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TITLE

An *In Vitro* Study into the Accuracy of a Novel Method for Recording the Mandibular Transverse Horizontal Axis

SUMMARY

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 10mm 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 57.5mm left and right of the midline to represent the position of the temporo-mandibular 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 ± 1.01mm. 61.3% of the axes lay within 3mm of the true axis, and 99.2% of the axes lay within 5mm 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.

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 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, 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 1mm 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.

MATERIALS & 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 900mm, 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 6x5cm at a working distance of 15cm. 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 7mm diameter wooden rod between the models posteriorly, behind the last standing molars. This provided about 10mm 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 10μm 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 (Figure 1). The upper model also contained the actual articulator hinge. Three points on the upper model were noted, upper right second molar palatal cusp tip, upper left second molar palatal cusp tip, and upper right central incisor mesioincisal corner. Three points were similarly identified in the lower arch. These were the points from which all future measurements were taken. In fact, in the following experiment, our scans can be thought of as 'carriers' which are used to align the pre-existing models created in the ST scanner (in much the same way as traditional inter-occlusals records and stone models).

Each of the 60 scans were used as templates to position these 'wallpapered' models relative to each other. The alignment algorithm used was the Normal-Distributions Transform[20]. From each pair of scans (teeth apart and teeth together), an axis of rotation was calculated. This was achieved by aligning the three points in both upper scans to create a common coordinate system. Then the 3x4 transformation matrix was calculated that represented the movement of the three points in the lower model, from 'Closed' to 'Apart'. The upper left 3x3 sub-matrix of the transformation matrix was used to calculate the orientation of the axis of rotation, and the degree of rotation around the axis. There are an infinite number of spatial locations for this axis, each with a different translation vector applied following the rotation. In order to find the position of the axis corresponding to the hinge on the articulator, a point was tracked from the start position to the end position. A solution was found that constrained the translation vector to a direction coincident with the calculated axis. This provided a vector equivalent to a point on the axis, and also the magnitude of the translation vector along the axis (Figure 2). The latter vector should theoretically be zero. Finally, a standard horizontal reference plane was created using three points: the position of the hinge axis at the left and right TMJ (see below) and an arbitrary point located 43mm superior to the upper right incisal edge. The real articulator axis was visible on the scans and the centre point of the 4mm diameter hinge cylinder was selected at the left and right extremes (131mm apart) to define the position of the true hinge (Figure 3).

The locations of these axes were then plotted in sagittal planes located at 57.5mm left and right of the midline to represent the position of the temporo-mandibular joints (TMJs). The repeatability and accuracy, of axis location was assessed, along with variation in orientation, and variation in degree of rotation.

RESULTS

The scan of the flat board deviated from true with a standard deviation of 14μm. The scanner sampled points every 50μm.

A total of 900 axes were calculated by combining the scans in all possible combinations (Figure 4).

The error radii of axis location for all the pairing combinations are shown in Table 1.

The mean radius of error for all 900 axes, regardless of viewpoint, and combining the left and right TMJs was 2.65 ± 1.01mm (standard deviation).

61.3% of the axes lay within 3mm of the true axis, and 99.2% of the axes lay within 5mm of the true axis. The maximum error radius was 5.57mm.

The mean calculated degree of rotation around the axis was 7.71 ± 0.09°. The range over the 900 axes was 0.43° (7.51 to 7.94°).

The mean angle between calculated axes and the true axis was 2.11 ± 0.90°. The range over the 900 axes was 4.26° (0.46 to 4.72°).

The mean translation along the axis was 0.24 ± 0.13mm. The range over the 900 axes was 0.62mm (0.00 to 0.62mm).

DISCUSSION

Our scanner used two cameras, not one, because the quality of their lenses was superior to that of our projector. This should lead to less image distortion, and more accurate 3D data. The precision of our calibration target could be questioned as the quality of ink jet printers is probably unreliable below 50 micrometers. This may, in fact, be the limiting factor in scanning accuracy and we will look at acquiring higher precision calibration targets. A 30° angle between cameras was chosen as a mathematically good compromise between depth accuracy, and X-Y accuracy.

