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ORIGINAL ARTICLE

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Inguinal hernia: Measurement of the biomechanics of the lower abdominal wall and the inguinal canal

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Abstract *Background*: The stability of the lower abdominal wall may play a considerable role in the development of inguinal hernia. Therefore, the strength of the individual wall layers needs to be quantified. Despite numerous advances in hernia repair, comparatively few systematic biomechanic and morphometric analyses have been performed. Our aim was to establish and apply a standardised procedure for testing the abdominal wall layers' stability. *Methods*: After dissecting the abdominal walls of 16 cadavers into separate layers, we used a spherical punch and a force transducer to investigate the forces necessary to foraminate the layer. In addition, maximum tensile-strength and suction tests and histologic morphometry were performed. *Results*: The transversalis fascia was torn up on an average of 10.5 N, the peritoneum including pre-and subperitoneal tissue on 46.6 N, the aponeurosis of obliquus internus abdominis muscle on 51.7 N, and the aponeurosis of obliquus externus abdominis muscle on 92.6 N. Tensile tests of tissue strips obtained from defined areas showed comparable results. In contrast, surgical mesh revealed values between 60 and 150 N in punching tests. Left-right comparisons, as well as comparisons of the individual areas, revealed considerable intra- and inter-individual differences. *Conclusions*: Biological hernia repair should focus on a reinforcement of the tissue layers with the highest biomechanic stability. Reinforcement of the transversal fascia must be questioned according to our results of poor mechanical resistance.

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Introduction

Groin hernia surgery is the most frequently applied surgical intervention. Traditional hernia surgery, e.g. Bassini's repair, has been replaced by more recent treatments, which claim better clinical outcomes with fewer recurrences. Therefore, the frequency of recurrence interventions ought to decrease. Users of more recent strategies of hernia surgery state a reduction of recurrences to values of less than 3%. Therefore, the total number of hernia recurrence surgery should decrease accordingly. However, statistics with adequate quality control in surgery reveal nearly unaltered rates of recurrence surgery—up to 13% [1]. Similar numbers were reported from the comprehensive Swedish Hernia Register [2].

The methods of groin hernia surgery have been discussed extensively [3, 4, 5, 6, 7, 8, 9, 10, 11, 12]. Various schools favor different treatment methods. However, a gold standard in hernia surgery has not been established yet, as concluded by the Cochrane study group [13] based on a meta-analysis of 34 published reports. This report also showed that the overall recurrences did not differ between laparoscopic and open techniques.

Furthermore, the situation is complicated by the fact that both classic and more recent methods are frequently performed with individual modifications by the surgeon. This certainly contributes to different outcomes. Prerequisites for comparative studies are clear anatomic definitions and a strict adherence to standard procedures.

The urgency to revise the anatomy of the inguinal region was also described in detail by Annibali [14] and by Colborn and Skandalakis [15]. Arregui [16] studied the inguinal region against the background of the different perspective in laparoscopic hernia surgery. Skandalakis et al. [17] investigated the embryogenesis of the antererior abdominal wall below the umbilicus and the descent of the gonads.

All surgical groin hernia repair techniques aim at reinforcement, e.g., stabilisation, of the ventral abdominal wall. The anatomical structures in the region of the inguinal canal were extensively described. Studies containing an exact quantification of the mechanical resistance of the inguinal region are still sparse. Junge et al. [18] analysed the stability of the posterior wall of the inguinal canal in total after Shouldice repair in cadavers. Peiper et al. [19] managed to quantify intra-operatively the traction forces that occur during Shouldice repair while adapting the lateral edge of the rectus sheath and the iliopubic tract. Additionally, investigations were performed with the Valsalva manoeuvre and simultaneous measurement of the intra-abdominal pressure.

However, data of the properties of the individual layers, particularly with regard to mechanical stability, are lacking.

Thus, we have investigated all different components of abdominal wall contributing to the inguinal canal and examined their biomechanical quality with different methods. The aim was to establish a standardised measuring procedure and to define the biomechanical properties as a basis for future hernia repair improvements.

Examined tissues and methods

Twenty-five cadavers provided by the Institute of Anatomy and Institute of Pathology, University of Mainz, Germany, were used for this study from June 2000 until April 2001. Three were formaldehyde embalmed; 22 were unfixed, obtained within 24 h post mortem. The mean age was 62.5, ranging from 44–86, 12 were males, 13 females. Cadavers that had evidence of any previous abdominal or groin surgery or of hernia were not considered for this study. All embalmed preparations and six of the unembalmed preparations were used for establishment of the measurement methods; the remaining 16 were included in the study.

