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An analytical model to design circumferential clasps for laser-sintered removable partial dentures

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ABSTRACT

Objective. Clasps of removable partial dentures (RPDs) often suffer from plastic deformation and failure by fatigue; a common complication of RPDs. A new technology for processing metal frameworks for dental prostheses based on laser-sintering, which allows for precise fabrication of clasp geometry, has been recently developed. This study sought to propose a novel method for designing circumferential clasps for laser-sintered RPDs to avoid plastic deformation or fatigue failure.

Methods. An analytical model for designing clasps with semicircular cross-sections was derived based on mechanics. The Euler–Bernoulli elastic curved beam theory and Castigliano's energy method were used to relate the stress and undercut with the clasp length, cross-sectional radius, alloy properties, tooth type, and retention force. Finite element analysis (FEA) was conducted on a case study and the resultant tensile stress and undercut were compared with the analytical model predictions. Pull-out experiments were conducted on laser-sintered cobalt–chromium (Co–Cr) dental prostheses to validate the analytical model results.

Results. The proposed circumferential clasp design model yields results in good agreement with FEA and experiments. The results indicate that Co–Cr circumferential clasps in molars that are 13 mm long engaging undercuts of 0.25 mm should have a cross-section radius of 1.2 mm to provide a retention of 10 N and to avoid plastic deformation or fatigue failure. However, shorter circumferential clasps such as those in premolars present high stresses and cannot avoid plastic deformation or fatigue failure.

Significance. Laser-sintered Co–Cr circumferential clasps in molars are safe, whereas they are susceptible to failure in premolars.

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1. Introduction

Removable partial dentures (RPDs) are essential cost-effective components of the dental prosthesis industry. They are used to restore missing teeth in partially edentulous patients, improving their quality of life. Millions of patients are affected by this treatment worldwide; over 13% of the adult population in North America and Europe wear RPDs [1].

Despite their widespread use, RPDs present a few challenges [2–4] such as problems related to comfort and appearance [4,5] and their vulnerability to mechanical failure by fatigue [6]. This failure mostly occurs at the metal clasp, a critical component that retains the denture to teeth at the undercut area [7]. A clinical study has shown that clasp failure is the most common complication of RPDs and the main reason why 50% of RPDs should be replaced after 5–6 years of usage [2].

The performance of clasps is governed by the clasp material properties (i.e. fatigue strength) and design. RPD frameworks and clasps are commonly made from cobalt–chromium (Co–Cr) alloys because of their suitable cost, biocompatibility and excellent corrosion resistance [8]. A substantial enhancement in the material properties of Co–Cr alloys is difficult because it is a function of the composition of the alloy [9]. Hence, improving the clasp design is necessary for enhancing the performance of RPDs.

Clasps are traditionally made along with RPDs using a casting technique. However, casting is influenced by the skill of dental technicians and does not allow for precise control over the design of the clasps, which results in ill-fitting of RPDs [10]. Recent advances in CAD/CAM technologies [11], particularly additive manufacturing techniques such as laser sintering [8,10,12], allow the fabrication of very precise designs which opens the window for improving the design and fit of clasps in RPDs. Laser-sintered Co–Cr RPDs provided better fitting [10] as well as improved fatigue resistance [8] and patient satisfaction [13] compared with cast Co–Cr RPDs.

The RPD industry still depends on traditional guidelines in driving the design of clasps [14]. These guidelines have valuable merits that the industry has amassed over the years. However, they are generally empirical and qualitative. In addition, the current design practice heavily relies on the skills of dental technicians and designers [14]. The traditional empirical and *ad hoc* design approach can render huge variation in clasp design, and subsequently vast variation in the performance of RPDs and patient experience [10,13].

The lack of a systematic approach based on engineering principles stimulated previous research into finding new methods for designing better clasps. Warr argued that the possibility of fracture due to faulty design is underestimated and proposed a numerical framework to evaluate the performance and quality of clasps [15,16]. Brockhurst provided a systematic method for determining clasp cross-sections based on theoretical analyses [9]. However, both Warr and Brockhurst used the straight beam theory to calculate the maximum bending stress, which is questionable for the curved clasp where the neutral axis is shifted toward the clasp's inner curvature. In addition, the practical application of Warr's formula was not possible at that time due to difficulty in obtaining the required measurements [16,17].

More recent studies carried out FEA to identify the stress distribution and deflection of clasps upon loading [18–21]. However, these studies did not provide mathematical design models. Further, the type of finite element used in most cases were 8-node linear order brick elements with three degrees of freedom per node [18–20], which causes shear locking effects making the reaction to bending stiffer and hence may lead to quantitatively questionable results [22]. The use of quadratic order or reduced integration brick elements with adequate mesh density would solve this problem [22].

Apart from retention caused by spring and friction forces, physical forces such as surface tension within the denture-saliva-palate system play an important role in retention due to the phenomena of capillarity and wetting [23]. Researchers have worked extensively on developing suitable expressions for the adhesion force due to surface tension [24,25]. Retention due to surface tension has only been considered for denture bases on soft tissues, where capillary forces are more significant compared with clasps on teeth. However, combining capillary, friction, and spring forces in modeling clasp retention would provide a complete representation for the different forces involved.

Despite the various theoretical and numerical studies, a predictive mapping to help determine the optimal clasp design remains nonexistent to the best of our knowledge. The objective of this study is to use mechanics to identify design equations for circumferential clasps of RPDs processed by laser-sintering. Only molar and premolar teeth are considered because clasps are generally placed on posterior teeth for esthetic reasons. Prosthodontic experts provided feedback on the design of clasps related to their placement (i.e. molars versus premolars) and dimensions [14]. However, this feedback was based on experience and among the goals of this manuscript is to investigate whether the model results will agree with the common practice. Our hypothesis is that the proposed model could predict the safe performance of laser-sintered circumferential clasps.

2. Materials and methods

A mechanics analytical model for clasp design was derived based on Euler–Bernoulli curved beam theory and Castigliano's method [26,27]. Spring, friction, and adhesion retention forces were incorporated into the model. The model incorporates the effect of tooth anatomy, maximum stress, alloy properties, undercut and required retention force. Next, FEA of a case study obtained from the analytical model was carried out. Finally, to validate the model experimentally, different clasps were produced using the laser-sintering technique and the retention force required for clasp dislodgement was measured and compared with the retention force provided by the analytical model.

2.1. Analytical model

A circumferential clasp engages the undercut as shown in Fig. 1. Considering a clasp being pulled out of the undercut