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Biomechanical Test Setup for the Investigation of Forehead Suture Techniques

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Abstract: Wound healing can be delayed if the biomechanical stability of the wound closure is inadequate. Therefore, it is necessary to investigate different suturing techniques for their biomechanical stability.
In this study, suturing techniques suitable for the forehead area were investigated. For this application, a special test setup was developed to simulate the curvature of the forehead and the corresponding physiological configuration. The average forehead curvature is 62.24 ± 4.11 mm in radius. To simulate this curvature, the skin specimens are subjected to tensile stress over the spherical surface using a standard uniaxial testing machine. For the evaluation, an automated evaluation tool for MATLAB was also developed. Three different suturing techniques (Straight, Lazy-S, Zigzag) were investigated and tested for their biomechanical stability.
Of the three suturing techniques, the Zigzag suture proved to be the most stable with the highest stiffness of 44.23 ± 8.18 % and the highest final failure of 32.60 ± 4.95 % (relative to the control sample without incision).
The study has shown that the test setup can be used to investigate different forehead suture techniques.

Keywords: Biomechanics, Suture, Forehead, Tensile Test

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1 Introduction

High tension on wounds can lead to delayed wound healing [5], resulting in unstable scars and even necrosis at the wound edges [3, 5]. Sufficient biomechanical stability of the wound closure is therefore crucial for wound healing. High tensions on the skin and wound can occur, for example in the area of the forehead. Movement of the forehead and hair care can cause this tension. Treatment of injuries or skin incisions in the forehead area may be necessary due to a large laceration or after surgical procedures such as hair reduction.
In order to analyse different suture concepts (suture material, type of suture [5]) with regard to their biomechanical stability, an appropriate experimental setup is required. In the past, suturing techniques were mainly tested based on standardised tensile tests [4, 7], but only slightly adapted to the later application. To investigate specific suturing techniques for the forehead area, a test setup was developed to more accurately simulate wound expansion and physiological loading in the forehead area. In addition, a standardised method for determining the stiffness of the suture-skin construct was established.

2 Methods

The following describes the experimental setup used to study the suturing techniques in the forehead area and presents the evaluation methodology for the tests.

2.1 Forehead Curvature

The first step was to determine the curvature of the forehead for the test setup (Fig. 1). The curvature was measured on eight human skull models. The 3D models were created using computed tomography and 3D scanners and made freely available on the sharing platform Thingiverse. Meshmixer (Autodesk) was used to define the region of the forehead for all skull models. This was then processed as a point cloud in MATLAB 2020b (MathWorks) and a sphere was fitted iteratively (1000 iterations) to the 3D point cloud using the pcfitsphere function. The average curvature for all eight skull models was 62.24 ± 4.11 mm radius (mean ± standard deviation).

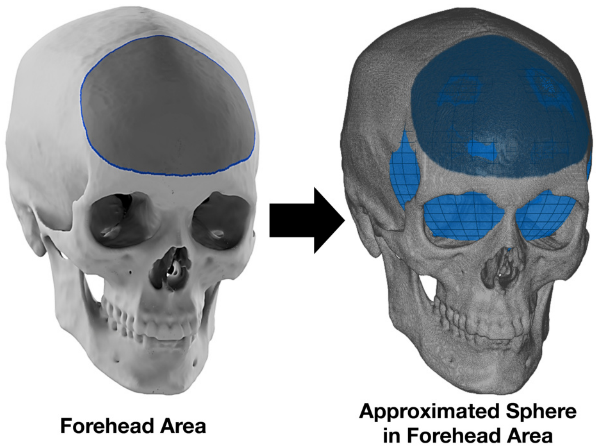

Fig. 1: Skull where the forehead area was first marked and then an approximate sphere was calculated for this area using MATLAB. (Skull from [1])