The accuracy of our scanner has not been robustly investigated to industry standards. However, all hinge axis calculations, and measurements were performed using points from the models scanned in the Lava ST scanner, which has an accuracy of <10μm when tested against testing standard VDI 2634/2. Our scans are simply a positioning aid for these virtual models. We cautiously presume this positioning is accurate enough for clinical use, based on the accuracy with which the hinge axis is located, and the fact that our scans merged seamlessly with those of the ST scanner. However, further verification is required that our inter-occlusal records are sufficiently accurate and this will be the focus of future work. The practical benefit of our method is immediately applicable to digital workflows. It may also be possible articulate conventional stone models, using a mechanical linear stage set to a value determined by our system. This is a further area we plan to investigate in the future.

The most commonly used method for locating the THA is to locate an arbitrary point anatomically and record this with a facebow. This method has been shown to locate the THA with a mean radius of error of 4.7mm and a standard deviation of 2.9mm[21].

Electronic pantographs are more expensive, take longer to use, and consequently are generally restricted to use in highly specialized practice or as a research tool. The Cadiax Compact (GAMMA Co, Klosterneuberg, Austria) has been shown to reproduce the THA with a typical discrepancy of <0.2mm[22].

Our method lies somewhere between these two techniques, with a mean radius of error of 2.65 ± 1.01mm. However, workers have shown that the *radial* location of this error has a greater effect on introduced occlusal discrepancies than the radius of error[6,21]. Broadly speaking, errors in the posterior-superior and anterior-inferior quadrants have less influence on occlusal discrepancies. In our experiments, if the 'Closed' scan was taken from the labial view, the calculated axis tended to be located in the favourable posterior-superior quadrant (Figure 4). The viewpoint of the 'Apart' view had less influence. One reason for this might be the behaviour of the alignment algorithm. When the teeth are closed, the lower arch is partially obscured by the overbite. Alignment relies on a feature-rich surface and it could be that the narrower lower incisor teeth provide more defined embrasures than the wider posterior teeth so the labial views have more useful points to align. The alignment of the 'Apart' views may show less variation because a sufficient area of the lower arch is always visible, regardless of viewpoint. Furthermore, the relatively flat labial segment may produce more dense scans with many points being visible to both cameras. Conversely, the 'Right' and 'Left' views may have less mutually visible points due to the curvature of the arch. The pattern of axis locations when a less favourable viewing angle has been used appears to be broadly linear horizontally, particularly on the side from which the scan took place. This might imply that alignment is successful superior-inferiorly, but that the lower model can 'slide' antero-posteriorly when insufficient data are captured. The effect of this linear error on the quality of the inter-occlusal records needs further investigation. Furthermore, the effect of using different dental models, with different tooth morphologies and arch forms requires investigation.

The orientation of the calculated axes was always close to that of the real axis (2.11 ± 0.90°). If analysis was restricted to labial 'Closed' scan sets (but any 'Apart' view) the deviation of the orientation of the axes improved to 1.12 ± 0.33°. Previous analyses of the occlusal effects of axis location errors tend to have simplified the problem to 2D, and considered the left and right TMJs in isolation[6,21]. However, the real situation is 3D, and each axis is defined by a pair of points (left and right TMJs). Future work should be directed at the effect of the skew in the axes in 3 dimensions.

The calculated degree of rotation about the different axes showed very little deviation (7.71 ± 0.09°), suggesting that our method calculates the relative orientations of the occlusal planes accurately. Small errors in our 'virtual' inter-occlusal records will be a cause of differences in degree of rotation about, and angulation of, our calculated axes. The magnitude and effect of these errors at the occlusal level requires further investigation. Our inter-occlusal records need to be far more accurate than the hinge axis location. It is the aim of future work to investigate the accuracy of our inter-occlusal records, but indirect evidence can be gained by looking at the predicted magnitude of occlusal errors for an axis located in the posterior-superior quadrant. Morneburg[21] shows that, with a 5mm radius error, and an opening of 2mm, we can expect occlusal errors up to a maximum of 180μm, and generally less than 100μm, at the second molar region. At half this error radius (as our method produces) we can predict that our inter-occlusal records are accurate to below 100μm but further work is needed to verify this.

The magnitude of the translation along the axis should theoretically be zero. However, inaccuracies in scanning and alignment lead to slight inaccuracies in the angulation of the axis, and 'force' the computer to introduce a shift along the axis to compensate. If several scans have been taken, as would seem sensible clinically, the axis with the smallest translation should be the one most closely aligned to the true axis. This error checking mechanism, in relation to the actual occlusal discrepancies of the inter-occlusal records, will be the subject of future work.

