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Prototyping Artificial Jaws for the Bristol Dento-Munch Robo-Simulator

‘A parallel robot to test dental components and materials’

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Abstract— **This paper presents the robot periphery for the Robotic Dental Testing Simulator based on a Parallel Robot (i.e. Stewart Platform) to simulate the wear of materials on dental components, such as individual teeth, crowns or a full set of teeth. Current chewing simulators move in only 1 or 2 degrees of freedom (DOF) and therefore lack accuracy. The Bristol simulator has been developed to replicate accurate human chewing patterns in 6-DOF. This paper describes the artificial jaws and compliance module of the robot. The jaws have been reverse engineered and represent a human-like mandible and maxilla with artificial teeth. Each clinically fabricated tooth consists of a crown and glass ceramic roots which are connected using resin cement. Correct occlusion of the artificial jaws assembly was assessed by a dental teaching simulator. A compliance module had to be built between the lower jaw and the robot platform to sustain the fluctuating forces that occur during normal chewing in the occlusal contact areas, where these high bite forces are major causes of dental component failure. A strain gauge force transducer has been integrated into the machined lower jaw, underneath the second molars, to measure axial biting forces applied to the posterior teeth.**

Index Terms – Chewing simulators, Stewart platform, control of biting forces, compliance module, masticatory system

I. INTRODUCTION

The UK dental market is worth over £2.5bn per year of which dental restorations represents over a third. This is likely to grow over the coming years as the public becomes more aware of the advances in aesthetic ceramic materials and dental implants and as these become more affordable and readily available [1]. New oxide and silicate ceramics, such as In-Ceram, Procera or Empress are used in restorative dentistry for inlays, onlays, crowns or bridges. Despite the frequent use of ceramics and composites in dentistry, their physical parameters, such as the modulus of elasticity, flexural strength, material hardness and their interactions with respect to wear and fatigue are often poorly understood [2-3].

In the process of developing new dental restorative materials, manufactures must therefore be able to predict new materials wear performance before launching them into a competitive market [4]. In vivo/Clinical trials are time-consuming and expensive [5]. In vitro, tests provide an accelerated screening of the clinical wear at relatively low cost under controlled and reproducible laboratory conditions [4].

During last 20 years, many different wear simulators have been constructed for dental materials study [6]. In 2001 the International Standard Organization, ISO published a technical specification on two- and/or three-body contact ‘Guidance on testing of wear’ (ISO, 2001) describing eight types of oral wear simulators, which are currently used in dentistry [3,7]. However, not one of them is able to reflect the clinical performance. Above all, the results of study on the most established in vitro three-body wear simulator, the ACTA (Academic Centre for Dentistry Amsterdam) [8-13] carried out by Kunzelmann [14] and later updated by Zappini [7] and Heintze [3] confirming that different wear simulators do not even correlate with each other. A recent critical review of these simulators by Heintze [15] indicates that the MTS hydraulic simulator designed by DeLong and Douglas [16] has still the best motion control in 2-DOF. However, from a kinematical point of view a potential limitation of all the current simulators is that they cannot replicate accurate movement of the human jaw, according to the latest biomedical findings by Koolstra [17].

The University of Bristol is developing a Dental Testing Simulator based on the Stewart Platform that can move in 6-DOF. The usage of this parallel kinematics makes in vitro testing more accurate [1, 18-20]. The overall aim of the project is to design a testing machine with force and position feedback control, capable of emulating the muscles responsible for the movement of the human mandible. The robot will then be used to simulate the complex motion of the jaw in 6 DOF to perform accurate simulation of wear of dental materials on dental components.

II. ‘DENTO-MUNCH ROBO-SIMULATOR’

A. *Mechanics*

The robot consists of actuated struts connected together at passive joint nodes [1, 18] as it is shown in Fig. 1. The base (bottom plate) is fixed and cannot move. The platform (top plate) of the parallel robot is moveable in 6-DOF by varying the length of one or more of the actuators. The basic

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mechanism is developed by Stewart in 1965 [21]. To control chewing motion with the Stewart platform, the lower mandible is attached to its top plate and the upper maxilla is fixed to its fixture assembly. The struts are driven by six electrical actuators. Selected attributes of the robot are presented in Table 1.

