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ScienceDirect
British Journal of Oral and Maxillofacial Surgery 49 (2011) e67–e71
BRITISH Journal of Oral and Maxillofacial Surgery
www.bjoms.com

Missing facial parts computed by a morphable model and transferred directly to a polyamide laser-sintered prosthesis: an innovation study

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Accepted 24 February 2011
Available online 31 March 2011

Abstract

Mirroring of missing facial parts and rapid prototyping of templates have become widely used in the manufacture of prostheses. However, mirroring is not applicable for central facial defects, and the manufacture of a template still requires labour-intensive transformation into the final facial prosthesis. We have explored innovative techniques to meet these remaining challenges. We used a morphable model of a face for the reconstruction of missing facial parts that did not have mirror images, and skin-coloured polyamide laser sintering for direct manufacture of the prosthesis. From the knowledge gleaned from a data set of 200 coloured, three-dimensional scans, we generated a missing nose that was statistically compatible with the remaining parts of the patient's face. The planned prosthesis was manufactured directly from biocompatible skin-coloured polyamide powder by selective laser sintering, and the prosthesis planning system produced a normal-looking reconstruction. The polyamide will need adjustable colouring, and we must be able to combine it with a self-curing resin to fulfil the requirements of realistic permanent use.

Keywords: Biomedical engineering; Computer-aided design; Facial neoplasms; Maxillofacial prosthesis; Nose; Statistical models; Three-dimensional imaging

Introduction

The engagement and exploration of technological solutions is a key factor in the future development of facial prosthetics.[1,2] The computer-aided design and computer-aided manufacturing (CAD-CAM) technique is usually used to produce mirror-image templates from the unaffected side of the face for realistic remodelling of the ear and orbital prostheses.[3–7] However, this does not realise its full potential to transform the manufacture of prostheses from an artistic process into a biomedical manufacturing one.[2] First, the problem remains of what should be regarded as normal or ideal, if the defect has no healthy mirror image. Secondly, the labour-intensive transfer of the CAD-CAM template into the final prosthesis

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doi:10.1016/j.bjoms.2011.02.007

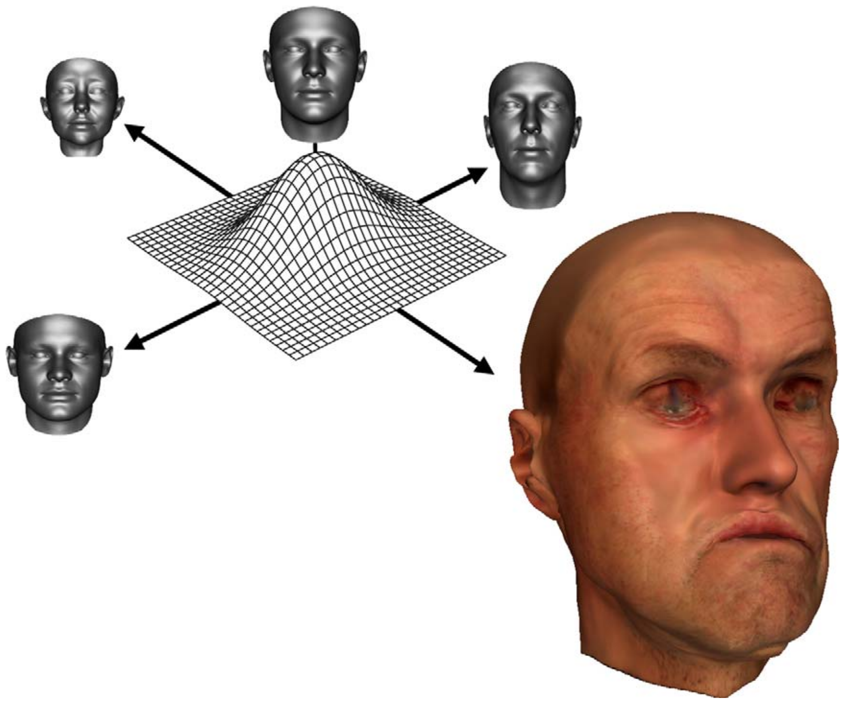

Fig. 1. The morphable model is a statistical one that is computed from 200 three-dimensional facial scans of young adults. These can form continuous transitions between the individual faces. The healthy part of the patient's three-dimensional facial scan is expressed in terms of this morphable face model, which consecutively provides a reconstruction of the missing facial part. The generated reconstruction is unique, statistically consistent with the patient's face, and independent of the artistic skills of a prosthetist.

remains. We therefore explored innovative solutions to these two challenges.

We have used a morphable model to plan the facial prosthetics, which allows reconstruction of a patient-specific shape in cases where the mirroring technique is neither applicable nor desirable. We also looked into automatic definition of the margin using distance mapping, and the use of a skin-coloured, medical-grade, polyamide laser-sintering process as a manufacturing tool for facial prosthetics.