In our system, the projector is set to a screen resolution of 640x480 (its maximum native resolution) and our cameras are 1.3 Mega pixels (1280x1024). These are low by today's standards, and illustrate how quickly cheap technology becomes available. An upgrade in hardware would only cost a few hundred pounds, and we could expect a 2 to 4 times increase in resolution. This is a key benefit of the use of digital technology in dentistry, and requires further investigation. Another benefit is the complete lack of any further distortions or warping of the data. Our errors are absolute. In general practice, many unknowns such as storage time and temperature of materials, incorrect handling of materials, loosening of screws on transfer jigs during postage/transportation or human error accumulate during the mounting of study casts, or the fabrication of prostheses. It seems reasonable to expect that, with a reduced number of variables in the procedure, a more consistent result will be achieved. A clinical comparison of traditional techniques and our new method is warranted.

Our clinical method would require the patient to be positioned in CR. This may decrease the repeatability of the method, although with minimal training, or using patient-guided techniques, this position is considered reproducible[23,24]. We would suggest the use of a leaf gauge to position the patient in CR, followed by the use of a thicker leaf gauge to provide the 'Apart' record.

CONCLUSIONS

Our new method for locating the THA is accurate and repeatable within clinically acceptable limits. The method works best when the first scan of the pair is captured viewing the full anterior labial segment. The accuracy of our inter-occlusal scans requires further investigation to determine if they are accurate enough at the level of the occlusion, and not just the THA, to justify clinical use.

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TABLES

Group	Left TMJ		Right TMJ		Combined	
	Mean	SD	Mean	SD	Mean	SD
Labial to Labial	2.40	0.47	2.70	0.49	2.55	0.50
Labial to Right	1.49	0.50	1.72	0.30	1.61	0.42
Labial to Left	2.30	1.05	3.36	0.42	2.83	0.95
Right to Right	3.12	0.33	2.40	0.93	2.76	0.79
Right to Labial	4.00	0.28	2.58	0.65	3.29	0.87
Right to Left	3.82	1.05	2.87	0.68	3.34	1.00
Left to Left	1.80	1.04	3.73	0.41	2.77	1.25
Left to Labial	1.41	0.71	3.28	0.57	2.35	1.14
Left to Right	2.22	0.83	2.46	0.47	2.34	0.68
All Combined	2.51	1.17	2.79	0.81	2.65	1.01

Table 1. Mean error radius of axis location in the sagittal plane (all measurements in mm). Groups are described in terms of the sets of views used in calculating the axes. For example, 'Labial to Right' means that the 10 Labial views of the teeth together, and the 10 Right side views of the teeth apart, were used to calculate 100 axes.

