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An *in vitro* study into the accuracy of a novel method for recording the mandibular transverse horizontal axis

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ABSTRACT

Objectives: To assess the accuracy of a novel, non-invasive method for determining the axis of rotation of articulated dental study casts.

Method: A 3D structured light scanner was constructed using a projector and two CMOS cameras. Dental stone casts were arbitrarily mounted on an average value articulator. With the teeth together, sets of 10 scans were taken from three different viewpoints. Each scan captured approximately six upper teeth and six lower teeth. The teeth were then propped open, creating 10 mm of incisal separation, and the three sets of 10 scans were repeated. From each pair of scans an axis of rotation was calculated using custom software. A total of 900 axes were created this way. The locations of these axes were plotted in sagittal planes located 57.5 mm left and right of the midline to represent the position of the temporomandibular joints (TMJs). The accuracy of axis location was then assessed.

Results: The average radius of error of the individual axes, compared to the real axis, was 2.65 ± 1.01 mm. 61.3% of the axes lay within 3 mm of the true axis, and 99.2% of the axes lay within 5 mm of the true axis.

Conclusions: The accuracy of this method is clinically acceptable. Further studies are required to confirm the accuracy of the virtual inter-occlusal records at the level of the dentition. Clinical studies are then indicated to determine whether the transverse horizontal axis on a patient can similarly be determined.

1. Introduction

The transverse horizontal axis (THA) is defined as 'an imaginary line about which the mandible may rotate in the sagittal plane'.[1] In restorative dentistry, recording this axis is important during diagnosis, treatment planning and prosthodontic reconstruction. The method for recording this position has remained largely unchanged for more than a century.[2] Typically, in clinical practice, a facebow is used to determine an arbitrary axis which is assumed to lie close to the true axis. Alternatively, the true axis can be found kinematically, for example, using the Lauritzen method.[3] Although taught at dental school, most dentists do not continue to use these techniques in general dental practice.[4]

The reasons given by general dentists for abandoning the use of these techniques include the clinical time required to perform the recording, the expense of the equipment and the

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perceived lack of efficacy of these procedures.[4] The findings of recent studies are divided on the latter point. Some workers have found that using a facebow reduces the probability of inducing occlusal errors when compared to mounting dental models using average values.[5–7] Meanwhile, others found no significant improvement in occlusal outcomes.[8] A clear theme is that no method is perfect, and all result in dental prostheses which are likely to need occlusal adjustment in the mouth. However, the amount of adjustment required should be reduced if the models can be mounted in a better approximation to the patient's anatomy.

There is a clinical need to devise a simpler, quicker and more economical method for recording the THA, which will provide a starting point for mounting dental models on an articulator to reproduce the patients jaw movements *in vitro*. This method must be conducive to use in the general practice setting if the majority of patients are to benefit from an improved level of occlusal care.

This paper proposes a novel method for locating the THA, using 3D scans of the labial surfaces of the maxillary and mandibular incisors.

Our new method relies on the mathematical principle of the instantaneous axis of rotation (IAR), initially described by Leonhard Euler in 1775–1776,[9] and further refined by Olinde Rodriguez in the 19th century.[10] This states that the movement of a rigid body between two points can be described as a rotation around an axis, and a translation along it. The idea of modelling mandibular movements using IARs is not new,[11–14] although this has generally been applied in relation to habitual paths of closure. Our clinical method would require that the recordings be made with the mandible positioned in centric relation (CR), to 'force' the IAR to coincide with the THA. Our method is similar to a previously reported technique, except the jaw registrations are recorded optically, rather than with wax.[15] This has the potential to reduce clinical time and eliminate errors caused by physical manipulation and distortion of the inter-occlusal wax records.[16,17] The use of a computer to calculate the THA, rather than attempting to construct bisecting perpendicular lines on 1 mm graph paper, using a pencil, may also enhance the accuracy of this technique. In the 1970s, Long[15] found this method to be prone to error and it consequently disappeared from the literature as quickly as it had appeared. In our method, the hinge about which the mandibular movement has occurred can be derived mathematically by tracking the movement of the mandibular teeth, using the maxillary teeth as a fixed point of reference.

We present the method and test its accuracy *in vitro* on dental study models mounted on an articulator. We define accuracy in two respects. Firstly, the repeatability of measurements, as described by the standard deviation of multiple repeated measures. Secondly, the absolute accuracy of the measurement, as compared to the true hinge axis location. We then consider our results in the context of existing methods to elucidate whether clinical studies are warranted.

2. Materials and methods

A structured light 3D scanner was constructed using a DLP projector (Optoma PK201, Optoma Europe Ltd., Watford, UK) and two monochrome CMOS cameras (UEye UI-1240LE-M, IDS Imaging, Obersulm). Phase modulation patterns were encoded in the projector[18] and gamma compensation was applied to the projector-camera pairs.[19] The cameras were mounted on a rigid metal bar at an angle of 30° to each other, and a baseline separation of 900 mm, such that their principle points were focussed on the same point in space. To ensure camera alignment, a calibration target of circles was printed using an Epson Stylus Photo 1400 (Epson UK Ltd., Hemel Hemstead), and mounted on an aluminium block which had been machined flat using a toolmakers block and a milling machine (Clarke CL500M, Clarke International, Epping). The relative alignment of the cameras was calculated using this target, and bespoke software utilising the OpenCV library (http://opencv.org). The projector was mounted equidistant between the two cameras. The field of view allowed a scanning area of 6×5 cm at a working distance of 15 cm. This meant one scan could typically capture six upper, and six lower teeth of the anterior labial segment. The projector served only to provide 'phase texture' to the scanned object, in order to reliably identify corresponding pixels in both camera images, for 3D calculations. Software was developed in-house to record and process 3D data using the PointCloudLibrary (http://pointclouds.org). The scanner was tested by scanning the aluminium calibration block, and measuring the deviation from true of a horizontal cross section.

Dental stone casts were arbitrarily mounted on an average value Freeplane articulator. With the teeth together in maximum intercuspation, 10 scans were taken with the aim of capturing from the mesial cusps of right first permanent molars, to just beyond the midline anteriorly. Between each scan the scanner was picked up and replaced to ensure slightly differing viewpoints and simulate the clinical situation. This procedure was repeated with 10 more scans aiming to capture the labial region from right canine to left canine, and a final set of 10 scans were taken capturing the mesial cusps of the left first permanent molars, to just beyond the midline anteriorly. The teeth were then separated by inserting a 7 mm diameter wooden rod between the models posteriorly, behind the last standing molars. This provided about 10 mm of vertical separation at the incisors. Without moving the models, the scanning process was repeated as before, to provide 10 more scans of the teeth apart, from each of the three viewing positions. In total, 60 scans were taken (30 'teeth apart' and 30 'teeth together').

In order to determine the direct relationship between the hinge on the articulator and the stone casts, 14 more scans of the arches were captured, starting from the left hinge of the articulator, and working around the model to the right hinge. The stone models were then removed from the articulator and scanned in a dental model scanner (Lava Scan ST Scanner, 3M EPSE, St Paul, MN) which has an accuracy of 10 μm according to testing standard VDI 2634/2. The scanned models were exported as .stl files into MeshLab software (http://meshlab.sourceforge.net/) along with the 14 scans previously taken of the articulated models. These scans were then aligned by 'wallpapering' our labial scans on to the models. This produced a dense point cloud, based on the highly accurate ST scans, but with more points on the buccal and labial surfaces (Fig. 1). The upper model also contained the actual