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A surgical simulation system of skin sutures using a three-dimensional finite element method

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Abstract

Objective. To establish a surgical simulation system of skin sutures using a three-dimensional finite element method.

Design. Three-dimensional finite element models were developed from point data obtained with a rapid three-dimensional surface-measuring device and postoperative profiles were evaluated using these models.

Background. Since suturing a wound may result in undesirable skin extrusion, it is important to make the extrusion as inconspicuous as possible. We have investigated a means of determining appropriate suture methods to decrease the extrusion.

Methods. Affected body parts were measured non-invasively with a rapid three-dimensional surface-measuring device. Finite element models were prepared, and an appropriate method for reducing skin extrusion was evaluated by attempting various suturing methods.

Results. Two kinds of finite element models were prepared: a conventional spindle model and a modified S-shape model. The height of the extrusion of the modified S-shape model was decreased by 40% in comparison with that of the spindle model. These results agreed with clinical findings.

Conclusions. Due to this surgical simulation system of skin sutures, with a rapid three-dimensional surface-measuring device and three-dimensional finite element analysis, it was possible to design an appropriate suturing method and to evaluate the postoperative skin profiles. The modified S-shape suture method would be a recommendable method.

Relevance

Using this surgical simulation system of skin sutures, a surgeon can evaluate an appropriate suturing method before operation. It is expected that this system will reduce a surgeon's labor.

Keywords: Surgical simulation system; Three-dimensional surface-measuring device; Finite element method; Skin suture

1. Introduction

Plastic surgeons are commonly called upon to remove small tumors or birthmarks, then to suture the postoperative wounds. After suturing a spindle-shaped wound, both edges extrude (Fig. 1), causing a "dog ear" formation, so-called due to its appearance. If the skin extrusion is very high, a further operation is necessary to revise the extrusion. Thus, it is important to make the extrusion of these postoperative wounds as inconspicuous as possible.

A surgical simulation system [1–3] for postoperative skin suture would reduce the labor of plastic surgeons. To establish the surgical simulation system, a three-dimensional (3-D) finite element analysis is used to model the skin suture based on 3-D postoperative profiles of affected parts of patients.

In the present study, a human skin surface was measured non-invasively with a rapid 3-D surface measuring device, then the skin suture was analyzed used the 3-D finite element method (FEM). By using the appropriate suturing method determined from the results of the FEM, a clinical operation was performed and the clinical result was compared with the FEM result.

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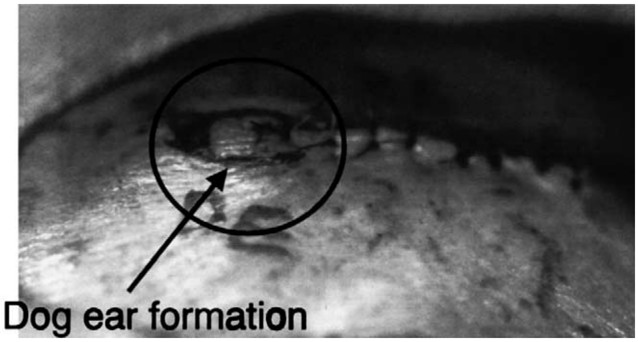

Fig. 1. Extrusion of spindle model in clinical skin suture.

2. Methods

This surgical simulation system of the skin suture can be defined as "constructing 3-D FEM models to acquire effective information for the skin suture". The procedure involves both measuring to construct the FEM models and analysis evaluation of the model results.

The process of surgical simulation of the skin suture was as follows. Affected parts of patients were measured non-invasively with a rapid 3-D surface-measuring device (SURFLACER VMH-600R, Unisn, Japan). The measuring system consists of a main measuring system unit (a slit-ray that projects 670 nm wavelength light from a semiconductor laser and four CCD cameras to read the image), a slit-ray image processor and a computer controller, giving a trigonometric survey of the skin surface. In this study, the data interval was 1 mm, the measurement accuracy was ± 0.1 mm and the measuring time was 10 s or less. Individual coordinate points were defined as nodes, and three-node thin shell elements were prepared for 3-D FEM models. The FEM analysis was carried out and then we evaluated the most appropriate method to decrease the extrusion by changing the shapes of the suture models.

