J Mater Sci: Mater Med (2006) 17:759–765
DOI 10.1007/s10856-006-9687-7

Artificial midline-fascia of the human abdominal wall for testing suture strength

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Received: 22 September 2003 / Accepted: 24 October 2005

Abstract To reduce testing of human abdominal wall closure-modalities in test animals, a fibre reinforced rubber with identical mechanical properties compared to the human midline fascia (linea alba: LA) was developed. The microscopic structure of the human LA, stress-strain behaviour, maximum tensile force and macroscopic failure mechanism in tensile tests with human LA were defined as indicators for the required properties of the fibre reinforced rubber.

A composite consisting of latex rubber and cotton fibres was developed that shows mechanical properties comparable to the human abdominal wall. The results of the tensile tests on sutured artificial LA were highly similar to those performed on sutured human LA. The material presented in this study is proposed as a substitute for human and animal tissues presently used to test suture techniques. A protocol for an approach to develop artificial fibrous soft tissue like fascie and tendon was drawn up.

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1. Introduction

Abdominal surgery still has to contend with the problem of incisional hernia, i.e. the protrusion of organs or fat tissue through a defect in the abdominal wall [1–7]. The reported incidence of incisional hernia varies from 9–19%. Incisional hernia often necessitates repair with recurrence rates up to 45% [1–7]. Abdominal surgery is frequently performed through a midline incision through the linea alba, a fibrous and collageneous structure, representing a part of the midline of the abdominal wall. The linea alba is fixated at the xiphoid process and the pubic symphysis and is constituted by the interlacing aponeurotic fibres of the internal and external oblique abdominal muscles and the transverse abdominal muscles [8,9]. After a midline incision (the most frequently used incisior [10]), the linea alba is the structure to suture.

Until now, no consensus exists on the etiology of incisional hernia. One of the supposed main factors with respect to the occurrence of incisional hernia is suture technique [11]. However, also with regard to best suture practice no consensus exists. To analyze and compare the many suggested suture techniques a vast amount of experiments have been and still are performed, but systematic study of these suture techniques is severely impeded by a number of problems.

First of all, it is hard to control all variables that influence suture technique in clinical studies. Variables in suture technique include suture frequency, distance from the incisional edge (tissue bite size) and the use of single or running sutures [3,12,13,14]. Therefore, prior to clinical studies laboratory studies with cadaveric tissue are required to develop a suture technique that can be applied in clinical studies. However, the availability of human cadaver tissue is very limited. Therefore test animals are used, most commonly rats. In addition to ethical objections and logistic problems with regard to the use of test animals, a second problem is that the anatomy of rats is considerably different from human anatomy for studying suture techniques. In this respect the extremely narrow linea alba of the rat must be noted. Additionally, biological tissue has a high degree of natural variation, both inter-individual and intra-individual, implicating large numbers of tests.

Because of the above mentioned problems to current research on optimal suture techniques, there is a strong need for an alternative test material. Unlike prostheses that are used to replace organs or limbs this alternative material will be used in research. Therefore it should have identical mechanical properties compared to the human linea alba.

Mechanical properties of the linea alba are highly correlated to its microscopic structure. Main factors in the relation between microscopic structure and mechanical properties of human tissue are the orientation of collagen fibres in the tissue and the ratio in which different oriented fibres occur in the tissue (fibre orientation ratio) [15,16]. In the linea alba two groups of oblique oriented fibres (45 degrees and −45 degrees) and one group of transversely oriented fibres (0 degrees) are observed [8,9,10,17].

The aim of this study is to develop an artificial linea alba with mechanical properties comparable to the human linea alba that can be used as an alternative test material for testing suture quality.

2. Materials and methods

Based on the knowledge that mechanical behaviour of human tissue is intensely related to its microscopic structure, the basic assumption of this study was that the development of artificial tissue with mechanical properties identical to those of certain human tissue, should focus on imitating the microscopic structure of this specific human tissue.

