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Dento-Munch and Dento-OS inventions

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The article describes the motivation and technological innovation behind the design of Dento-Munch and Dento-OS, products which may have an impact on the society and could revolutionise the future of dental research and also have an impact on other medical applications.

The Dento-Munch invention

Dentistry is an area of medicine where the study of human biomechanics such as chewing has the potential to improve patient care. A simulator of the human masticatory system can be used to study structural and functional interactions in dental components like implants to analyse their durability and failure rate. Furthermore, finite element methods (FEM) can be applied with the aim of improving the design of materials, structures and manufacturing procedures, leading to improved clinical results in implantology. Dentistry has also taken advantage of many of the technological advances in medicine, particularly in the area of data gathering and vision. Amongst all the health science specialties it is probably dentistry and plastic surgery that have the highest interest in anatomic topographical (surface) imaging. As a result, technological improvements in computer-aided design / computer-aided manufacture (CAD/CAM), computer-aided engineering (CAE) and vision-based reverse engineering technology are used to enhance the overall efficiency of manufacturing procedures of dental elements such as crown and bridge production and restoration of teeth which, in turn, improve patient care.

Despite the frequent use of metals, polymers and ceramics for tooth restoration, properties such as the modulus of elasticity, flexural strength, hardness, wear and fatigue are often poorly understood. Without this knowledge the likely long-term performance of the materials cannot be assessed. Although the UK, for example, spends £ 2.5 billion each year on dental materials to replace or strengthen teeth, dental development is still hindered by the lack of an adequate method of field testing. Randomised clinical trials are time-consuming and expensive, and by the time a new material has been evaluated, the market has often moved on. Current laboratory simulators are limited to only two to three degrees-of-freedom (DOF) where human chewing is 6 DOF. Therefore, they are unable to reflect true clinical performance and indeed, results from different simulators are often inconsistent.

For that reason, a Dental Robotic Testing Simulator called Dento-Munch (Fig. 1) was invented at the University of Bristol to act as surrogate mouths with 6 DOF to emulate the human neuromasticatory system, which, via feedback control of the robot actuators, will accurately replicate the forces and dynamics sustained by the teeth in situ. However, the complexity of this task is deceptively large. The Bristol dental robotic simulator consists of two parts, the mechanics and the controller. The design inspiration is based on a human

Fig. 1: The Dento-Munch, the world's first 6-DOF dental chewing simulator.

skull (structure), a spider (general look) and an aircraft simulator (dynamics and control of chewing).

The mechanics

The design differs from the human jaw in terms of muscle actuator layout. The human jaw relies on the temperomandibular joint (TMJ) to create 6 DOF. Given space constraints around the skull, humans need a compact structure to masticate, which is made possible by the high versatility of muscles. Muscle actuators can represent the main muscles of mastication but the geometric distribution and size of muscle actuators determine the efficiency of effort generated. Due to limited space inside the skull, it is difficult to find a sufficiently small actuator capable of generating a load of up to 850 N that is commercially available.

The simulator design is based on the Stewart Platform concept, with the muscle actuators placed purely on the outside of the skull and attached only to the lower mandible. This means that almost any size actuator can be used to simulate the human masticatory apparatus. Given this, and the fact that there was no need to simulate the TMJ, it was decided to adapt the most popular configuration with six legs or limbs (spider looks) of the Stewart Platform in the design of the Dento-Munch. A Stewart Platform is a highly stable structure, originally designed as a flight simulator. It is currently used for many applications that require precise positioning and orienting. This mature technology is fully capable of emulating human masticatory movement through a suitable closed-loop feedback control system.

The Dento-Munch simulator consists of a rigid framework inside which sits a Stewart Platform, or a hexapod positioner. The upper jaw or maxilla is fixed to the rigid frame as is the bottom of the Stewart Platform (Fig. 2). This whole structure enables simulation of the masticatory movements of the human as it can be moved in 6 DOF by varying the lengths of one or more of the six linear / muscle actuators.