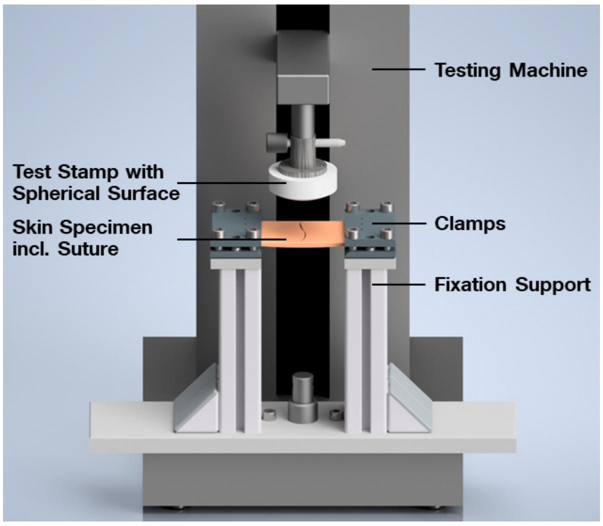

Fig. 2: Digital model of the test design for biomechanical testing

2.2 Test Setup

A standardised uniaxial testing machine (Zwicki 1120, Zwick Roell GmbH Co. KG) was used to perform the suture tests (Fig. 2). A stamp with a spherical surface was milled of POM-H (polyoxymethylen homopolymer) to imitate the forehead curvature and to apply the tensile stresses in the physiological state to the various suture techniques via the testing machine. Based on the calculations of the forehead curvature, a spherical surface with a radius of 60 mm was produced.
In order to ensure the comparability of the tests with previous tensile skin test studies, the skin samples should be prepared as described in Wachtel et al. and Wilhelm et al. [9, 11]. This method with 3D-printed incision pattern templates allows a standardised preparation of the skin samples. The skin flaps had a size of 170 x 60 mm and a incision with a length of 40 mm in the centre. Clamping plates with interlocking grooves were used to apply sufficient pressure and friction through the screw connection to prevent the skin samples from slipping out during the tensile tests.
The test protocol provides a preload of 5 N to minimise slack and the specimen is then continuously stretched at a rate of 100 mm/min. The test runs of the individual sutures is recorded using testXpert V12.0 (Zwick Roell GmbH Co. KG) and the test is considered to be completed when failure or a maximum deformation of 35 mm occurs to avoid collision with the test fixture.

2.3 Experiments

Fresh dorsal pig skins from the butcher were used as test specimens (Fig. 3). The skin samples were prepared to include epidermis and dermis and cut out with the 3D-printed template.

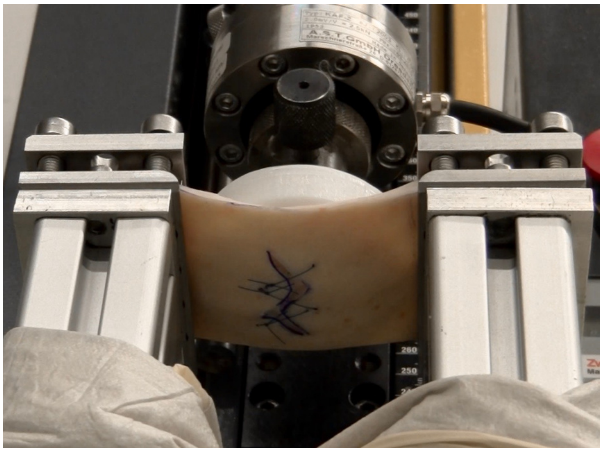

Fig. 3: Biomechanical testing of the forehead suturing technique Zigzag

For the study, skins from two different pigs were used and brought into relation with the help of control samples (samples without incisions). The study compared three different suturing techniques. These were the Straight, Lazy-S and Zigzag suturing techniques described in Wachtel et al. [9]. The suturing techniques were created by a medically trained person using the 3D-printed templates to achieve reproducible suturing results. Five specimens were examined for each suturing technique. To ensure that the condition of the pig skin from two different animals did not affect the results, the results were normalised using the control samples (without incision).