In this study, the microscopic structure of the human linea alba was imitated using fibre reinforced materials consisting of fibres and a matrix. Cotton fibres and a matrix of latex rubber and oil (cis-cis linoleic acid) were combined in a composite. Fibre orientation and fibre orientation ratio in the composite were based on human anatomy [8,9].

Resemblance between mechanical properties of sutured human linea alba and sutured artificial linea alba was based on stress-strain behaviour, maximum tensile forces and macroscopic failure mechanism in tensile tests. Stress-strain behavior was established on the bases of stress-strain curves. Macroscopic failure mechanism was defined as the pattern in which the suture tore through the linea alba. This was visually inspected on video recordings.

The results of tensile tests with sutured artificial linea alba and sutured human linea alba were compared. To validate the basic assumption of this study, a third tensile test was performed with a composite consisting of cotton fibres and latex rubber in which fibre orientation was different to that of the human linea alba.

2.1. Test specimens

Test specimens of 50 × 50 millimeters were used in all tests. Human specimens were consistently taken from the human abdominal wall, the linea alba being located in the midline of the specimen (Fig. 1).

Before testing thickness of linea alba was measured using sliding callipers.

2.2. Sutures

Specimens were incised through the midline and sutured with a continuous suture with a tissue bite size of 7 mm. Stitches were placed at intervals of 7.5 mm. This resulted in six stitches divided over 50 mm width (Fig. 1). To achieve consistently sutured specimens, a mould was used. All sutures were made using PDS II (polydioxanon, absorbable, monofilament).

2.3. Dynamometers

Both human tissue and composites were tested on a Testometric, Rochdale England, type DBBMTCL, 100 kgf dynamometer, with a speed of 5 mm/min.

Test 1–Mechanical properties of sutured human linea alba

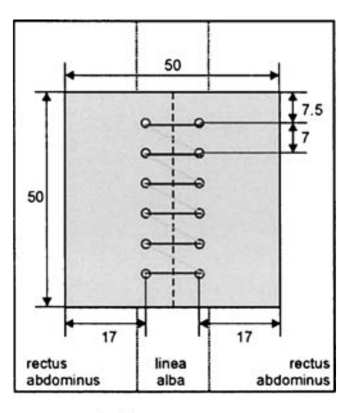

Fig. 1 Test specimens sutured human and artificial linea alba tissue (measurements in millimeters).

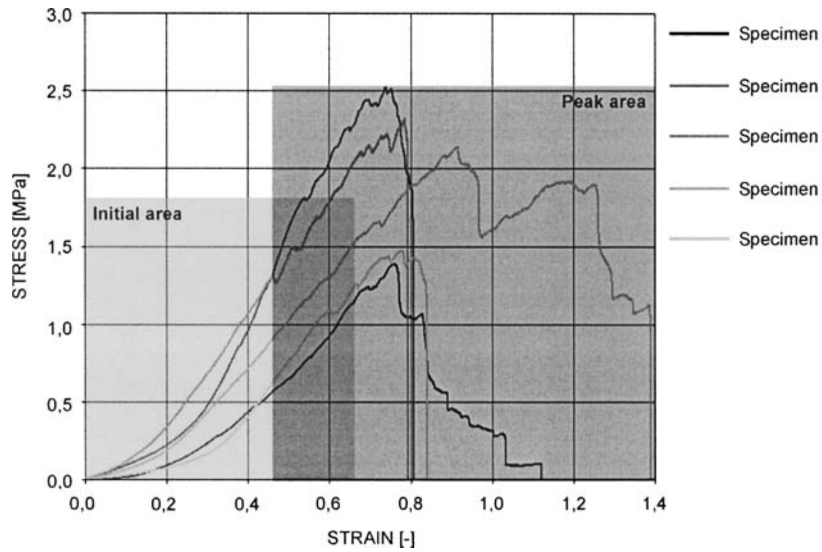

Fig. 2 Stress-strain curves of sutured human linea alba and required areas for placement of initial region and peak region.

Tensile tests of sutured embalmed human linea alba resulted in stress-strain curves, maximum tensile forces and macroscopic failure mechanism.