Materials and methods

The study was approved by the ethics committee and met the ethical standards of the Declaration of Helsinki. The patient was referred to us with a recurrent sclerosing basal cell carcinoma of the nose. He had had a total rhinectomy, including resection of the anterior nasal floor, premaxilla, and anterior wall of the right maxillary sinus.

To model the missing facial area we developed a morphable model of human faces.[8] This was computed from a dataset of 200 three-dimensional scans of white male and female faces. Dense point-to-point correspondences to a reference face were computed for the individual faces. This resulted in a single vector space of faces, and in this way the morphable model can generate continuous transitions between the faces and form linear combinations.

The patient's face was scanned three-dimensionally (ABW, Frickenhausen, Germany). The scan of the face was automatically matched with the morphable face model using a non-rigid recording algorithm.[9] This produced a complete face that was congruent with the healthy parts of the patient's face.

The margins of the prosthesis were defined using an automated distance-mapping process. The borders of the facial defect protruded inwards, while the shape of the nose that was generated protruded outwards. The points of minimal distance formed the margin. The final plan of the prosthesis was superimposed on to a computed tomographic (CT) scan of the patient. This allowed us to check the quality of the bone at the planned positions for the implant, and the leeway for precision attachments at these positions.

The planned prosthesis was directly manufactured on an EOSINT P machine (EOS, Munich, Germany) using carbon dioxide-laser sintering of PA2200 polyamide powder in a layer 0.1–0.15 mm thick. The margins of the prosthesis were adapted to the patient's facial movements by milling off areas of interference. Four magnetic precision attachments were polymerised into recessed boreholes at the sites of implant. The surface of the prosthesis was finished using watercolours and a layer of varnish.

The prosthesis was scanned by a laser (VI-910, Konica Minolta, Munich, Germany) before and after the adaptation of the margin. Both scans were superimposed on the unchanged nasal shape and a false-colour area map was

Fig. 2. A laser-sintered prosthesis direct from the plan made of biocompatible, skin-coloured, PA2200 polyamide powder. The margin of the prosthesis as defined by distance mapping resulted in complete coverage of the defect with circumferential skin contact, but it would need fine adjustment with a self-curing material to make it inconspicuous. It was not possible to match the extrinsic staining of the patient's skin colour because of the intrinsic staining of the PA2200 polyamide, which was too dark and did not vary. (Photograph published with the patient's consent.)

Fig. 3. Polymethylmethacrylate duplication of the laser-sintered prosthesis with conventionally adapted margins. The nasal reconstruction based on the morphable model generated a naturally shaped reconstruction of the nose that fitted harmoniously in the patient's face. (Photograph published with the patient's consent.)

used to analyse the extent of necessary reduction of the margins.

Results

The algorithm of the morphable model of the face generated a reconstruction of the nose with a natural-looking shape (Fig. 1), which fitted harmoniously into the patient's face. The polyamide laser sintering resulted in a nearly homogeneous surface, which was polished with standard millers and polishers. The intrinsic stain of the PA2200 polyamide was darker than the patient's skin colour, which could not be corrected by a coat of paint (Fig. 2).

The automatic definition of the margin achieved by distance mapping led to complete coverage of the defect. As polyamide cannot be added to self-curing resin, the line of the margin was planned with a circumferential safety border of 2 mm. Adaptation of the margins of the prosthesis on the patient resulted in a maximum reduction of 3.9 mm. This was necessary at the nasal bridge, below the right lower eyelid, and at the nostrils.

The transition between the margins and the skin could not be levelled out completely, because polyamide does not combine with self-curing resin. As a result of these shortcomings, a duplicate polymethylmethacrylate prosthesis was constructed in which adaptation of colour and margin were optimised, while keeping the nasal shape unchanged (Fig. 3). The duplicate prosthesis was used permanently.

Discussion

Morphable modelling

The face is the visible part of a person's unique identity. In central facial defects and after total rhinectomy there is no other side available to act as a reference to the shape for reconstruction, and the method of choice is often a prosthetic reconstruction.[10,11] In these cases, the shape of the prosthesis lies in the hands of the maxillofacial prosthetic technician, whose artistic skill gives the patient back the facial identity. Morphable modelling can provide complete three-dimensional information about the shape of a missing facial part based on the remaining facial characteristics of the patient. In the present case the shape of the nose that was generated was comparable with that observed in photographs of the patient's original state (Fig. 4).

Overall, the generated nose was not quite prominent enough, one reason being that the morphable model was based on 200 facial scans of young adults, and the nose is known to become more prominent throughout life.