The abdominal wall was harvested by dissecting the overlying skin from the umbilicus down to the inguinal ligament. The specimen was excised cutting horizontally at the umbilicus, then vertically down to the anterior superior iliacal spine, and along the inguinal ligament to the symphysis. After photo documentation, the different layers were separated: external oblique abdominal muscle aponeurosis, internal oblique abdominal muscle aponeurosis, transversalis fascia, and the underlying peritoneum with pre- and subperitoneal tissue, which could not be separated from the peritoneum itself without injuring the smooth layer. The isolated layers were photographed with a digital camera (Nikon, Coolpix, Düsseldorf, Germany). The recorded images were printed out and used for documentation of the measurement points. As a rule, eight defined points of interest were examined (Fig. 1).

Surgical meshes

To get an idea of the resistance of meshes in comparison to human tissue, we tested the tensile strength of some synthetic meshes, which are actually in use for hernia surgery. The following meshes were tested: Vypro II (multifilament, polypropylene, nonabsorbable); Prolene, (nonabsorbable monofilament); Mersilene (nonabsorbable polyethylenterephthalat filaments; all by Ethicon, Johnson & Johnson, Norderstedt, Germany); and Premilene (nonabsorbable, polypropylene; Braun Aesculap, Tuttlingen, Germany).

Suction device

The marked points were measured first with a skin-elasticity meter (Cutometer SEM 575, probe diameter 4 mm; Courage & Khazaka Electronics, Cologne, Germany). The measuring principle is based on suction and elongation. The device generates negative pressure, which can be varied between 20 and 500 mbar. The tissue area to be measured is sucked into the aperture of the handheld probe by the negative pressure. The penetration depth of the tissue into the aperture is determined contactless by an optical measuring system consisting of a light emitter and a light acceptor. Two opposing glass prisms transmit the light from emitter to acceptor. The light ratio changes proportionally to the penetration depth of the tissue. Variations in the tissue

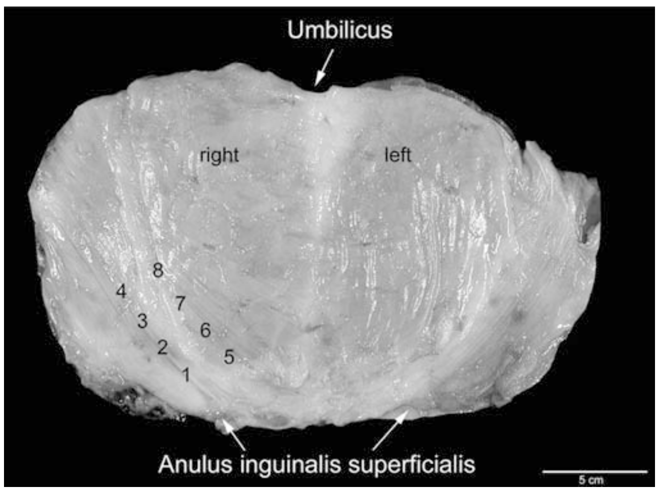


Fig. 1 Preparation of the lower abdominal wall. View of the external oblique abdominal muscle aponeurosis. Position of measuring points for suction and breaking-strength test shown on the right side of the specimen. Distance between the measuring points is 2.5 cm. Note the heterogeneity in the density of the obliquely running fibre bundles within the external oblique abdominal muscle aponeurosis

elevation in response to suction are recorded by a computer. The time-strain mode was used with three cycles of 1-s traction under negative pressure of 300 mbar, separated by 1-s relaxation periods. We were particularly interested in the immediate elastic distension after 1 s and in the first maximum amplitude as indicators for the firmness of the tissue.

Maximum tensile-strength test

Subsequently, we obtained with a punching device test strips for the tensile-strength test orientated vertically to the fibre direction. The test strips had a defined hourglass form with 5 mm width at the narrowest part, constituting a predetermined breaking point. Test strips without an hourglass form would inevitably tear at the wedge grips, where the tissue is already bruised. The design of the hourglass form was based on material testing standards [20, 21]. All tensile-strength tests were carried out vertically to the main fibre courses, since the collagenous fibre texture dilatation is of higher importance for the development of a hernia than the longitudinal, axial tensile strength of the fibres.

Our breaking-strength-test device (modified according to Schlenger) [22] consisted of two opposing gripping jaws to fix the tissue strip (Fig. 2). The electric-engine-driven gripping jaws were moved apart with a constant speed of 3 mm/s, which resulted in load onset rates of less than 0.05 N/s. The endpoint was the ultimate load (in N), which is the maximum load the specimen sustained during the test. A position encoder (WA300) was used to register the covered distance. A force transducer for traction and compression (S2, maximum value 150 N) was used to quantify the power impacting on the tissue strip. The resulting values were amplified by a multiple channel PC measuring device (Spider8) and plotted as way-power curve (software: Catman 3.0, all HBM Hottinger Baldwin Messtechnik, Darmstadt, Germany) (Fig. 3).

