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The Validation of a New Articulator System for Orthognathic Model Surgery

By

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Téa my homework is finished now. It’s time to play.

DECLARATION.

This thesis represents the original work of the author.

…………………………………

Pauline E. Paul.

June 2010

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DEFINITIONS/ABBREVIATIONS:

Articulator.	A mechanical device to which models of the upper and lower arches are attached and which reproduces recorded positions of the mandible in relation to the maxilla.
Axis orbital plane	An imaginary line joining orbitale and the axis of the mandibular rotation (the most prominent palpable area of the condylar head)
Campers plane.	Imaginary line running from the inferior border of the ala of the nose to the superior border of the tragus of the ear.
Dentatus.	Manufacturer of semi-adjustable articulators and face bows.
Natural head position	The position of the head when an individual is sitting or standing erect with the head level and eyes fixed on the horizon.
Face bow.	An instrument used to record the transverse horizontal axis (hinge axis) of the mandible and relating this recording to the maxilla to facilitate anatomical mounting of the maxillary cast to an articulator.

Frankfort horizontal plane	A plane passing through the lowest point of the floor of the left orbit (orbitale) and the highest point of each external auditory meatus (porion).
Kinematic face bow.	Used in conjunction with an articulator. The ends can be adjusted to permit location of the axis of rotation of the mandible.
Maxillary occlusal plane	A plane passing through the occlusal or biting surfaces of the maxillary teeth. It represents the mean of the curvature of the occlusal surface.
Semi-adjustable Articulator.	A mechanical device, which can be adjusted to replicate the many movements of the mandible relative to the maxilla.

PREFACE:

This study was carried out at the University of Glasgow Dental Hospital and School, with the practical part of the study carried out at the West of Scotland Regional Maxillofacial Prosthetics Laboratory at the Glasgow Southern General Hospital under the supervision of Professor A. Ayoub, Dr B. Khambay, Mr F.S.Walker, Professor J.C.Barbenel, and Professor K.F. Moos O.B.E.

The study represents the original work carried out by the author, and has not been submitted in any form to any other university.

ABSTRACT:

A review of the literature showed that the outcome of orthognathic surgery may differ from the planned outcome, that casts mounted on semi-adjustable articulators show systematic errors of orientation and that there may be a causal connection between them.

It was demonstrated that the movements of casts mounted on, and moved relative to, a standard articulator produced movements of different magnitudes relative to the natural head position. A mathematical model was developed to quantify the difference and the predictions of the resulting equations were confirmed in a photographic study using image analysis.

The second stage of the study compared a standard and the orthognathic articulator. Plastic model skulls were mounted at different angulations to represent different natural head positions. Casts of the maxillary teeth of the skulls mounted on the orthognathic articulator accurately reproduced the occlusal plane angles of the skulls, but those mounted on the standard articulator showed systematic errors of up to 28°. Surgical movements of the maxilla were reproduced using perioperative wafers constructed on casts mounted on the standard and orthognathic articulators. The accuracy of the maxillary repositioning was assessed at five anatomical reference points on the skulls. The results indicated that the orthognathic articulator was significantly more accurate than the standard articulator.

1

INTRODUCTION

1.1.Introduction.

1.1.1.Orthognathic Surgery.

Orthognathic surgery or the surgery for the correction of jaw deformity has been routinely carried out in most Maxillofacial units over many years. This form of surgery has commonly involved either a single jaw or both upper and lower jaws.

The procedure normally requires the collaboration of a multidisciplinary team including the surgeon, an orthodontist and a Maxillofacial technologist to plan the surgical procedure.

The surgeon:

Assesses the patient by clinical examination and appropriate radiographs and prescribes the jaw movements required to correct the aesthetic and functional orthognathic abnormalities. These can be vertical, horizontal as well as both antero-posterior and lateral movements, and less commonly rotational movements of the patient's jaws based on an assessment of the patient in the natural head position. This is carried out by sectioning and repositioning the jaws into a prescribed optimum position, using templates in the form of perioperative wafers.

There are several systems that assist the surgeon in predicting the movements required to correct the skeletal abnormalities of the patient. One of the original prediction planning techniques utilizes a lateral cephalogram and scaled lateral photograph. This is used in conjunction with a profile analysis such as Ricketts to diagnose the required movements for correction of a deformity. Although this is an older technique it still finds favour with many Maxillofacial surgeons today. There are in addition several computer surgical prediction packages for example Opal, Dolphin and CASSOS. The latter of the two are useful tools that can produce a print out of the patients' hard and soft tissue profile, however there are limitations with these programmes as they do not always accurately predict soft tissue movements. Technology is now moving more towards 3D analysis using photogramitry and it hoped eventually this will provide a superior method of pre-surgical prediction planning.

The orthodontist:

- Re-aligns the dental arches and de-compensates the dentition prior to surgery and carries out any occlusal adjustments to the dentition post surgery .

To ensure that the jaws have been positioned into the prescribed relationship at the time of surgery a technique known as orthognathic model surgery has been employed to make certain that this surgery will be achieved through the optimal desired safe movements of the jaws.

The technologist:

- Simulates the prescribed movements on dental casts mounted on an articulator and then proceeds to produce perioperative wafers for the surgeon to use and to guide the placement of one or both jaws at this time of orthognathic surgery, into the preplanned position.

An articulator is a mechanical device that represents as closely as possible the relevant anatomical landmarks of the upper and lower jaws upon which dental casts are mounted to reproduce a recorded occlusal position, usually the position of centric occlusion or the rest position which would have been recorded with a wax registration. The upper arm of the articulator hinges (normally rotates) to allow the separation of the mandibular and maxillary teeth and simulates the opening of the mandible for planning purposes.

Even when an accurate wafer has been constructed this cannot guarantee an accurate surgical outcome in relation to the prediction plan. The following are the errors that are frequently associated with this procedure:

- Surgical errors, the surgeon may not follow the prediction plan accurately, due to difficulties in theatre when trying to achieve the movements required, or may accept a compromise of the occlusion or change the planned movement to achieve an acceptable occlusion.
- Systematic errors in the laboratory preparation of the wafer may occur due to the face bow recording, its transfer and the casting and mounting of the dental casts.
- For the majority of articulators it is well recognized that they do not reproduce jaw movements precisely and therefore accurately, reposition the occlusion and they may not place the jaws themselves into an optimal or stable position.

An accurate surgical outcome could not be achieved with inaccurately recorded occlusal records, which were transferred to a reliable articulator, without some form of surgical compromise.

1.1.2. Model surgery and wafer construction.

The first stage of model surgery is simply that of recording the current occlusion followed by the taking of a face bow registration, the purpose of which is to orientate the dental casts relative to the articulator cross member and, it is assumed, relative to an anatomical plane such as the Frankfort plane, and to register the anteroposterior position of the maxillary cast relative to the hinge axis of the mandible. The upper cast is then mounted onto the articulator using the face bow recording. This is followed by the mandibular cast being mounted on the articulator using an appropriate wax registration of the maxillary jaw relationship. Reference lines, both vertical and horizontal, which will be used for the repositioning of the jaws, are drawn on the side of the upper and lower casts and the mounting plaster. The casts are then individually separated from the mounting plaster and moved to reproduce the movements prescribed by the surgeon. Acrylic wafers are then constructed to reposition each jaw to their new position in the agreed final occlusion to be obtained at the time of surgery

It should be highlighted that the articulators which are in current use, were designed as mechanical devices that represented the temporomandibular joints and the bones of the jaws. They have been used in dentistry for many years to obtain the correct articulation for dentures compatible with the anatomical dentition. Several types of articulators have been used for the purpose of orthognathic model surgery, usually without modification. These types include simple hinge articulators, full anatomical articulators and semi-adjustable articulators. The design of these will be discussed further in chapter 2.

Orthognathic model surgery planning has generally been carried out using one of two techniques but each Maxillofacial unit has tended to have their own modifications of one of the following planning methods.

The Lockwood key spacer technique **(Lockwood, 1974)** has used plaster wafers to reposition the dental casts for the correction of dento-facial deformity using a simple hinge articulator. This technique used a plaster wafer between the master cast and the mounting plaster to re-position the cast (Fig.1.1. & Fig.1.2.). The space created between the mounting plaster and the dental cast in its new position was filled with plaster (Fig.1.3. & Fig.1.4.). This then became the plaster wafer. This in turn was measured to produce the measured movement required. The Lockwood Key Spacer technique has been used for the planning of bi-maxillary and segmental osteotomies.

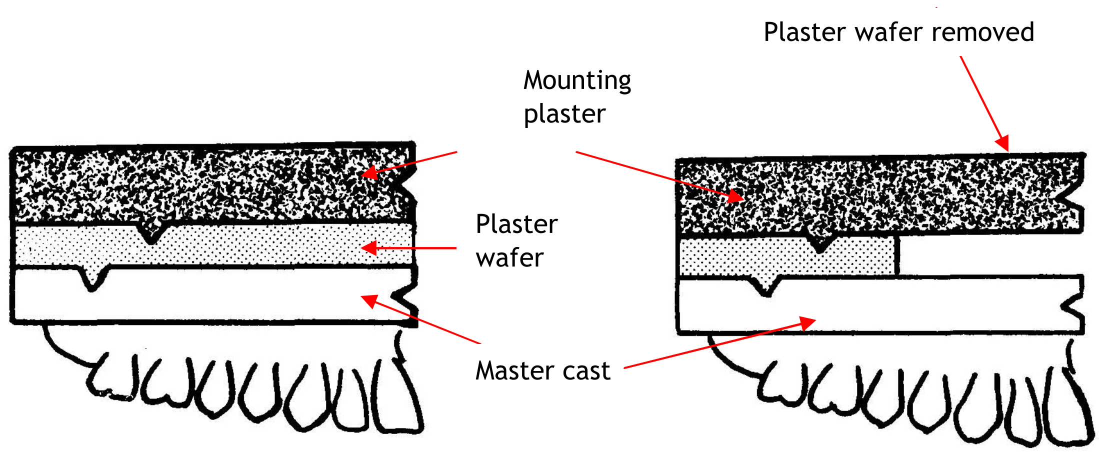


Fig.1.1: Master cast with localising grooves cut into the base of the model with plaster wafer in place.

Fig.1.2: Master cast with wafer removed.

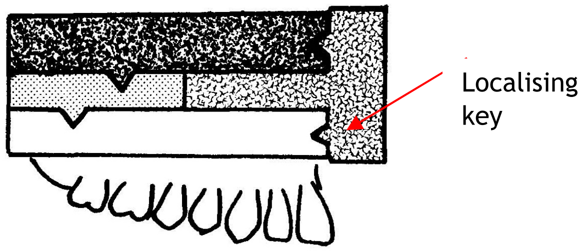


Fig.1.3: Master cast with localising key in position.

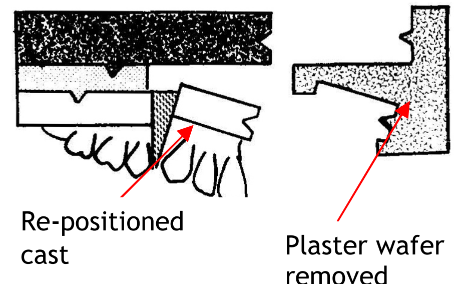


Fig.1.4: Segmental cast reposition with plaster wafer removed

Another technique developed was the Eastman Dental Hospital anatomically orientated model surgery technique **[Anwar, Bamber and Harris, (1990)].** This advocated the use of a semi-adjustable articulator with a face bow recording with the patient in a supine position. The casts were mounted, then horizontal and vertical reference lines were drawn on the mounting plaster to register the pre-operative position of the maxillary and mandibular segments. Vertical movements were measured between the A line and the cusp reference point (Fig.1.5.), VM = mesial buccal cusp of the last molar tooth, VB = the buccal cusp of a premolar, VC = the canine cusp (Fig.1.6.) and VF = the inter-incisor midline at the crown tip if the teeth or the maxilla were asymmetrically rotated (Fig.1.7.). The most anterior point at the incisor edge was used for VF. Antero-posterior movements were measured between VF and the articulator pin (Fig.1.8.).

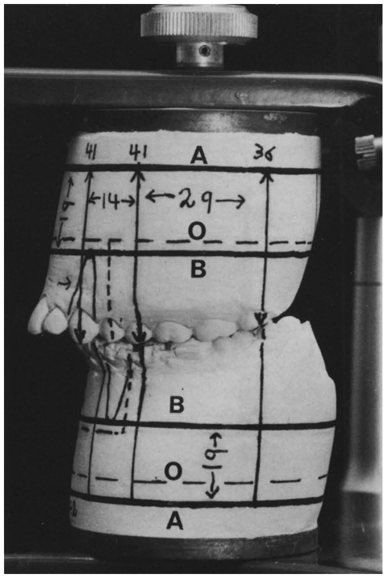


Fig.1.5: Articulated dental models showing reference lines and the measurements.

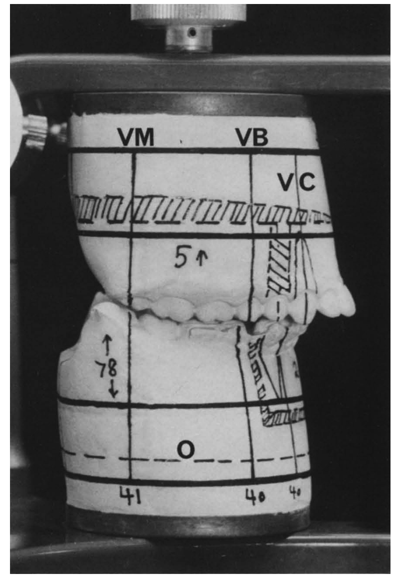
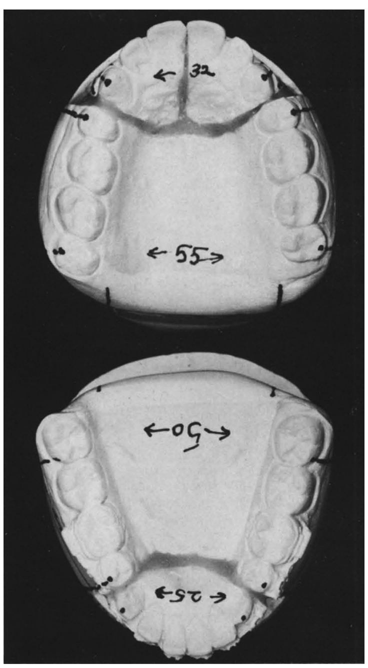


Fig.1.6: Models showing vertical reference lines VC,VB,VM.



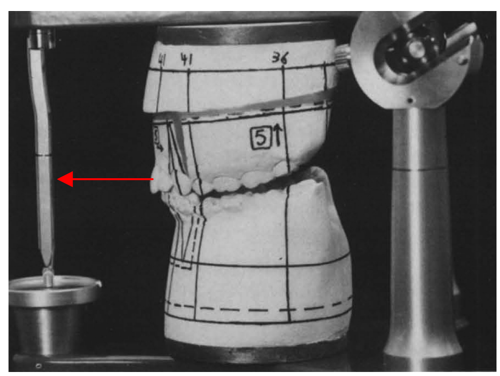


Fig.1.8. Models showing measurement of the antero-posterior movement (VF)

Fig.1.7: Occlusal view of post-operative dental Casts showing medial-lateral measurements

The transverse relationship had to be checked visually using the vertically inscribed lines on the models. The casts had to be detached from the articulator and the planned movements were then carried out, trimming the model's mounting plaster when necessary, and the segments were then reassembled into the pre-planned post-operative position using sticky wax. The wax could be softened and the maxillary and mandibular segments were then repositioned, and when necessary minor late adjustments could be made.

The Glasgow Model Surgery Technique has been evolved over several years with help of various visiting orthognathic surgeons from around the world, this was originally similar to the Eastman Model Surgery Technique. The technique employed the use of a face bow and a registration taken in the upright position. After the casts were articulated in the centric position (or when necessary the rest position) the casts were marked out with two horizontal and several vertical lines. The horizontal lines were adequately separated to allow sufficient trimming when a maxillary impaction was required. The vertical lines were colour coded. Those lines were used to re-orientate the casts back to their original position should a change in planning be necessary. Centric occlusion i.e. the start position had to be marked out at a tooth level with a drawn pencil line on the posterior teeth. This line had to be coincident with both maxillary and mandibular teeth (Fig.1.9.). Two vertical lines positioned in the molar region were drawn on the posterior wall of the maxillary cast. These lines were used to ensure the maxilla did not inadvertently rotate at the centre of the palate when the anterior midline needed to be shifted (Fig.1.10.).

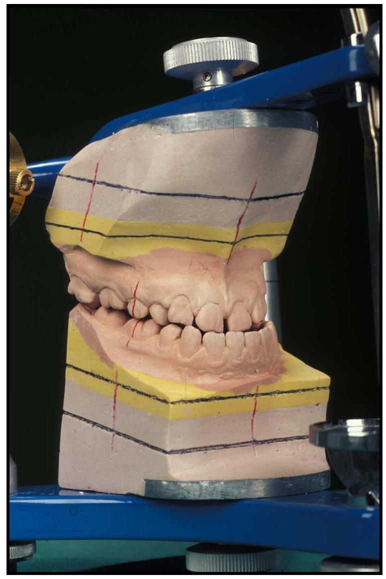


Fig.1.9: Vertical repositioning lines on mandibular and maxillary casts.

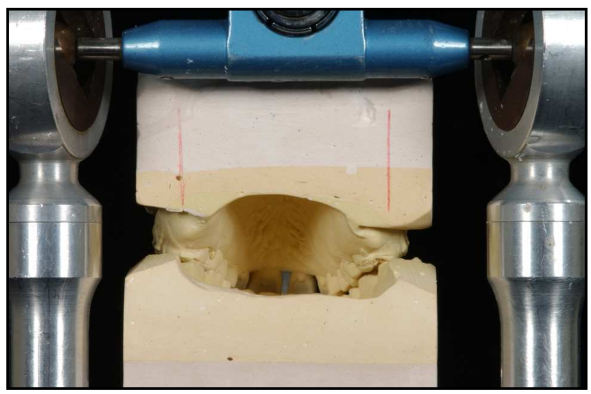


Fig.1.10: Posterior maxilla rotation lines scribed on the cast.