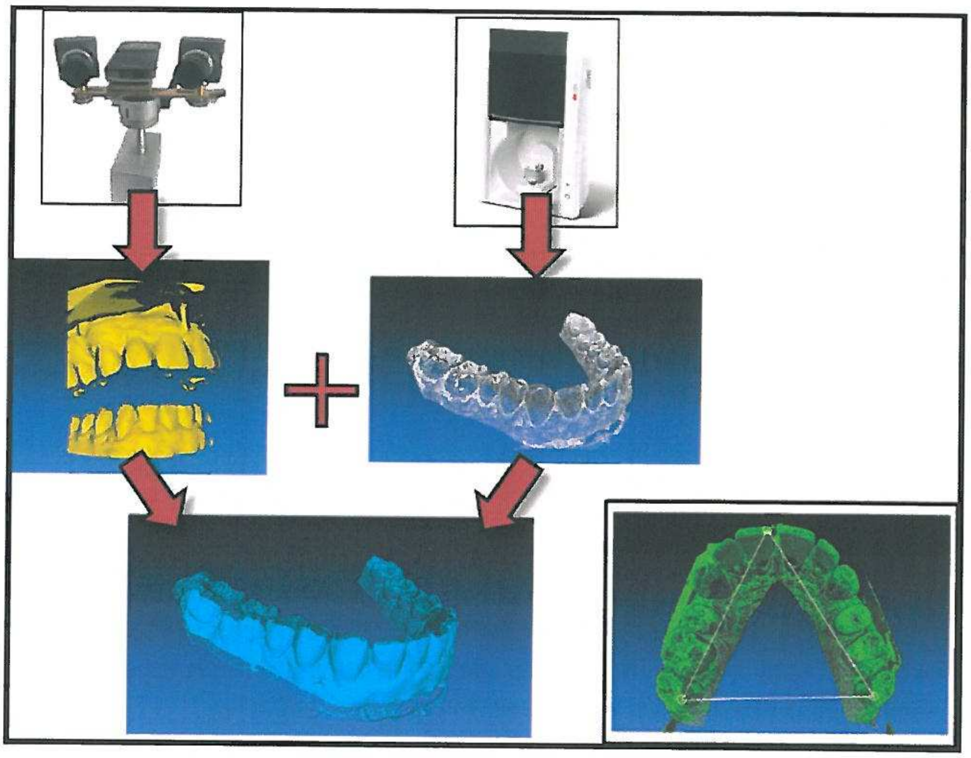


Figure 1 Building the models. 14 buccal & labial scans are taken with our scanner starting from one hinge of the articulator and working around to the other (left). The upper and lower models are then scanned using the Lava ST scanner (right).All scans are merged to produce master models which have been 'wallpapered' buccally and labially with our dense point cloud scans. We define 3 points from the ST scan models in a tripod from which to take measurements (lower right).