Test 2–Mechanical properties of sutured artificial linea alba with microscopic structure identical to human linea alba

Tensile tests of sutured artificial linea alba with a microscopic structure identical to that of human linea alba resulted in stress-strain curves, maximum tensile forces and macroscopic failure mechanism. These results were compared to the results of Test 1. This comparison led to insight into the usefulness of the adjusted artificial linea alba tissue as an alternative test material.

Test 3–Mechanical properties of sutured artificial linea alba with microscopic structure different from human linea alba

Tensile tests of sutured artificial linea alba with a microscopic structure different from that of human linea alba resulted in stress-strain curves, maximum tensile forces and macroscopic failure mechanism. These results were compared to the results of Test 1. This comparison led to insight in the validation of the basic assumption of this study.

3. Results

Test 1–Mechanical properties of sutured human linea alba

Maximum tensile forces for sutured human linea alba tissue are presented in Table 1. Based on these results, a maximum tensile force of approximately 200 N was postulated for the sutured artificial linea alba.

Figure 2 shows the stress-strain curves resulting from the tensile tests. The following characteristics were distinguished to define the stress-strain curve of sutured human linea alba:

Table 1 Maximum tensile forces (F_max) of sutured human linea alba.

Test	Specimen thickness [mm]	F_{max} [N]
1	0.9	62
2	0.8	101
3	1.4	162
4	1.8	193
5	2.1	155

1. Concave shape of initial region
2. Position of initial region
3. Presence of peak
4. Position of peak

Requirements for characteristic 2 and 4 were drawn up based on the results of Test 1. Figure 2 shows the required areas for both the initial region and the peak. Table 2 shows the values for stress and strain that correspond with these areas.

Figure 3 shows the macroscopic failure after a representative tensile test of sutured human linea alba tissue. The suture tore through the tissue in the vertical direction.

Test 2–Mechanical properties of sutured artificial linea alba with microscopic structure identical to human linea alba

Table 2 Characteristics that describe the stress-strain curves of the sutured human linea alba.

Characteristic	Values for stress and strain
1. Concave shape of initial region	—
2. Position of initial region	$\sigma_{\text{end of initial region}} < 1.8$ MPa $\varepsilon_{\text{end of initial region}} < 0.65$
3. Presence of peak	—
4. Position of peak	$\sigma_{max} < 2.5$ MPa $\varepsilon_{\text{begin of peak}} > 0.45$ $\varepsilon_{\text{end of peak}} < 1.40$

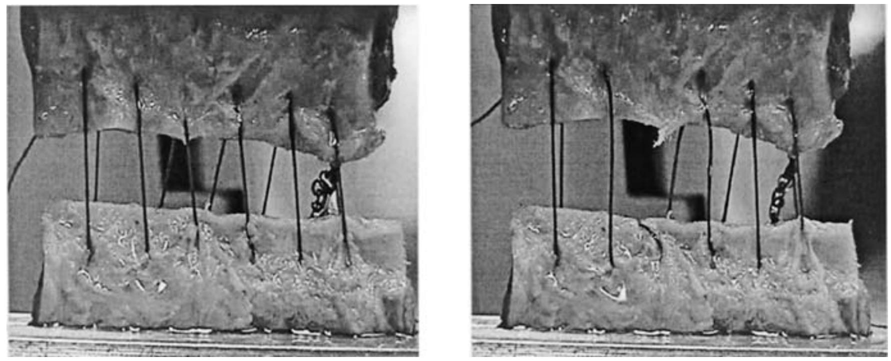

Fig. 3 Macroscopic failure mechanism sutured human linea alba tissue.

Table 3 Mechanical properties of sutured adjusted artificial linea alba: latex rubber Silipol (PolyService) with cis-cis linoleic acid (ratio 3:1 and 4:1 for latex rubber:acid) and 8 layers of 100% cotton thread fibre (DMC Border Machine, 50, 25 gr). Cotton fibres within separate layers had a density of 17 thread/inch. Stacking sequence expressed in fibre orientation of separate layers was 0°/0°/0°/0°/45°/45°/-45°/-45°.