Once model surgery had been carried out to incorporate the prescribed movements a final interocclusal wafer was constructed to guide the jaws into their new pre-determined position in theatre. This wafer was constructed in a self-curing clear acrylic. The mandibular cast was then separated from the articulated mounting base and repositioned into its pre-surgical position. This would then be the intermediate position if bimaxillary surgery was being undertaken. An acrylic wafer was then constructed in an ivory self-curing acrylic to eliminate confusion with the final wafer in the operating theatre.

1.1.3. Outcome of surgery

The outcome of surgery can differ significantly from the prediction plan provided prior to surgery as has been shown by **Anwar & Harris (1990), Bryan & Hunt (1993), Donatsky et al (1997), Donatsky et al (1992), Friede et al (1987). Jacobson & Sarver (2002), McCance et al (1992), Sharifi et al (2008), Van Sickels et al (1986) and Wolford (1999).** They provided some numerical data, generally as mean values of the errors, due to the discrepancy between the planned surgical movements and the actual outcomes. The errors, however, incorporated the direction e.g. over-advancement was reported as a positive number and under-advancement as a negative number. Their results had to be interpreted with care as in calculating the sum of the positive and negative values they could to some extent eliminate each other, which would result in a small mean error, but a large standard deviation. As a result statistical tests have led to the misleading conclusion that the mean error was not significantly different from zero**. Bamber and Harris (2001)** reported a mean vertical error of 0.0mm (Standard Deviation, 1.0mm), but a range of error between -2.3 and 2.4 mm.

Van Sickels (1986) had reported a significant mean horizontal error of 3.6 mm.

Sharifi et al (2008) reported that 50% of surgical outcomes showed inaccuracies, defined as values greater than one standard deviation from the mean. **McCance et al (1992)** described individual orthognathic surgical movements compared to the predicted outcomes as “disappointing”, with errors of up to 6 mm being reported.

Pospisil (1987) reported that 60% of their outcomes showed “significant inaccuracies” defined as errors greater than 20% of the planned movement. **Polido et al (1991)** reported that 48% of vertical movements and 29% of horizontal movements had an error of 2 mm or greater; the equivalent values reported by **Jacobson & Sarver (2002)** were 20 – 30%.

Although there was strong evidence of inaccuracies of surgical outcomes, the causes were then unclear, as few papers **Donatsky et al (1997) & (1992)** provided details of prediction and planning procedures. **Pospisil (1987)** reported that 33% of inaccurate outcomes were due to surgery deviating from the prediction plan, in 17% the surgery was satisfactory but the treatment plan was inaccurate and in 50% the surgery was satisfactory, but the outcome was unsatisfactory for undetermined reasons. Although Pospisils’ study was comparing the accuracy of computerised surgical prediction planning to the post-operative cephalograms it is necessary to mention the inaccuracies that occur. Pospisil has evidenced his findings in his results section however **Eales et al (1994) and Eales et al (1995)** have disputed these findings in their own published scientific evaluations.

Errors in cephalometric technique, inaccurate prediction of the autorotation of the mandible, face bow recording errors, the difference in mandibular position in upright and supine patient and inaccurate surgery were all suggested as possible causes for the inaccuracies and unreliability of orthognathic surgery **Bryan & Hunt (1993), Friede et al (1987), Pospisil (1987), Olszewski & Reychar (2004), Sharifi et al (2008).** However, no clear evidence was presented that these errors actually occurred, nor was there any discussion of the magnitude of the outcome errors that each might produce. Only **Sharifi et al (2008)** identified clearly the now well-established discrepancy in the orientation of models mounted on articulators using conventional face bows as a possible source of error in surgical outcome.

1.1.4. Summary

The literature has stressed that the actual outcome of surgery did not replicate the prediction plan in many cases. This could have been for the following reasons as mentioned previously:

1. Inaccurate face bow recording and transfer
2. Unreliable casting and mounting of dental models on the articulator especially the failure to appreciate the horizontal changes which occur with vertical repositioning and autorotation of the mandible
3. Lack of care with the construction of the inter-occlusal wafer
4. Surgical error (usually related to the surgeon deviating from the original plan)

Orthognathic model surgery has been used to assist the surgeon with the repositioning of the upper and lower jaws into a predicted position. This should be achievable when the articulated models replicate the relationship of the patient's jaws and teeth to the base of the skull prior to model surgery. The literature had identified and stated that the orientation of the dental models mounted on articulators using conventional face bows did not necessarily replicate the orientation of the patient's teeth and jaws, **Sharifi et al (2008), Walker et al (2008),** introduced the principle of the development of a systematic error. These errors usually will have been incorporated into the inter-occlusal wafer, prepared for the surgeon by the technologist and by using that template for major repositioning of the maxilla and mandible there was a significant risk of serious adverse effects on the surgical outcome (details of which will be explained in chapter 4.

2

ARTICULATORS AND FACE BOWS

2.1. Background

The articulator is a mechanical device that supports, and relates, the upper and lower dental casts. There have been several types of articulators used for the purpose of orthognathic model surgery.

The simple hinge articulator was suitable for certain single jaw procedures such as mandibular advancement or setback and maxillary procedures without any change of vertical height. This device allowed the upper cross-member, which includes a maxillary cast to rotate about a fixed axis.

Fully anatomical articulators and semi-adjustable articulators allow not only the rotation of the simple hinge articulator but also reproduce additional interdental positions, but for this they require the additional use of a face bow. The semi-adjustable articulator reproduces three interdental positions, protrusive and right and left lateral excursions obtained by wax interdental records of their three positions. Fully anatomical articulators record and are able to reproduce additional interdental positions. A gothic arch tracing is used with a kinematic face bow to record the true centre of rotation of the mandible. This is a functional record obtained by recording the patient's mandibular excursions in right, left and protrusive positions, and is a useful tool for jaw registration used for the diagnosis of functional anomalies associated with the jaws and the construction of dental prostheses. Although a useful diagnostic tool, it is of little relevance in the orthognathic model surgery field.

According to the literature the semi-adjustable articulator is the most commonly used articulator system for orthognathic model surgery. **O'Malley and Milosevic (1999)**. Semi-adjustable articulators fall into two types, arcon or non-arcon. Arcon articulators have the condylar head component situated on the lower cross member of the articulator replicating the anatomy of the lower jaw. The non-arcon articulator has the condylar component attached to the upper articulating arm. The non-arcon type does not follow the anatomy of the mandible.

Maxillary and mandibular casts are attached to the semi adjustable articulator using a face bow and bite fork, the function of which is to relate the position of the maxillary teeth to anatomical landmarks relative to the position of the maxilla.

Face-bow recordings use three points of reference, which are recorded in relation to the articulator with this instrument. These points are anatomically positioned. All face bow registrations require the maxillary occlusal plane to be registered in an occlusal wax bite supported by a bite fork, which is attached to the face bow. This provides the first reference point; additionally two others are employed, either the two condylar heads or the auditory meati. Consequently this includes the occlusal plane inclination, orbitale (lowest point of the infra-orbital margin), nasion (most retruded point on the bridge of the nose) or Campers plane (an imaginary line from the inferior border of the ala of the nose to the superior border of the tragus **F.J.Harty (1994) (**Fig 2.1)**.** The position of the maxillary teeth is recorded using a bite fork attached to the face bow.

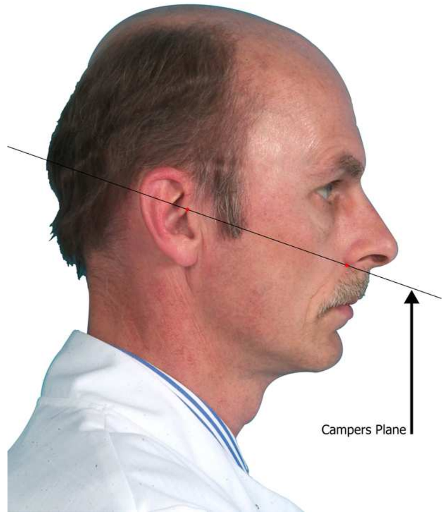


Fig 2.1. Image illustrating Campers plane.

There are two types of face bows, the arbitrary face bow (average value face bow) and the kinematic face bow. The kinematic face bow recordes the true axis of mandibular rotation with the use of adjustable condylar location components. This is most commonly used in the construction of dental prostheses **Walker (2006).**

The Dentatus is an arbitrary condylar face bow, which uses the position of the condylar heads and orbitale to define the axis orbital plane. Another type of face bow is the Denar face bow, which uses the external auditory meati and Camper's plane to define the anatomical plane **Walker (2006).** The Kavo face bow uses the external auditory meati, nasion or left orbitale and also has pointers to indicate the position of the condyles **(KaVo Dental GmbH, Germany);** the SAM system uses also the external auditory meati and nasion **(SAM PRÄZISIONSTECHNIK GmbH, Germany).**

The face-bow itself is then transferred to the articulator with the maxillary cast mounted using the bite fork record, the mandibular cast is mounted on the articulator in the patient's centric or rest position with the aid of a wax bite registration taken previously.

Face-bows and articulator systems have been developed for dental rehabilitation and not for orthognathic model surgery and have significant limitations if used for the latter purpose. The most important problem is the orientation of the mounted casts. For prosthodontics the casts are generally orientated relative to Camper's plane or a nominal Frankfort plane (Fig. 2.2.) and there is no need to relate the casts to the position of the skull or the anatomically defined Frankfort plane, which is essential for accurate orthognathic model surgery.

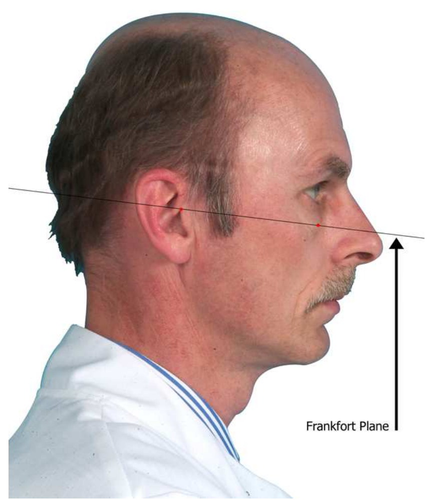


Fig. 2.2. Image illustrating the Frankfort plane.

The data sheets and information supplied by articulator manufacturers do not generally specify the mechanics by which the mounted casts are related to the nominal Frankfort plane. Dentatus, for example, claims that mounting the upper cast using the orbital pointer and the orbital-axis plane indicator relates the upper cast to the Frankfort plane (personal communication, J. Roosaar, Product manager, Dentatus), but gives no reason why this should be so and no evidence that it was so.

It appeared that in the design of many articulator systems it was assumed that the Frankfort and orbital-axis plane were parallel **Pitchford (1991)** or at a fixed angle to each other.

There was doubt about the actual orientation of casts when mounted on semi-adjustable articulators and this has been the subject of research, which is to be reviewed in the next section.

2.2. Accuracy of mounting maxillary casts using face bow registration.

Gonzalez and Kingery (1968) investigated 21 edentulous patients with complete dentures to determine which, was the least variable reference plane that had been used to mount dental casts. The relationships between the Frankfort plane and the axis-orbital, residual ridge and denture occlusal planes were analysed using lateral cephalograms. Metal markers were used to identify the planes from the cephalogram. A metal bead 1.5mm in diameter had been fixed over the left Beyron point (Arbitrary condylar head position 13mm anterior to the most posterior part of the tragus of the ear on a line to the outer canthus of the eye) (Fig 2.3.) to allow the axis-orbital plane to be identified; tin foil strips were placed on the incisal edge of the left maxillary central incisor, on the mesiobuccal cusp of the left maxillary first molar on the subject's upper denture in order to identify the occlusal plane and foil on the crest of the left maxillary ridge. The results showed that none of the 3 planes was parallel to the Frankfort plane, but that angle between Frankfort and the axis-orbital plane was the most consistent finding. The angle varied between 3º and 12.2 °, mean 5.9 ° and standard error 0.6 °.

Gonzales and Kingery (1968) devised an arbitrary adjustment to align the axis-orbital plane with the Frankfort plane when using a face bow. The orbital pointer could be placed 7mm below orbitale on the patient or the orbital pin of the face bow could be raised 7mm. The magnitude of the correction was based on the average value of 5.9 °, but the range of difference was so great that many of the mounted casts would have a significant error.

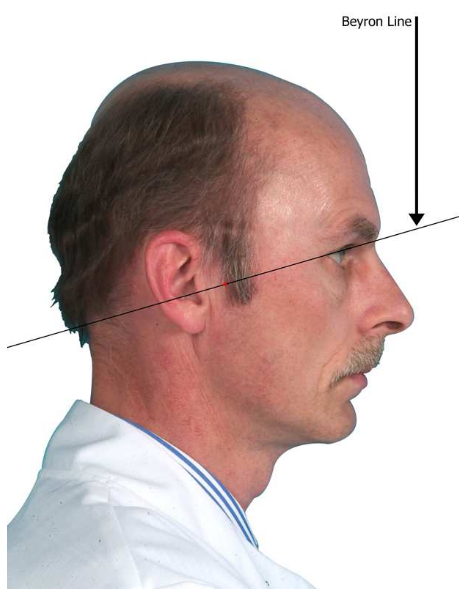


Fig 2.3. Image illustrating Beyron line. Beyron point is highlighted in red.

Stade et al (1982) attempted to identify and quantify the possible aesthetic errors in the use of a conventional face-bow by investigating ten subjects, all of whom were with complete natural dentitions and no obvious facial asymmetries.

The articulator system used in the study was the Hanau 130-28 articulator and the Hanau model 132-2SM face-bow. This articulator system was selected as a preference of the author, no reason was offered for this choice of instrument. The face bow was modified by attaching 2 pivoting bubble gauges, the angles of which could be adjusted to record an antero-posterior and medio-lateral plane. The articulator was supported on a flat, triangular plastic board 20mm thick; three threaded bolts, one at each corner of the triangle, allowed the angle of the board and the articulator to be tilted.

Each patient was placed in the aesthetic reference position (natural head position), defined by Stade et al as "standing erect with eyes fixed in the horizontal plane". The face bow recording was taken and the bubble gauges were centered, thus recording the relationship of the face bow to the aesthetic reference plane. The face-bow was then attached to the articulator using the manufacturer's specifications. The bolts supporting the triangular platform were adjusted to centre the bubble gauges and duplicate the aesthetic reference position. The amount the board was raised at each corner was recorded. The platform was raised anteriorly by 14mm to 53mm, mean 34.65mm and standard deviation 11.4mm. The left rear elevations ranged from 2mm to 17.5mm, mean 6mm and standard deviation 6.86mm. The mean right posterior elevation was 1.15mm and standard deviation

2.29mm. Student's t-test showed that all the changes except the right posterior measurement point were significantly different from zero at the P=.01 level.

The results indicated that casts mounted using the conventional face bow technique were misaligned by an average of 10º relative to the horizontal plane, defined by the aesthetic reference position or natural head position, although the authors referred to the incisor rather than the cast angulation. The results were further analysed to show that the misalignment ranged from 3.9 º to 14.6º **(JCBarbenel, personal communication).**

It was suggested that the misalignment could be corrected and the casts mounted relative to the aesthetic reference position by raising the height of the articulator cross member by 16.4mm; this was an average value correction, but the range of errors was so large that many of the mounted casts would still have a significant error. The suggested correction was considerably more than the 7mm elevation suggested by **Gonzalez and Kingery (1968),** but that related to mounting the casts relative to the Frankfort plane.

Bailey and Nowlin (1984) investigated the accuracy with which maxillary casts could be mounted using a conventional face bow by comparing the angle between the occlusal and Frankfort planes measured from cephalometric radiographs with the angle between the upper cross member of a Hanau articulator and the occlusal plane of the mounted cast.

Ten patients with a full maxillary dentition were selected for the study. All subjects had a lateral cephalometric radiograph taken by the same radiographer. The radiograph was marked to show the Frankfort plane (porion to orbitale) and the maxillary occlusal plane (lowest point of the central incisor and the mesiobuccal cusp on a first molar tooth). The angle between the 2 lines was measured with a protractor to the nearest 1°.

An upper maxillary impression and a face-bow registration using the Hanau 132-25m face-bow was taken for each subject. The face-bow used recorded three points of reference, the right and left Beyron points and the right orbitale. Using the face bow the maxillary casts were mounted on a Hanau model 130-28 articulator following the manufacturer's specification.

A customised Fox plane (Dentsply International Inc., York, Pa.) was used to define the maxillary occlusal plane of the mounted cast and this was extended posteriorly to the upper cross member of the articulator. The angle between these two planes was measured with a protractor to the nearest 1° (Fig.2.4).

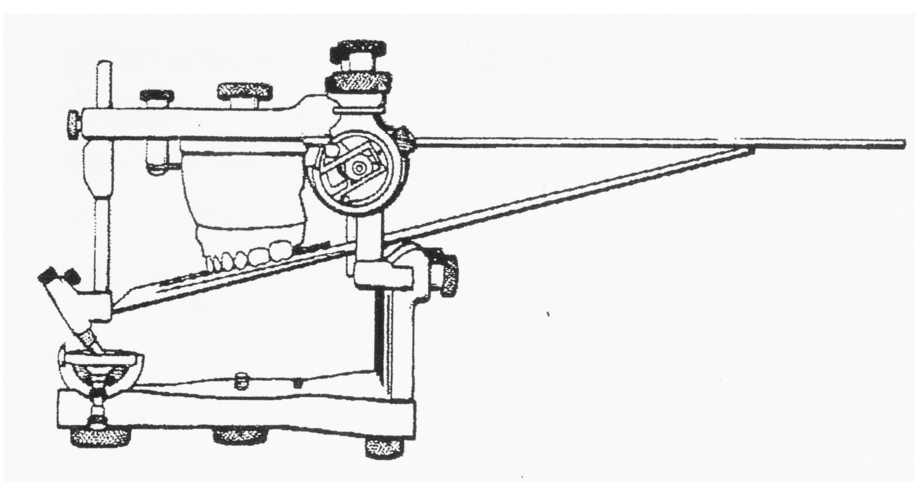


Fig.2.4. Articulator with Fox Plane modified for angle measurements.

The angles recorded on the articulator were all greater than those determined from the radiograph, indicating that the occlusal plane of casts mounted using the conventional face bow technique were misaligned by an average of 7.5º (standard error 1º) compared to the Frankfort plane. There was also considerable variability, with the discrepancy ranging from +4º to +12º.

The authors showed that the inaccuracy could be largely eliminated by aligning the face bow with a notch on the incisal pin, which reduced the misalignment to an average value of -2º.

