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Fabricating nasal prostheses using four-dimensional facial expression models

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Abstract

Purpose: Patients with facial prostheses face challenges such as maintenance of the prosthesis in place, especially around the margins, because of movement of surrounding facial skin. Conventional facial prostheses are fabricated on stationary models based on two points: neutral expression and smiling expression. We developed four-dimensional (4D) facial expression models which shape facial expressions that change over several points in time using a morphing technique. We fabricated facial prostheses using 4D models and evaluated their accuracy and fit compared with prostheses generated with the two-expression technique.

Methods: Seven patients with nasal defects or nasal deformities participated in this study. Facial expression morphing prostheses were fabricated based on the 4D scanned data of each patient, using five points between neutral expression (0%) and smiling (100%). Five nasal prostheses, one for each point, were evaluated in each patient objectively and subjectively for accuracy and fit.

Results: On subjective evaluation, the nasal prostheses fabricated using the 4D facial expression models had better marginal sealing over the range from the neutral expression to smiling, and showed better attachment during facial movement on objective evaluation.

Conclusions: Facial prostheses fabricated using 4D facial expression models provided better marginal sealing than those fabricated using conventional two-point modeling.

Keywords: 4D facial expression model, Facial prosthesis, Morphing, Homologous model

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1. Introduction

Facial prostheses are used in patients with facial defects caused by cancer, trauma, inflammation, or congenital anomalies. The main purpose of facial prostheses is to recover an esthetic facial configuration and improve patients' social functioning and self-image. Facial prosthetic rehabilitation can be considered successful when patients can appear in public without the fear of attracting unwanted attention [1]. One problem with facial prostheses is the difficulty in maintaining the position of the prostheses as facial expressions change. In particular, the marginal fitting of a facial prosthesis, which is placed on the skin surface, is prone to deformation due to the high complexity of the movements of facial muscles. It is difficult to accommodate these morphologic changes even with soft silicone material. A method of fabricating facial prostheses that addresses the complexity of facial expressions is therefore required [2].

Digital technology has been applied for prosthodontic treatment [3] and fabricating facial prostheses [4-6]. Authors have applied three-dimensional (3D) digitizers and rapid prototyping systems to fabricate orbital prostheses [7]. Results have shown that the time

needed for constructing, fitting, and adjusting a prosthesis has reduced and patient satisfaction has increased. In a previous pilot study [8], we presented a method for fabricating "3D facial expression models" based on a morphing technique, which uses computer software to model facial expressions over time via smooth transformation of one image into another in small steps [9]. These 3D facial expression models were successfully fabricated and high accuracy was achieved for normal subjects and patients with nasal defects.

In the present study, we define a four-dimensional (4D) facial expression model and attempt to fabricate nasal prostheses using 4D facial expression models over several points in time from neutral to smiling expressions; we also evaluate the fit and clinical practicality by comparison with models fabricated by conventional modeling techniques using the two points of neutral and smiling expressions.

2. Materials and Methods

Seven patients (three males and four females) with nasal deformities due to cancer participated in this study (Fig 1). Their mean age was 75.9 ($\pm$ 5.0). Informed consent was obtained from each subject. This project was approved by the ethics committee of our institution (No. 497).

2.1. Fabrication of 4D facial expression models

Using our previous methodology [8], we fabricated a template model and generated 3D images (3dMD face System, 3dMD LLC,

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Fig. 1. Images of subjects participating in this study.

Atlanta, GA, USA) for neutral and smiling expressions (Fig. 2). We employed digital deformation to create homologous models (Fig. 3) with equal numbers of vertices to allow the use of morphing methodology. The 4D facial expression model was fabricated using two homologous models and morphing methodology (Fig. 4) [8,10].

2.2. Printing the working cast for fabricating the prostheses

The five points from neutral to smiling expressions on the 4D facial expression model were selected for fabricating the working casts. A neutral expression was considered to be the absence of smile components whereas a smiling expression was the presence of all smile components. Imaging data of expressions with 0%, 30%, 50%, 70%, and 100% smile components were selected and exported in STL format by the STL editing software (Geomagic Design X, Geomagic, Cary NC, USA) and fitted to the working cast so that the defect could be centered in the cast and the thickness of the base could be adjusted for 3D printing. Six ball-shaped keyways without undercut were designed on the cast so that the upper and lower molds could be refitted when packing with silicone material. The resulting working cast data were printed using a 3D inkjet printer (Z650®, 3D Systems, Burlington MA, USA) with a hybrid plaster. After printing and drying, the casts were treated with a coating agent, which was allowed to impregnate the plaster (TB7761®, Three Bond, Ltd., Tokyo, Japan). Five working casts of five different expressions were fabricated for each subject.