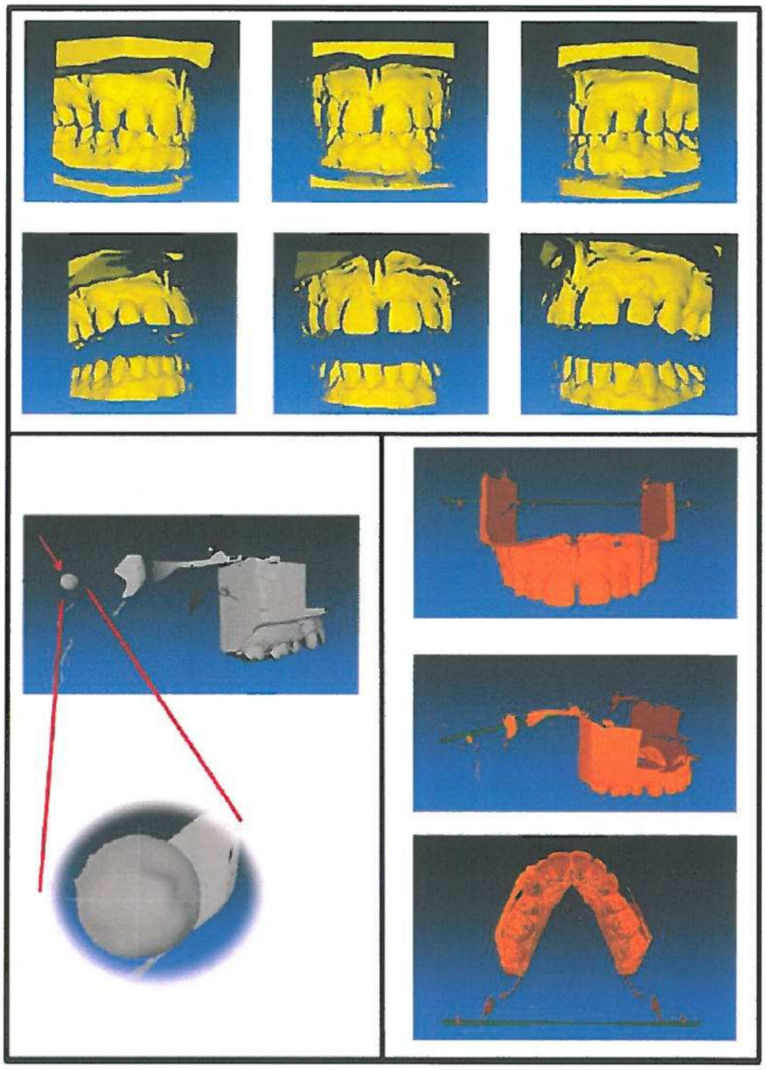
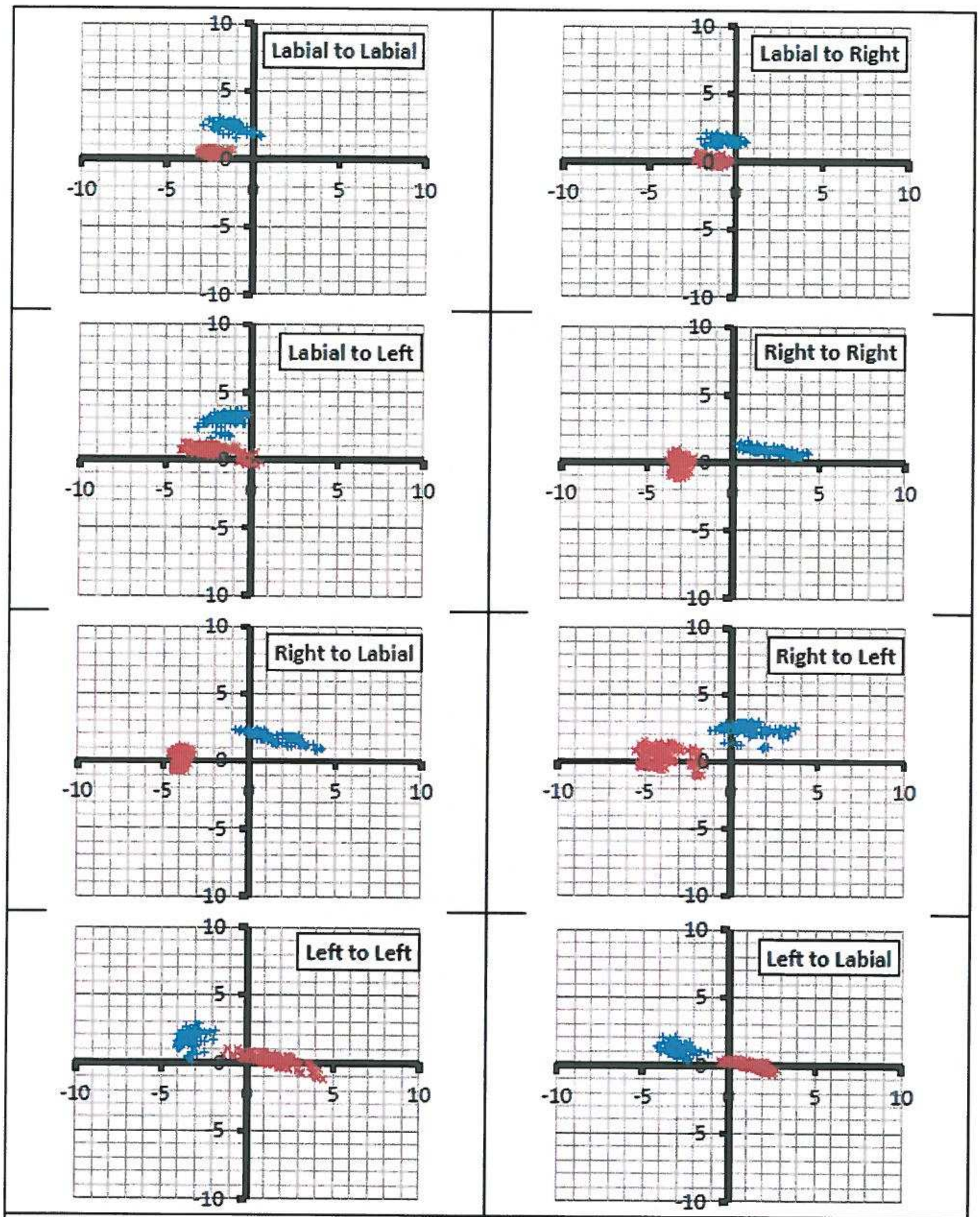


Figure 3 Top: Examples of the different views. 10 scans were taken for each viewpoint. Lower Left : Identifying the true hinge axis. The ends of the articulator hinge are identified in the scan and the centre point is found (right hinge shown in picture). Lower Right : Example of the calculated axes. 100 axes are shown overlaid in green, representing all the axes calculated using the 'Labial Closed' to 'Labial Apart' scans.