O'Malley and Milosevic (2000) investigated the maxillary occlusal plane angle of casts mounted using three different semi-adjustable articulator systems. Twenty patients were selected for the study, 10 symmetrical skeletal Class II and 10 symmetrical skeletal Class III. The angle between the Frankfort and maxillary plane angle was measured for each patient from a cephalogram, which was remeasured to assess the accuracy of the measurement.

The Dentatus Type ARL, Denar MKII, and the Whipmix Quickmount 8800 articulator systems were investigated. The base and upper arm of the articulators were set horizontal with spirit levels and the maxillary casts were mounted using the appropriate face bow. After mounting the cast the face bow was left in place and its angle relative to the horizontal was measured using a Rabone angle setter. It was assumed that this was the angle between the occlusal plane and the articulator upper arm. The authors assumed that the horizontal upper arm of the articulator was parallel to the Frankfort plane.

The casts of five patients were remounted and remeasured to confirm the reproducibility.

The angle between the maxillary occlusal plane and the horizontal articulator upper arm measured from the bite fork extension to the upper articulator arm was compared with the Frankfort - maxillary occlusal plane angle measured from the cephalographs; the 'gold standard' was the cephalogram angle. The Whipmix was closest to the 'gold standard' showing a mean difference of –1.9º, which was significant ($P<0.05$). The Denar and the Dentatus flattened the occlusal plane more severely on the articulator by 5.2º ($P<0.001$) and 6.5º ($P<0.001$). The difference may relate to the Whipmix using nasion as a third point of reference unlike the Dentatus and the Denar which use orbitale. Whether the angles were greater or less than the actual maxillary occlusal plane angle this would still have an effect on the accuracy of the position of the upper incisor edges resulting in inaccurate model surgery movements. The effect of altering the steepness of the occlusal plane was investigated diagrammatically (Fig 2.5)(their Figure 3).

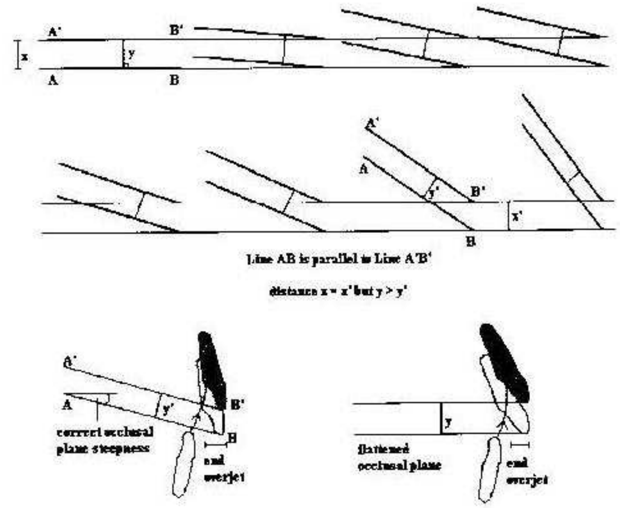


Fig.2.5. (their Figure 3) Diagram to show the effect of altering the steepness of the occlusal plane on mandibular autorotation. (A) Where line AB is the existing occlusal plane, & line A'B' is the new occlusal plane following a mandibular impaction of given distance x. Distance y is the perpendicular distance separating the two occlusal planes and indicates the distance the mandible is permitted to autorotate. Notice how distance y reduces to y' as the steepness of the occlusal plane increases; (B). The clinical relevance of this geometric effect on autorotation model surgery on a flattened occlusal plane predicts greater autorotation than during the actual operation. O'Malley and Milosevic (2000)

It was suggested that for every 1º that the occlusal plane was flattened on the articulator compared with the true occlusal plane, the upper incisors looked 1º more proclined and the lower incisors 1º were more retroclined on the articulator. This meant that movements of the models at right angles to the upper arm of the articulator would result in an unwanted and unnoticed anterior shift of the maxillary incisors because of the discrepancies between the patient's and the articulator's reference planes. It was suggested that for a 10º discrepancy a 6mm impaction of the maxilla would produce an unwanted and unnoticed advancement of 1 mm, which appeared to be produced by a rotation of the upper incisors. The under impaction that would also occur was not identified.

Ellis et al (1992) undertook a study to assess the accuracy of face bow transfer of maxillary dental casts to the corresponding articulator for the purpose of orthognathic model surgery. Twenty-five subjects who were undergoing orthognathic surgery were recruited for this study. The patients required orthognathic model surgery on models mounted on an anatomical articulator prior to their operation. The articulator system used for this study was the Hanau Model H2 semi-adjustable articulator. The face bow for this system used the external auditory meati for the posterior reference points, a bite fork for the maxillary position and right orbitale as the anterior reference point. This system came with a removable mounting jig, which according to the manufacturer properly located the maxillary cast. The author commented that using this type of face bow only gave an estimation of the location of the mid-point of the mandibular condyles, but by using this method it was thought to locate the intercondylar hinge axis within a 5mm radius of the true hinge axis.

The accuracy of the face bow transfer was assessed by comparing the angle between the occlusal plane and the Frankfort plane obtained from lateral cephalograms with the angle between the occlusal plane and articulator upper cross member of the mounted maxillary models.

A lateral cephalogram was taken for each subject. A protocol was devised for taking measurements from this allowing for the magnification that generally arose when taking these radiographs. Four reference points were traced on each lateral cephalogram, porion and orbitale, which were used to define the Frankfort plane, and the most anterior incisor and the most posterior molar points, which were used to define the occlusal plane. A line was drawn along the Frankfort horizontal plane and a measurement using a compass was recorded between the orthodontic bracket on the maxillary incisor and the bottom of the articulator cross member. This was then transferred to the lateral cephalogram and an arc was drawn with the compass when using the central incisor bracket; the same technique was employed for drawing an arc using the molar reference point (Fig. 2.6). A line was then drawn tangential to the two arcs recorded. The angle between this line and the Frankfort plane was calculated by digitising both lines on the tracings. The angle between the lines should have been 0º if the transfer had been accurate. The mean angle was, however, 6.8º with a standard deviation of 3.5º. The mean value was significantly different from 0º (paired t test, P<0.001).

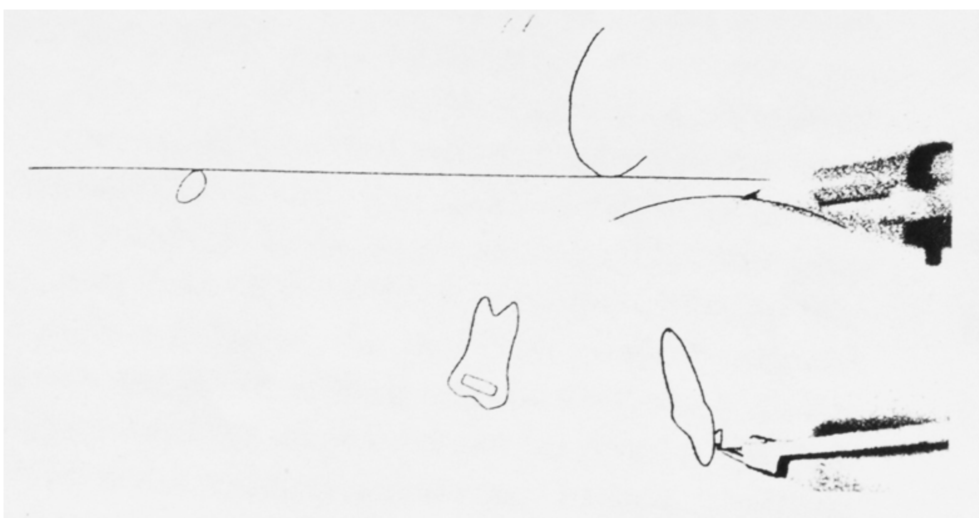


Fig.2.6. The compass is used to scribe the distance on a cephalometric tracing, which included porion, orbitale (Frankfort horizontal), the incisor and the terminal molar. Ellis et al (1992)

All of the twenty-five cases showed a transfer and mounting error. Twenty-three cases recorded an increase in the maxillary occlusal plane angle and two a decrease. The differences in the occlusal plane angles with the cephalograms and articulators were presented as histogram and appeared to show that the differences were between -3 ° and 13.5°.

This study proved that the mounting of the maxillary cast was inaccurate. Ellis et al noted that when carrying out bi-maxillary surgery the maxilla moved into the author's new position predetermined by model surgery. The authors reached the qualitative conclusion that if the maxillary-occlusal plane angle relative to the Frankfort plane was under estimated on the articulator impacting the maxillary cast vertically during model surgery, this would produce a wafer that would alter inappropriately both vertical and horizontal movements during surgery.

Ellis et al devised a method to improve the accuracy of mounting, suggesting that the mounting error could be corrected by measuring the angle between the occlusal plane and the Frankfort plane from a lateral cephalogram and rotating the face bow attached to the articulator to reproduce this angle. This was suggested to be the only reliable way of measuring the angle between the occlusal plane and Frankfort plane so as to allow the relevant corrections to be achieved. However, it is unsafe to consider the articulator to be capable of representing the anatomical points required in Ellis' study. This is due to anomalies incorporated in articulator design.

Pitchford (1991) investigated three aspects of the accuracy of face bow transfers. The first investigation of nine subjects was to determine the ability of the face-bow to record and transfer the vertical position of the maxillary occlusal plane when the patient's Frankfort plane was parallel to the reference horizontal, using the distance between the subject's orbitale and upper central incisor to quantify the accuracy of the transfer.

The position of the subject's orbitale was located and marked. The position of the subject's head was adjusted to make the Frankfort plane horizontal as determined by using a builder's level. A Boley Gauge (a measuring caliper) was then used to measure the distance between orbitale and the edge of an acrylic resin bar attached to the central incisors. Allowing for the thickness of the bar gave the distance between orbitale and the incisors. A Hanau 159-4 face-bow was placed in the conventional manner; the subject's head position was checked to ensure that the Frankfort plane was horizontal and the face bow indexed to the Frankfort plane and the horizontal using two bubble gauges mounted on the face bow. The face bow was transferred to a Hanau 158-H2. The tip of the orbital pointer was put in contact with the orbital indicator of the articulator and the distance between the orbital indicator indentation in the wax record representing the central incisor was measured. The face bow was then adjusted to render it parallel with the Frankfort horizontal plane and the measurement was repeated. The mean difference between orbitale and the central incisor measured from the patient and the articulator with the orbital pointer in contact with the orbital plane which was 0.17 mm showing a high degree of accuracy. With the face bow indexed to the horizontal Frankfort the mean difference was 3.34mm; Pitchford suggested that this indicated that the transfer with the Frankfort plane horizontal was "reasonably accurate".

The second part of Pitchford's study tested the ability of the face bow to transfer the aesthetic reference position to the articulator. The procedure used in the first part of the study was repeated, but an additional set of measurements were made with the subject placed in the aesthetic reference position, “sitting erect, head level and eyes gazing at the horizon”. The face bow was indexed to this position using a second pair of bubble gauges. The mean orbitale -incisor distance measured from the articulator using the aesthetic reference position was 13.45 mm less than the value obtained with the orbital pointer in contact with the orbital plane, which would increase the maxillary occlusal plane angle on the mounted casts.

The third part of the study was to determine the vertical distance between the porion and orbitale. A steel rod bearing a spirit level was attached to an earpiece from a Hanau face bow. Each of twenty subjects assumed a patient selected aesthetic reference position, “standing erect with head level and eyes staring straight ahead into a wall mirror”. The rod was levelled using the spirit level and the vertical distance between the rod and subject’s orbitale measured. The mean distance was 11.4 mm, with a standard deviation of 5.24 mm implying that casts mounted using the orbitale or the aesthetic reference position would have very different angular orientations.

Pitchford concluded that the face bow could transfer distances fairly accurately from the patient to the articulator, but that neither the Frankfort nor the axis – orbital plane was parallel to the reference horizontal in the aesthetic reference position. His results indicated that the axis – orbital plane was at 13º and the Frankfort plane 8º to the reference horizontal.

Although this study was carried out for the purpose of dental prostheses, the findings were very much applicable to orthognathic model surgery. This study did not use cephalograms, which would have determined the position of porion for measuring the Frankfort Horizontal Plane.

Gateno et al (2001) undertook a study that compared the occlusal plane inclination of models mounted using three different systems for the face bow recording transfer for use with the S.A.M.2 articulator. The three different face bows used in this study were The S.A.M. Anatomical Face bow, the Erickson Surgical Face-bow and a new technique developed by Gateno et al that considered the individual anatomical variations among subjects.

Twenty-two subjects were investigated and three alginate impressions were taken for each subject and the angle between the maxillary occlusal plane and the Frankfort plane were measured on a cephalometric radiograph.

Each patient then had a face bow recording taken according to the manufacturers' specification. The first technique used the SAM Anatomical face bow, and the second the Erickson Surgical face bow, which was a modified SAM Anatomical face bow, which used nasion as well as left orbitale as an anterior reference point. The third technique was that of Gateno et al. The vertical separation between the face bow and bite fork was adjusted to match the value obtained from an additional cephalographic radiograph.

The maxillary casts were mounted on the articulator using the different face bows, and were then detached from the articulator and measured using an Erickson Model Block and Platform. The vertical height of the incisal edge of the right central incisor and the tip of mesiobuccal cusp of the right first molar and the horizontal distance between them were measured and the angle of the occlusal plane was calculated.

The mean occlusal plane angle of the mounted models using the conventional S.A.M. face bow was 7.8º greater than the angle measured on the radiograph and the Erickson Surgical Face-bow was 4.4 º greater; both these differences were statistically significant ($P<0.05$). The angle produced by the method of Gateno et al was not significantly different from that on the cephalogram. The authors concluded that the articulator upper member was not parallel to the Frankfort plane, confirming previous results. The method described by Gateno et al was accurate, but required an additional radiograph, making it unsuitable for routine use.

The effect of the occlusal plane misalignment on the surgical outcome was investigated diagrammatically for the case when the axis-orbital plane was 12º steeper than the patient's value. The diagram suggested that a 10mm maxillary advancement relative to the articulator would result in a surgical under advancement of 1.5mm. The diagram also showed a vertical error that was overlooked by the authors.

2.3. Articulators for orthognathic model surgery planning.

Various articulators and techniques have been designed specifically for orthognathic model surgery. The aims were to simplify the movements of casts to the prescribed positions before wafer production or allow maxillary casts to be mounted to replicate the orientation of the occlusal plane seen in the patient. Simplified methods of cast movement were described by **Angelillo et al (1977), Schwestka et al (1991) and Junger et al (2003).**

Angelillo et al (1977) produced a device that located the upper and lower casts on spring loaded mounting plates that held the models in place without using plaster. The casts could be remounted at any time using the marking holes located in the mounting posts. The upper and lower casts could be moved independently in a lateral, vertical and antero-posterior direction and the upper cast could be rotated to correct anterior and posterior open bites. The device was mounted on a semi-adjustable articulator and a Whip Mix auricular face bow was used to locate the upper cast on the articulator. The mounted casts, therefore, incorporated the error of orientation discussed above. (Fig. 2.7.)

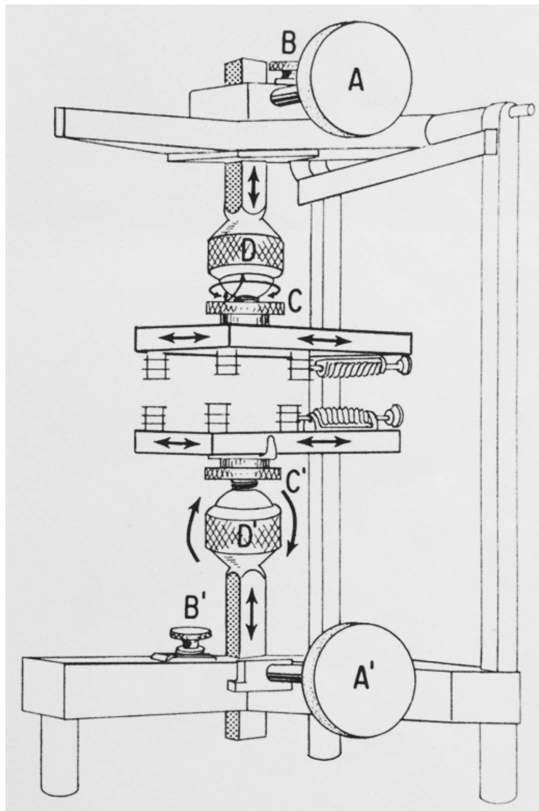


Fig.2.7. A & A provide vertical movement. B & B allow lateral movement. C & C allow anterior- posterior movement and D & D allow the casts to be rotated. Angelillo et al (1977).

The use of the S.A.M. cast positioning device (S.A.M. PrazisionstechNik GMBH: www.sam-dental.de) was reported by Schwestka et al (1991). The positioning device allowed 3 dimensional repositioning of either the upper or lower mounted dental casts without sectioning the mounting plaster. The device was used in conjunction with a S.A.M. semi-adjustable articulator and face bow. Once again the mounted casts incorporated the error of orientation discussed previously.

Junger at al (2003) described the use of the three-dimensional orthognathic surgery simulator **(3-d-oss, Girrbach Co, Pforzheim, Germany)** developed by Krenkel, which allowed the independent movement of the mandibular and maxillary casts in 3 dimensions. The paper and illustrations were rather unclear, but there were no details of how the casts were orientated for mounting in the system. The means for mounting casts to replicate the orientation of the occlusal plane seen in the patent have been considered in several publications, some of which have been reviewed above.

Gonzalez and Kingery (1968) suggested a standard way of correcting face bow records by rotating the face bow around the intercondylar axis 5.9 º by raising the orbital pin of the face bow by 7mm. The values were derived from their experimental results. However, this average value correction will only be appropriate for a few individual patients, notably those undergoing orthognathic surgery, who may be anatomically very variable i.e. asymmetric patients.

Ellis et al (1992) and **Gateno et al (2001)** described correction techniques of mounting dental casts on articulators appropriate for individual patients based on the use of lateral cephalograms. Ellis et al (1992) suggested that the angle between the occlusal plane and the Frankfort plane be measured from a lateral cephalogram and the face bow attached to the articulator rotated to reproduce this angle. Gateno et al (2001) adjusted the vertical separation between the face bow and bite fork to match the value obtained from an additional cephalographic radiograph. Neither method has been widely applied because of their complexity and, in the case of Gateno et al (2001), the need for an additional unacceptable radiograph.

