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Experimental and numerical evaluation of simulated dental arch expansion during orthodontic therapy

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Abstract: In this publication, methods are presented to improve predictions of perioral soft-tissue changes following the expansion of the dental arches during orthodontic therapy. Acrylic veneers with different thicknesses were reversibly attached to the buccal surfaces of the upper and lower incisors to simulate their protrusion. The resulting morphological changes of the perioral soft-tissue surface were determined by 3D face scans. Experimentally-determined 3D soft-tissue changes are compared to numerical predictions using detailed finite-element (FE) models of the face of two individuals differing in the body mass index (BMI). The results suggest that common estimates of material constants used by the detailed and individualized FE models might be sufficient to explain absolute soft-tissue displacements although differences occurred between experimental and modeling results regarding the directions of displacements. The aim of this investigation is to create predictions of post-treatment appearance that are helpful for therapy planning.

Keywords orthodontics, facial soft-tissue, incisor protrusion, finite element model.

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1 Introduction

Orthodontic therapy may restore or improve functional impairments of the stomatognathic system and improve facial aesthetics. The exact impact of such therapeutic interventions on the facial soft-tissue morphology, however, is hard to predict due to the complex anatomy of the involved soft-tissues [1]. As facial aesthetics are a primary concern of patients, greatly influencing psychological well-being [2,3], predictions of post-treatment appearance are highly desirable. To address this problem, we are developing methods to create detailed and individualized finite element (FE) representations of the involved anatomical structures. This requires knowledge about the mechanical properties of hard- and soft-tissues. The latter might be further compartmentalized into muscles, fat, skin and mucosa. Mechanical properties of tissues are characterized by the selection of an appropriate constitutive law governed by corresponding material constants [4,5]. For instance, a simple linear elastic material requires knowledge about Young's modulus E and Poisson's constant μ. These parameters are typically hard to measure in biological systems and may undergo dynamic changes, e.g. due to muscle contraction.

In this study mechanical properties of the lips and surrounding structures are experimentally determined to allow the validation of FE models of the face. For this purpose, we temporarily placed acrylic veneers with different thicknesses on the four upper and four lower incisors. This leads to a corresponding change of the facial soft-tissue contour which was measured using structured-light scanning. Using the relation of veneer thickness and facial shape, reference material parameters from the literature can be individualized. As an initial step, this study investigated the agreement of experimental facial contour changes and corresponding changes determined by FE simulations using common estimations of the parameter. The whole approach has the additional benefit of providing orthodontists with concrete quantitative information about the facial soft-tissue changes induced by incisor protrusion or retraction.

2 Methods

2.1 Veneer experiments

Six individuals (3 males, 3 females) with an age ranging between 21 - 27 yrs. were examined. These subjects did not undergo orthodontic treatment, had no facial syndromes or specific malformations and had not been subject to orthognathic surgery. Alginate impressions were taken from both jaws in all subjects. Corresponding plaster casts were scanned (d-Station^{3D}, Breuckmann GmbH, Meersburg, Germany) to create digital models of the dental arches. Acrylic veneers were produced to simulate an increase of the dental arch in frontal (2-2) and buccal (3-7) directions using 3D processing software (Autodesk Meshmixer 2.0). Veneers with of 1, 2, 3, and 4 mm thickness were designed and 3D-printed (Asiga Max^{TM}, Scheu-Dental, Iserlohn, Germany) using methacrylate-based resin (see Figure 1). Before positioning the veneers on the teeth, soft-tissue landmarks were marked in the perioral region to track the changes of facial contours in the resting position of the face after veneer placement. These included the Labrale Superius (LS) point at the medial vermillion border of the upper lip. The faces of the participants were scanned using a structured light face scanner (OptoTop HE, Breuckmann GmbH, Meersburg, Germany). Participants were instructed to relax their facial muscles during the scanning process. Five different scans were obtained from each participant: one without veneers and four corresponding to the four thicknesses of the veneers on the upper and lower incisors. All scans were superposed using OptoCat 2015 software (Breuckmann GmbH, Meersburg, Germany). Superposition were based on the forehead and on the nasal region that were assumed to be unaltered by veneer placement. Subsequently, soft-tissue changes in the perioral region were obtained by determining the 3D movement vectors of each landmark in relation to the scan without veneers. While the magnitude was described by the Pythagorean distance, the direction was represented by the angle between horizontal and vertical movement components.