The proposed shape of the morphable model can be adjusted manually with respect to three facial attributes: male

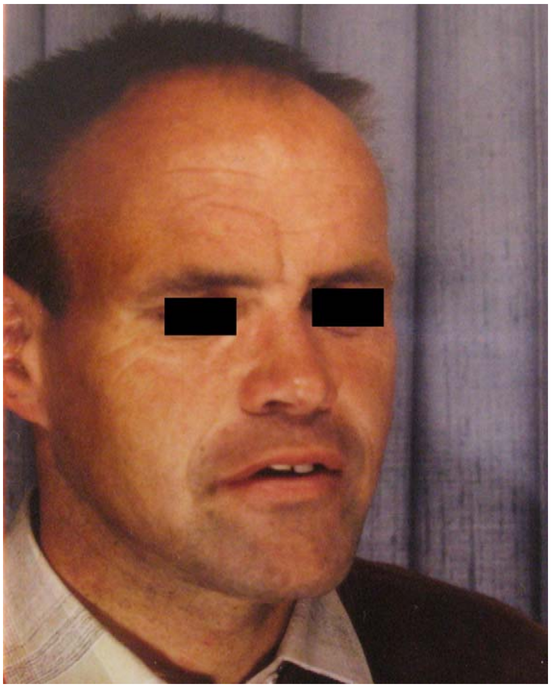

Fig. 4. The patient's original nasal shape seen on an old photograph. The automatically generated nose (Fig. 3), slightly lacked prominence compared with the original shape, which can be attributed to the young age of the reference faces on which the morphable model was based. (Photograph published with the patient's consent.)

or female, bony or fleshy, and the degree to which the face differs from the average face.[8] This allows for fine adjustments according to the patient's facial characteristics and wishes. Attributes related to age and ethnicity would also be helpful to complete the medical applicability of the morphable model.

Two-dimensional photographs of the patient's original state are traditionally used to guide the technician in the shaping of a wax model. Our morphable face model allowed a three-dimensional visualisation to be produced from scanned two-dimensional photographs of the patient in his original state.[12] Currently such a visualisation does not contain sufficient information about the three-dimensional shape for transformation into a rapid-prototype model. However, it can be used for the fine adjustment of the proposed shape in the morphable model.

The combined set of data from the CT and planned prosthesis allows a simultaneous visualisation of bony conditions, and the thickness of the prosthesis and the soft-tissues. This helps to define the optimal position of the implant and the type of implant. If necessary, the marked position of the implant and its axis can be used for intraoperative navigational support.

Simulation systems for craniofacial surgery have become an important tool for the clinician. The trend towards web-based applications, as seen in home computing, might also increasingly affect craniomaxillofacial applications.[13] The algorithm of the morphable model has been published, and open-source implementation is therefore technically feasible.

Laser sintering

A crucial step in the manufacture of a prosthesis is to find the correct colour and make an inconspicuous transition to the skin. The application of CAD-CAM techniques allows both to be achieved if manual adjustments are made on a wax template and we use silicone.[14] This might improve the results achieved by the maxillofacial prosthetist, but it does not substantially shorten the manufacturing process of a manual prosthesis.

A rapidly made material for direct prosthetic use would shorten the manufacturing process, and would open up new opportunities for facial prosthetics by reducing the time and effort of manual manufacturing. We need to change facial prosthetics from an art into an aspect of biomedical engineering, attract industrial partners, and make facial prosthetics more widely available. The latter will include devising new applications such as temporary prostheses or combinations of prosthesis and dressing.

Polyamide is available as a rapidly constructed, biocompatible, and skin-coloured material. PA2200 polyamide is a fine powder based on a polymer of lauryl lactam ($C_{12}H_{23}NO$) and has been tested for prolonged skin contact according to International Organization for Standardization ISO 10993-1. After laser-sintering the polyamide becomes a physically and chemically durable material of low density (0.9–0.95 g/cm^3), which renders the material suitable for fixation with glue or with magnetic attachments.

The direct manufacture of realistic facial prostheses requires two improvements to PA2200 polyamide: first, the intrinsic staining must be adjustable to make it a better match for the skin colour, and secondly a self-curing material must be combined with PA2200 to level out the transition between the prosthesis and skin. The margin of the prosthesis, as defined by distance mapping, resulted in complete coverage of the defect with circumferential skin contact, but it needs fine adjustment with a self-curing material to become inconspicuous.

Material scientists could solve these shortcomings. The development of a soft, rapidly constructed material is also necessary, as a soft material usually fits better at the margins and conforms better with facial movements.

Acknowledgements

The authors thank the Swiss National Science Foundation for funding the "Systems Face: Computer Aided Treatment of Facial Disease" project, which is part of the National Centre of Competence in Research for Computer Aided and Image Guided Medical Interventions (NCCR-CoMe). The sponsor did not influence any step of the study or the publication of this report.

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