Specimen	Ratio latex rubber: cis-cis linoleic acid	Specimen thickness [mm]	F_{max} [N]	Shape initial region	$\sigma_{end\ of\ initial\ region}$ (< 1.8 MPa)	$\varepsilon_{end\ of\ initial\ region}$ (< 0.65)	Peak present	σ_{max} (< 2.5 MPa)	$\varepsilon_{begin\ of\ peak}$ (> 0.45)	$\varepsilon_{end\ of\ peak}$ (< 1.40)
1a	4:1	2.0	148	Concave	0.70	0.32	Yes	0.98	0.32	0.50
1b	4:1	2.0	121	Concave	0.67	0.30	Yes	0.95	0.30	0.55
2a	3:1	2.4	118	Concave	0.94	0.27	Yes	1.46	0.27	0.52
2b	3:1	2.4	117	Concave	0.87	0.38	Yes	1.19	0.38	0.63

Maximum tensile forces are shown in Table 3. All specimens meet the criterion $F_{max} < 200$ N.

Figure 4 shows the stress-strain curves resulting from the tensile tests. The stress-strain curves satisfy all demands, except for the strain at the beginning of the peak region, which is too small for all specimens. Figure 5 shows that the macroscopic failure mechanism of sutured adjusted artificial linea alba is similar to that of sutured human linea alba tissue.

Test 3–Mechanical properties of sutured artificial linea alba with microscopic structure different from human linea alba

Maximum tensile forces are shown in Table 4. It should be noted that in tests with specimen 1 and 5 the suture broke prior to failure of the composite.

Figure 6 shows the stress-strain curves resulting from the tensile tests in which the composite failed. The initial region has a concave shape and a peak is present, but the

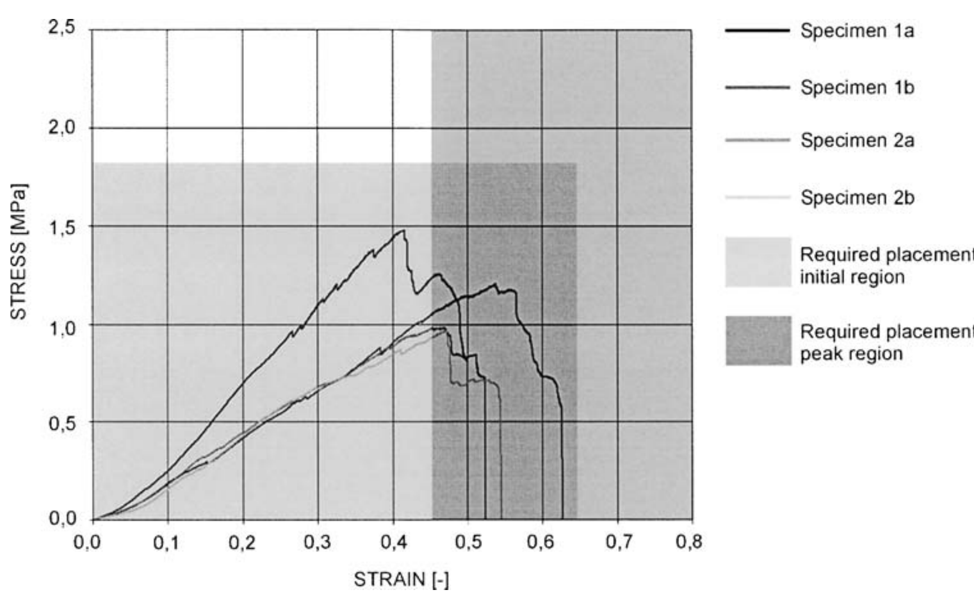

Fig. 4 Stress-strain curves of sutured artificial linea alba and required areas for placement initial region and peak region.