Figure 1: 3D printed frontal veneers (4 mm thickness) with corresponding plaster model.

2.2 FE Simulations

Experimental soft-tissue changes were compared to corresponding changes determined by FE-modelling. To facilitate the creation of FE-models, a reference CT (Voxel size: 1x1x1 mm) was created from high-quality CT's of four Caucasian patients that underwent angiographic examination of the head. The CT's were made symmetrical with respect to the mid-sagittal plane and averaged using customary software [6]. The reference CT was segmented with respect to hard- and soft-tissue using Slicer3D [7]. Soft-tissue was compartmentalized into muscle, fat/connective tissue, skin and mucosa. As a result, reference surfaces were created that fully enclose these different material types. By mapping the reference CT onto the subject-specific CT's, a diffeomorphic transformation was created, that could be used to morph the reference surfaces into their subject-specific shape [6]. Transformations were created for two additional patients termed Subject 1 (BMI > 30) and Subject 2 (BMI < 25) that also underwent angiographic examination. Therefore, a total of six patients provided CT-data for the simulation: four to create a reference CT and two to create FE-models. The resulting volumes of Subject 1 and Subject 2, enclosed by the transformed surfaces, were meshed with tetrahedrons. Sliding contacts were defined between the labial/buccal and alveolar mucosa as well as between the labial/buccal mucosa and the teeth. Movement was fully restricted at the soft-tissue/bone interface while no restrictions were placed on the movement of the facial skin. A linear elastic constitutive approach was used for all types of soft tissue (Muscle: E = 50 kPa, μ = 0.45; Skin: E = 20 kPa, μ = 0.45; Fat/Connective tissue: E = 10 kPa, μ = 0.45) [8] while hard tissue was treated as a rigid body. Tests were performed on the mesh to ensure appropriate representation of stress gradients. The resulting mesh included ca. $1.6*10^6$ elements. Veneers were represented by two rigid parts (for maxilla and mandible) that coincided with the surface of the incisors at the beginning of the simulation and subsequently moved into frontal direction till a displacement of 4mm was reached. The advancement of the simulated veneers was carried out in small sub steps, dictated by numerical requirements. FE computations were performed using Ansys (Ansys Inc., Canonsburg, USA).

Corresponding changes in perioral soft-tissue morphology between experiments and FE-modelling were compared using Matlab software (The MathWorks Inc., Natick, USA).

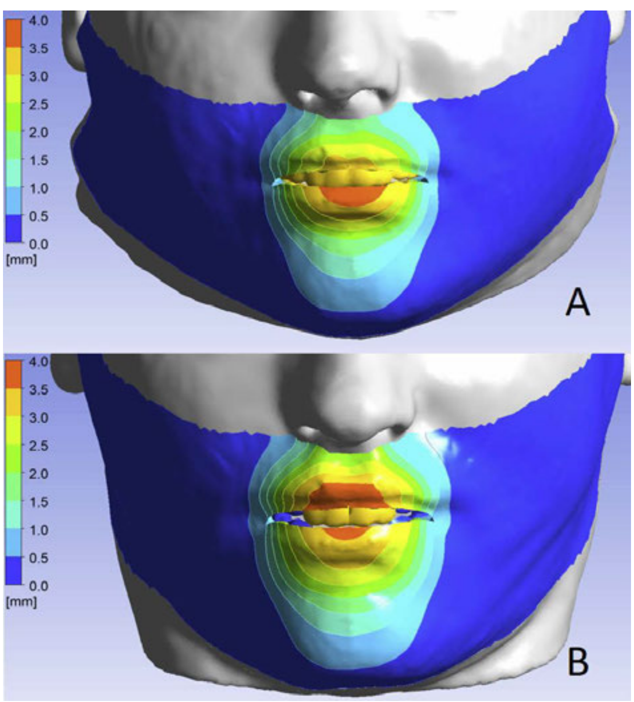

Figure 2: Simulation of protrusions corresponding to veneers with 4 mm thickness. A and B depict results for Subject 1 and Subject 2 respectively.

3 Results

The experiments demonstrated veneer-induced soft-tissue changes in the perioral region. Generally, the largest deformation was observed at the median lip regions. Changes in soft-tissue contour increased with veneer thickness. However, a substantial variability between individuals was found. Variations were observed with regard to the amount of lip protrusion as well as the extend of soft-tissue deformation around the mouth.