Fig. 2 Tensile-test specimen. View of the two gripping jaws with clamped surgical mesh punched in hourglass form

Punching test

A punching test was performed in eight cadavers and in all meshes. By replacing the gripping jaws of the tensile-strength test machine with a clamping-ring (40-mm diameter) and a spherical punch (10-mm diameter) and moving the punch through the clamped tissue with a speed of 3 mm/s, we obtained a punching-test device (Fig. 4). In this setting, the tissue was fixed in the clamping ring (Fig. 5a, Fig. 5b). Due to the dimensions of the clamping ring, we confined our measurement series to the medial inguinal region corresponding to point six of the tensile-strength tests (Fig. 5c). Before the punching test, all probes were measured with the above-mentioned suction device. The results were plotted as way-power curve (Fig. 6).

Histology

After the punching out of the tensile-test specimens, the remaining tissue was harvested for histology and subsequent collagen-fibre analysis. Analogue probes were harvested after the punching test. The 2×4-mm specimens were fixed over 24–48 h in buffered formalin (4%). After dehydration and embedding in paraffin, they were cut in 5-μm thick sections orientated exactly vertical to the main fibre course. The sections were stained with haematoxylin and eosin, sirius red, elastica van Gieson, and Masson-Goldner, according to standard protocols. The thickness of the collagen layer was measured by light microscopy (Axiophot, Zeiss, Jena, Germany) using the morphometry software Diskus 4.15 (Hilgers, Königswinter, Germany). The mean thickness of the different specimens was obtained by the average of ten measurements per probe.

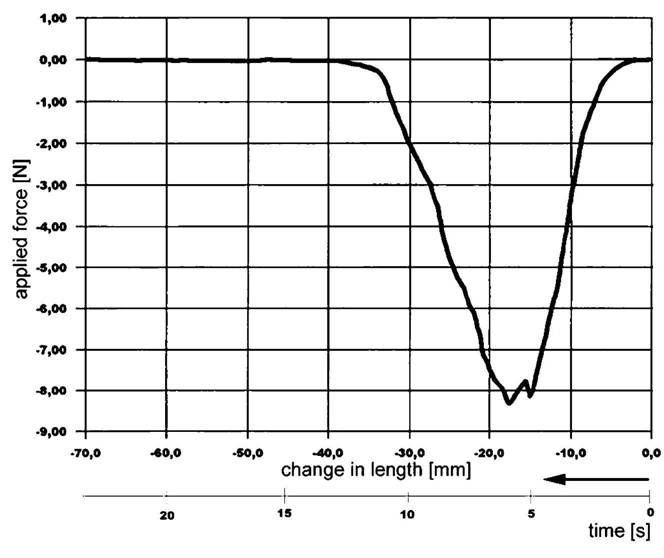


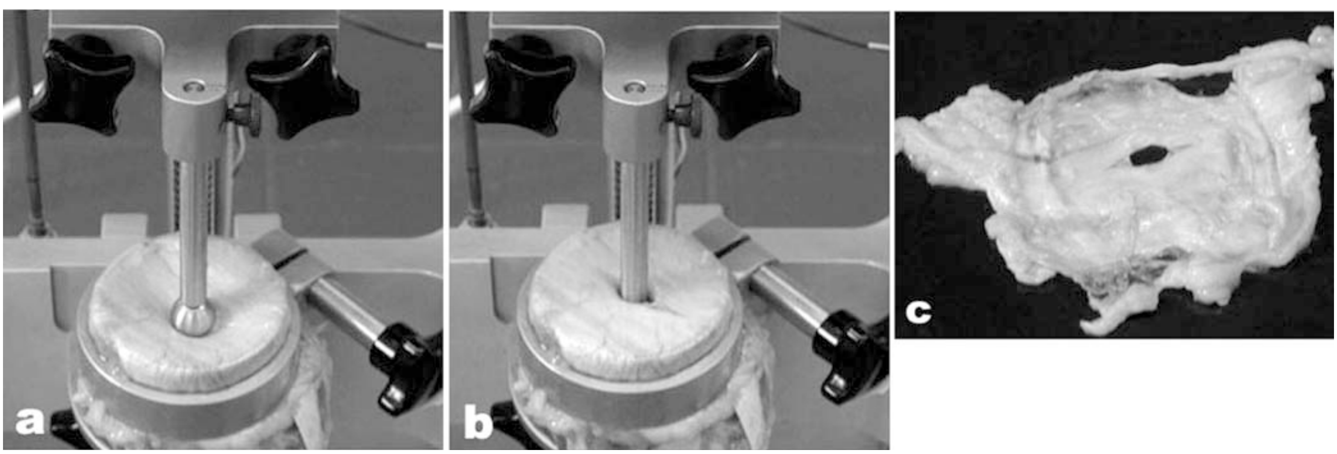
Fig. 3 Measurement of ultimate tensile load. Values plotted as way-power curve. Speed is 3 mm/s. Starting point of the curve is on the right side. Breaking point located at the minimum of the curve

Fig. 4 Tensile-test device with applied punching test adapter (clamping ring and spherical punch)

Statistics

Statistical analyses were performed with SigmaStat 3.2 (Jandel Scientific, Erkrath, Germany) and SPSS 10.0.7 (SPSS, Chicago, Ill., USA) for normal distribution and to determine differences. All analyses were drawn out using SigmaPlot 5.0 (Jandel Scientific, Erkrath, Germany). Differences among the groups were tested by *t*-test for significance. All *P* values to be presented in the following should be regarded as descriptive *P* values, since they were not formally adjusted for multiplicity. A *P* value <0.05, therefore, indicates local statistical significance; all significance tests were performed and should be interpreted in a two-sided manner. The difference of the means between groups and the 95% confidence interval of the difference of the means is given.