Simulator design inspired by the biomechanics of the jaw

The basic design process was divided into two separate steps: structure synthesis (i.e. topological synthesis related to the biomechanics of the jaw) and structure optimization (i.e. dimensional synthesis related to the occlusal table). “Synthesis” refers to the process by which a suitable mechanism is conceived based on functional requirements such as chewing patterns. Structure and dimensional synthesis are closely linked and they are derived from the nature of chewing patterns where chewing effort is highly sensitive to both: the teeth topology (structure) and the occlusal table of the simulator mechanisms (i.e. joints and legs or limbs; including muscle actuators).

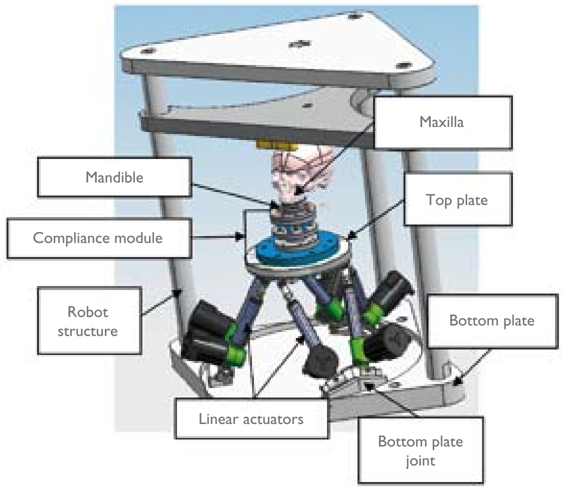

Fig. 2: The Dento–Munch concept design based on the Stewart Platform.

Structure synthesis of mechanisms was used as a design tool to classify simulator structures based on specific characteristics of the occlusal table, enabling the developers to systematically find a suitable machine solution for a given chewing pattern early in the design process. The outcome of the structure synthesis was the foundation for the dimensional synthesis of the mechanism involving all structure components of the Dento-Munch simulator.

Skull

It was necessary to study and analyse the biomechanics of human mastication with critical view to normal clinical occlusion when assembling the artificial jaws (i.e. mandible, maxilla and teeth) and their interface to the simulator structure. Analysis on the human skull helped to elaborate part of the simulator product design specification. It also revealed that lateral excursion of the mandible during mastication can follow three generally defined patterns and these mastication patterns are controlled by many characteristics particular to the individual such as follows:

The balanced occlusion describes a pattern in which the posterior teeth (molars) are in contact on both the working and non-working side of the jaw. This pattern is determined by the topology of the molar cusps.

- In the pattern group function occlusion, only the working side posterior teeth are in contact.
- In the canine protected occlusion, lateral excursion is guided by the incisors and first pre-molar.

Figure 3 shows the hybrid design of the completed skull assembly when reverse engineering and CAD assembly modelling were integrated to maintain normal clinical occlusion. It also shows some of the skull non-functional features to chewing were simplified for ease of manufacture and assembly.

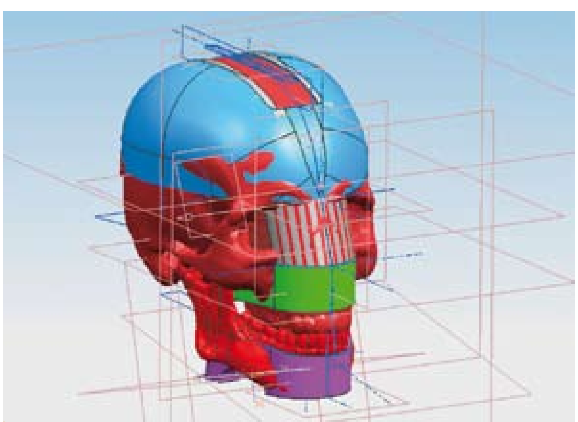

Fig. 3: Hybrid design of the completed skull with integrated reverse engineering and CAD assembly modelling.

Jaws

The dental mechanical jaw simulator maintained the geometrical relationships (Fig. 4) between the lower jaw (mandible) and the upper jaw (maxilla) using Andrew's six keys to normal occlusion and the measurement of the curve of Spee, the curve of Wilson and the curve of Monson for the clinical jaws assembly.