In this study, we studied two body parts: a face (face model) and an arm (arm model) (Figs. 2(a) and (b)). The shapes of these models were designed as a conventional spindle model (face-Sp, arm-Sp) and a new modified S-shape model (face-Si, arm-Si), and the length of the major axis of the wounds was 21 mm in order to remove a circular tumor of 9 mm diameter (Figs. 3(a) and (b)). Face-Sp had 1083 nodes and 1797 elements; and arm-Sp

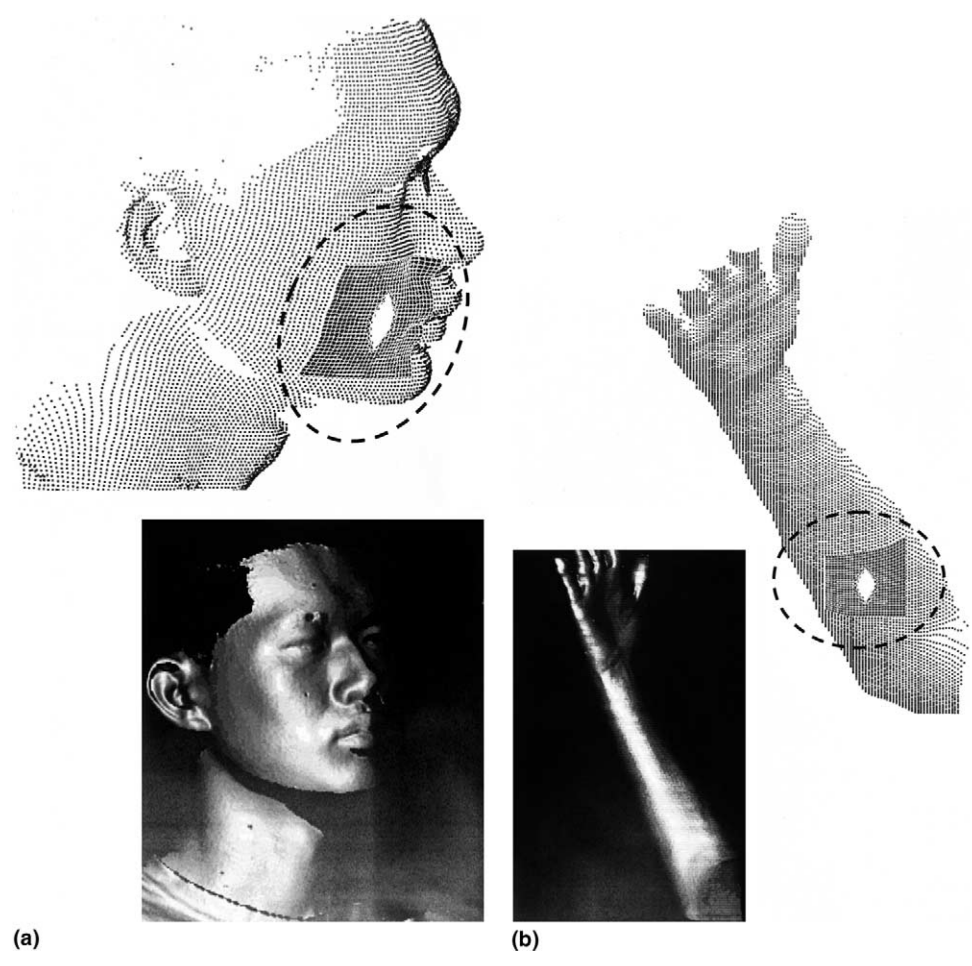

Fig. 2. (a) Face model; (b) Arm model.