Walker et al (2008a; 2008b) stated that accurate positioning of casts was essential for reliable orthognathic treatment planning, but that mounting dental casts on a semi-adjustable articulator using a conventional face bow was inaccurate and unreliable, and went on to describe the development of an articulator and face bow system specifically for orthognathic surgery planning.

Walker et al (2008a) described the development and evaluation of a novel face bow that could accurately transfer the relationship between the natural head position and the absolute horizontal plane to an articulator. The reproducibility of the natural head position was evaluated in ten normal volunteers. A mark was placed in the right condylar region and right side near the tip of the nose, although no reason was given for the choice of this landmark. Each subject assumed the natural head position; the subjects sat upright on a chair, which was positioned two meters from a full-length mirror with a vertical line on it. The subjects looked into their own eyes reflected in the mirror, with the vertical line centralled on their reflected image. Each subject was photographed laterally under studio conditions on three separate occasions at intervals of an hour apart; the facial marks and the height of the chair remained constant. A horizontal line was placed across the image and the angle between this horizontal and a line joining the facial marks was measured to 0.5º using a protractor (Fig. 2.8.). There was considerable difference in angle between the subjects, but the measurements of each subject made on different occasions were similar, showing non-significant differences (Freidmann's test; $P > 0.05$). The median difference of the replicate measurements was 1.75º and the 95% confidence interval of the median using a Hodges-Lehmann estimate was 1.25º.

Having established the reproducibility of the natural head position relative to the absolute horizontal, the next stage was to construct a face bow to transfer this relationship to a Dentatus ARH semi-adjustable articulator. The orbital pointer of a Dentatus average value face-bow was replaced by a circular spirit level, which could be levelled and locked in place, recording the horizontal plane. (Fig.2.9, 2.10).

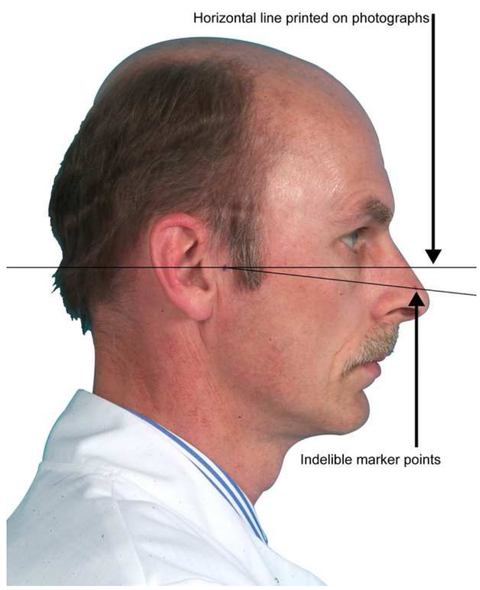


Fig.2.8. Natural head position showing the head position angle. Walker et al (2008).

Six patients requiring orthognathic surgery, without serious facial asymmetry were selected. Each patient had a lateral cephalogram taken with the head in the natural head position. Two face bow recordings were taken for each patient, one with the conventional orbital pointer and the other with the spirit level on the modified face bow. Two sets of dental models were prepared for each subject.

A horizontal line was drawn on each subject's lateral cephalogram parallel to the horizontal edge of the nasion rest and the occlusal plane was drawn on the radiograph from the central incisor tip to the lowest tip of the maxillary molar tooth, usually the mesio-buccal cusp of the first molar.

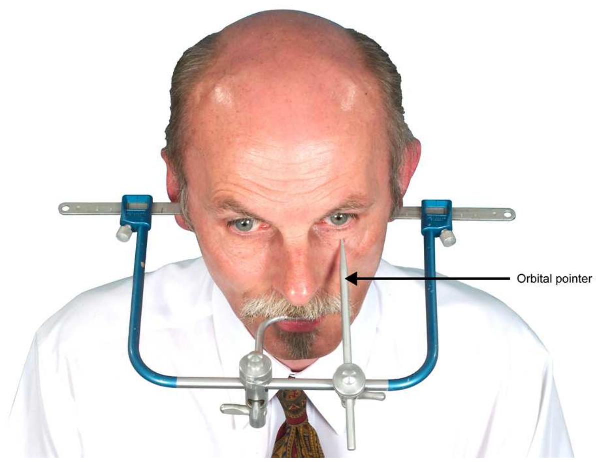


Fig.2.9. Dentatus average value face bow with orbital pointer. Walker et al (2008a).

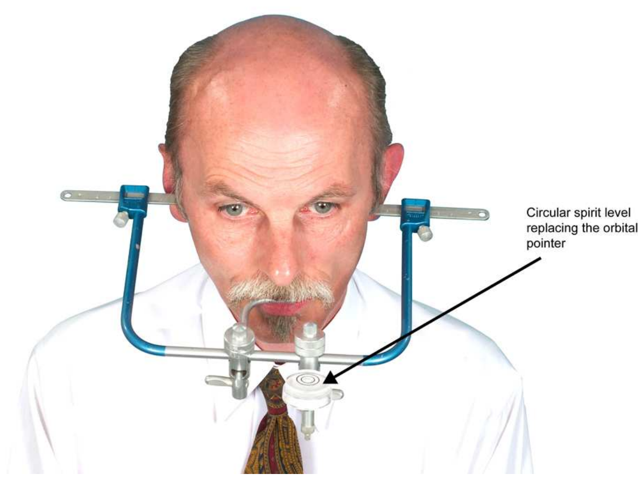
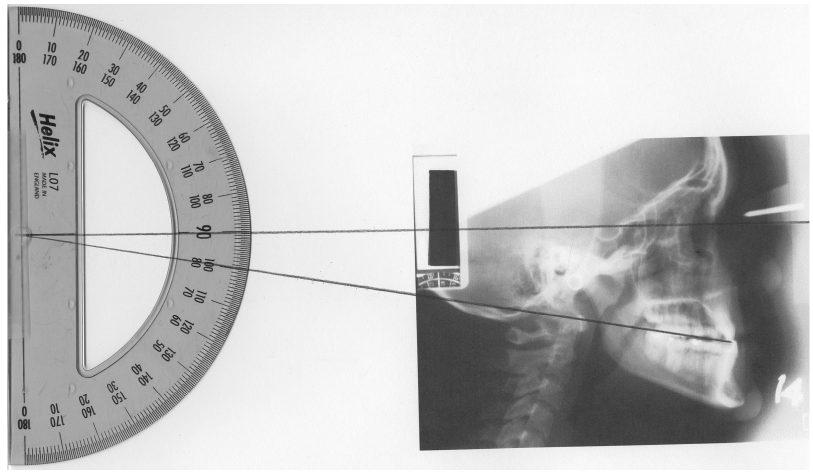


Fig. 2.10. Dentatus average value face bow with attached circular spirit level. Walker et al (2008a).

Both of these lines were extended posteriorly and the angle between them measured using a protractor (Fig.2.11.).

Fig.2.11. Measurement method to determine the maxillary occlusal plane. Walker et al (2008aa).



The angle was measured twice; the median difference between the first and second measurement was 0.5°, and the Hodges- Lehmann 95% confidence interval of the median was 0.5°

Following this, both the replicate casts were mounted on an articulator. One cast was mounted using the conventional technique with the orbital pointer in contact with the underside of the orbital plane indicator (Fig. 2.12). The second cast was mounted using the spirit level face bow, which was positioned on the articulator and rotated about the condylar rods by raising or lowering the anterior rod of the face bow to centre the spirit level (Fig. 2.13).

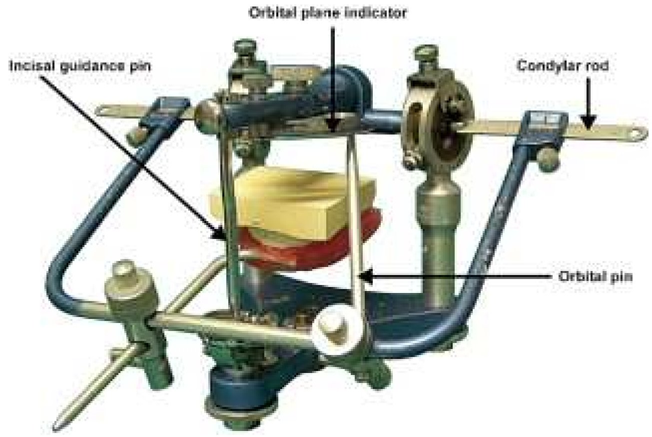


Fig.2.12. Cast mounted on an average value Dentatus face bow using the orbital pin and orbital plane guide. Walker et al (2008a).

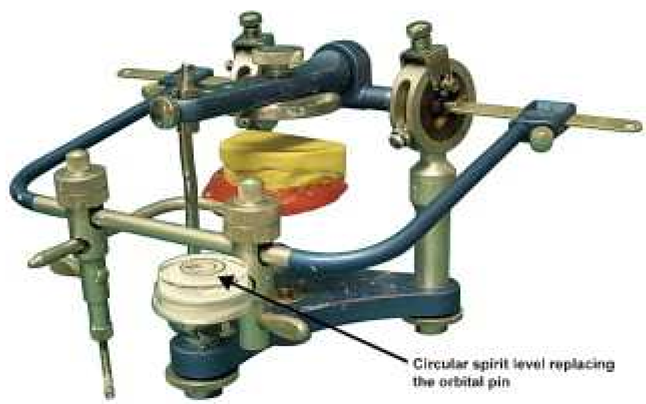


Fig.2.13. Cast mounted using spirit level face bow. Walker (2008a)

A flat plane was placed across the occlusal plane of each mounted cast and the angle between articulator cross member and the maxillary occlusal plane was measured (Fig. 2.14). The values of the horizontal-occlusal plane angle for each method of mounting were compared with the mean value of the angle measured from the cephalograms.

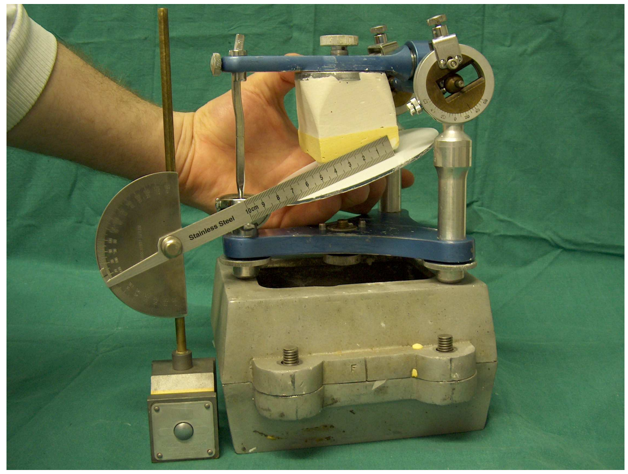


Fig.2.14. Protractor on a slide fit stand to measure the maxillary occlusal plane angle. Walker (2008a).

The differences between the measurements taken on the cephalogram and the model mounted using the conventional face bow were found to be large. The difference between the mean values of the angles measured from the cephalogram and the cast mounted using the spirit level was 1.0º with a Hodges-Lehmann 95% confidence interval of 1.25˚. The equivalent values for the casts mounted using the orbital pointer were -10.75˚ and 11.5˚.

The differences between the three methods of obtaining the horizontal-occlusal plane angle were highly significant (Friedmann's test, $p<0.001$). There was a significant difference between the cephalographic values and those for the model mounted using the orbital pointer (Nemenyi's test, $p<0.005$) but not for the models mounted using the spirit level ($p>0.05$).

The photographic study proved that the subjects could repeatedly assume the same head position under the same conditions. The sample size used in the second part of the study was considered to be small, although statistically significant results were obtained. This study confirmed that there were significant systematic differences between the occlusal angle measured from the cephalogram and the models mounted using the orbital pointer, confirming the previous criticisms reviewed in the previous paragraphs. Models mounted using the spirit level face bow accurately replicated the values obtained from the cephalogram and Walker et al suggested that the novel spirit level face bow should be accepted as a new method for mounting models on an articulator and for planning orthognathic operations. Walker et al (2008) indicated it was possible to record the lateral angle between the horizontal and occlusal planes (cant) using the spirit level face bow, reflecting the asymmetry often seen in craniofacial deformity cases. It was, however, impossible to mount casts to replicate this angle on currently available articulators and an orthognathic articulator was required to realise the potential of the spirit level face bow.

Walker et al (2008b) reported the design, construction and initial evaluation of an articulator for orthognathic surgery planning. A primary design consideration was that the articulator could adjust to fit the spirit level face-bow recording of the patient so that no error would be built in when transferring the face-bow to the articulator, and it would be able to incorporate the asymmetries often present in patients undergoing orthognathic surgery. These aims were achieved by making it possible to adjust the position of each of the condylar components of the articulator in three directions, vertically, antero-posteriorly and laterally as well as rotate about a vertical axis. The condylar head elements were adjustable for major and fine adjustment of the vertical position of the condylar head. Antero-posterior and lateral positions were achieved by mounting the condylar components on curved horizontal arms with a slot cut in an arc to allow horizontal movements.

Walker et al also felt that it would be advantageous to have more space between the lower and upper cross-members and that the movement of the mandible be replicated by rotation of the lower cast instead of the upper cast. These requirements were incorporated into the new orthognathic articulator. The articulator body was made of aluminium (Fig.2.15.). The articulator consisted of a triangular shaped base with supporting feet, a long square central pillar and a maxillary cross member (Fig.2.16). This gave plenty of room for mounting the maxillary and mandibular casts. The maxillary cast was mounted using a mounting plate attached to the central pillar. The mandibular cast was positioned using a support on the condylar component and two curved ramus frames. A spring was used on each side of the casts to keep the casts in occlusion.

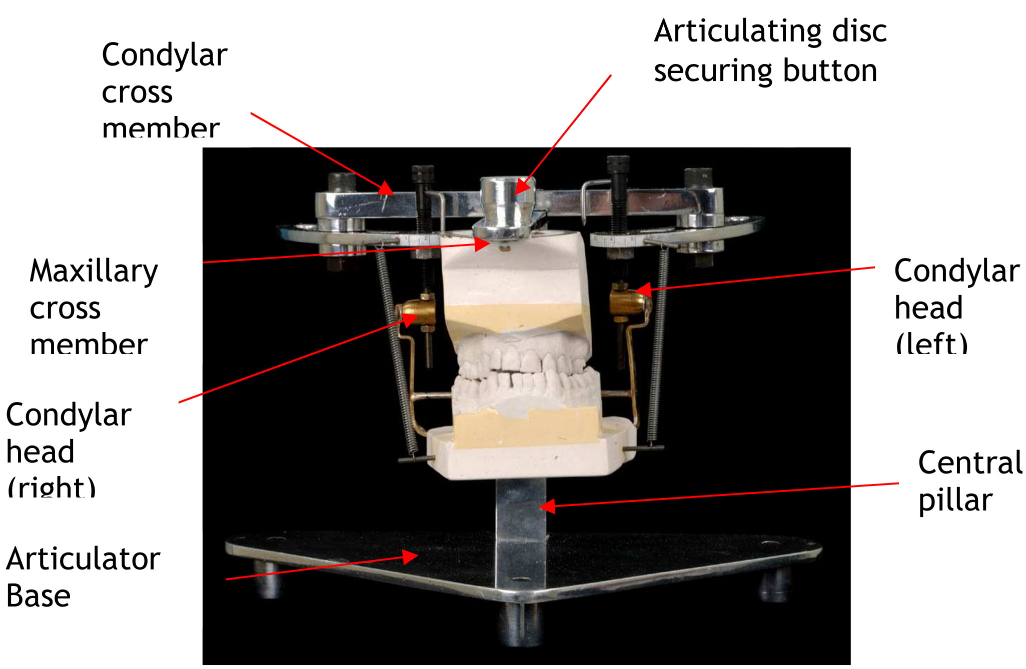


Figure.2.15. Frontal view of the maxillary and mandibular cast mounted on the Orthognathic articulator.

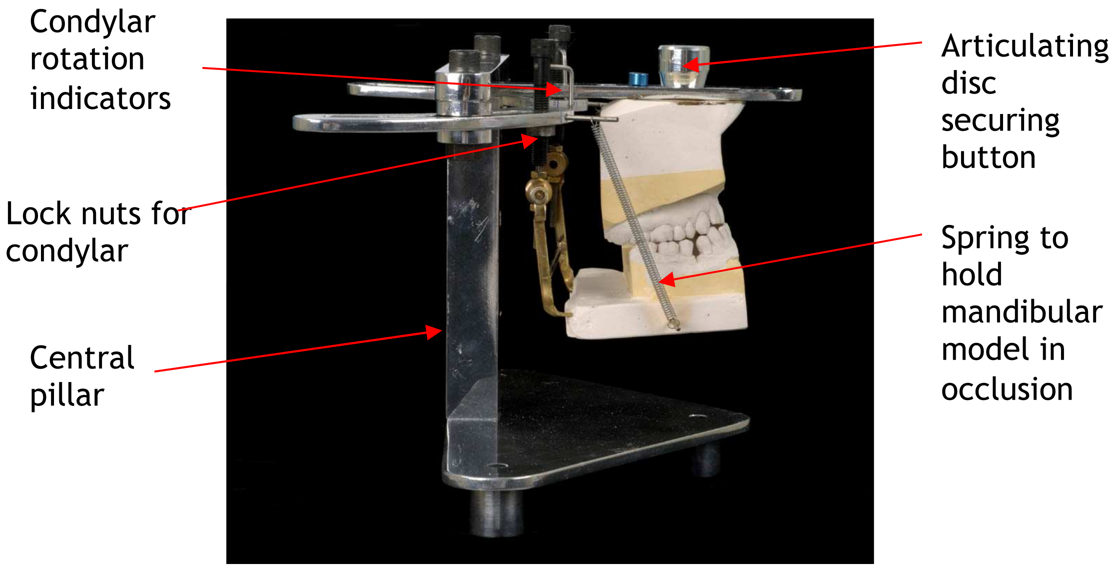


Figure.2.16. Lateral view of the maxillary and mandibular cast

The face bow and articulator system were evaluated on twelve patients, six with severe facial asymmetry and six patients with no asymmetry. Lateral cephalograms were taken for each patient and postero-anterior cephalograms taken for patients with facial asymmetry; the nasion rest was visible in each radiograph and was used as a horizontal reference. The postero-anterior horizontal-occlusal plane angles were measured from each lateral cephalogram using the technique employed for cephalograms taken in the face bow study; the lateral-occlusal plane angles, (cants) were measured from the postero-anterior cephalograms. The distance between the most lateral point of each condyle was identified and measured.