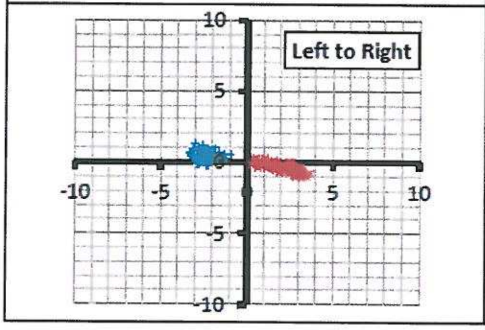


Figure 4 Distribution and radius of axis location errors for all combinations of scan sets. Each chart shows 100 axes calculated from 10 'Closed' views and 10 'Apart' views.
The coordinates are in mm, with superior-inferior (Y) and anterior-posterior (X), with positive X pointing anteriorly.
BLUE Plus : Left TMJ
RED Cross : Right TMJ

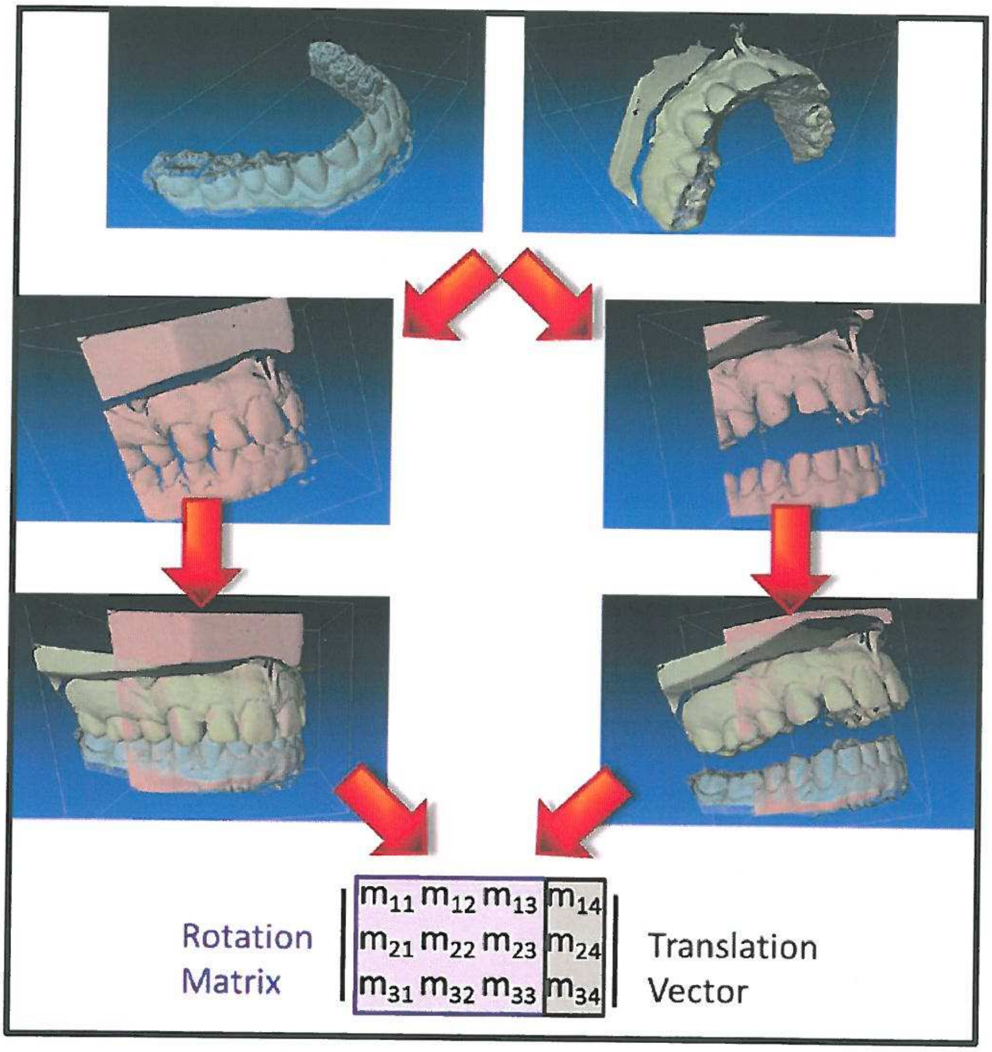


Figure 2 Summary of the method. The models built in the preceding stage are aligned to each of the 'Closed' and 'Apart' scans. A 3x4 transformation matrix is then calculated for the movement of the lower arch. There are an infinite number of possible solutions for the translation part of this matrix. To find the solution that coincides with the THA, the matrix is further decomposed using vector mathematics under the constraint that any translation must occur along the direction of the axis of rotation.