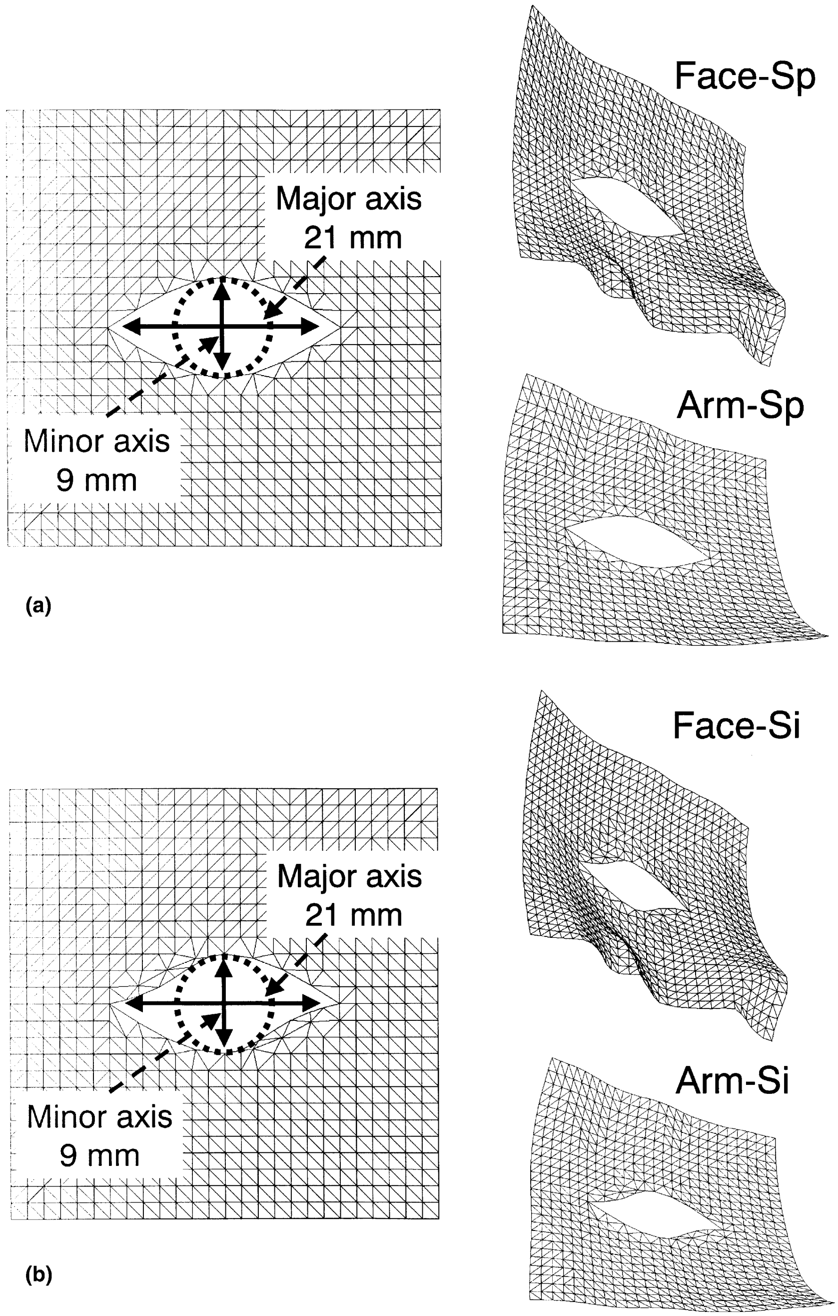

Fig. 3. (a) Spindle models (Face-Sp and Arm-Sp); (b) Modified S-shape models (Face-Si and Arm-Si).

had 922 nodes and 1478 elements; face-Si had 1093 nodes and 1813 elements; and arm-Si had 934 nodes and 1496 elements. The overall lengths of the curves of each model were the same and the thickness of the skins was set as 1.3 mm. The curves of the wounds of each model were defined with the Sp-line function.

Gap elements were introduced beneath the skin to reproduce the friction and contact conditions between the skin sub-surface and subcutaneous tissues. Gap elements can slide on the gap interface under shearing forces, and can separate from the interface under tensile forces, but transfer compressive forces in the direction normal to the interface. Gap elements start to resist compressive forces when the skin elements approach and contact the surface of the gap elements, and this preset distance was defined as the gap distance of 1 mm. The surface of the gap elements was fixed in all directions.

The material properties of the skin were assumed as follows: Poisson's ratio was 0.49 and the nonlinear relation in the tensile stress–strain diagram was defined by $\sigma = \exp(-7.26 + 5.54\varepsilon)$ (where σ is stress in MPa and ε

is strain and Young's modulus was 0.42 MPa in the compressive stress–strain range [4–6]. The skin elements were defined as isotropic materials of an elastic body. The surrounding nodes of the skin surfaces of each model were fixed in all directions. The nodes on both curves along the open wound boundary were moved to locations equivalent to intermediate points between the pair nodes, with compulsory displacements. ABAQUS Ver.5.7-3 (Hibbitt, Karlsson & Sorensen, Rhode Island, USA) was used as the FEM solver and I-DEAS Master Series Ver.6 (Structural Dynamics Research Corporation, Ohio, USA) was the preprocessor and postprocessor on an IBM PC/AT compatible personal computer used for the analysis.

This surgical simulation system of skin sutures could be adapted to an arbitrarily affected part of an individual patient. However, since the profile and thickness of skin differ between affected parts of individual patients, the height of the extrusion would vary in accordance with the part of the skins. The changes in extrusion height should therefore be investigated based on the radius of curvature of the skin surface and on the skin thickness. In this experiment, the parametric studies of the radius of curvature were performed on smooth curved surfaces defined as a part of virtual column, with the radius of curvature based on spindle models with a major axis of 70 mm and a minor axis of 30 mm. Studies of skin thickness used the face-Sp model.