Face bow recordings were taken for each patient with the spirit level face bow and used to mount upper and lower dental casts of the patient on the orthognathic articulator. The horizontal-occlusal plane angles were measured on the maxillary casts usIng a flat Plane placed across the dentition and a protractor adapted to allow vertical adjustment. The inter-condylar width on the cast was measured using the vernier gauge as on the cephalograms.

The values of the occlusal plane angles obtained from the radiographs were compared to the values obtained from the mounted casts. The results showed considerable variation between patients, but less variation in individual patients; the measurements obtained from the radiographs and mounted casts did not differ significantly (Wilcoxon signed rank test, $p>0.05$). The paper did not report the comparison of the inter-condylar widths, but **Walker (2006)** reported that there was no significant difference between the measurements obtained from the postero-anterior radiograph and the mounted casts (Wilcoxon signed rank test, $p>0.05$).

It was suggested that in addition to the high accuracy of mounting casts, a great advantage of the face bow and articulator system was that it was possible to mount casts of asymmetrical faces to reproduce the cant shown clinically, unlike any other articulator. In discussing the use of the system, the need to simplify the coupling between the articulator and face bow was identified. Walker et al concluded that the accurate mounting of occlusal models on the new orthognathic articulator would improve orthognathic planning and prediction, but that the assumption needed to be verified.

This system is unique in that it was designed specifically for orthognathic surgery planning. It would be presumed that using this new articulator system would enable the production of more accurate surgical wafers, which in turn would aid accurate orthognathic surgery to be carried out. A further evaluation of the practical application of the system is required.

2.2.Summary.

Although a few attempts have been made to construct orthognathic articulators using available semi-adjustable articulators for the purpose of orthognathic model surgery, there are none commercially available that take into consideration the inaccuracies that arise when the corresponding face bow is transferred to the articulator. **Walker et al (2008a), (2008b)** has taken into consideration and highlighted all the shortfalls and limitations of the systems available and developed a system that overcomes these problems. Walker's system was designed especially for planning craniofacial deformity patients where the position of the condyles could be asymmetric.

3

AIMS AND OBJECTIVES

Aims and Objectives.

Hypothesis:

The null hypothesis of the study proposes that the new orthognathic articulator system is not more accurate than the standard articulator system presently used.

The literature reviewed in the preceding chapters suggested that there was evidence that:

- The final outcome of surgery using perioperative wafers prepared on commercially available semi-adjustable articulators may differ from the prediction plan.
- Casts mounted that have been articulated on semi-adjustable articulators using the corresponding face bows following the manufacturers guidelines have systematic errors of cast orientation.
- There were suggestions that there is a connection between misalignment of the casts used for model surgery and inaccurate surgical outcomes but there has been no reliable objective evidence to support these suggestions, only from individual case histories.

This gave the motivation to undertake this study, the first aim of which was to investigate the errors produced by cast misalignment.

The specific objectives were to:

- Demonstrate whether the misorientation of casts mounted on conventional semi-adjustable articulators produced errors in the maxillary cast movements at the time of model surgery.

- Develop a mathematical model to quantify the magnitude of the errors occurring during movement of the casts.
- To experimentally validate the mathematical analysis.

There appeared to be only one face bow and articulator system specifically designed for orthognathic model surgery planning. The natural head position was used to reproduce on the articulator the maxillary occlusal plane angle seen in the patient. Although the accuracy of the cast orientation had been established, the accuracy of the perioperative wafers constructed on the orthognathic articulator remained unknown. This fuelled motivation to undertake a study to evaluate the Orthognathic Articulator system, the aim of which was to compare the accuracy of the Orthognathic articulator system with a Standard semi-adjustable articulator system.

The specific objectives were to:

- Mount plastic skulls and adjust their angulations to represent subjects with differing natural head positions.
- Mount dental casts taken from the plastic skull on both a Standard Dentatus semi-adjustable articulator and on the Orthognathic articulator.
- Compare the accuracy of outcome of simulated orthognathic surgery using inter-occlusal wafers prepared on each articulator.

4

ERRORS PRODUCED BY CAST MISALIGNMENT

The vertical and horizontal displacements prescribed by the surgeon are relative to a set of reference axes, the horizontal axis being parallel to a horizontal plane with the head in its natural position and the vertical axis at right angles to the horizontal axis; these axes will be called the reference horizontal and vertical axes. Conventional articulators and face bows have been designed to replicate a few interdental occlusal relations, not to reproduce the position of important anatomical features relating to the maxilla and skull **O'Malley & Milosevic(2000), Walker (2008a).** The maxillary cast was mounted relative to the horizontal axis defined by the upper cross member of the articulator, which often differed significantly from the reference horizontal axis and anatomical planes such as the Frankfort plane which was assumed to be horizontal, **Bamber & Harris (2001), Downs (1956), Ferrario, et al (2002), O'Malley & Milosevic (2000), Pitchford (1991), Walker (2008).**

The difference between the axes based on the articulator cross member and on the natural head position is shown in Fig.4.1, in which a maxillary model has been mounted on an articulator cross member that is horizontal. The axis H_a is parallel with the articulator cross member and V_a at right angles to H_a. The reference horizontal and vertical axes, H_r and V_r, are also shown. Ideally both sets of axes should coincide, but mounting models using a conventional face bow produces the discrepancy of orientation discussed above and there is an angle θ between the two sets of axes.

In the laboratory the prescribed displacements of models have been made relative to the axes based on the cross member of the articulator, not in relation to the reference horizontal and vertical axes that were used by the surgeon to define the displacements required.

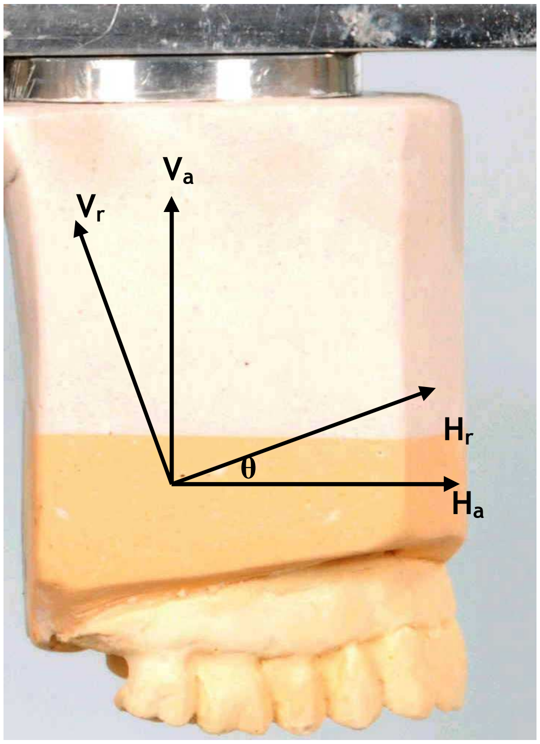


Fig.4.1.The axes based on the articulator cross member are at an angle θ to the reference axes based on the natural head position.

This would produce erroneous and inaccurate occlusal wafers, which are used routinely to reposition the maxillary segment perioperatively. The magnitude of the inaccuracies depended on the discrepancy between the orientation of the reference horizontal axis, and the horizontal axis based on the articulator cross member; differences of up to 20º have been reported, Walker (2008b). Out of six cases Walker carried out, the results of the maxillary occlusal plane angle study were found to overestimate the maxillary occlusal plane angle and two of the cases showed errors of -20º and –20.5º.

4.1 Qualitative illustration.

Movement of a model relative to axes (H_a and V_a) based on the articulator on which it is mounted also produces movements of the model relative to the reference axes (H_r and V_r) based on the patient's natural head position, but the magnitude of the movements will be different. This is shown in (Fig.4.2), in which the reference axes are at an angle θ to the articulator axes.

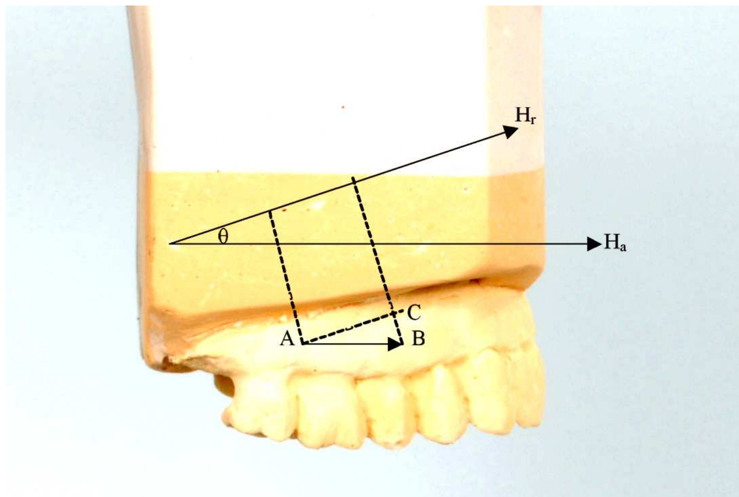


Fig.4.2. Model displaced by a distance AB parallel to the axis H_a parallel to the articulator cross bar produces displacements relative to the reference axes H_r and V_r.

The horizontal axis H_a was parallel to the articulator cross bar. A horizontal movement of the maxillary model by a distance h_a (shown as the line AB in Fig.4.2.) produce two movements of the model relative to the rotated reference axes H_r and V_r, a movement AC (distance h_r) parallel to H_r and a movement CB (distance v_r) parallel to V_r ; these were horizontal and vertical movements relative to the reference axes. ABC is a right angle triangle with AB as the hypotenuse and hence h_r was smaller than h_a; v_r was greater than v_a, which was equal to zero for a horizontal movement relative to the articulator axis.

Thus relative to the reference axes the model is under-advanced and down-grafted.

4.2. Mathematical analysis.

Mathematical analysis of the general case of model movements both parallel and at right angles to the articulator axes (Appendix 1) showed that movements relative to the articulator and to reference axes at an angle θ to each other are related by the equations

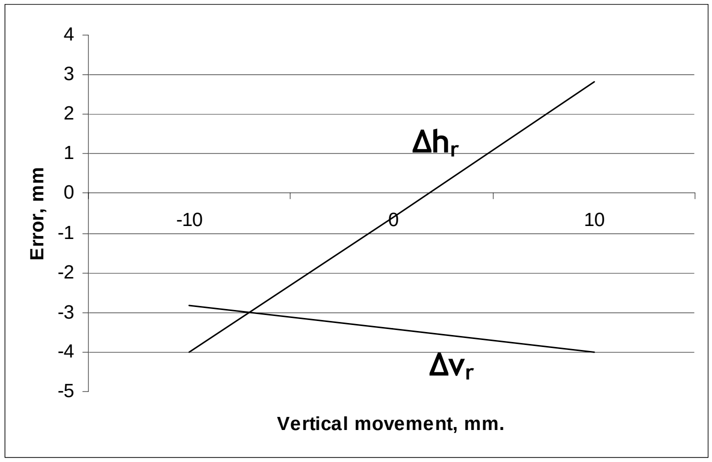
$$h_r = h_a \cos\theta + v_a \sin\theta \qquad \text{Eqn 1a}$$

and

$$v_r = v_a \cos\theta - h_a \sin\theta. \qquad \text{Eqn 1b}$$

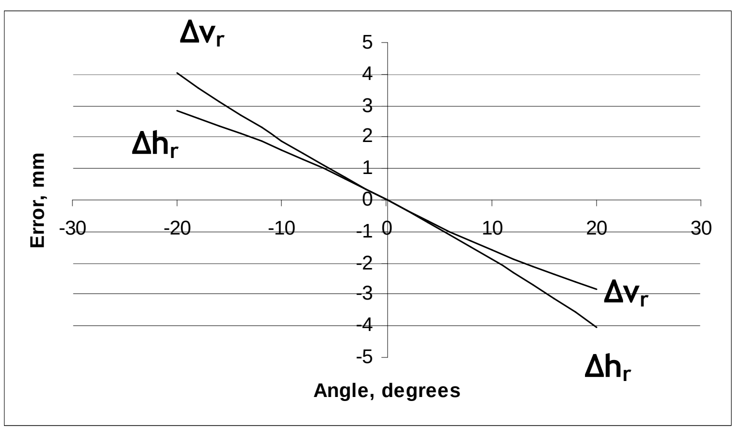
The magnitude of the vertical and horizontal errors depended on the magnitude of the movements made relative to the articulator and to the angle between the articulator and reference axes.

Graph 4.1. showed how the vertical and horizontal errors, Δv_r and Δh_r depend on the magnitude of the vertical movement of the cast relative to the articulator for an advancement of 10 mm. The graphs were linear because both the advancement, h_a, and the angle, θ, between the articulator and reference axes were constant. The greatest error was 4 mm in a movement of 10 mm.



Graph 4.1. The dependence of the vertical and horizontal errors, Δv_r and Δh_r, on the vertical movement, v_a. The horizontal movement, h_a, was an advancement of 10mm. θ is 20º.

The dependence of the error on the angle θ was more complicated because it depends on trigonometric functions of the angle. Graph 4.2. showed a typical result and over the restricted range of θ of clinical relevance, the relationship was only approximately linear.



Graph 4.2. The dependence of the vertical and horizontal errors, Δv_r and Δh_r, on θ. The horizontal movement, h_a, was an advancement of 10 mm and the vertical movement, v_a, was a downgraft of 10 mm.

4.3 Experimental Photographic study to confirm mathematical analysis.

The validity of the equations derived theoretically were evaluated by an experimental photographic study in which dental casts were moved parallel and normal to a horizontal articulator axis and the resulting movement relative to a reference axis at 20º to the articulator axis was determined by image analysis.

4.3.1 Materials and Methods:

The Orthognathic Articulator was reproducibly located on a drilled wooden board placed upon a chair which was firmly secured and parallel to the wall; the feet of the articulator were located and secured in holes pre-drilled in the board. This was done in order to prevent any lateral, posterior or anterior movement. The base and top arm of the articulator were then levelled using a spirit level.

A maxillary cast had been previously mounted on the Orthognathic Articulator using a metal cast mounting plate and a threaded rod. The upper arm of the articulator had been set horizontal using a spirit level. The sides of the plaster block were trimmed at right angles using a set-square to ensure uniformity. Spacers were used to produce defined, accurate and reproducible vertical movements. Two aluminium spacers were constructed, one 10mm thick and the other 20mm. Slots were made in the spacers to ensure their easy positioning whilst the images were being taken. A 10mm spacer was used to represent the start position of the maxilla so that the spacer could be removed, producing a 10mm impaction. Replacing the 10 mm spacer with the 20mm spacer produced a 10mm downgraft.

Horizontal movements were standardized by drilling three holes 10 mm apart through the cross bar. The model was initially mounted using the central hole, but could be moved 10 mm forwards or backwards by remounting the model using one of the additional holes.

In order to eliminate parallax errors when viewing and photographing the model, a red reference point was marked on the model and two plumb line threads hung vertically in front of a red reference mark and aligned so that they superimposed when viewed at right angles to the model (Fig.4.3.).

A second black reference point was used to define the position of the models.

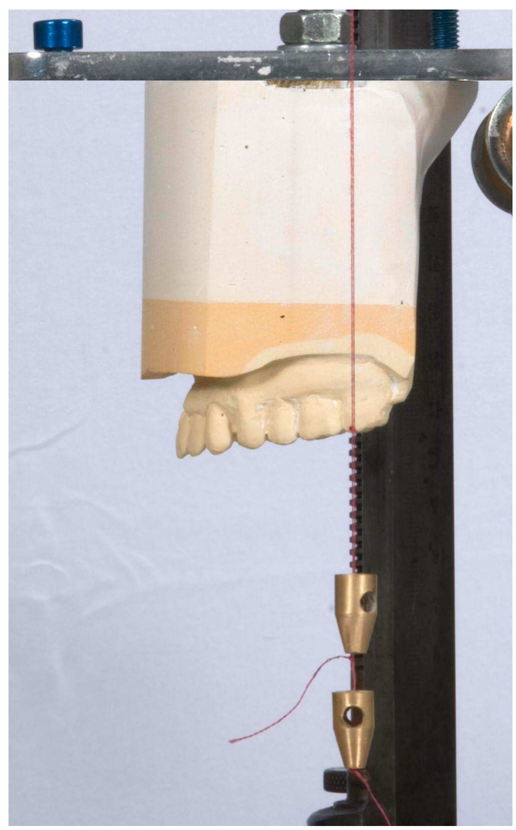


Fig.4.3. Maxillary model in initial position. Each of the two red threads supports a brass bob.

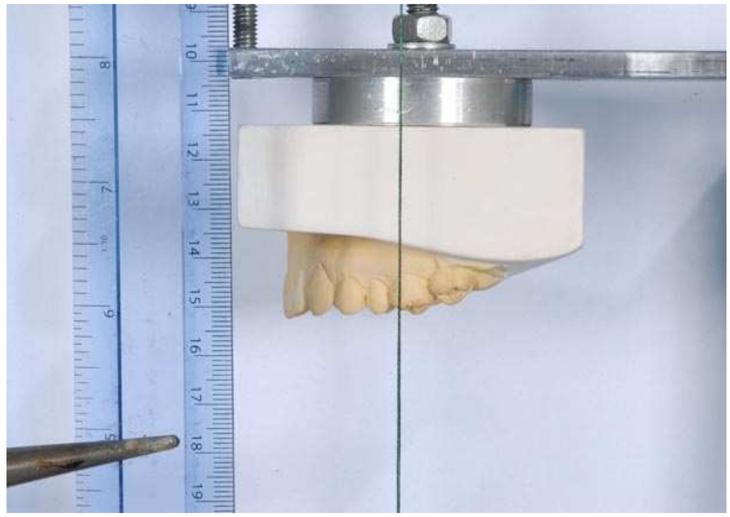
A matrix was constructed using lab putty that would cover the posterior side of the mounting plaster. The maxillary cast, the top arm and vertical post of the articulator were then incorporated in this matrix. This would ensure that no rotational movement was incorporated when the cast was moved into the different positions. A ruler was placed vertically within the picture frame so that the image could be sized, and to ensure that the scale was demonstrated to be one to one.