2.3. Fabricating a wax prototype and jig

Conventional molds of the patients' former facial prostheses were utilized. Skin-colored wax was poured into the molds to obtain the external form of the wax prototype. Five wax prototypes were made for each patient. One of the wax prototypes was applied onto a cast of neutral expression and trimmed or extended at the margins. A jig for alignment was then fabricated using a light-cured resin sheet (Splint-Resin LC; GC Corporation Ltd, Tokyo, Japan) covering the wax prototype and the cast. The rest of the wax prototypes were

applied with wax onto the casts of 30%, 50%, 70%, and 100% smile components using the jig so that all wax prototypes were aligned in the same position. Final modification was then done on the margins.

2.4. Fabrication of the facial prostheses

Silicone material (Silfy fast®, GC) was used to fill the upper molds, which was packed with functional intrinsic skin color (honey) (FactorII, Incorporated, Lakeside AZ, USA) with an intention load of 20 kgf. After curing, the mold was unpacked and trimmed. The five prostheses made for each patient will be referred to as S0, S30, S50, S70, and S100. (Fig. 5)

2.5. Evaluation of the fit of the nasal prostheses

The five nasal prostheses were fitted on each patient by first cleaning the patient's skin and then attaching the prosthesis using a moisture-proof agent (Duracoat GC, Japan). Three maxillofacial prosthodontists with experience in fabrication of facial prostheses subjectively evaluated the fitting for neutral and smiling expressions. The "falling-off test" was then conducted, which is assessing the nasal prosthesis during several sets of previously rehearsed facial movements that particularly result in detachment of the nasal prostheses [11]; these consist of pronouncing "a," to open the mouth widely; "i," to pull the angles of the mouth horizontally ; "u," to contract the orbicularis oris; and squeezing the face to the center to contract the procerus muscle and the upper lip alar levator. The time until detachment was measured. The falling-off test was performed five times with each prosthesis after the subject had become accustomed to the facial movements; the mean of the five measurements was used as the representative value. The time values were standardized to the time value for S0 and analyzed statistically using the Kruskal–Wallis test and the Wilcoxon signed-rank test. All statistics were analyzed using commercial software (Statistical Package for Social Sciences [SPSS], version 18, IBM, Chicago IL, USA).

Fig. 2. Fabrication of the scanned model.

3. Results

3.1. Fit of the nasal prostheses

Fit of the upper margin of the dorsum of the prosthetic nose and the lateral margin of the prosthetic alar nasal sulcus were evaluated during both neutral and smiling expressions. Figures 6 and 7 show the small gaps between some prostheses and the skin in neutral and smiling expressions. In both expressions, S30 and S50 of patient A, S50 of patient B, S30 of patient C, S50 of patient D, S50 of patient E, S70 of patient F, and S50 of patient G were evaluated to be well-fitted on both margins (Fig. 6,7).

3.2. Falling-off test

Statistically significant differences were seen between S0 and S30, S0 and S50, and S0 and S70. (Fig. 8). Prostheses remained in place significantly longer for S30, S50, and S70 than for S0.

4. Discussion

Research on the human face and body captured during computer-mediated communication formats has been increasing. Face plays a highly important role in communication, which differs as a source of communication to verbal messages [12]. According to Mehrabian, 55% of a message pertaining to feelings and attitudes is in the facial expression, versus 7% in spoken words and 38% in the way the words are spoken [13]. Systems such as Skype allow face-to-face communication using a computer, greatly aiding smooth communication.

The facial synthesis technique plays an important role in the human interface field [14,15]. Time-series analysis for facial motion is prominent in computer graphics. Terzopoulos et al. reported a facial model that could create an expression by estimating the muscle parameters from the analysis of video sequences of faces [16]. Ahn et

Fig. 3. Digital deformation of the template model to the same shape as the respective scanned model.

Fig. 4. 4 Morphing methodology was applied to the homologous model to complete the 4D facial expression model. The figure shows eleven static facial models instead of a motion picture of the 4D facial expression model.

Fig. 5. Working casts were fabricated by selecting five points on 4D facial expression model, from neutral expression to smiling. Five facial prostheses were then fabricated using morphing technique.

Fig. 6. Five facial prostheses were evaluated for fit in Subjects A-D during a neutral expression and when smiling in regard to the upper margin and lateral margin (arrow).

