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The chewing robot: a new biologically-inspired way to evaluate dental restorative materials

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Abstract— **This paper presents a novel *in vitro* dental wear simulator based on 6-6 parallel kinematics to replicate mechanical wear formation on dental materials and components, such as individual teeth, crowns or bridges. The human mandible, guided by a range of passive structures moves with up to six degrees of freedom (DOF). Currently available wear simulators lack the ability to perform these complex chewing movements. In addition simulators are unable to replicate the normal range of chewing forces as they have no control system able to mimic the natural muscle function controlled by the human central nervous system. Such discrepancies between true *in vivo* and simulated *in vitro* movements will influence the outcome and reliability of wear studies using such approaches. This paper summarizes the development of a new dynamic jaw simulator based on the kinematics of the human jaw.**

I. Introduction

Over the past 20 years, much research within dental biomaterials science has focused on the development of new direct and indirect dental restorative materials and components, (figure 1). Although many of the physical and chemical parameters of these materials are well characterized e.g. corrosion resistance, coefficients of expansion, solubility strength and hardness etc., how these components respond to different types of wear within the mouth is often poorly understood [1].

When developing new dental restorative materials, manufacturers must be able to predict the properties of new materials and their performance in the mouth. One way of achieving this is by conducting clinical trials. However, such trials are often difficult to set up, are expensive to run and are also time consuming, often a minimum of two to three years to complete [2]. An alternative strategy is to use dental wear simulators (chewing simulators) which will be able to provide a route for accelerated study of dental wear and at a relatively low cost. A summary of eight different *in vitro* wear simulators can be found in [3].

A lower jaw, guided by the temporomandibular joint (TMJ) and the teeth, moves with up to six DOF, translating and rotating along each of the Cartesian axes [4-5]. In comparison to the human jaw, dental wear simulators currently available to dental researchers often possess only two to three DOF. In addition to restricted movement, current equipment is unable to replicate the normal range of chewing forces [6]. The discrepancies between *in vivo* and *in vitro* movements and forces will influence the outcomes and therefore reliability of any wear studies using such approaches. Certainly there is evidence to support this view, as shown by the work of Hu [7], comparing two different wear test conditions and the work of Heintze, where a round robin test of different materials using five types of masticatory simulators demonstrated significant variation in material properties between the simulators [8].

Fig. 1 Selected dental restorative materials and their raw material

The aims of this study are to simulate the dynamics of the human masticatory system and develop an accurate and reliable chewing simulator which is capable of moving with six DOF to replicate typical jaw movements and occlusal forces. This project, jointly conducted by the Department of Mechanical Engineering, Bristol and Bristol Dental School, is divided into two major work packages: virtual modeling of the human masticatory system and physical development of an advanced *in vitro* wear simulator.

This paper summarizes the work conducted by the first author [9]. It will summarize the development stages of a new *in vitro* wear simulator to generate habitual mechanical wear on dental components following a previous conceptual study conducted by other members of the research group [10]. The paper will also highlight the development of a new dynamic jaw model to study the kinematics of the human jaw and that of chewing simulators. The paper is organized in the following manner. In section II, a brief outline of the mandibular kinematics and selected components of the human masticatory system is given. Section III outlines the acquisition of main wear affecting parameters that are used as input data for the robot controller and the virtual jaw, while section IV outlines the procedure of animating

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digitized jaws [9,17] in a Siemens PLM software package. In section V, the developed mechanics and the controller of the physical chewing robot are presented. This paper is concluded with a discussion of future work.

II. Mandibular kinematics and orofacial system

Mandibular movements in relationship to the maxilla such as opening, closing, protrusion and laterostrusion are complex three dimensional motions in space [4-5]. These 3-D movements are the consequence of combined basic translational and rotational movements powered by the masticatory muscles. The complex muscular system of the human masticatory system consists of more than 20 muscles [11] divided into two main muscle groups: jaw opening muscles, such as the masseter and the temporalis, and jaw closing such as the digastric and geniohyoid muscles. The movements of the jaw are constrained by a range of orofacial passive structures such as the temporomandibular joint (TMJ), constraining the motion of the mandible posteriorly and the incisor teeth as well as the cuspal anatomy of the molar teeth constraining the motion anteriorly [4-5, 12].