Fig. 5 Punching test **a** Spherical die penetrating the tissue layer **b** Ruptured tissue example **c** The tissue around the disruption was harvested for histology. Note the obvious gap in the fibre bundles



Results

The sharp dissection of the individual layers of the lower abdominal wall was easily accomplished in all specimens. Difficulties arose only in some cases in the triangle between the inguinal ligament, the inferior epigastric vessels, and the lateral margin of the rectus sheath (Hesselbach), when the profound layer of the transversal fascia was dissected from the muscle fascia of the transversal abdominal muscle (superficial layer of the transversal fascia). This resulted in a too-thick layer of the transversal fascia.

Tensile-strength tests

At first glance, contradictory results were achieved in the tensile test, as shown in Fig. 7. The ultimate tensile load decreases from an average of 6.0 N (SD 4.5) in the external oblique aponeurosis to 1.7 N (SD 1.9) in the transversal fascia. The peritoneal layer, with a mean of 7.5 N (SD 11.5), is even stronger than the internal oblique abdominal muscle with 3 N (SD 3.0). However, it should be remembered that this tensile test was performed vertically to the main collagenous fibre bundle course. No preferential direction is evident in the peritoneal layer, whereas the fibre bundles in the external and internal oblique muscle aponeurosis are strongly parallel-orientated. So a comparatively high resistance was to be expected irrespective of the layer thickness. The analysis of the individual defined measurement points did not reveal significant differences because of the surprisingly high inter- and intra-individual variability (data

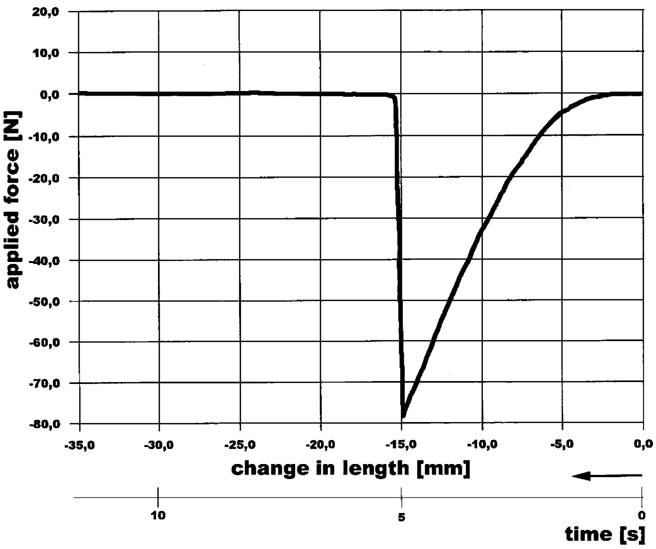


Fig. 6 Punching test. Way-power curve. Speed is 3 mm/s Curve runs from right to left. Breaking point located at the minimum of the curve

not shown). The surgical meshes show values from 2.3 up to 15.5 N. Thus, they are in the range of the tensile strength of the abdominal wall's layers (Table 1).

Specific ultimate tensile strength

From the ultimate loads, which resulted in tissue disruption and the thicknesses of the layers, a specific ultimate load was evaluated, indicating the ultimate tensile strength (N/mm2) (Table 2).

Suction tests

Fig. 8 shows the results obtained with the suction device. Even though some differences are significant, we suggest that these are arbitrary differences requiring a thorough discussion.

Punching tests

Fig. 9 shows that the external oblique abdominal muscle aponeurosis has with a mean of 96.3 N (SD 35.3) the highest resistance against transmurally applied pressure. The internal oblique muscle with a mean of 51.7 N (SD 24.7 N) contributes to a significantly lesser extent to the abdominal wall stability. Surprisingly, the peritoneum with the preperitoneal tissue, with a mean of 43.6 N (SD 21.5), has a significantly higher resistance than the transversal fascia with 10.7 N (SD 8.3).

The explorative tested surgical meshes revealed values of 60 to more than 150 N, significantly higher values than the internal oblique abdominal muscle aponeurosis and the fascia transversalis (Table 1).