The photographs were taken using a Nikon D1x digital camera, with a 105mm macro lens. A qualified photographer positioned the camera using a tripod stand thus ensuring it was parallel to the wooden base that located the articulator. The camera was leveled using a spirit level. The camera was set at right angles to the model by moving it laterally until the plumb lines superimposed and ran through the centre of the red reference point. A white background was used during the taking of the images to ensure a clear representation of the specimen being photographed. Two Broncolor miniplus C80 flash heads were placed at 45^0 angles to ensure even lighting of the subject. To ensure the highest quality, photographs were taken using NEF files.

A photograph was taken of the model in its initial position. The model was then moved relative to the articulator cross bar by defined distances and re-photographed.

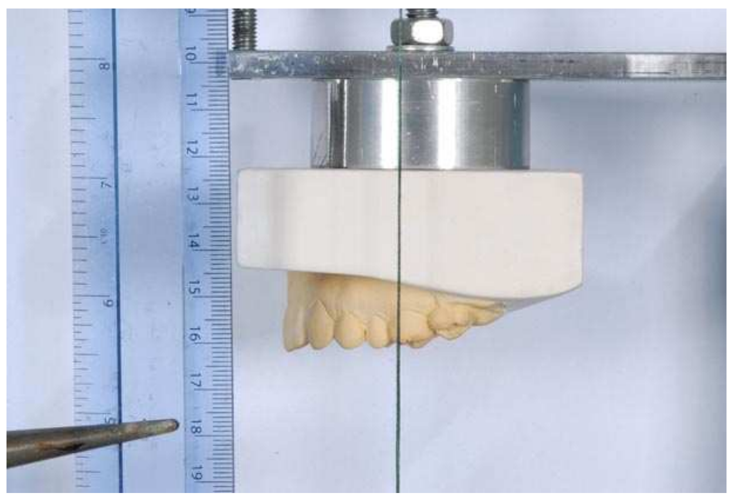
The first image was taken in the start position using the 10mm spacer (Fig.4.4.).

Fig.4.4. Cast in start position using a 10mm spacer



The second image was taken in the downgrafted position (10mm downgraft incorporated) using the 20mm spacer (Fig.4.5.).

Fig.4.5. Cast in downgrafted position using a 20mm spacer



The third image was taken in the impacted position (10mm impaction incorporated) with no spacers used (Fig.4.6.).

Fig.4.6. Cast in impacted position no spacers incorporated

The digital images were transferred to a computer and sized one to one using the image of the reference ruler. The digital images were then analyzed by a graphic designer using Adobe Photoshop CS3 Illustrator computer package.

An image of the model in the displaced position was super-imposed over the image of the model in the initial position. The opacity of the superimposed image was reduced to 60% so that the black reference marks on both models were visible.
A line was superimposed on the threads to produce a vertical articulator axis. A line was drawn at 70º to this vertical axis to produce a reference axis at 20º to the articulator horizontal axis (Fig.4.7.).

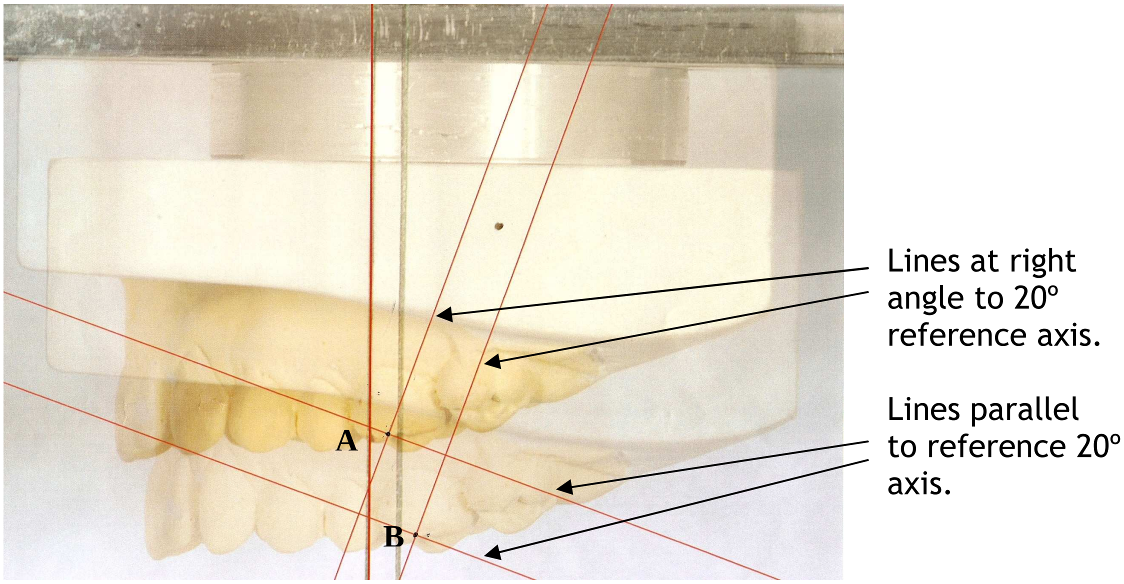


Fig.4.7. Superimposed images of model in initial and displaced positions. Vertical and parallel lines pass through the black reference mark on the model in the displaced (A) and initial (B) position.

Vertical and parallel lines pass through the black reference mark on the model in the displaced (A) and initial (B) positions (Fig.4.7.).

The co-ordinates of the black reference points were recorded and lines parallel and at right angles to the reference axis were drawn through each of the reference points.

The lengths of the sides of the resulting rectangles, which were equal to the horizontal and vertical displacement of the models relative to the reference axis, were calculated from the coordinates of the corners of the rectangle. Two estimates of the displacements were obtained from each rectangle and the analysis was repeated to produce four values.

4.3.2 Results.

The values of the displacements of the models relative to both the articulator and reference axes are shown in Table 4.1. Each of the values of the measured displacements relative to the reference axis was the mean of the four values mentioned above.

Direction and distance, mm, of movement relative to articulator axis.	Direction and distance, mm, of movement relative to reference axis.		
Up	Movement	Measurement	Theory
$h_a = 0.0$	h_{20}	3.40	3.42
$v_a = 10.0$	v_{20}	9.43	9.40
Down			
$h_a = 0.0$	h_{20}	-3.62	-3.42
$v_a = -10.0$	v_{20}	-9.34	-9.40
Forward			
$h_a = 10.0$	h_{20}	9.46	9.40
$v_a = 0.0$	v_{20}	-3.30	-3.42
Forward +Up			
$h_a = 10.0$	h_{20}	12.84	12.82
$v_a = 10.0$	v_{20}	5.83	6.00
Forward+down			
$h_a = 10.0$	h_{20}	6.25	6.00
$v_a = -10.0$	v_{20}	-12.84	-12.82

Table 4.1. Comparison of theoretical predictions and experimental measurements.

Horizontal and vertical movements, h_a and v_a, relative to articulator axes produced displacements, v_{20} and h_{20}, parallel, and at right angles to, reference axes at 20º to articulator axes. Forward (advancement) and up grafting movements were positive.

h_A = Movement parallel to articulator cross bar (horizontal).

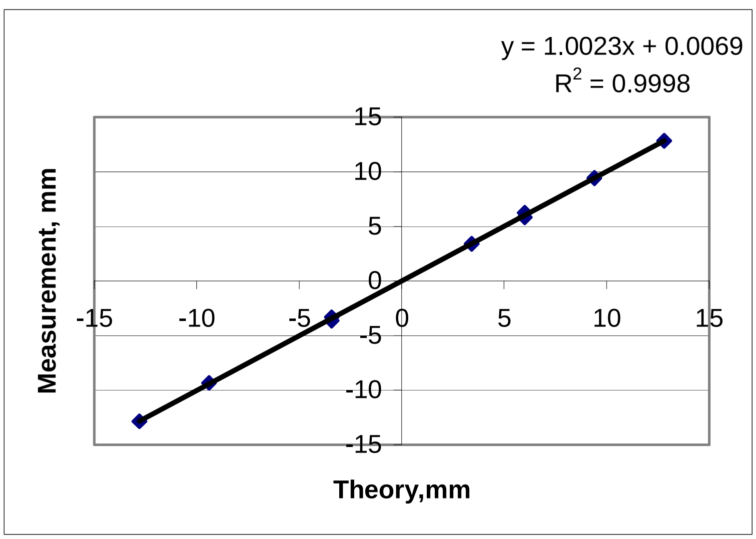
v_A = Movement normal to articulator cross bar (vertical).

h_{20} = Movement parallel to 20º axis.

v_{20} = Movement normal to 20º axis.

The results were also shown graphically in the Graph 4.1., together with statistical parameters. The R^2 value of 0.998 indicated that the there was a strong and highly significant linear correlation between the predicted theoretical values of the displacement and the experimental values obtained by image analysis of the photographs.

Calculation of the 90% confidence limits of the values of the intercept and gradient of the line of best fit in the Graph 4.3. show that the values of 0.0069 for the intercept was not significantly different from 0 and the value of 1.0069 for the gradient was not significantly different from 1 *ie* the best straight line was not significantly different from the line of identity Measured value = Theoretical value.



Graph 4.3: A statistical representation of the correction between the predicted theoretical values of the displacement and experimental values obtained. Data from table 4.1.

4.4 Conclusion:

The mathematical analysis presented above quantifies the errors produced by discrepancies between the reference and articulator axes. The experimental study based on photographs of specific movements of a maxillary model mounted on an articulator followed by image analysis validated the results of the analysis, there being no significant difference between the experimental results and the theoretical predictions from the equations.

Impacting the maxilla when it has not been mounted relative to the natural head position produced unwanted advancements. Downgrafting the maxilla when it has not been recorded relative to the natural head position produced unwanted setbacks.

5

EVALUATION OF AN NEW ORTHOGNATHIC ARTICULATOR SYSTEM

The results reported in the previous chapter implied that the occlusal wafers produced on casts mounted on a semi-adjustable articulator would be inaccurate. **Walker et al (2008a,b)** described an orthognathic articulator and face bow system for orthognathic model surgery based on the reproduction of the patient's natural head position, that would eliminate the systematic errors of cast orientation that occur with the use of semi-adjustable articulators, and they suggested that wafers prepared on the orthognathic articulator would be more accurate, leading to an improved surgical outcome.

No direct validated evidence was presented to support this claim. This has now been evaluated in order to determine whether the orthognathic articulator did, indeed, produce more accurate results.

5.1 MATERIALS AND METHODS.

The accuracy of perioperative wafers constructed on a Standard semi-adjustable and an Orthognathic articulator were compared by carrying out simulated surgery on five plastic model skulls where the "natural head position" could be predictably altered.

5.1.1. Plastic Model skulls.

The plastic model skulls (K_Med Uk) used for this study were similar but not identical. A mounting plate was incorporated into the underside of the skull using cold cure acrylic resin. (Fig. 5.1).

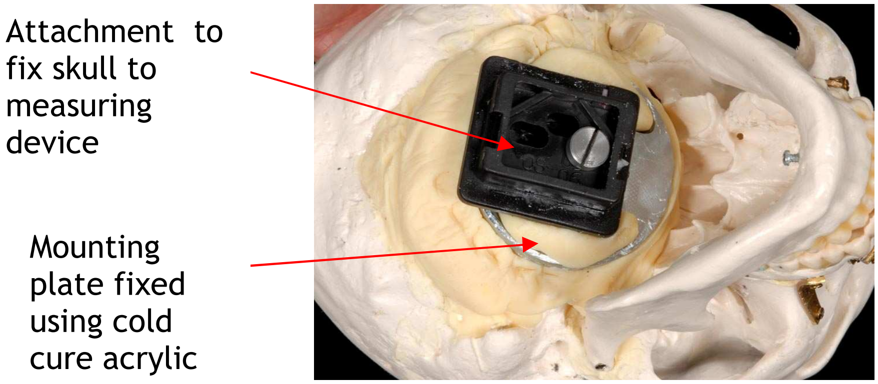


Fig.5.1. Mounting plate attached to the base of the skull.

Duplicate impressions were taken of the maxillary and mandibular dentition using silicone-duplicating material (Metrosil, Metrodent Ltd); Bone screws were screwed through the condylar head of the mandible and the fossa to ensure a fixed path into centric occlusion.

A line was drawn on the maxilla to replicate the position of a Le Fort I osteotomy cut. Holes were drilled above and below this line at the zygomatic buttress and the pyriform aperture, on the left and right sides, anterior-posteriorly. Sufficient room was left for a 5mm impaction. 0.5 mm lengths of 0.7mm stainless steel wire were fed into the drilled holes and were glued into place. These wires were used as reference points for measurements. Four brass plates representing bone plates were adapted to the pyriform aperture and zygomatic areas of the maxilla, bridging where the Le Fort I cut would be. Two screw holes were drilled at each end of the vertical plate for 2mm diameter cortical titanium screws to be inserted to fix the bone plates to the maxilla (Fig. 5.2).

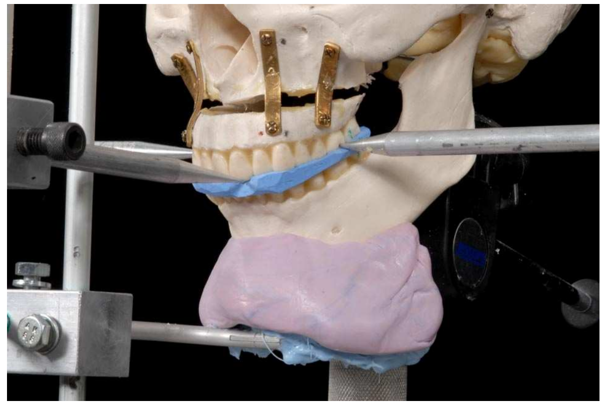


Fig. 5.2. Brass plates with cortical titanium screws fixing the maxilla in place.

A centric registration of the bite of the upper and lower dental arches was taken in rubber base impression material. The lower portion of the maxilla was then detached from the plastic skull by carrying out the Le Fort I osteotomy cut and re-attached it to the skull using the pre-fixed bone plates in the centric bite position.

The skulls were then attached to a custom made measuring device made from a 44.5cm x 28cm x 0.635mm rectangle aluminium base plate. Adjustable feet made of 7mm threaded stainless steel bolts with 1.3mm nuts to secure them in place, each with rubber attachments were attached at each corner of the plate. (Fig.5.3.).

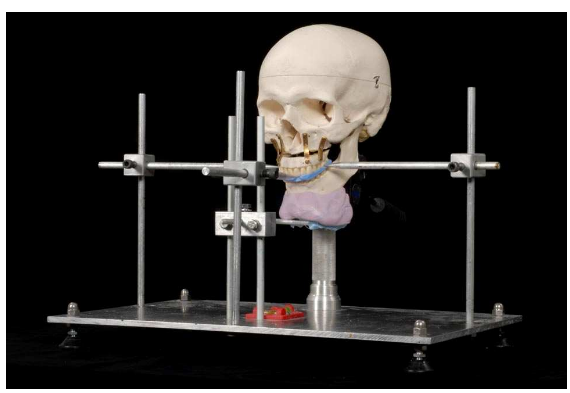


Fig. 5.3. Custom measuring device base.

Spirit levels were attached to the plate to ensure accurate levelling. (Fig. 5.4.).

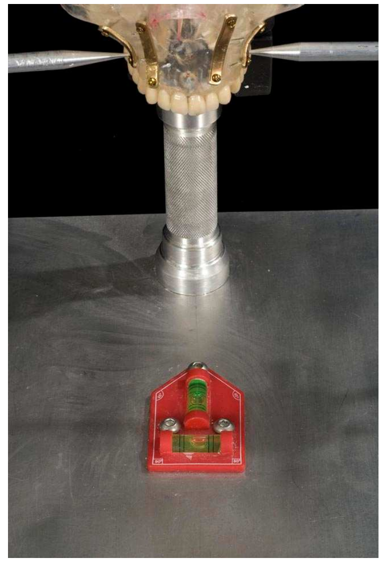


Fig.5.4. Spirit levels attached to measuring device base.

An aluminium rod 4cm in diameter and 14.5cm long was fixed in the centre of the base plate of the measuring device. The upper end of the rod carried a plate that had been taken from a tripod stand used previously for supporting a camera, which incorporated a ball joint that could be rotated and locked into position. (Fig.5.5b.).

(a) (b)

Fig.5.5a&b. Aluminium rod with tripod attachment in place.

The mounting plate attached to the under-side of the skull could be locked onto the camera support.

The antero-posterior angle of the skull was adjusted to simulate different natural head positions. Each of the plastic model skulls was positioned into one of five predetermined angles, -20º, -10º, +10º, +15º and +20º. The angles were derived from the maxillary occlusal plane angle study **(Walker 2005)** where the largest error recorded was –20.5º. Using a ruler and a spirit level, a line was drawn along the Frankfort Horizontal Plane on the skull ensuring that it was level relative to the true horizontal. (Fig.5.6.).

Fig.5.6. Frankfort horizontal plane being levelled to the true horizontal.

The upper portion of the skull (i.e. the skull vault) was then removed, and the remaining part of skull was levelled both medio-laterally and antero-posteriorly. A flat plane was placed across the levelled skull and an angle finder (protractor) was used to record the initial antero-posterior angle of the cut surface. (Fig.5.7.).

Fig.5.7. Angle finder (protractor) placed on the remaining part of skull.

The antero-posterior orientation of the skull was then adjusted until the desired angle plus the initial angle was achieved. (Fig.5.8.).

Fig.5.8. Adjusting the skull to achieve the angle required.

Once the skull was fixed in the angular position required a circular spirit level was fixed using cold cure acrylic to the top of the skull. (Fig.5.9a&b). The spirit level was positioned so that it was level. This would ensure the correct position of the skull and that it remained so throughout the study.