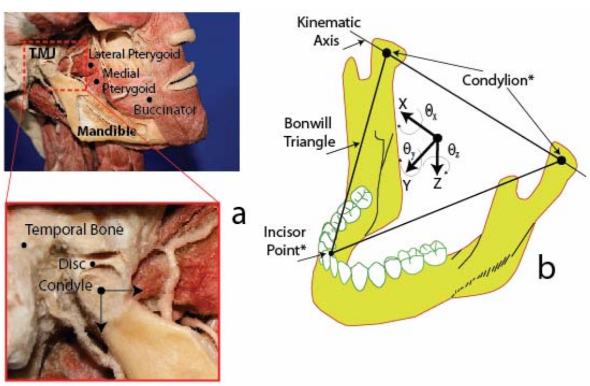

Fig. 2 (a) Sagittal view of human masticatory system and TMJ region (picture adapted: Dr Gunther von Hagens, Gubener Plastinate GmbH, Germany), (b) Bonwill Triangle and Kinematic Axis of jaw (adapted: [5])

Complex 3-D mandibular movements are supported by the unique feature of the synovial TMJ. The articular disk, shown in figure 2, is able to translate anteriorly with the condyle of the mandible, while the latter is simultaneously rotating around the kinematic axis (figure 2b) which passes through both condylar heads [13]. A general incisor trace can be sub-divided into four phases [14]: opening, turning, closing and occlusal contact phase (figure 4).

III. Motion and force recording

The complexity of the human masticatory system, with its active and passive components, makes it difficult to replicate exactly in mechanism design. In biologically inspired design, anatomical complexity can be simplified by concentrating on key functional attributes rather than on an exact replication of the entire system. Important attributes for the generation of two-body mechanical dental wear in the occlusal phase of the masticatory cycle are the eccentric occlusal sliding motion D (mm) (i.e. the buccal cusps of the mandibular teeth moving along the lingual inclines of the buccal cusps of the maxillary posterior teeth in lateral excursion) and the normal occlusal force F *(N)*. This is shown in the following equation [15] calculating the possible loss of volumetric wear V *(mm^3)* on dental restorative materials

$$V = K \times \frac{F \times D}{H}$$

where K is a dimensionless constant that depends on the wear mechanism and H (Pa) is the hardness pressure of the selected dental restorative material being tested. Selected quantities of the two important functional attributes for testing two-body mechanical wear are summarized in table 1.

TABLE 1
-Selected charateristics-

Normal chewing force	20 to 120 N
Temporary chewing force (Bruxism)	Up to 1000 N
Tooth sliding contact	0 to 2.5 mm
Normal chewing frequency	1.2 to 1.6 Hz
Number of chewing cycles per day	800 to 1400

Lower jaw movements were recorded using a six DOF motion capturing system (Vicon MX) situated in the Bristol Robotics Laboratory. This system consists of eight infrared cameras and a camera controlling hardware unit. To record typical mandibular movements, a special paraocclusal framework was developed in collaboration with Bristol Dental School, carrying three non-collinear positioned retro-reflective markers.

Fig. 3 6 DOF motion capturing using a special paraocclusal framework attached to the lower set of teeth to record mandibular movements and a headband with three retro-reflective markers to record cranium movements

While recording, the framework was rigidly attached to the lower set of teeth of a volunteer (the author) using orthodontic fixed appliances. Care was taken to ensure the band margins were below the occlusal surfaces such that at no time did the band interfere with the contact between opposing teeth during simulated mastication. In order to correct for head movement during the jaw movement, a second set of markers, attached to a headband, defines another local coordinate frame. The marker position with respect to the mandible and the cranium are illustrated in figure 3. One representative motion trace of a single occlusal point after correcting the jaw movement by the cranium motion and after applying finite difference smoothing is shown in figure 4.