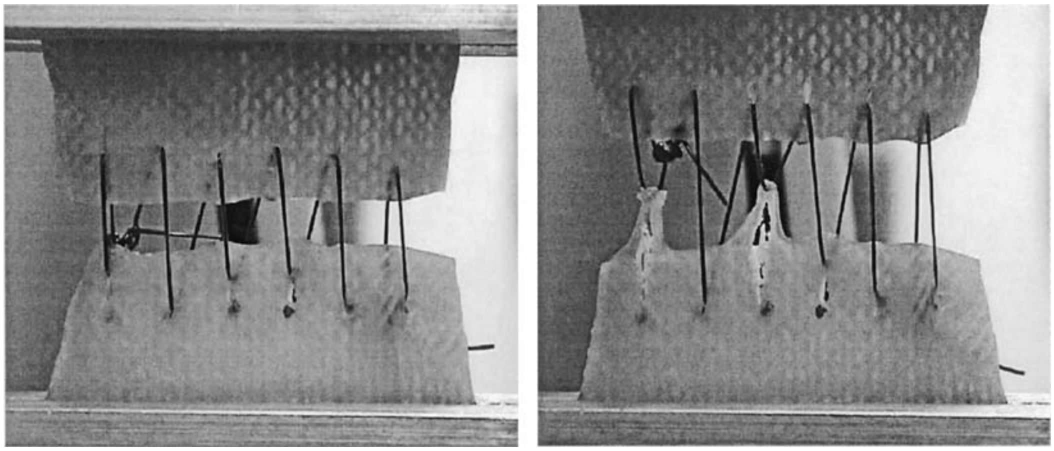

Fig. 5 Macroscopic failure mechanism sutured adjusted artificial linea alba.

Table 4 Maximum tensile forces (F_{max}) of sutured artificial linea alba: latex rubber Silipol (PolyService) and 6 layers of 100% cotton 0/90 woven fabric. Cotton fabrics within separate layers had a density of 17 thread/inch. Stacking sequence expressed in fabric orientation of separate layers was 0°/0°/0°/0°/45°/45°.

Specimen	Specimen thickness [mm]	F_{max} [N]	Suitable (Yes if $F_{max} < 200$ N)	Comments
1	1.8	231	No	Suture itself failed prematurely
2	1.8	244	No	—
3	1.8	233	No	—
4	1.8	237	No	—
5	1.8	219	No	Suture itself failed prematurely

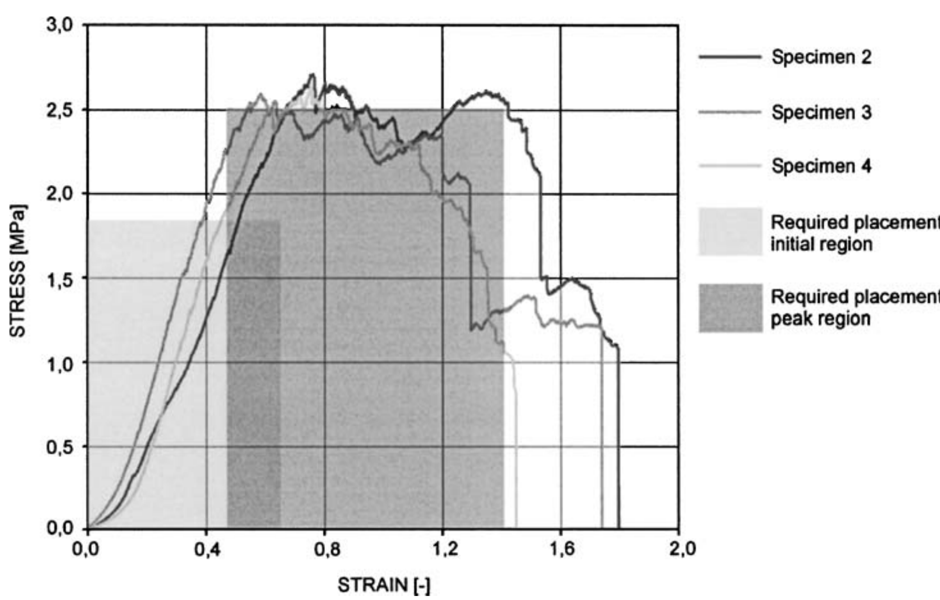

Fig. 6 Stress-strain curves of sutured artificial linea alba with different microscopic structure than human linea alba for tests with failure of specimen and required areas for placement initial region and peak region.