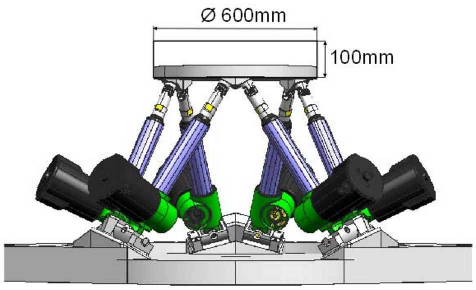


Fig. 1 Working range of 6 DOF parallel robot

TABLE I

Selected parameters of Parallel Robot

1	Parallel kinematics	6 DOF
2	Actuator stroke [mm]	100
3	Actuator force [N]	1000
4	Height (without frame)	~370mm

B. *Controller*

Feedback controller is used to emulate the dynamics of the human masticatory system. When chewing, a combination of both force and position control is needed. The human masticatory system achieves this through a combination of neural control and inherent dynamics emergent from the characteristics of muscle and their geometric information [17]. Muscle can alter the inherent stiffness of the jaw, and this can very rapidly. It is this property, for example that prevents damage to the teeth and jaw if a hard piece of food suddenly gives way. The Bristol parallel robot mechanism and its six electric actuators have very different dynamics. These are altered to match them more closely to the human jaw's dynamics using inner-outer loop control and composite measurements (i.e. position and force). The cascaded design architecture encompassing current, speed and position control. The control of contact forces is achieved using a compliance module introduced in section 3 of this paper. The software controller is based on the xPC-target solution where a graphical user interface has been developed as a tool to plan and program the robot trajectory [1, 18].

III. DESIGN OF THE ROBOT PERIPHERY

The complete assembly of all periphery components is shown in Fig.2A. It consists of three basic modules: a reverse engineered lower jaw (mandible) model, including force transducer, artificial anterior/posterior teeth and separate glass ceramic roots, and a compliance module, as well as an adapter plate to mount the periphery equipment to the robot mechanics.

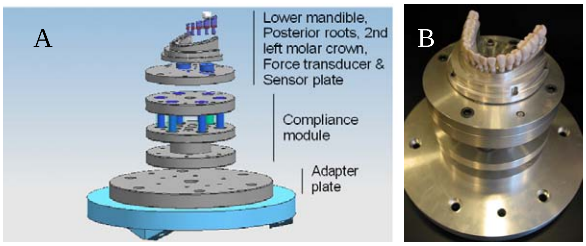


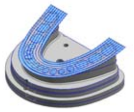
Fig. 2 Robot Periphery of Bristol's Dento-Munch Robo-Simulator

A. *Reverse Engineering and Evaluation of LowerJaw*

The complex geometry of a lower jaw was reverse engineered using KaVo study models and teeth. Instead of 3-D geometrical information, 2-D key data, such as the position of teeth in the x/y-plane, and the depth of teeth (Phase 1, Table 2), were measured to reduce the complexity of the 3D modelling. Based on this key information the 3-D model of the artificial jaw was designed (Phase 2) and later manufactured from PROLAB (a machinable plastic wood) and aluminium (Fig.2B).

TABLE II

Design Phases of the Lower Jaw

- Phase 1 – Key-data scan data	**- Phase 2 -** 3-D model of the mandible
	

Before manufacturing the final aluminum mandible, correct occlusion of the artificial jaws assembly was assessed by a KaVo Cranium G50 adjustable dental teaching simulator (Fig.3B). The G50 meets all clinical requirements for checking the function of clinical dentures. It represents the natural conditions of the human masticatory system and is therefore sufficient for checking occlusion. The radius of the Curve of Spee was also measured as an important jaw characteristic indicator.

In terms of prosthodontics, this curve can be defined as "the anatomic curve established by the occlusal alignment of the teeth, as projected onto the median plane, beginning with the cusp tip of the mandibular canine and following the buccal cusp tips of the premolar and molar teeth" [22]. This definition of the Curve of Spee is the basic reference for the measurement of the curve in our study. In practice, it can be made by drawing a straight line between the mesiolingual cusp of the second molar and the buccal cusp of the canine. From there, lines normal to the cusp tips of the premolars, the first molar and second molar can be drawn. The longest of these distances represent the depth of the Curve of Spee [22]. Following this procedure, the longest distance from the reference line was identified for the first molar tooth. Based on these findings the radius r of the curve was calculated by applying standard geometry where s is the distance between the mesiolingual cusp of the second molar tooth and buccal cusp of the canine tooth. The depth of the curve is named h in the formula below.

$$r = \frac{h^2 + \left(\frac{s}{2}\right)^2}{2h} \tag{1}$$

Accurate design of the Curve of Spee with respect to the final lower jaw model, including separate roots and crowns, was achieved by modelling a plane supporting surface for all tooth roots into the mandible design (Fig. 3A). By doing this, an exact replica of the Curve of Spee is given by adjusting the height of each simulated tooth root, since they are separate from the crowns and manufactured independently.

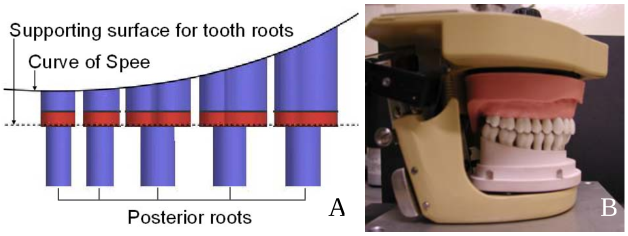


Fig. 3 Design of the Curve of Spee & KaVo Cranium G50

The occlusal surface of the mandible was assessed based on ‘Andrew’s six keys to occlusion’ [23] and by utilizing a fully adjustable dental teaching simulator (KaVo Cranium G50). The designed jaw very nearly represents an ‘optimal’ occlusion where almost all of the six keys are fulfilled (Fig.3B). Only the fact that the anterior teeth are slightly malaligned and the requirement a flat occlusal plane (Key VI), which implies a flat Curve of Spee, violate Andrew’s six keys philosophy for normal occlusion. The present jaw can therefore be seen as a step towards representing a natural human-like occlusal plane as reported by Risse [24-26].