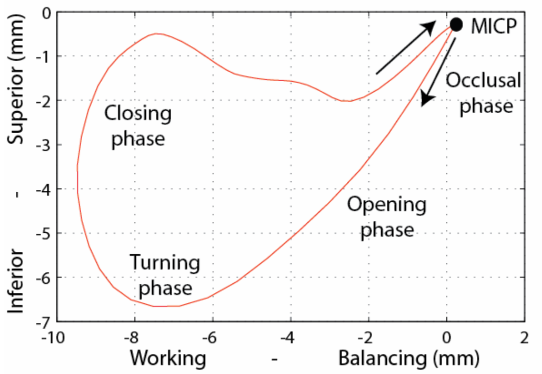

Fig. 4 Phases of one representative recorded motion trace of the Mesial Incisor Corner of the lower left central incisor during normal chewing

Static and dynamic occlusal forces along the dental arch were recorded using a T-Scan III System from Tekscan and a newly developed force measuring device, measuring forces per tooth rather than tooth section as performed by the Tekscan system. The newly developed device uses three resistive based Flexiforce sheet sensors with a maximum load capacity of 440N.

IV. Simulation of Mandibular Movements

Having recorded the input data for the chewing robot, a dynamic analysis of the system was carried out. This was achieved in two steps using Siemens's PLM software package and Mathwork's MATLAB software. Firstly, through the transformation of the geometric robot/mandibular model designed in NX6 into a dynamic non-elastic model using the integrated CAE tool and secondly, by linking the animated mandibular model to MATLAB which pre-calculates the active joint inputs for the simulation from the Cartesian Motion Inputs X. Using the 'spreadsheet run' function in the motion tool, arbitrary chewing patterns can be simulated (figure 5). The tracing of selected contact points at the occlusal surface allows investigation of the effects of 6 DOF mandibular movements compared to purely linear translational jaw movements as performed by current chewing simulators such as the MTS simulator [16]. This contributes to the understanding of how the kinematics of different chewing simulators affects the wear formation on dental elements.

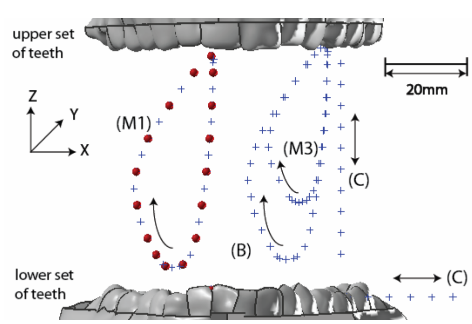

Fig. 5 Motion of biaxial operated chewing simulators vs. 6 DOF mandibular motion (border movements) – (M1) Motion Trace of Misial incisal corner of the lower left central incisor, (B) Motion Trace of Disto buccal cusp of the lower left first permanent molar for a purely 3 DOF translational motion and (M3) during 6 DOF natural mandibular motion; (C) Linear translational movement of biaxial operated chewing simulator

V. Building a Physical Chewing Robot

A suitable physical mechanism for the robot must be capable of accurately reproducing mandibular movements for a range of different chewing patterns and force profiles. The well known Stewart-Gough Platform consists of six identical kinematic chains, each incorporating a passive joint attached to the base. Opposing this is another passive joint, also attached to the moving robot platform and the actuated (active) joint. This allows 3-D motion of the robot platform to which e.g. a single dental element (figure 5a, c) or a cast of an entire dental arch (figure 5b) can be attached. The current setup of the wear simulator is shown in figure 6a.

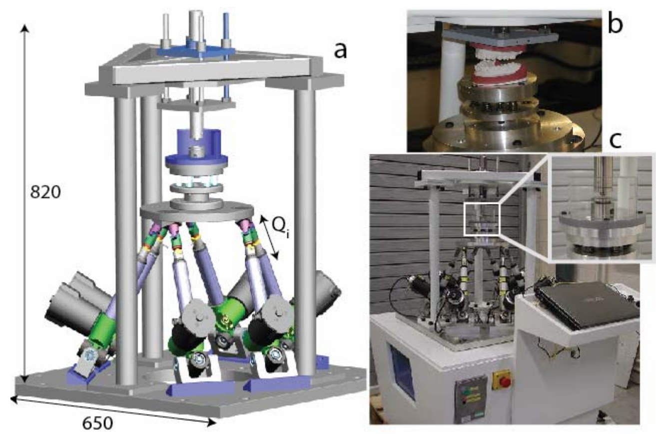

Fig. 6 (a) Geometric model of Dental Mastication Robot including robot periphery to test single dental elements (Q_i – robot joint reference inputs), (b-c) Dental Mastication Robot situated in Bristol's BLADE Laboratory