3. Results

Fig. 4 shows the deformation and height of extrusion of the face models. The maximum height of the extrusion peak of face-Sp was 2.04 mm, and the height of face-Si was 1.25 mm. The extrusion peaks were found in the centers of the edge nodes of these models. The deformation results of the arm models are shown in Fig. 5. The maximum height of the extrusion peak of arm-Sp was 1.70 mm, and the height of arm-Si was 0.98 mm.

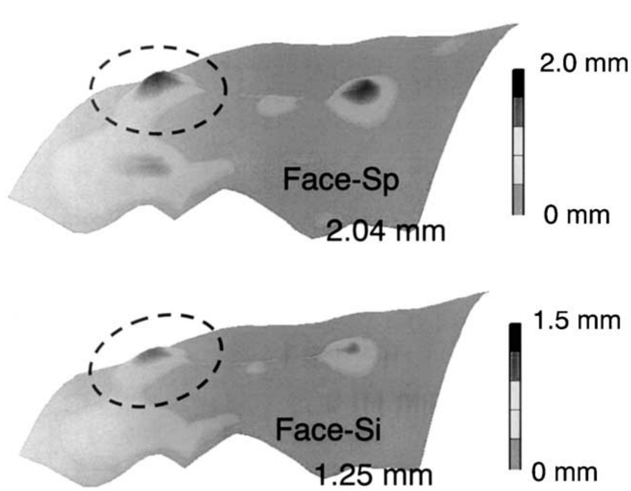

Fig. 4. Deformation of face models.

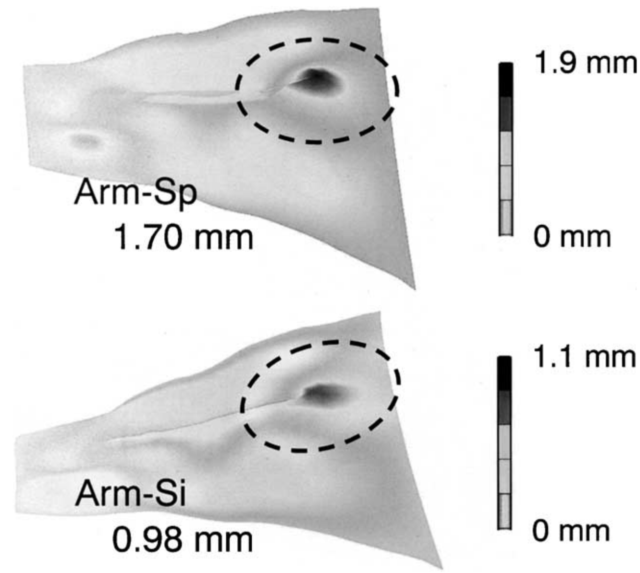

Fig. 5. Deformation of arm models.

Figs. 6 and 7 show the changes of the extrusion height, based on the radius of curvature and the skin thickness, respectively. The normalized extrusion height is the ratio of the extrusion height to the length of the minor axis (Fig. 6). An increase of the radius of curvature results in a decrease of the extrusion height. An increase of the skin thickness generally leads to a decrease in extrusion height (Fig. 7).

4. Discussion

In the face model, the height of the extrusion of the face-Si model (1.25 mm) decreased by 40% in comparison with that of the face-Sp model (2.04 mm). A similar 40% decrease was also seen in the arm model. Therefore, since the height of the extrusion decreased, the new

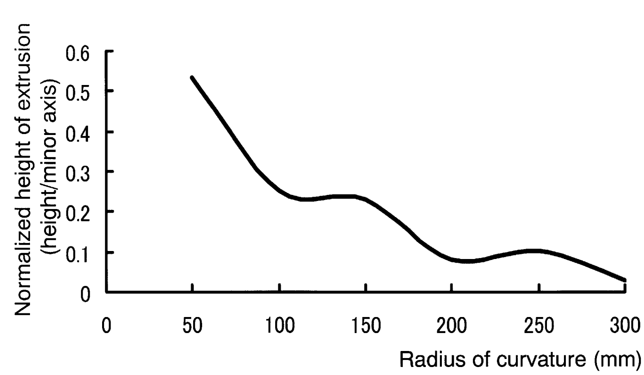

Fig. 6. Radius of curvature and height of extrusion.