Histology

The biomechanical findings on the punching tests parallel the thickness of the collagen fibre bundles within the individual layers, as shown in Fig. 10. The external and internal oblique abdominal muscle aponeurosis, with 471.9 μm (SD 210.1) and 398.6 μm (SD 352.5), respectively, have significantly thicker collagen fibre

Fig. 7 Tensile test of the individual layers of the lower abdominal wall. Pooled data from all measurement points. Values are plotted as box plot with first to third quartile and median. Whiskers indicate 10th and 90th percentile, circles indicate 5th and 95th percentiles. 95%-CI difference of means (mean difference in parentheses): * 2.0–4.0 (3.0); ** 3.4–5.2 (4.3); *** 0.6 – 2.0 (1.3); **** 2.3–6.7 (4.5); ***** 3.6–7.9 (5.8). For specific ultimate tensile-strength test results, see Table 2. ext. obl. abd. = external oblique abdominal muscle; int. obl. abd. = internal oblique abdominal muscle; transv. fascia = transversalis fascia

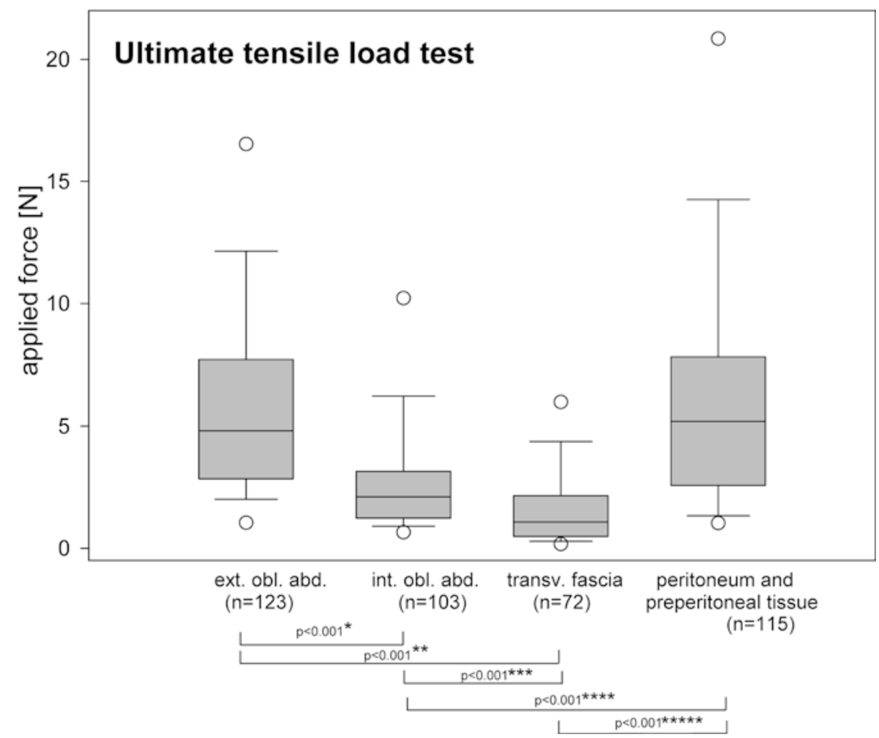


Table 1 Ultimate tensile loads of four surgical meshes

	Ultimate tensile load parallel to main fibre course [N]	Ultimate tensile load vertical to main fibre course [N]	Punching tests [N]
Premilene	15.57	13.04	> 150 [a]
Mersilene	12.73	9.67	76.62
Prolene	7.535	2.29	> 150 [a]
Vypro II	6.16	–	59.48

[a] Due to the limit of the force transducer, values higher than 150 N were not recorded

Table 2 Specific ultimate tensile strengths were calculated from the ultimate loads in the tensile-strength tests and the histologically determined layer thicknesses. All values are mean values

	Ultimate tensile load [N]	Layer thickness [μm]	Area [mm^2]	Specific ultimate tensile strength [N/mm^2]
external oblique abdominal muscle	6.02	472	2.36	2.55
internal oblique abdominal muscle	3.02	399	1.99	1.51
transversalis fascia	1.74	60	0.3	5.80
peritoneum and preperitoneal tissue	7.5	161	0.81	9.32