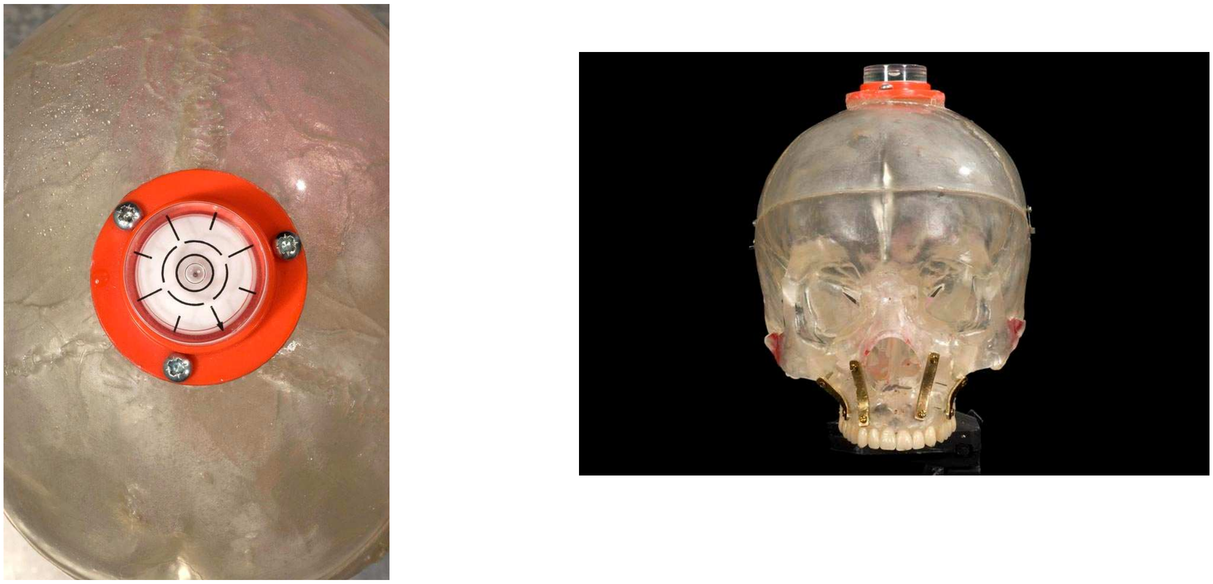


Fig.5.9.a&b. Circular spirit level secured to top of skull.

The mandible was fixed in centric occlusion using a lab putty matrix supported by a face bow bite fork attached to an anterior vertical rod. (Fig.5.10.).

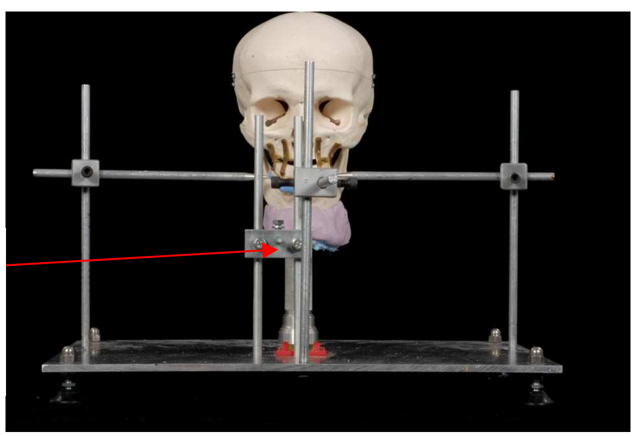


Fig 5.10. Skull with fixed mandible.

5.1.2. **Wafer construction and simulated surgery.**

Duplicate impressions were taken of the maxillary and mandibular dentition using silicone-duplicating material (Metrosil, Metrodent Ltd), which were then cast in a hard stone according to the manufacturer's specification. A face bow recording was taken of the skull in the start position using the Orthognathic face bow, (Fig.5.11.) which used spirit levels and the Standard face bow, which used an orbital pointer. (Fig.5.12.).

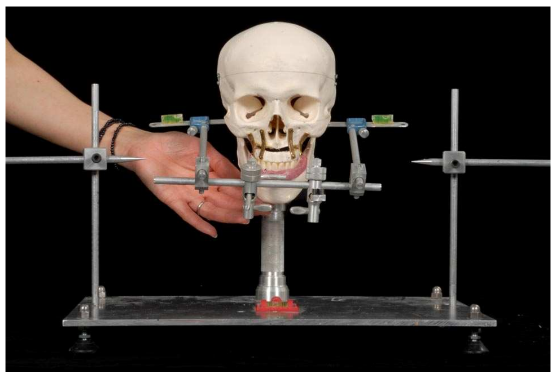


Fig.5.11. Face bow recording using the face bow appropriate to the Orthognathic articulator.

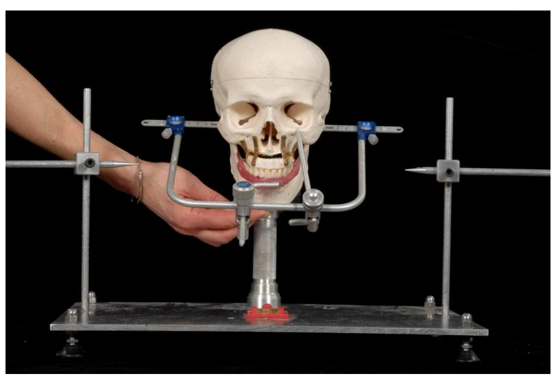


Fig.5.12. Face bow recording using the face bow appropriate to the Standard articulator.

A maxillary cast was then mounted on both the Orthognathic and the Standard articulators using the appropriate face bow.

Three maxillary movements were carried out for each skull:

1. Forward 10 mm
2. Forward 10mm & up (impaction) 5mm
3. Forward 10mm & down (downgraft) 5mm

When carrying out the articulating procedure a 5mm aluminum disc was positioned between the underside of the articulator's upper cross member and the articulating disc, this would be known as the "start position" (Fig.5.13.). Removal of the disc impacted the cast by 5mm. Replacing the 5mm disc with one 10mm thick produced a 5mm downgraft.

Aluminium Articulating disc

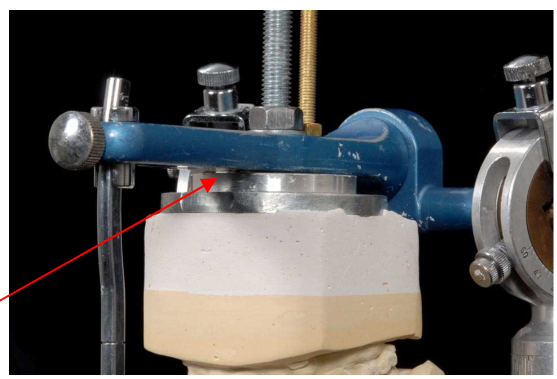


Fig.5.13. Maxillary cast mounted using aluminium disc.

The mandibular cast was articulated using a centric rubber based registration bite. The mandible was fixed in centric occlusion using a lab putty matrix. Horizontal advancement of the cast to simulate model surgery was made using a hole in the upper cross members of each articulator, 10mm in front of the hole used to mount the cast in the start position.

Two thin surgical acrylic wafers had been constructed previously in cold cure clear acrylic on duplicated upper and lower casts. These were then placed on the articulated casts that had undergone the necessary displacements. The wafers were trimmed occlusally until there was tooth-to-tooth contact between the upper and lower dentition also ensuring that the incisal pin was touching the anterior table. The wafers were then sealed together with sticky wax. This was now the final perioperative wafer. (Fig.5.14.).

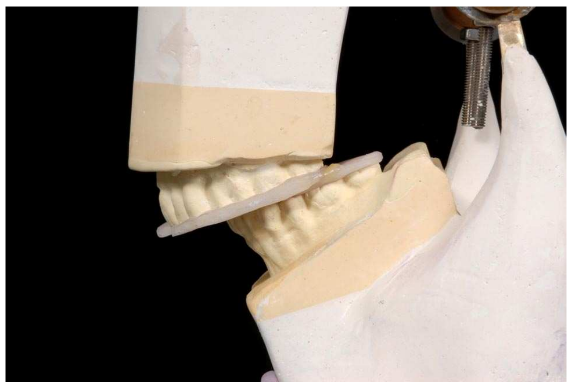
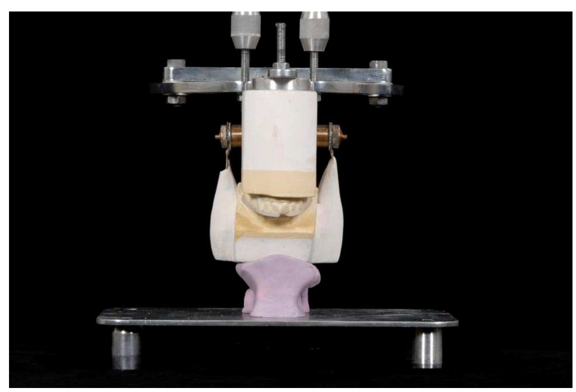


Fig.5.14. Perioperative wafer with maxilla and mandible occluding.



Standard **(a)** Orthognathic **(b)**

Fig.5.15a&b. Standard and Orthognathic articulators with predicted movements carried out on the upper model and surgical wafer in place.

The maxilla of the model skull was detached by removing the custom-made bone plates from the pyriform aperture and zygomatic buttress. The maxilla was repositioned using the perioperative wafer constructed firstly on the Standard articulator, simulating surgery. The mandible was in a fixed position, the wafer was fitted to the mandibular teeth and then the detached maxilla was positioned with the dentition occluding the wafer and mandibular teeth. Dental sticky wax was used to seal the maxilla in place and re-attach it to the skull. (Fig.5.16.).

The procedure was repeated using a wafer constructed using the orthognathic articulator.

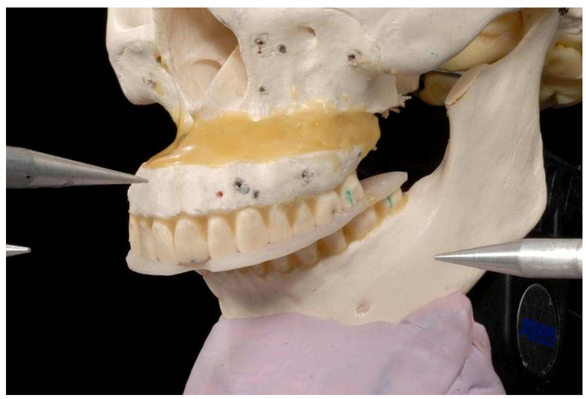


Fig.5.16. Maxilla repositioned using the perioperative wafer held in place with sticky wax.

The process was carried out twice for each of the five angles i.e. for ten plastic skulls. The mandible was in a fixed position so there would always be a fixed point of reference as the simulated surgery was carried out only on the maxilla. The mandible was also de-rotated when there was a downgrafted displacement, but this was calculated accordingly to allow for this displacement.

5.1.3 Measurements and measuring frame.

The displacement of six reference points and the maxillary occlusal plane angle were used to quantify the movements of the maxilla after simulated surgery.

The simultaneous displacements carried out were:

1. Antero-Posterior movement, using a reference point on the upper left central incisor. (Fig.5.17.).
2. Anterior vertical movement measured between a reference point at the nasion to the left central incisor tip.
3. Posterior vertical height right side measured between two reference points previously placed above and below the Le Fort I cut line on the plastic skull. (Fig.5.17.).
4. Posterior vertical height left side measured between two reference points. (Fig.5.17.).
5. Anterior vertical height right side measured between two reference points. (Fig.5.17.).
6. Anterior vertical height left side measured between two reference points.

(Fig.5.17.).

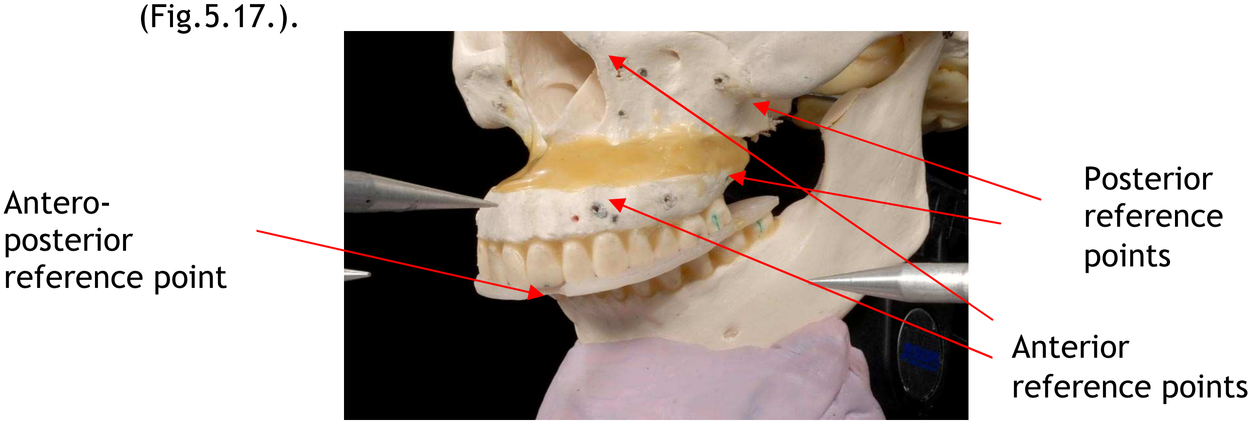


Fig.5.17. Reference points used to quantify the movements of the maxilla after simulated surgery.

Measurements were made with the skull supported in the measuring frame. A 8mm aluminium measuring rod was attached vertically to the base plate of the device opposite the frontal position (Fig.5.18).

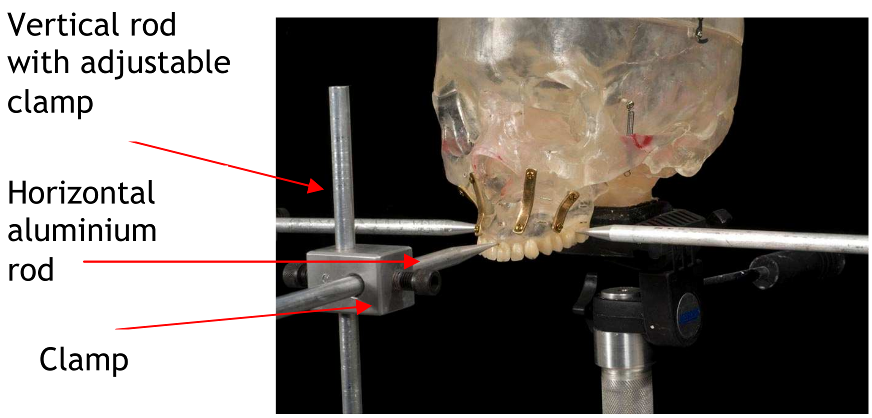


Fig. 5.18. Aluminium rod attached horizontally by a clamp.

A 8mm rod with a pointer at one end was attached horizontally using a clamp that allowed the rod to be moved antero-posteriorly and vertically.

The antero-posterior measurement was taken by bringing the pointed tip of the horizontal rod into contact with the reference point on the upper left central incisor and measuring the length of rod protruding from the clamp using a electronic digital calliper with a resolution of a hundredth of a mm.

Vertical measurements were made using a vertical height calliper (Chesterman, Sheffield) with an analogue vernier scale with a resolution of 0.5mm. (Fig.5.19.).

The maxillary occlusal plane angle was measured relative to the true horizontal using a flat plane and a protractor adapted with a sliding fit on a right-angled stand **Walker et al (2005).** This allowed the measure of the anterior-posterior angle and the medio-lateral angles.

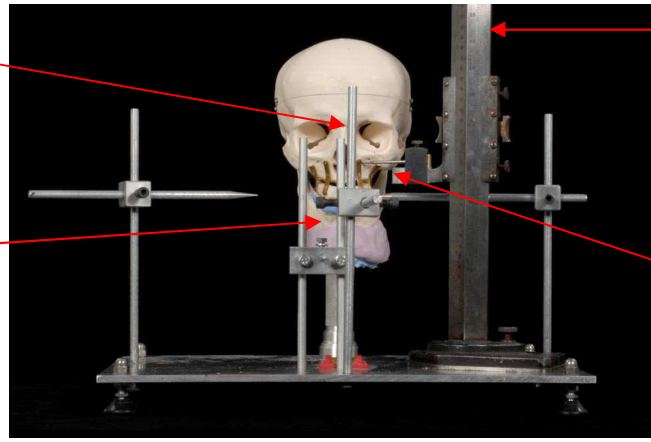


Fig.5.19. Plastic skull set in a predetermined angle with the vertical calliper for measurements.

Measurements were made on the skull in the start position prior to and after simulated surgery and the changes in the position of the maxilla were calculated. The full process was duplicated to reduce any error in the method.

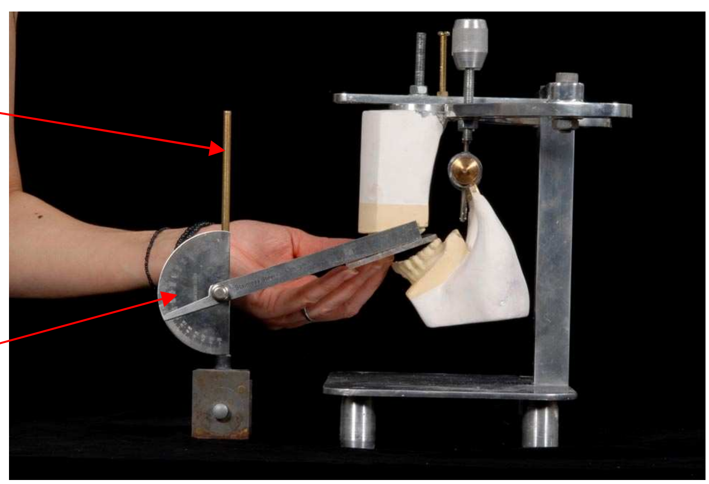


Fig.5.20. Protractor on a sliding fit stand measuring the maxillary occlusal plane angle.

5.2. Results.

The results were displayed as histograms and Bland – Altman plots and analysed using a non-parametric test; each value was the mean of two measurements. The errors analysed were the difference between actual and predicted movements calculated for both the Standard articulator and the Orthognathic articulator; where the actual movement was greater than the predicted movement the difference was written as positive and as negative when it was less.

Using a sign to denote the direction of movement was useful for displaying the nature of the errors, but produced statistical problems. The effect on the calculation of the mean value has been outlined in Chapter 1, but using positive and negative values also produced a problem in the non-parametric statistics, which is best illustrated by an example. An error of 3mm is obviously greater than an error of 0mm, but if there is under-advancement the 3mm error will be recorded as -3mm; 0 is larger than -3 and hence the 0mm will be classified as the greater error when ranking the results for statistical comparison.

