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Procedia CIRP 49 (2016) 199 – 202

www.elsevier.com/locate/procedia

The Second CIRP Conference on Biomanufacturing

Design and Analysis of 3D Customized Models of a Human Mandible

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Abstract

Polymer-based composites are ideal for applications where high strength-to-weight and stiffness-to-weight ratios are required. In the biomedical field, fiber-reinforced polymers have replaced metals, emerging as suitable alternative. Reverse engineering and additive manufacturing methods are required to achieve the design of customized devices with specific shape and size. At the same time, micro-mechanics and macro-mechanics play an important role in the development of highly functional composite materials.

The aim of this research is to develop customized 3D models of a human mandible using reverse engineering, additive manufacturing and composite material technology. Experiments were carried out by loading the models through the condyles and the results show the potential to reproduce the mechanical behavior of a human mandible. Taking into account the curves of the load-arch width decrease, the stiffness of the 3D composite model was 14.1± 1.9 N/mm, which is close to the tested human mandible (17.5 ± 1.8 N/mm).

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Keywords: Mandible; Reverse Engineering; Stereolithography; Fiber-reinforced composites; Experimental Testing

1. Introduction

Over the last decade, there have been great strides in the development of using emerging fabrication techniques and new materials for prosthetic and tissue engineering applications [1-36]. Acrylic mandibular models are often utilized for medical teaching, training and research. This work examines the process of developing and validating a synthetic human mandible that has implications for *in vitro* studies of dental implants and superstructures [25].

A key challenge in this area is the difficulty in finding cadaveric skeletal segments and the fact that the mechanical properties of the bone structure vary. The motivation of this work is to develop a realistic mandibular model that has close resemblance to the actual part in terms of geometry and its mechanical properties [37, 38].

The aim of this research is to enhance the design and development of a customized model of a human mandible using a combination of reverse engineering, additive manufacturing and composite materials. The properties of the produced model would be analyzed and compared to the current 3D polymeric and human mandibles.

Previous authors have developed different polymeric models of temporal bone by integrating reverse engineering with rapid prototyping techniques [1, 25, 39]. However, the design of the trabecular and cortical bones have not been properly modelled through synthetic models because they behave like homogeneous isotropic materials. In addition, the mechanical anisotropy of trabecular [40-44] and cortical bone [43-46] is also often neglected. Such anisotropic behavior can be observed in the trabecular bone of the condyle [47] and in the mandible body [48, 49] and the elastic modulus of those

Peer-review under responsibility of the scientific committee of The Second CIRP Conference on Biomanufacturing
doi:10.1016/j.procir.2015.11.016

parts vary along the different directional planes. Taking the mechanical properties of the human mandible in consideration, the mechanical anisotropy of cortical bone can be found in the mandible body [50] and in the ramus [39] as demonstrated through the elastic modulus [25].

Anisotropic edentulous mandible models made of a polymethylmethacrylate (PMMA) core and a glass fiber reinforced outer shell are often designed using reverse engineering methods and produced with composite materials [25, 37]. Medical grade samples use 3D customized models that consist of a PMMA-based bone cement as the core of the actual structure that simulates the trabecular bone, and an outer shell made of glass fiber reinforced epoxy composite to mimic the cortical bone. The glass fibers of the outer shell were oriented at angles of 0° and 90° with respect to the axis of the mandible corpus and at angles of ± 45° in the ramus to reproduce the cortical bone anisotropy. In our previous works [37, 38], the PMMA-based core was obtained through a multi-step procedure. A model of the core was first manufactured by inkjet printing and a silicone rubber mould was developed from the core prototype. The material was then poured into the customized mould.

In the current research the core was directly fabricated by additive manufacturing.

2. Materials and Methods

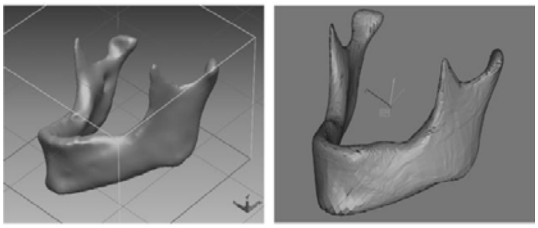
Three-dimensional (3D) composite edentulous mandibles were first produced using stereolithography (SLA) technique with composite materials. A 3D scan of a human mandible was performed using a Cyberware Mini Scanner and the data from the scanner was analyzed and repaired through the use of Rapid Form and Materialise Magics to ensure that the CAD geometries were water-tight and suitable for fabrication.