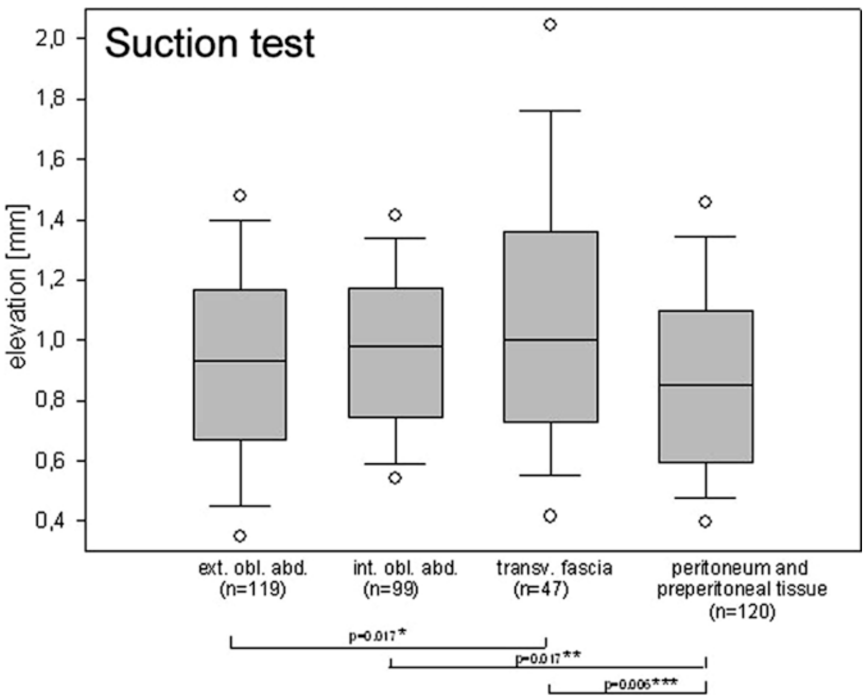


Fig. 8 Suction test of the individual layers of the lower abdominal wall. Pooled data from all measurement points. 95%-CI difference of means (mean difference in parentheses): * 0–0.3 (0.2); ** 0–0.2 (0.1); *** 0–0.4 (0.2). ext. obl. abd. = external oblique abdominal muscle; int. obl. abd. = internal oblique abdominal muscle; transv. fascia = transversalis fascia

layers than the transversal fascia and the peritoneum. Again, the differences between transversal fascia and peritoneum with preperitoneal tissues are significant.

Discussion

Inguinal groin hernia repair strategies have been improved during recent decades. However, approximately 13% of all procedures are still done for recurrent hernias [7]. There is no doubt that surgical experience and dedication contribute to the therapeutic outcome. This is also true for the adherence to standard operating procedures, which does not always happen. Muschaweck et al. (http://www.hernien.de), e.g., pointed out that out of 721 patients undergoing recurrence surgery after Shouldice repair, more than 36% were definitely not treated correctly, according to Shouldice with doubling of the transversal fascia.

Even though the rate of myoaponeurotic repair techniques in general decreases, these techniques still accounted for 66% of repairs in 1995 [23]. Others claim that tension at the suture line is the prime aetiologic factor in hernia recurrence after tissue repair. Lichten-

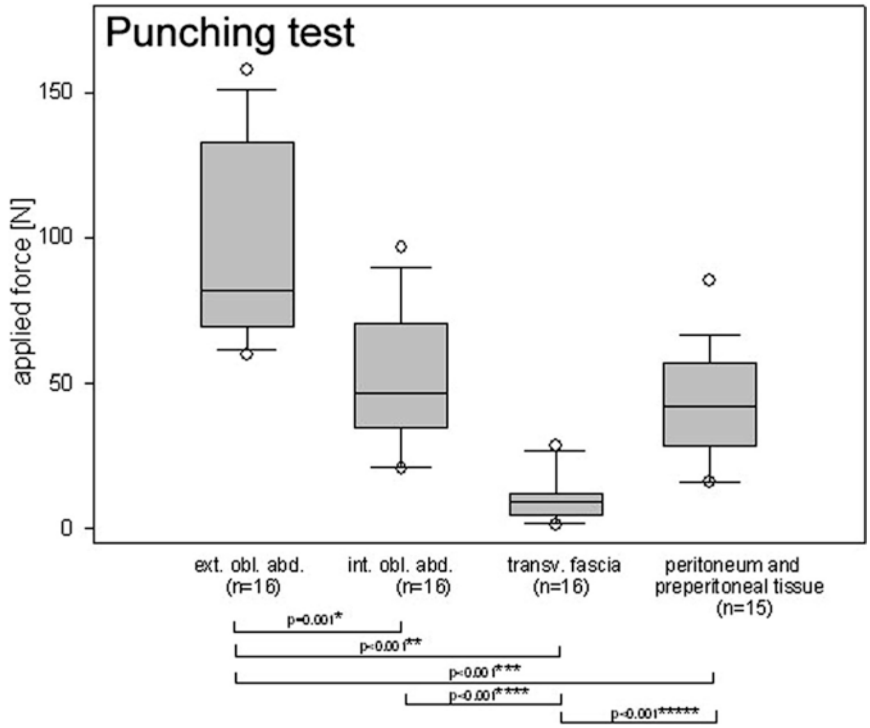


Fig. 9 Punching test of the individual layers of the lower abdominal wall. 95%-CI difference of means (mean difference in parentheses): * 21.7–67.5 (44.6); ** 66.4–104.8 (85.6); *** 31.2–74.2 (52.7); **** 25.6–56.3 (41.0); ***** 20.4–45.4 (32.9). ext. obl. abd. = external oblique abdominal muscle; int. obl. abd. = internal oblique abdominal muscle; transv. fascia = transversalis fascia