Fig. 7. Five facial prostheses were evaluated for fit in Subjects E-G during a neutral expression and when smiling in regard to the upper margin and lateral margin (arrow).

al. simulated facial expressions by digitally fitting a wire frame to a facial image, calculating the position of facial muscles at chosen points, and estimating the muscle parameters [17]. However, these facial motions were simulated on a simplified facial model; reproducing 3D facial expressions on actual human beings is difficult. In this study, we used a morphing technique to reproduce facial expressions digitally,

which allowed the resulting prosthesis to accommodate changes in facial expressions without resulting in detachment.

Subjective evaluation by skilled prosthodontists showed that two of S30, five of S50, and one of S70 prostheses were well-fitted around all margins during both smiling and neutral expressions, while two of S30, six of S50, five of S70, and seven of S100 prostheses were

Fig. 8. Results of the falling-off test

well-fitted on only the side marginal area during both activities. It was difficult to fabricate a facial prosthesis that would not result in a gap at the lateral margin during smiling, thus, achieving marginal sealing all around. Marginal sealing during smiling was not obtained for S0, which was fabricated based on the neutral expression only for each patient. The better fit of S30, S50, S70, and S100 morphing-generated prostheses suggests that using 4D facial expression models is better. Subjective evaluation by the patients was not performed in this study because they may not be able to evaluate the fit alone due to their personal preferences, which include fit, retention, comfortability, appearance, and color matching. Commonly, color matching is the most complicated part of fabricating facial prostheses. Further study should be conducted to include a color-matched 4D facial expression model.

The results of the falling-off test showed that the performance was optimal for S30, S50, and S70 prostheses. Further, these nasal prostheses—fabricated using 4D facial expression models—had better fit and there was less space between the prosthesis and skin compared to S0, which is same as those fabricated using conventional models with the neutral expression.

To print a working model for fabricating facial prostheses, we selected the data for 0%, 30%, 50%, 70%, and 100% smile components on 4D facial expression models. Kubon reported a technique to create an adaptable margin for an auricular prosthesis through maximum range of motion in which the cast was modified around the margin by trimming the range of deformation during opening and closing of the mouth [8]. This technique was considered to correspond to the 100% smile component in our study. While the range of motion of an auricular prosthesis is limited to the temporal area, which would work for a 100% smile, nasal prostheses have a larger range of motion and more complex motions around all the margins should be considered. In this study, the S100 prostheses were well-fitted on the lateral margins for the smiling expression but poorly fitted on the upper margins in all patients. Results showed that S30, S50, and S70 were the best fitted for both neutral and smiling expressions, albeit the degree of fit varied among patients. Despite this variation, an optimal fit was achieved in each patient for at least one point using the morphing technique. The participants in this study differed with regard to defect size, skin texture, and richness of expression. These characteristics likely account for the variation among the results; however, further study is necessary to confirm this.

A moisture-proof agent was applied between the nasal prosthesis and the skin during the evaluation of fit and falling-off test. Clinically, detachment of the facial prosthesis with facial movement could occur

several hours after it is placed on the skin with skin adhesives. In this study, the moisture-proof agent was applied to simulate the condition of the skin adhesive that is similar to what it would be after several hours of being placed on the skin.

The falling-off test was defined in this study as a challenge to facial prosthesis adherence for several sets of facial movements and measurement of the time until the prosthesis fell off. The head position was stationary during the test to avoid detachment due to movement associated with positional changes of the head. Five repeated trials performed prior to the test to verify the validity of this test showed little variance. Accordingly, the test allowed us to evaluate the resilience of the prosthesis adhesion to motion of the face solely during facial expressions.

In this study, nasal prostheses fabricated using 4D facial expression models fitted better, for both neutral and smiling expressions, than conventional nasal prostheses fabricated from a cast of the neutral expression. Good marginal sealing was achieved when subjects changed their facial expressions. Moreover, because facial movements were analyzed on the 4D model and actual modification of the cast was unnecessary, fabrication of nasal prostheses became simpler.

The simulation of facial movement achieved in this study was more accurate than that in previous studies. While other studies have used digital technology to fabricate facial prostheses [4–7, 19], most of these appear to emphasize the methodology, material, or color matching rather than the improvement of fit. However, it is important for patients with facial prostheses to be able to appear in public without fearing prostheses detachment. In this study, facial prostheses were fabricated using a 4D time-series analysis of facial movements. Though this study mainly focuses on nasal prostheses, facial prostheses for other regions, along with patient satisfaction, should be evaluated in further study. This 4D simulation can be adopted for the development of materials for facial prosthesis fabrication by digital processing; however, further study is necessary.

5. Conclusions

Nasal prostheses fabricated using 4D facial expression models fitted better than conventional nasal prostheses for both neutral and smiling expressions.

Conflict of Interest

The authors declare no conflicts of interest associated with this manuscript.

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