Andrew's six keys are 1) Molar relationship, 2) Crown angulation, 3) Crown inclination, 4) No rotation (i.e. rotated teeth occupy more space within the dental arch), 5) No space (i.e. all contact points are tight) and 6) Flat occlusal planes (i.e. the curve of Spee is present). The curve of Spee has a radius of 65 to 70 mm and it is 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". The curve of Wilson is defined as the mesiolateral curve that makes contact with the buccal and lingual cusp tips of each side of the arch. The curve of Monson is, in effect, a combination of the curve of Spee and the curve of Wilson in a 3D plane. It is a 3D sphere that passed through the incisal edges and occlusal surfaces of the mandibular teeth. It has a radius of 101.6 mm and it is more widely accepted than the curve of Spee.

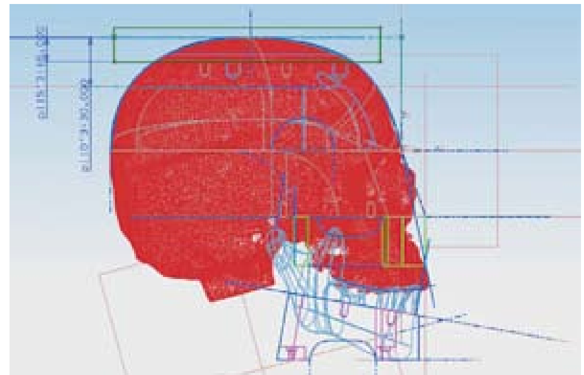

Fig. 4: Franfurt horizontal, Camper's plane, Balkwill angle, occlusal plane, incisal point, and inter condylar distance 110 mm.

Teeth

To customise the teeth design for individual chewing patterns, Dento-OS was invented (see later). The 2D conceptual design of teeth was based on the clinical approach used in the University of Bristol Dental Hospital and dental laboratory (Fig. 5a). Figure 5b shows the normal occlusion of a pair of second molars, the upper jaw and a prosthetic device supported by implant inserted into jaw bone, including teeth morphology and implant design.

The simulator controller

The Dento-Munch chewing simulator and its six muscle actuators have very different dynamics characteristics. These are altered to match them more closely to the human chewing patterns and motions using feedback control. In the design architectures, control of position, force and combination of the two are used, including inner-outer loop control, composite measurements and human chewing patterns as a reference-control model to make the muscle actuator behave like a human muscle and tendon in response to load and activation level changes in chewing process. The current simulator controller is based on the xPC-target solution, where a graphical user interface has been developed as a tool to plan and program the chewing simulator patterns.

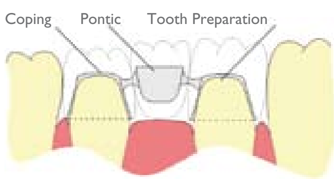

Fig. 5a: 2D conceptual design of teeth.

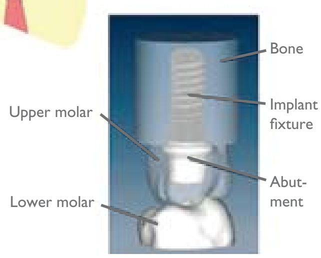

Fig. 5b: Pair of second molars with implant design.

The potential of the Dento-Munch

The Dento-Munch simulator has widespread future potentials, and has already been patented in the United States. Its dental applications include:

Dental (bio)materials and components

The use of the simulator permits a systematic evaluation of the wear and fatigue testing of restorative materials used in dental components. Moreover, the device is utilized to help create collaborative partnerships between the university and the dental industry to enhance testing to the benefit of both dentists and their patients.

Oral care management

In oral care management, the Dento-Munch permits the laboratory study of tooth wear, particularly attrition and abrasion, in a manner that is more representative of the clinical scenario. It also is used to develop an evidence base when choosing dental restoratives and component designs for particular applications. Further research on the cost-effectiveness of current dental treatments is promoted.

Technology

The robo-simulator supports the development of new applications and enhances emerging technologies in dental practice, including diagnostic devices and methods, dental CAD/CAM, and technology / genetic engineering.