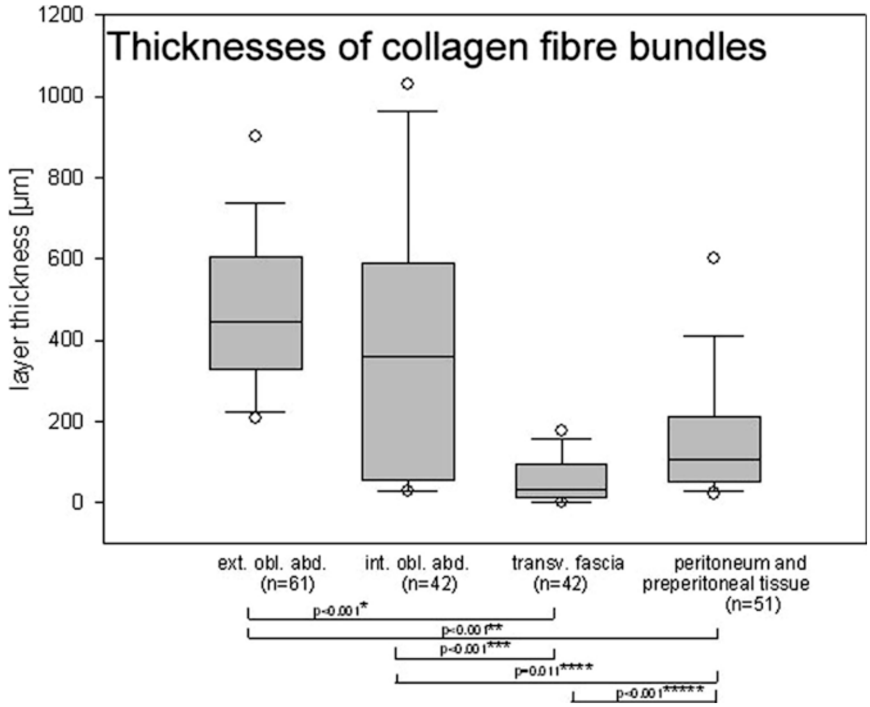


Fig. 10 Microscopic measurements of the thickness of collagenous fibre bundles in the abdominal layers of the inguinal region. 95%-CI difference of means (mean difference in parentheses): * 350.8–474.2 (412.5); ** 237.7–389.8 (313.7); *** 200.8–473.1 (336.9); **** 95.5–380.8 (238.2); ***** 156.4–41.2 (98.8). ext. obl. abd. = external oblique abdominal muscle; int. obl. abd. = internal oblique abdominal muscle; transv. fascia = transversalis fascia

stein et al. properly stated that “all pure tissue repairs, namely Halsted, Shouldice, and McVay, regardless of their modifications, have shared one common disadvantage: tension at the suture line” [24]. However, the works of Junge et al. [18] denied this in the case of Shouldice repair.

Irrespective of that, it should be noted that the pathophysiological basis of groin hernia, as well as the functional properties of the individual abdominal wall layers, are not fully understood. To our knowledge, theoretical considerations of the efficacy of individual surgical strategies prevail instead of functional, pathophysiological experiments, or measurements.

Within this study, we tried to assess the mechanical properties of the layers of the abdominal wall as a basis for further studies on improved repair techniques. It is