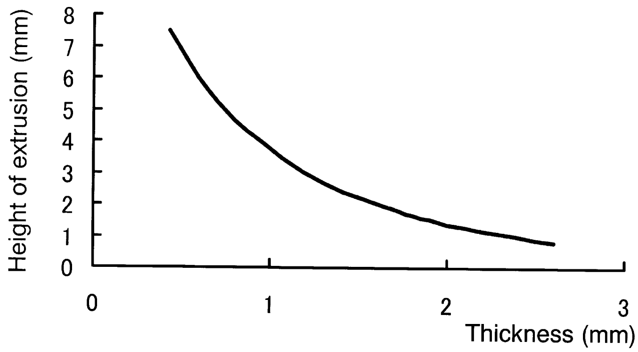

Fig. 7. Thickness and height of extrusion.

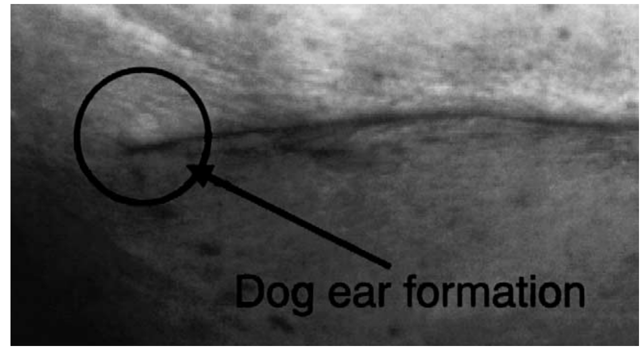

Fig. 8. Extrusion of S-shape model in clinical skin suture.

modified S-shape model suture method Si seems to be more appropriate method than Sp, a conventional spindle model.

Although the overall lengths of the wounds of the boundary curves of face-Sp and face-Si were the same, the heights of the extrusion peaks were different. We attempted to investigate this difference. It is thought that the height of the extrusion depends on the size of the intersection angle where two tangential lines on the edge node of the wounds cross and the extrusion peak appears. The intersection angle of face-Sp was 65°, while the intersection angle of face-Si was only 46°. As this angle decreases, the distance of the pair node decreases and the suturing distance (i.e., the compulsory displacement) decreases. Therefore, it is supposed that the decreased strain around the edge nodes in face-Si resulted in decreased deformation and decreased extrusion height.

Increased radius of curvature resulted in decreased extrusion height. Since increased skin thickness also led to decreased extrusion height, and skin thickness varies in individual parts of the human body, the results of face and arm models differed. If skin thickness could be measured, the height of the skin extrusion could be estimated from Fig. 7. Results of such analyses are expected to contribute to the surgical simulation system.

We attempted to compare the results of the FEM analysis of extrusion with those of clinical skin sutures in actual plastic surgery. Fig. 1 shows photograph of the extrusion of the skin in the arm of a patient when the major axis of the arm-Sp model was 21 mm, the minor axis was 9 mm, and the extrusion height was 1.5 mm. In the FEM analysis of the arm-Sp model, the extrusion height was 1.70 mm. Since the skin thickness would have wide variations, we considered that our FEM analysis simulated the behavior of the skin after suturing very well. The modified S-shape model is also called the "sigmoid" model, and Fig. 8 shows the deformation of this model in a clinical skin suture. The extrusion height was less than 1 mm, and was decreased compared with the spindle model of Fig. 1. This result agrees with the FEM result that gave an extrusion height of 0.98 mm in the arm-Si model. Therefore, it was proved that the modified S-shape method is the more appropriate method in clinical skin surgery.

Due to this simulation system, it is expected that skin suture operations will facilitate plastic surgery. However, there are several limitations to this method. For example, suturing would presumably lift the suture line above the original skin surface on a concave skin surface. In the simulation system, the gap surface is fixed in all directions and the subcutaneous surface is modeled as a rigid or non-deformable surface. In future study, we hope that these limitations would be examined and resolved.

The important features of this surgical system are as follows. In previous FEM analyses of skin sutures, analyses have been performed only two-dimensionally [7–12]. However, in this study, we carried out 3-D FEM analyses of skin sutures. 3-D human skin profiles can be easily brought into the FEM models by using a rapid measuring device. Since the measuring data are ASCII 3-D data, this method facilitates the development of FEM models. The 3-D measuring device enables rapid measurement of arbitrarily affected body parts. Thus, this simulation system could be adapted to perform FEM analysis in accordance with 3-D skin profiles of individual patients.

5. Conclusion

We have established a surgical simulation system of skin sutures with a rapid 3-D surface-measuring device, using 3-D FEM analysis to investigate appropriate suture methods to decrease skin extrusion. This allows us to design an appropriate suture model for skin sutures and to evaluate the postoperative profiles of the skin.

The results of the height of the extrusion peak in our FEM analysis agreed well with those in clinical suture surgery, and it is recognized that our models simulate the behaviors of the skin after suturing very well.

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