A decentralised control architecture was selected that incorporates one controller for each robot axis. It consists of an inner current loop and an outer velocity controller. Each actuator is equipped with a high resolution shaft encoder (500 pulses/revolution) to minimize measurement delays and create a sufficient position resolution (0.00096mm/count) to accomplish accurate control during the fine movements in the occlusal phase of the masticatory cycle.

From a control point of view, the chewing cycle can be divided into a contact and non-contact phase, which results in robot DOF subjected to force or position control. In the occlusal phase of the mastication cycle the robot interacts with the environment where the position and velocity in the z-direction is naturally constrained. The top level controller positions the dental elements in the x-y plane, maintaining a specified force during tooth contact in robot z-direction. In the opening, turning and closing phase of the masticatory cycle the robot is controlled only from the position controller and no force constraints exist.

The results of the robot joint control are shown in figure 7. The system is tested by converting the Cartesian motion inputs $X = [x, y, z, \theta_z, \theta_y, \theta_x]$ of a normal chewing motion as displayed in figure 4 to robot joint (leg) coordinates Q_i where $i = 1 \ldots 6$.

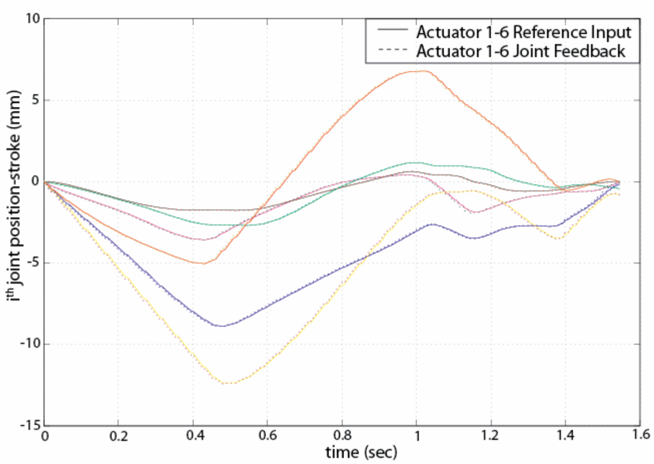

Fig. 7 Calculated robot joint reference inputs Q_i for one representative chewing cycle as displayed in figure 4 (only for a single point trace) vs. actuator joint feedbacks of the Dental Mastication Robot

Mechanical wear has been generated on a number of different dental materials. Figure 8 shows e.g. one wear trace generated on a soft sample over 30.000 chewing cycles (volumetric wear loss: $3.77mm^3$) using the robot setup as shown in figure 6a, including steatite ball as antagonist.

Fig. 8 (a) Generation of Wear Formations on sample material

VI. CONCLUSION AND FUTURE WORK

Despite the development of many different types of chewing simulators, all the existing designs are not able to reliably test dental materials. This paper summarized current achievements that lead to the development of an advanced 6 DOF *in vitro* wear simulator that aims to accelerate and improve current testing procedures. This first prototype is capable of replicating natural mandibular movements with up to 6 DOF and the normal range of chewing forces, as well as occlusal forces occurring during TMJ dysfunction and bruxism.

Our future research will expand on a number of fronts with respect to the wear simulator. In particular, we will compare the replicated jaw movements by the dental wear simulator to real human jaw movements in Cartesian space using a 6 DOF motion capturing system. We will also look at virtual and physical techniques to simulate conditions in which opposing teeth do not align normally. Furthermore, we intend to explore other control architectures for the chewing robot, including one based on emulating muscle dynamics. This approach would aim to create chewing patterns and tooth-food-tooth interaction dynamics as an emergent property rather than tracking a set of force and position trajectories. We also intend to expand our research to three body wear and combine different dental wear mechanisms in our study such as chemical and mechanical wear.

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