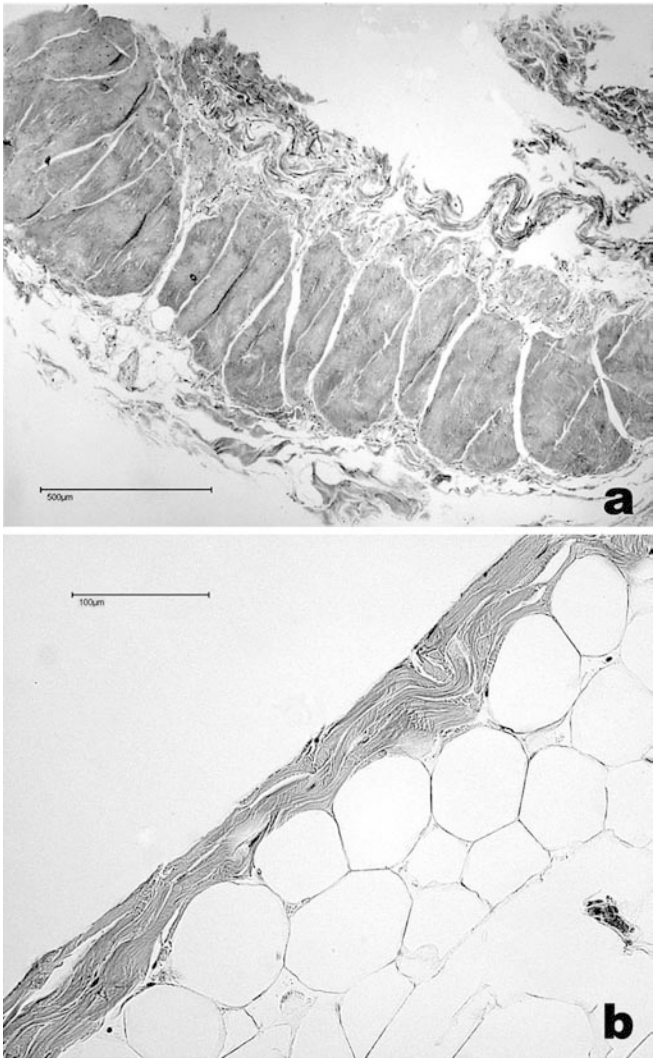


Fig. 11 **a** Cross-section of the obliquus externus abdominis muscle aponeurosis with parallel-orientated collagen fibre bundles. The gaps between individual bundles represent predetermined weak points. **b** Cross section of the peritoneum and preperitoneal tissue. Note the more irregular course and interweaving of collagen fibre bundles. Masson-Goldner stain. Magnification 45× in **a**, 170× in **b**

unquestionable that the abdominal wall of the inguinal region has to be seen as a complex functional system, in which the individual layers contribute to different extents to the biomechanical stability. To assess the impact of the individual layers, however, dissection and tests of the isolated layers were necessary. Three different approaches were chosen: tensile tests, punching tests, and elasticity measurements. The latter—performed with a suction device originally designed for skin-elasticity measurements—was already proposed by Pans et al. [25, 26]. Contrary to these authors, we regard this method, based on our own measurements, as unsuitable because of the limited reproducibility and high risk of artifacts in wet biological specimens.

Tensile-strength tests were performed with a speed of 3 mm/s. In biomechanical testing, e.g., of skin or scar tissue tensile strength, frequently speeds of 10–20 mm/min are used [27, 28]. However, the anterior body wall is frequently exposed to sudden mechanical stress, for example when coughing. Therefore, a significantly higher speed, which reflects the physiological stress more closely, was chosen.

Punching tests with transmurally applied forces revealed highly significant differences in the mechanical stability of the layers with lowest values for the transversal fascia. Obviously, the transversal fascia contributes to a lesser extent than the peritoneum, including the preperitoneal tissue, to abdominal wall stability so that the necessity and efficacy of doubling procedures of the fascia transversalis has to be questioned.

In our tensile tests, the difference between external oblique abdominal muscle aponeurosis and fascia transversalis was also clearly shown but not so markedly expressed as in the punching tests. At first glance, surprisingly good results were obtained in the tensile tests for the peritoneum together with the preperitoneal tissue. However, it must be considered that the tensile tests were performed vertically to the main fibre course. Thus, tissues like aponeuroses with strongly parallel-orientated fibre bundles (Fig. 11a) showed comparatively low tensile strength, whereas tissue with network-like interweaving collagen fibre bundles without a predominant course (Fig. 11b) had relatively higher values.

This also resulted in higher specific maximum strengths for the transversal fascia and the peritoneum.

Comparisons to the histological specimens again revealed that not only the total layer thickness but also the course of the collagen fibre bundles and the degree of interweaving of adjacent fibre bundles determines the resistance against transmurally acting pressure forces. Therefore, we regard the value of histological measurements alone as very limited, even though they may nicely show area-specific differences [29]. However, when assessing this structure-function correlation, other components influencing the abdominal wall stability, such as metalloproteinases, should not be forgotten. Comparisons of the transversal fascia in individuals with direct or indirect hernias showed in direct hernias an increase of interfibrillary matrix with numerous dense particles and a slight decrease of lysine-hydroxylation. Also increased expression of metalloproteinase-2 as an indicator for tissue alteration was observed [30, 31]. However, it remains unclear whether there is a causal relationship between these changes and the development of hernia or whether they simply represent a consecutive symptom. We also should note, that the examined specimens were from cadavers without hernia and who had no evidence of previous abdominal surgery or hernia.

Analyses of the defined individual measurement points did not reveal significant differences but a high inter- and intra-individual variability, which was not so markedly expressed in histology. This was also true for the region of the iliopubic tract, which was described by Teoh et al. [32] as a constant feature important for herniorrhaphy.

Explorative measurements of surgical meshes revealed significantly higher pressure and tensile-strength test results than the biological tissues. However, it can be expected that intravital pressure resistance is higher than in our postmortal setting, which acts on the aponeurosis, prevents to a certain extent the divergence of individual fibre bundles.

In summary, our results suggest that biological hernia repair should focus on a reinforcement of the tissue layers with highest biomechanical stability. According to our results, doubling procedures of the weakest layer—as done according to Bassini—will contribute only to a limited extent to significant increases of the abdominal wall stability.

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