2.4 Evaluation Tool

For the comparison of the individual suture techniques, the first and the final failure and the stiffness of the skin-suture

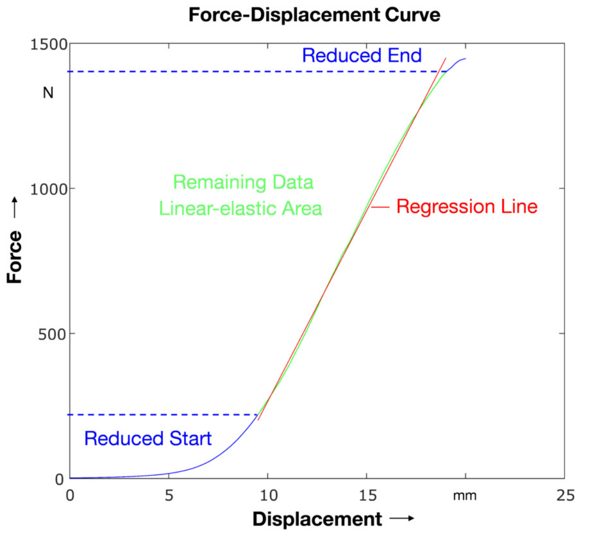

Fig. 4: Graphic illustration of the evaluation tool and stiffness determination

construct are used. These parameters of the different skin sutures are determined via the force-displacement curve, which is put out by the testXpert V12.0 testing software.

A custom-developed MATLAB script (MATLAB R2020a, The MathWorks) is used for an automated determination of the relevant parameters [6]. The first local maximum in the force-displacement curve is used to determine the first failure (first suture rupture) and the maximum force is used to determine the final failure. The stiffness of the suture-skin construct is specified by the gradient of the force-displacement curve within the linear-elastic range of the system (Fig. 4). First, however, the linear-elastic range must be filtered out automatically, since the transition from the initially not yet fully stressed skin system as well as the transition at the end into the plastic range is seamless.

Initially, only the data up to the first failure is considered. To determine the starting point of the linear-elastic range, the user first roughly determines the minimum and maximum percentage of the data to be removed at the beginning (so-called 'reduced start'). Then, an increment between the maximum and minimum percentages is specified. The same principle is followed for the end point of the linear-elastic range of the force-deformation curve (so-called 'reduced end'). A matrix is created from the possible combinations of the reduced start and end ranges (Tab. 1) and a regression line is generated from its remaining data points (per matrix entry) via MATLAB. For each regression line, the coefficient of determination (indicator of the regression analysis) is also put out, which indicates how well the line fits the data points. The linear-elastic range - and therefore the start and end point - is defined by the line of best fit (coefficient of determination closest to 1). However,

Tab. 1: Example matrix with the remaining amount of data after removing the data of reduced start and reduced end (grey values: defined as not enough data for regression line; more than 60 % required)

		Reduced End					
		0 %	**5 %**	**10 %**	**15 %**	**20 %**	**25 %**
Reduced Start	**0 %**	100 %	95 %	90 %	85 %	80 %	75 %
	5 %	95 %	90 %	85 %	80 %	75 %	70 %
	10 %	90 %	85 %	80 %	75 %	70 %	65 %
	15 %	85 %	80 %	75 %	70 %	65 %	60 %
	20 %	80 %	75 %	70 %	65 %	60 %	55 %
	25 %	75 %	70 %	65 %	60 %	55 %	50 %
		Remaining Data					

to avoid too many data points being removed by the reduced start and end, a limit or minimum amount of data can be set (e.g. Tab. 1 more than 60 %).

The principle was developed on the basis of Synek et al. [8] and adapted accordingly. Furthermore, the developed approach has already been successfully applied in a reduced form for the evaluation of various tensile tests [9, 10].

3 Results

Table 2 and figure 5 show the results of the study. The failure values (force values) as well as the stiffness values are normalised to the control specimens (without incision) and are therefore shown as percentages. The force reference values of the two pig skins were 1395.85 ± 40.81 N and 1315.65 ± 26.38 N and for the stiffness 144.24 ± 33.22 N/mm^2 and 127.38 ± 4.08 N/mm^2.