peak is not situated in the defined area. Figure 7 shows the macroscopic failure after a representative tensile test with sutured artificial linea alba. First, the suture tears through the tissue vertically. Subsequently, the cracks initiated by the stitches expand horizontally until they combine into one longitudinal crack. There is no pull-out of the suture from the composite.

4. Discussion

The artificial lines alba that was developed in this study shows maximum tensile forces and macroscopic failure mechanism that satisfy the demands that were posed. Our findings have demonstrated that the macroscopic failure mechanism of sutured adjusted artificial linea alba is sufficiently

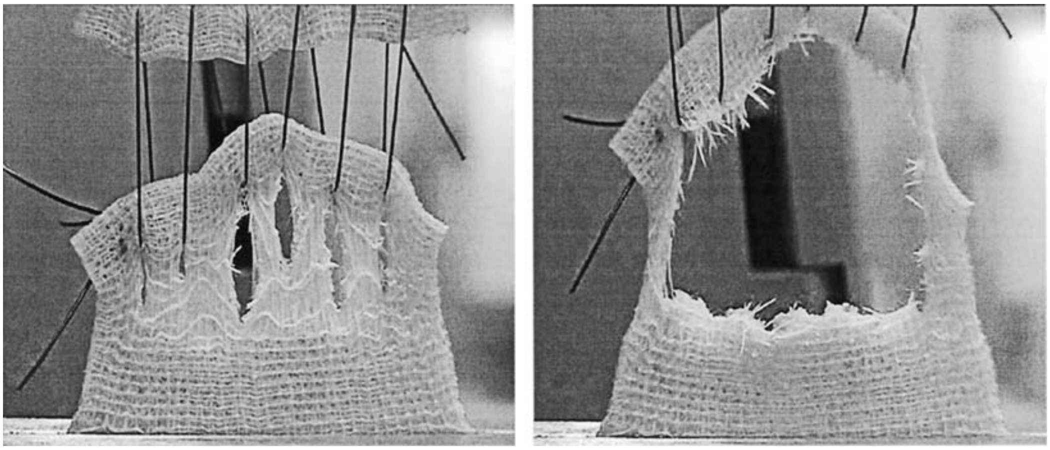

Fig. 7 Macroscopic failure mechanism sutured artificial linea alba with different microscopic structure than human linea alba.

realistic. Strains for this composite are too small which causes stress-strain curves with peak regions that start outside the required area. But based on the knowledge that adjustments to the matrix material allow additional tuning of the stress-strain curves, we are optimistic that the desired stress-strain curve can be approached more precisely by further adjustments to the matrix material. It is expected that a decrease of the share of cis-cis linoleic acid in the latex rubber-oil mixture will increase the composite's strain.

4.1. Composite

The choice for the development of a composite consisting of a matrix and fibres was based on the microscopic structure of the human linea alba. The human linea alba consists of collagen fibril bundles embedded in an amorphous ground substance (matrix). In addition to biochemical functions, such as feeding, the amorphous ground substance has a mechanical function: bonding the fibres and damping forces [personal communication H.R. Scholte, Erasmus MC, University Medical Center Rotterdam, Department of Biochemistry].

Because the composite is to be used in tests to compare the quality of different suture techniques, it should have handling behaviour similar to the human linea alba. This requires a matrix material that can be cut and penetrated with a needle. Since most rubbers satisfy this demand, it was decided to apply rubber in the test material. Latex rubber is already used in synthetic soft tissue models because of their resemblance with human soft tissue in handling characteristics [18]. However, latex rubber has a superior strain compared to the human linea alba. To reduce the strain of the latex rubber, oil (cis-cis linoleic acid) was added to the latex rubber.