Development of standards and guidelines

In this field, the Dento-Munch is used to develop in vitro test methodologies predictive of clinical behaviour in order to evaluate dental (bio)materials and assist in standards development. Furthermore, it is applied to standardise the protocols used for the clinical evaluation of dental (bio)materials and components.

Moreover, as chewing and ankle movement are similar motions, the Dento-Munch robo-simulator can be adapted to rehabilitate injured ankles. And while, until now, the complexity of the spine has limited our understanding of the mechanics of human joint spinac injury, the robo-simulator can be adapted to allow multi-dimensional control of joint loading scenarios, thus providing us with a better understanding of physiological joint movements.

The Dento-OS invention

Study of dental cast models is fundamental to diagnosis and treatment planning, and they are a standard component of orthodontic records, case presentation, evaluation of treatment progress and results, and record keeping. Typically, tooth size, crowding, or spacing, overjet, overbite, and Bolton analysis are measured by hand (i.e. calliper) on cast models. The information obtained from these dental casts is invaluable in helping the orthodontist classify malocclusions, and to formulate treatment objectives. As a static record of dental classification, models are used to visualise the morphology and position of the teeth in their respective dental arches, as well as the degree to which the teeth are malpositioned.

A 3D computerised digital occlusion of a patient's record can be used as an evidence to justify clinical decisions more accurately. Furthermore, this method can help to solve serious problems of storing dental casts in private dental clinics as well as in the University Dental Hospital.

Therefore, a dental optical scanner called Dento-OS was developed at the Department of Mechanical Engineering at the University of Bristol to digitise a dental cast or impression faster than the traditional mechanical or laser scanner, and a strategy for geometric modelling was developed, leading to 3D CAD model of teeth. Photonics, i.e. the science of light, is used with advanced CAD/CAM to machine the artificial teeth for the Dento-Munch robot. Already patented in the United Kingdom, the system can be used for a variety of other non-dental applications in engineering, forensics and dermatology.

The way Dento-OS works

Figure 6 shows the optical arrangement of the Dental Optical Scanner based on an approach known as structured light. It consists of the latest LED projector based on digital light processing (DLP) to generate a projection pattern very accurately using a CCD camera for image acquisition and a turntable. At the heart of the DLP is a digital micromirror device (DMD) supported with a micro-electronic mechanical system (MEMS) to generate a projection pattern of light and dark bands onto the surface to be scanned very accurately and precisely.

Fig. 6: University of Bristol Dento-OS setup.

Due to the 3D nature of the complex surfaces, the image captured by the camera is a deformed pattern (Fig. 7a). Depth information about the object is encoded into the deformed fringe patterns recorded by an image acquisition sensor (e.g. a CCD camera). The pattern images captured by the CCD camera are digitized and the phase distribution in the patterns is obtained by phase analysis techniques, such as phase stepping, the Fourier or wavelet transform technique. The phase map is unwrapped (Fig. 7b) and processed by the triangulation model to generate a dense point cloud (Fig. 7c).

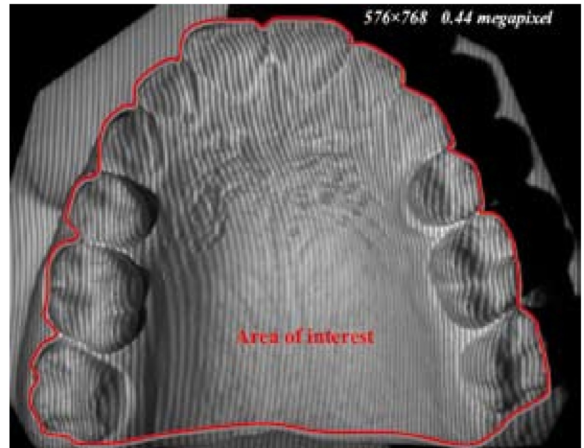

Fig. 7a: Digital fringe projection: deformed fringes.