In accordance with the experimental findings, FE simulations detected the most prominent changes at the LS point and gradual increases of soft-tissue contours with increasing veneer thickness (Figure 2). A detailed quantitative evaluation of FE modelling results at the LS point showed a nearly linear dependence between soft-tissue changes and veneer thicknesses (Figure 3).

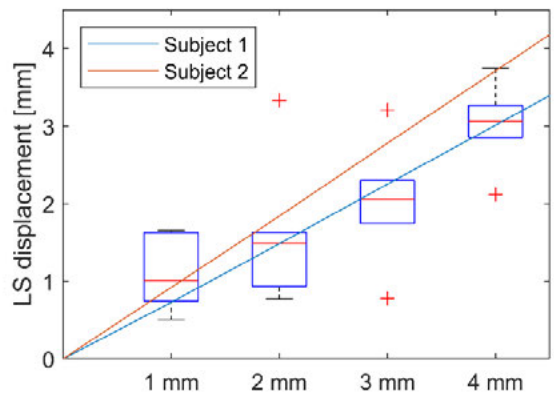

Figure 3: Absolut displacement of LS found by experiments (boxplots) and corresponding simulations for the two subjects.

However, the slope of the veneer thickness/soft- tissue displacement curves differed interindividually. Similarly, the directions of displacements were different (Figure 4) although they were constant for all veneer thicknesses.

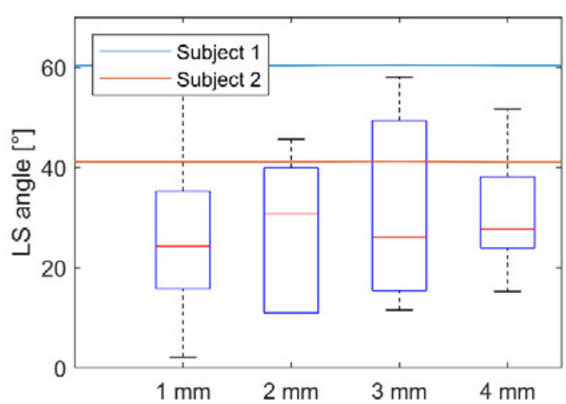

Figure 4: Direction of displacement of LS found by experiments (boxplots) and corresponding simulations for the two subjects.

4 Discussion

Although soft-tissue changes caused by the positioning of veneers on the labial incisor surfaces show considerable inter-subject variation with respect to magnitude and direction, experimental findings and simulations matched well at the centre of the vermillion border of the upper lip (LS point). For the smallest veneer thickness (1 mm), however, experimental measurements suggest displacement magnitudes that deviate from a linear thickness/displacement relation. Similar observations were reported by other authors [9]. Such non-linear behaviour is probably associated to inadequate constitutive relations for the soft-tissue. The direction of experimentally detected soft-tissue changes seems to be largely independent for the veneer thicknesses examined in this study. Inter-subject variation was also observed in the simulated results. As the material constants used in the constitutive relations of both subjects were identical, the differences of the thickness/displacement relations can be attributed entirely to geometrical aspects. More specifically, the thicker lips of subject 1 which also include a correspondingly thicker layer of soft fatty tissue seem to buffer the magnitude of the soft-tissue displacement. Our results indicated that a different lip thickness also causes a different soft-tissue displacement direction. While in subject 2 the displacement direction seems compatible with experimental results, subject 1 does not fit within the observed range. However, subject 1 differed considerably from the subjects included in the experimental group with respect to the BMI and might represent an extreme case were this parameter influences protrusion [10].

Obviously, experimentally-determined variations of soft-tissue changes can only partially be attributed to differences between subjects. It is also expected that errors during the acquisition and processing of the facial surface influence the results to a considerable degree. Specifically, the alignment of 3D surfaces that correspond to different veneers appears to be a procedure prone to errors. The FE method, however, has also several limitations. For instance, the constitutive equations describing the strain-stress relations of the material might be inadequate and the corresponding constants have not been adapted to the subjects. Moreover, the segmentation of the soft-tissue into skin, muscle and fat might not be sufficient with regard to the achieved spatial resolution.

It may also be considered a limitation that veneer-experiments and CT-scans originated from different groups of individuals, which limits the generality of the results. However, due to ethical reasons it is not possible to obtain CT- scans of subjects that participate in veneer-experiments.

Author Statement

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