The inner core of the composite model consisted of a photo-curable acrylic resin with mechanical properties similar to that of trabecular bone. The outer shell of the mandible model consisted of a photo-curable glass fiber reinforced composite and this material was used for the core to simulate the compact bone anisotropy of the mandible arch.

To validate the polymeric and composite mandible models, experimental tests were designed and conducted by loading the composite models through the condyles up to a maximum load of 20 N. The testing conditions reproduce the loading configuration that are found in previous scientific work [51, 52]. An extensometer was used to record the local displacement in the symphysis region. Finally, the results were compared to those of a human mandible.

3. Results and Discussions

3D reconstructions of a human mandible were obtained from 3D scan data, using dedicated software such as Rapidform (Fig.1a) and Magics (Fig. 1b).



(a) (b)

Fig. 1. 3D reconstructions of a human mandible obtained from 3D scan data, using dedicated software such as Rapidform (a) and Magics (b).

For the design of the mandible model, trabecular bone was replicated with an acrylic resin that has a Young’s modulus of 2.0 GPa (Figure 2) and this value is close to that measured for trabecular bone (2.2 GPa) in the mandible symphysis and along the bucco-lingual direction [49]. The next step was to subject the human mandible on load-displacement tests as shown in Figure 3.

(a) (b)

Fig. 2. Images of 3D customized polymeric (a) and composite models (b).

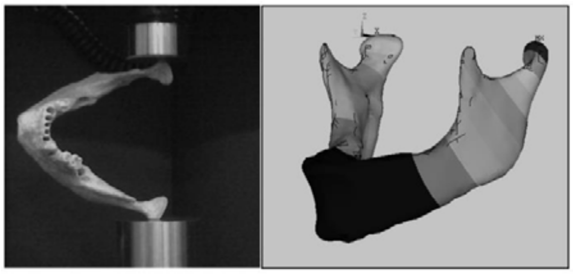


Fig. 3. Typical images of experimental and theoretical analyses performed on the human mandible.

Finally, the stiffness of both human and synthetic models were evaluated by examining the slope of the initial linear region of the load-displacement curves. Unlike the polymeric models, the composite model and the human mandible showed a load-arch width decrease curve which was linear up to the maximum load of 20 N (Fig. 4).

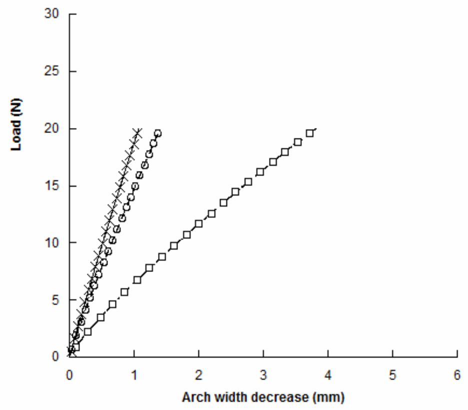


Fig. 4. Load-arch width decrease curves obtained from human mandible (x), polymeric (☐) and composite (o) models.

The stiffness of the polymeric and composite models loaded through the condyles was 5.1 ± 0.5 N/mm and 14.1 ± 1.9 N/mm, respectively; while for the human mandible, a value of 17.5 ± 1.8 N/mm was achieved. In line with Hobkirk and Schwab (1991), the load of pterygoid muscles at 16 N would equate to the reduction of 1 mm in terms of the distance between the condyles. As a consequence, the in-vitro stiffness of the mandible was 16 N/mm. The stiffness of the designed composite model is close to the values of a human mandible (17.5 ± 1.8 N/mm).

4. Conclusions

The design and development of dental implants will improve the understanding of biomechanical features such as those for synthetic mandibles. Even though the geometry and size of these models can be easily obtained from 3D scanned data, the mechanical features of the part must be mechanically validated. Fiber-reinforced composite materials have played a crucial role in reproducing the anisotropy of the mandible cortical bone [44] and they have the potential to mimic the mechanical properties of natural hard tissues. By varying the fiber content and orientation as well as the composition of the matrix, we have demonstrated that we can tailor the mechanical properties of the materials to mimic the anisotropy of a human mandible [53]. Finally, this work has contributed to new knowledge by demonstrating the process of designing 3D mandibular models using reverse engineering, additive manufacturing and composite materials technology with the final product being validated through robust mechanical testing.

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