Cotton was selected because of its relatively low maximum strength, compared to most reinforcement fibres, like glass fibre or carbon fibre, which have superior strength properties. It was assumed that the use of these strong fibres would produce a composite with a too high strength compared to the human linea alba.

Fibre orientation and fibre orientation ratio in the composite were based on human anatomy. In a ventral-dorsal direction collagen fibril bundles in the human linea alba are oriented in three different directions as a result of the pulling forces exerted to the linea alba by three respective muscles. Two oblique directions that are almost perpendicular to each other can be distinguished. Next to these, a third transversely oriented group of fibres is found [8, 9, 10, 17]. On average, about 50% of the fibril bundles in the linea alba are oriented transversely (0 degrees), about 25% of the fibril bundles in the linea alba are oriented in the first oblique direction (45 degrees) and about 25% in the second oblique direction (−45 degrees), which implicates a fibre orientation ratio of 2:1:1 for 0°:45°:-45°.

4.2. Basic assumption

The sutured artificial linea alba with 0/90 woven cotton fabric shows a macroscopic failure mechanism different to that of sutured human linea alba, which was attributed to the presence of a longitudinal fibre direction due to the use of 0/90 woven fabric in the artificial linea alba. Longitudinally oriented fibres (90 degrees) are not found in the human linea alba [19–22] and showed great resistance to pull-out of the suture in our tests. This finding validates the basic assumption that the development of artificial tissue with mechanical properties identical to those of certain human tissue, should focus on imitating the microscopic structure of this specific human tissue.

4.3. Protocol development soft fibrous tissue

The protocol used in this study has been proven useful for the development of a material with predetermined mechanical properties. It is expected that the protocol can be used in the development of other artificial soft fibrous tissues, such as tendons. Remarkable in this protocol is the use of the shape of stress-strain curves in the comparison of different materials. The shape of stress-strain curves was used as the most important indicator for mechanical properties, since it provides a practical instrument to compare a great number of mechanical properties of different materials. Different materials can show very differently shaped stress-strain curves.

Maximum tensile force was considered an important criterion because the alternative test material must be cut and penetrated in the same way as the human tissue. Maximum tensile forces were used as indicator for resemblance in handling behaviour.

The mechanical properties of human linea alba were established by tensile tests performed on embalmed human cadaveric tissue. A review of previous research shows that, except for a minor loss of mechanical strength, embalmed cadaveric tissue retains it biomechanical properties comparable to fresh cadaveric tissue [23] and therefore behaves sufficiently realistic.

This study focused on the mechanical properties based on tensile tests on sutured tissue in the direction of the horizontally oriented fibres in human linea alba, simulating the linear traction exented by the transverse abdominal muscles. Next to this traction, the abdominal wall is subjected to intra-abdominal pressure, which acts on the deep aspect of the abdominal wall [24]. A resemblance in mechanical properties based on this intra-abdominal pressure was not investigated. In future research bursting strength tests on sutured human linea alba and sutured artificial linea alba can be used to investigate the resemblance in mechanical properties based on the intra-abdominal pressure.

Furthermore, it is desirable that resemblance between mechanical behaviour of human linea alba tissue and artificial linea alba when sutured with different suturing techniques is investigated to extend the possibilities of artificial tissue as alternative test material.

5. Conclusion

From our study we conclude that a sutured composite consisting of a latex rubber-cis-cis linoleic acid mixture (ratio 4:1 for latex rubber:acid) and 8 layers of 100% cotton thread fibres with stacking sequence 0°/0°/0°/0°/45°/45°/-45°/-45°, shows mechanical properties highly similar to the sutured human linea alba. Minor adjustments to this composite will further approach the mechanical properties to those of the sutured human linea alba. The presented newly developed tissue is proposed as a substitute for poorly available human and animal tissues.

Acknowledgements The authors wish to thank Professor Van Tumhout and Mr. R Oosterom for their help in the selection of possible suitable rubbers for application in the test material, Ms N. Beuling, Mr W.F.G. Sengers for their help in the production of the composites.

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