Within the experiments, the first failure occurred with similar values for all suture techniques. However, a difference can be seen in the maximum failure force. From Straight to Lazy-S to Zigzag, the maximum failure force increases and thus Straight and Zigzag also differ significantly from each other ($p<0.05$). Similarly, the stiffness of the system increases from Straight to Lazy-S to Zigzag, but without significance.

Tab. 2: Results of the experimental testing of the suturing techniques in percent compared to the control sample (mean ± standard deviation); * significant difference with $p < 0.05$

Suture	**First Failure**	**Final Failure**	**Stiffness**
Straight	21.49 ± 4.64 %	25.43 ± 4.08 % *	37.52 ± 7.57 %
Lazy-S	21.92 ± 2.11 %	28.00 ± 5.32 %	40.93 ± 7.57 %
Zigzag	22.91 ± 3.71 %	32.60 ± 4.95 % *	44.23 ± 8.18 %

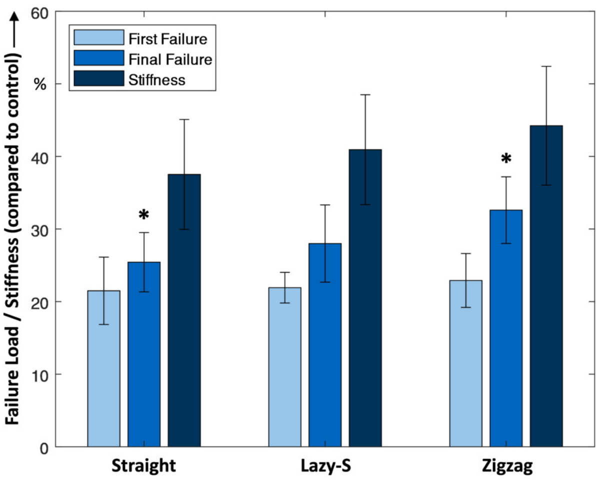

Fig. 5: Comparison of the suturing techniques in relation to the control sample (mean ± standard deviation); * significant difference with $p < 0.05$

4 Discussion and Conclusion

The study has shown that the presented test setup can be used to investigate different forehead suture techniques. The test setup is much closer to the physiological setup on the forehead than the previously tensile tests in the vertical tensile direction [4, 7]. However, the sutures in this study were placed on flat skin rather than curved skin. This would be closer to the treatment used in patients and its effect needs to be verified in further studies.

Tensile tests with a curved surface are only known to the authors from the textile sector. In addition to vertical tensile tests, the ball burst test (ASTM D6797, ASTM D3787, ISO 9073-5) is also used to evaluate textiles. However, the comparison of the two test concepts in the case of forehead suture techniques needs to be verified in a more extensive study. Nevertheless the same stability trends of the suture techniques as in Wachtel et al. [9] are already visible in this study. In addition, tests with human skin should be carried out in the future, as pig skin behaves differently from human skin.

It is also necessary to check whether four-point clamping of the skin sample is closer to physiology [2]. To do this, a larger skin sample must be chosen, otherwise the sample cannot be well-clamped at four points and may slip out. When the sample was clamped at two points, it did not slip out during the experiments. However, the availability and size of skin samples is limited, especially when using human skin.

Due to the geometry of the stamp and the relatively close clamping because of the size of the skin samples, high shear forces can occur in the area between the clamping and the stamp. However, these are negligible as they have no direct effect on the suture in the middle of the skin sample. They could, however, promote slipping and cutting of the skin at clamped site, but this did not occur in the experiments.

With the help of the evaluation tool, the measured values from the testing software can be evaluated in MATLAB so that even large investigations can be analysed quickly. At the beginning, however, it is necessary to determine the optimal parameters (reduced start, reduced end) for the evaluation based on a selection of tests. After this, however, a fully automatic evaluation is possible and the experimental data can be evaluated in a standardised way for comparability.

The study has shown that the test setup and the MATLAB evaluation tool developed for it can be used to investigate different forehead suturing techniques. However, further and more extensive studies on human skin will be required in the future to verify the difference compared to conventional tensile testing.

Author Statement

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