B. *Design of Posterior Roots and fixing of Ceramic Teeth*

The tooth anatomy/morphology can be generally divided into the visible part or the crown and the part in the jawbone, the root. This distinction is useful for the design of artificial teeth since it is beneficial to separate the tooth body into two parts. The root is manufactured using machinable glass ceramic (MACOR MGC), whereas the crown (denture tooth) is supplied from dental companies. The crown and root are connected using a universal resin luting cement system (Fig.4).

Fig. 4 Occlusal and proximal surface of 1st left mandibular molar

C. *Integration of Force Transducers*

Fig. 5A shows the top module of the robot periphery, including the sensor plate, force transducer, lower mandible, roots for first and second left molars as well as the crown of an earlier modelled second left molar tooth [19]. Strain gauge load cells were placed on a specially designed sensor plate exactly underneath the second molar teeth of the lower jaw (Fig.5A).

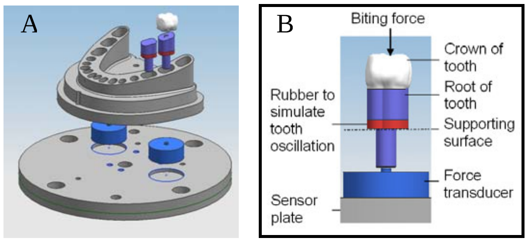


Fig. 5 A) Top module of Robot Periphery & B) 1 DOF Biting Force Sensor

During chewing, axial compression forces are sensed by the sensor in the crushing and grinding phase of the chewing cycle. Lateral forces due to, for example, friction or tooth fracture can not be measured. To enable this, a force transducer with at least 2-DOF would be necessary. For the purpose of sensing simple axial forces and working as an overload safety device, a 1-DOF force transducer was found to be sufficient for this application.

Apart from the crown and root, Fig. 5B shows rubber material placed underneath the main tooth body. This was done to simulate natural tooth oscillation and its damping when subjected to fluctuating compression forces, as it would occur with the natural periodontal ligament. The main purpose of the rubber is, however, to allow compliance towards the force transducer in order to sense an increase in compression force. Placed on a rigid support surface in their simulated sockets, the artificial teeth would not display the sufficiently elastic behaviour necessary to transmit the force from the cusp of the tooth to the sensing element. 2 mm thick rubber sheets were therefore located underneath the main root body to simulate natural tooth oscillation of the periodontal ligament which is usually between 0.1 and 0.4 mm in thickness [26]. Stable contact points allow all the teeth to be loaded but the biting force is only measured for second molar teeth. This can be seen as an analogy to Takanobu’s 2-DOF biting force sensor which allows sensing forces for a group of teeth [27].

D. *Compliance Module*

Having identified the dynamic conditions of the chewing [28-29,20], the purpose of the compliance module as a passive device; is to sustain the fluctuating of high bite forces that occur during normal chewing in the occlusal contact areas which are the major causes of dental component failure according to Heintze [15]. The main part of the module is a spring mechanism which consists of a compression spring, gliding shaft, two jig bushes, slotted pan head screw and washers. Six spring assemblies are integrated in the design as shown in Fig. 2A. The spring will compress when subjected to an axial force above 250 N. The module can sustain a maximum force of 575 N which corresponds to a spring deflection of approximately 11.4 mm. This is achieved by manufacturing steel shafts, which avoid buckling and give axial guidance with respect to the spring.

IV. ASSEMBLY OF THE ROBOT PERIPHERY

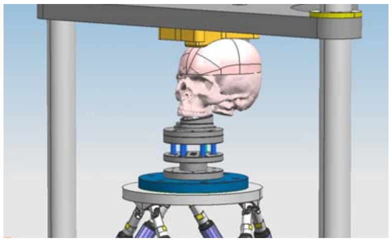


Fig. 6 3-D Assembly of the Dento-Munch Robo-Simulator

Fig. 6 shows the CAD model of the robot periphery attached to the robot movable platform and a reverse engineered 3-D model of a human-like replica skull attached to the top frame of the robot [1, 18-20].

V. CONCLUSION AND FUTURE WORK

Taking into account biomedical findings with respect to the tooth anatomy and dental occlusion, the entire periphery equipment for Bristol’s Simulator to simulate the wear on dental components was developed and manufactured. Despite the current achievements, there is still a long way to go to complete the prototype of the dental mastication robot. A major task for the forthcoming months is further development of the robot controller which is able to perform position and force control.

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