbank [4], clinical studies have been performed by researchers such as Tapper [7], Lanzer [5], and recently, McNicholas [6]. Degenerative changes in cartilage after meniscec-

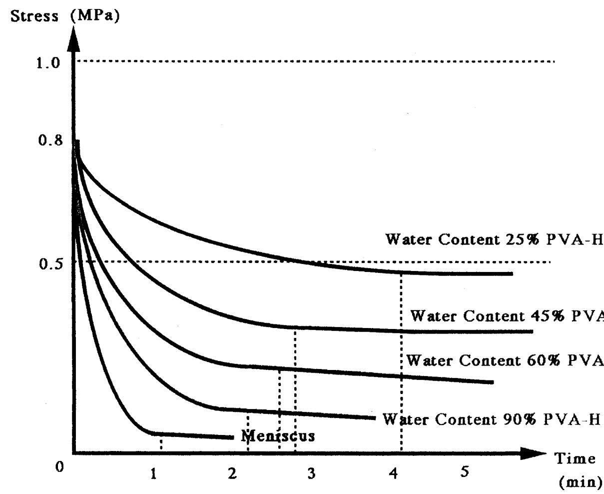

Fig. 4. Comparison of the stress–relaxation curves of PVA-H and meniscus specimens.

tomy have been considered unavoidable, though the degree of change may vary.

Although there have been only a few studies on the mechanism of osteoarthritis after meniscectomy, biomechanical studies have suggested that the loss of mechanical meniscus function (such as loss of the stabilization of joint movements that compensate for morphological incongruities between the femur and tibia, of the dispersal of the stress applied to cartilage during joint loading, and of the cushion-like role of the meniscus against impact load in the knee joint) might mechanically stimulate the surface of the articular cartilage in an abnormal fashion, resulting in osteoarthritic change. A study in the field of molecular biology has also indicated that stimulation by physical factors triggers the interactivation cascade for matrix metalloproteinases in the joint, which deprives chondrocytes of their repair function and degrades extracellular matrix, causing progression of osteoarthritic changes [22].

These studies on osteoarthritis suggest that, in order to provide meniscus function and prevent cartilage degeneration with an artificial meniscus, it is important to control the mechanical stimulation given to articular cartilage after implant replacement within certain limits, and the implant material should have the mechanical properties of natural meniscus.

Therefore, in this study, we used PVA-H as an artificial meniscus. PVA-H has been confirmed to have excellent durability and biocompatibility; more importantly, its viscoelastic properties can be changed by changing its water content [23].

A notable characteristic of human meniscus in the mechanical tests was a very low yield strength and marked stress–relaxation. This finding suggests that the meniscus readily changes its shape between the femur and tibia in accordance with knee joint movements but does not provide marked resistance to pressure on the articular cartilage under loading. In clinical practice, we often encounter patients who are asymptomatic despite having an abnormally shaped discoid meniscus; this may be because, owing to the unique viscoelastic characteristic of the meniscus, the surface of their articular cartilage is not markedly stimulated. Conversely, if this viscoelastic characteristic were poor, the risk of damage to the articular cartilage would be high, even if shock absorption of impact and contact load were possible in the knee joint as a whole.

Our results indicate that a PVA-H with a high water content is a promising material for an artificial implant that recovers meniscus function and prevents regressive changes in the articular cartilage. With increasing water content, the viscoelastic behaviour of PVA-H became more marked. However, the human meniscus had a higher viscosity than any of the PVA-H, which suggests that PVA-H for an artificial meniscus may need an even higher water content.

Regarding clinical applications, some problems still remain. The first is durability, which could be evaluated by fatigue and creep tests that were not performed in this study. Since no fracture of PVA-H occurred in any of the cases reported by Oka et al. [24–26], this material appears also to have adequate mechanical strength. However, considering that artificial menisci are semi-permanent implants, we intend to increase the degree of polymerization to improve anti-fatigability. Secondly, the biocompatibility of PVA-H should also be evaluated; these issues have been examined in animal experiments.

Though further studies are needed, the results of our mechanical experiments confirm the applicability of PVA-H with a high water content as an artificial meniscus.

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