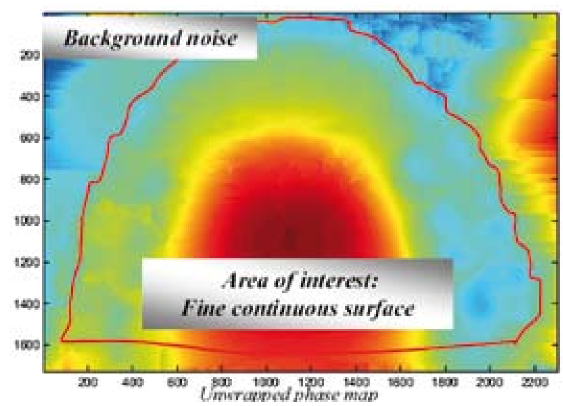

Fig. 7b: Phase unwrapping.

Fig. 7c: Point cloud visualization.

A methodology based on dental feature modelling developed to identify the maxilla morphology (i.e.

size and shape features such as teeth, gum, palate), even cusps within molars before 3D B-spline used to create boundary curves (Fig. 8). Curves are re-parameterised to make sure of continuity in surface patches or segments before surfaces are generated and merged together (Fig. 9a and 9b).

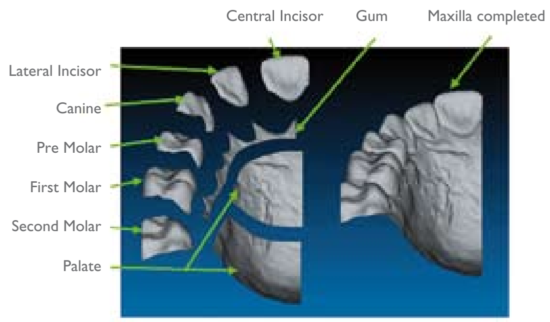

Fig. 8: Surface polygonization process.

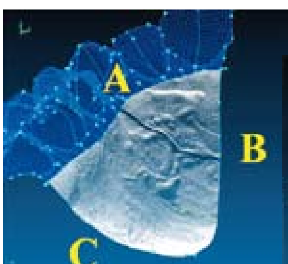

Fig. 9a: Boundary curves A, B and C for the palate.

Fig. 9b: Gum surfaces after merging.

Using this methodology, two surface models of dental casts of pre- and post- orthodontic treatment can be obtained. The third medial roga is used for alignment of pre- and post-treatment maxilla as a stable and clear landmark. Superimposing two surface models allows the 3D surface-to-surface evaluation to be virtually realized. The 3D digital measurement of an example case (Fig. 10) revealed that the central incisor on the right hand side of the maxilla had moved linearly by 1.1245 mm during treatment, and the right cuspid (canine) had moved 4.9309 mm.

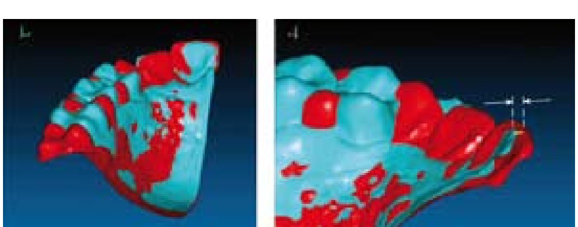

Fig. 10: 3D measurement of the pre- (red) and post- (blue) orthodontic treatment.

The Dento-OS and the developed surface modelling methodology can be used to record and measure morphological changes in the maxilla of infants with cleft lip and palate (CLP), thus allowing orthopaedic surgeons to make clinical judgments on the changes of the cleft width within the first few months of infancy prior to any surgical intervention. Further advances such FEM and fabricating artificial teeth can be carried out by creating a solid model of the maxilla (Fig. 11a). Figures 11b and 11c show the virtual machining and fabricated crown for the Dent-Munch respectively. ▮

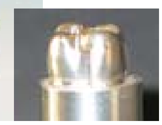

Fig. 11a: Solid model.

Fig. 11b: Virtual machining.

Fig. 11c: Fabricated crown.

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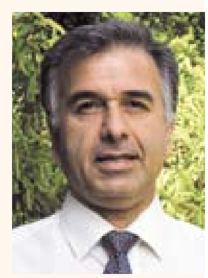

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