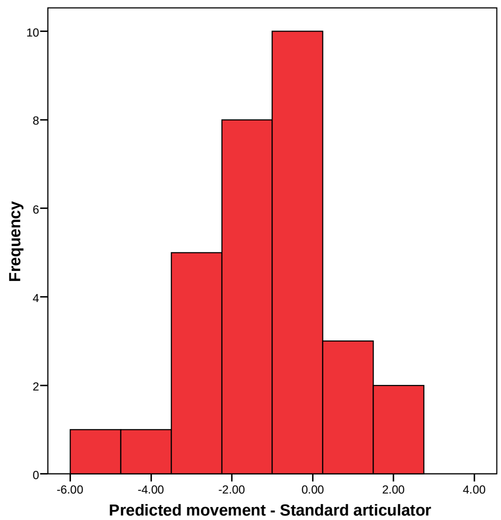
To eliminate the statistical problems the absolute values of the errors, without a sign, were used. Both the errors with signs and the absolute errors without signs were displayed.

The errors that occurred for the Standard and the Orthognathic articulator were displayed as histograms, with summary statistics. The histograms immediately showed the distribution of the grouped data and the errors of the axes for both articulators and the same scale was used to further simplify the comparisons. The x-axis showed the magnitude of error; the y-axis showed the frequency of the error. Each of the 30 results was the mean of two measurements.

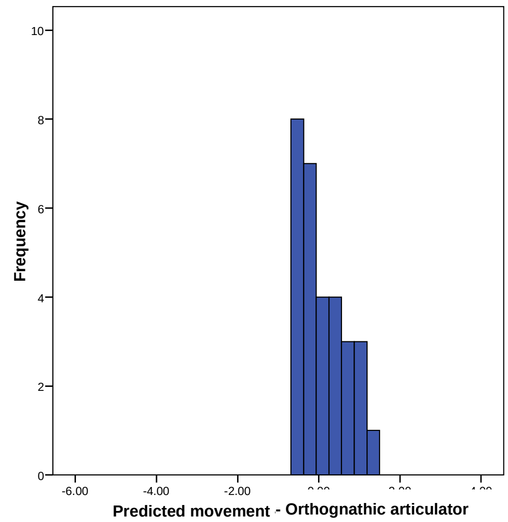
The errors produced by the two articulators were compared visually as Bland Altman graphs. (**Bland and Altman, 1986).** The y-axis of the Bland Altman plot showed graphically the individual errors of the Standard articulator (shown in red) and of the Orthognathic articulator (shown in blue). The x-axis was arbitrary and was the distance between a fixed datum point and the tooth used to measure the movement of the maxillary cast, which was identified for each comparison; the x-value shown for each error value was the mean measurement for each articulator. Ideally points should cluster close to 0, which represented no difference between the predicted movement plan and the actual movement. The spread of the error values indicated the variability of the error, with a narrow spread indicating consistency of a limited error. The magnitude and variability of the errors were characterized by the mean value (m) and standard deviation (s) of the errors. The graphs showed the mean error for each articulator (solid line) and the 95% confidence limits, defined as m ± 2s (dotted line). Finally, the differences between the absolute errors of the Standard and the Orthognathic articulators were compared statistically using the non-parametric Wilcoxon signed rank test. The test was a non-parametric analogue of a paired sample t-test. **(Zar, 2010).** The comparison of the analysis of both the signed and absolute errors will be treated in Chapter 6 Discussion and Conclusions.

The study produced a large amount of data. The results and analysis of the vertical and horizontal errors measured at the central incisors are presented in full in this Chapter. The other vertical errors are shown in full in **Appendices 1a-4d** and in a summary presented in this chapter.

5.2.1 Antero-posterior errors -central incisor.



(a)

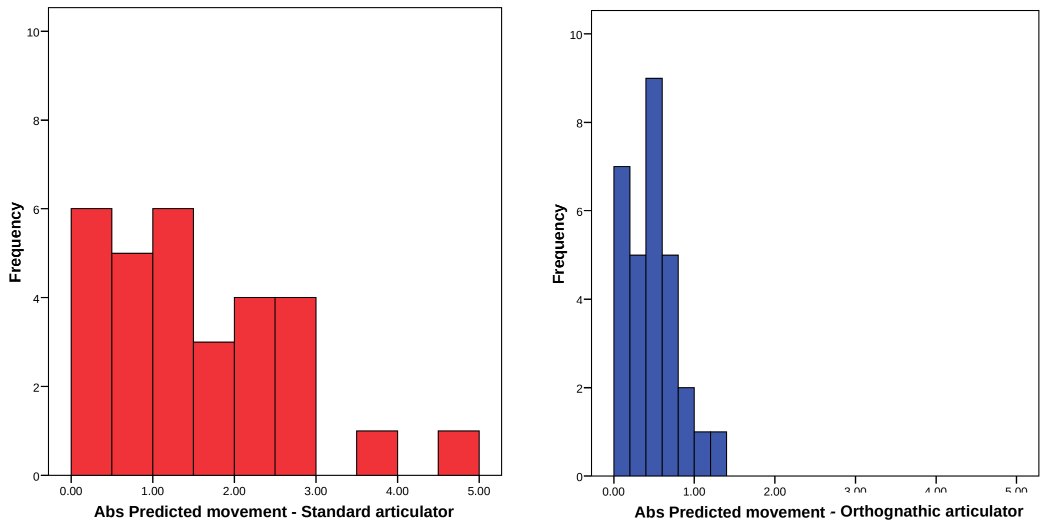


(b)

Graph 5.1a&b. Antero-posterior errors in mm Standard and Orthognathic articulators.

The histograms showed that the errors for the Standard articulator (Graph 5.1a.) ranged from –6mm to +2.5mm, mean = -1.03mm and the standard deviation = 1.621mm; the errors for the Orthognathic articulator (Graph 5.1b.) ranged from –0.75mm to +1.50mm, mean = 0.11mm and the standard deviation = 0.569mm.

The histograms showed that the errors for the Standard articulator were mostly negative errors, (an under-advancement of the maxilla) whereas the Orthognathic articulator errors were mostly positive, (over-advancement of the maxilla). This exacerbated the problem of ranking the results for statistical analysis mentioned above. The Standard deviation for both articulators showed that the Orthognathic articulator was more consistent and the errors there were smaller than the Standard articulator. The histograms also showed a lack of symmetry of the errors of both articulators.



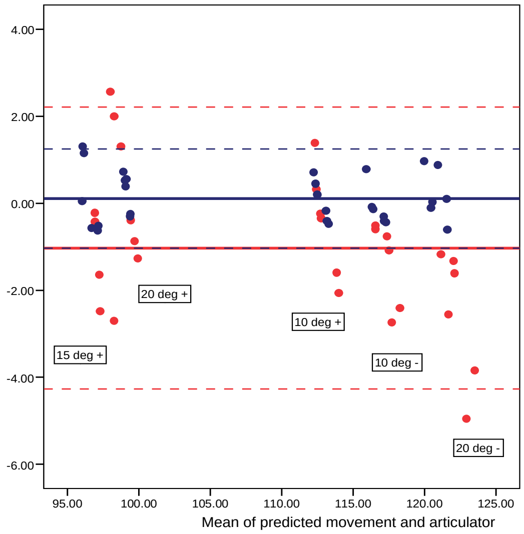
(a) **(b)**

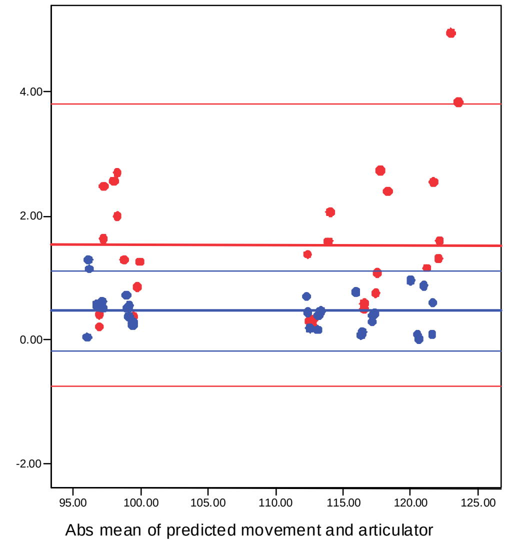
Graph 5.2a&b. Antero-posterior absolute errors in mm Standard and Orthognathic articulators.

Graph 5.2a. showed that the absolute errors for the Standard articulator ranged from 0mm to 5mm, mean = 1.53mm, with a standard deviation = 1.136mm; the errors for the Orthognathic articulator (Graph 5.2b) ranged from 0mm to 1.50mm, mean = 0.47mm, with a standard deviation = 0.324mm.

There was still a marked difference between the mean error for the Standard articulator and the Orthognathic articulator, which was in favour of the Orthognathic articulator.

Using absolute errors increased the mean error for both articulators, because positive and negative errors no longer cancelled each other, but the effect was greater for the Standard articulator, which had a predominance of negative errors. Using either the signed or absolute errors showed the Orthognathic articulator had a smaller mean error than the Standard articulator.





Signed errors (a) **Absolute errors (b)**

Graph 5.3a&B. Bland Altman plot showing antero-posterior errors (vertical axis) of Standard and Orthognathic articulators.

Bland Altman plot of the signed errors (Graph 5.3a.) confirmed the results shown in the histograms. The Orthognathic articulator (Graph 5.3b.) showed smaller errors, the mean being closer to zero than for the Standard articulator, which also displayed a much greater variability, as shown by the separation of the 95% confidence limits. This was difficult to interpret and it was compounded by the fact that the lower 95% limit of agreement for the orthognathic articulator (blue dashed) sat exactly on the solid line for the standard articulator.

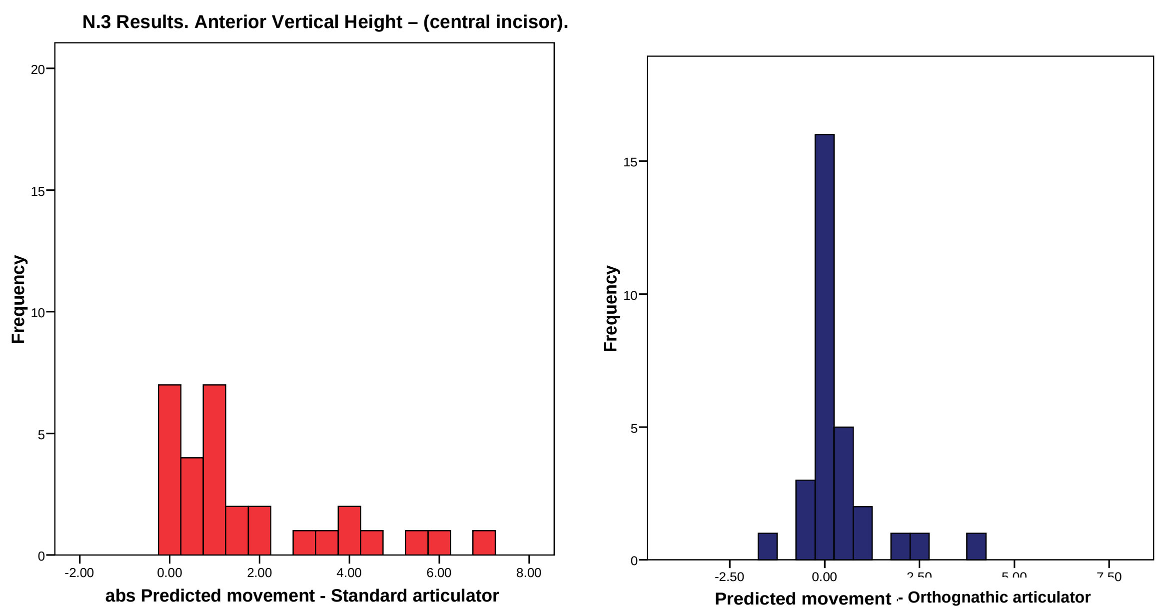
The data in Graph 5.3a appeared to fall into five separate groups, which were found to relate to the angulations of the skull. The boxed numbers in Graph 5.3a.e.g. $\boxed{\text{20 deg + or -}}$ represented the chosen angle the plastic skull was set at.

It can also be noted that the magnitude of errors increased with extreme change of the maxillary plane angle at -20° and +20°. This was readily detected with the standard articulator but not apparent with the Orthognathic articulator.

The Bland Altman plot of the absolute errors (Graph 5.3b) confirmed the results shown in the histograms. The Orthognathic articulator showed smaller errors, the mean being closer to zero than the Standard articulator. There were, however, a band of errors of c. 0.5mm for the Standard articulator

The Wilcoxon comparison of the absolute measures showed that the Orthognathic articulator showed larger error in 6 of the 30 paired comparisons. The value of the Wilcoxon parameter, z, was –3.877. The difference in the errors of the two articulators was highly significant, P<0.000.

5.2.1 Vertical errors -central incisor.



(a) **(b)**

Graph 5.4a&b. Vertical errors in mm, Central incisor. Standard and Orthognathic articulators.

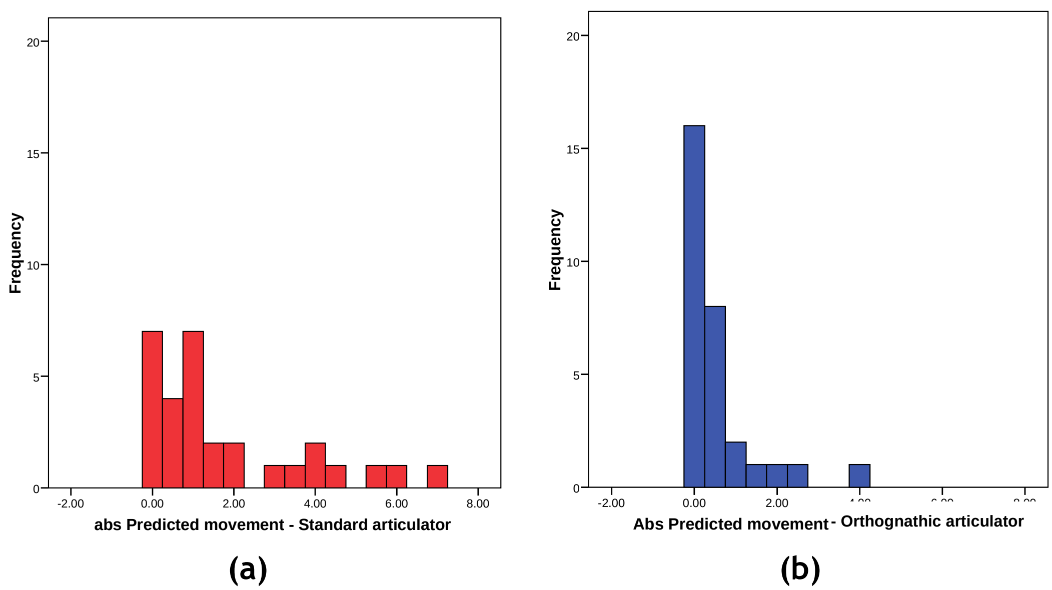
The Histograms showed that the errors for the Standard articulator (Graph 5.4a.) ranged from –4mm to 7mm, mean = 0.45mm and the standard deviation = 2.647mm;

the errors for the Orthognathic articulator (Graph 5.4b.) ranged from –2mm to 4mm, mean = 0.33mm and the standard deviation = 1.003mm.

The Standard articulator showed the larger error of the two articulators although the Orthognathic articulator still had a considerable error, resulting from systematic errors in the production of the wafers and of measurements.

The standard deviation showed that the errors of the Orthognathic articulator were smaller and more consistent.

The histograms again showed a lack of symmetry of the errors for both articulators.

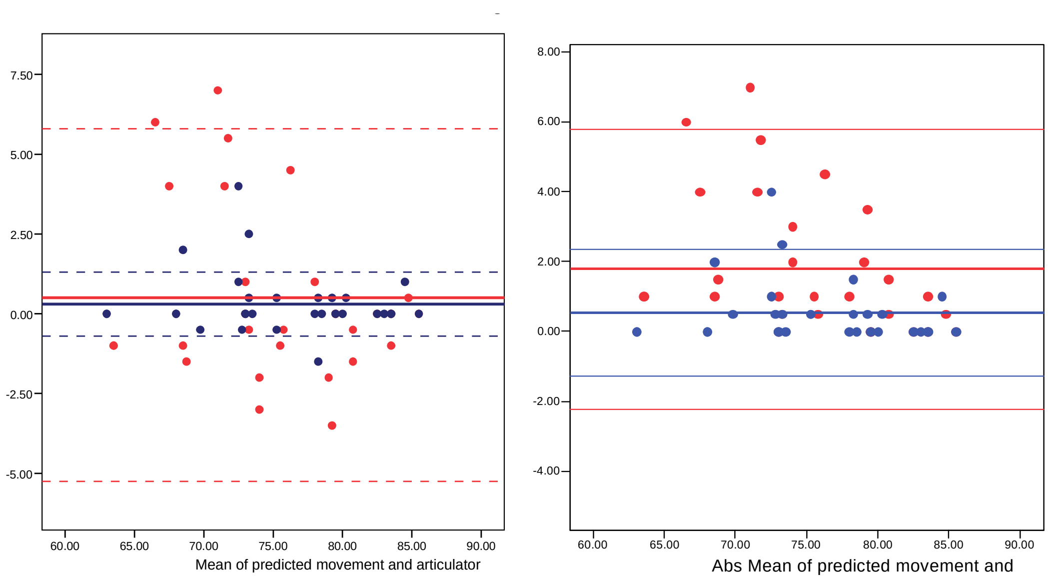


Graph 5.5a&b. Vertical absolute errors in mm, Central incisor. Standard and Orthognathic articulators.

The Histograms showed that the absolute errors for the Standard articulator (Graph 5.5a) ranged from 0mm to 7mm, mean = 1.78mm, with a standard deviation = 1.981mm; the errors for the Orthognathic articulator (Graph 5.5b) ranged from 0mm to 4mm, mean = 0.53mm, with a standard deviation = 0.909mm.

There was still a marked difference between the mean error of the Standard articulator and the Orthognathic articulator, which was in favour of the Orthognathic articulator.

Using the absolute errors again as in the Antero-posterior measurements, increased the mean error for both articulators, because positive and negative errors no longer cancel each other, but the effect was greater for the Standard articulator, which had a predominance of negative errors. Using either the signed or absolute errors showed the Orthognathic articulator had a less mean error than the Standard articulator.



Signed Errors (a) **Absolute errors (b)**

Graph 5.6a&b. Bland Altman plot showing Vertical errors (vertical axis) of Standard and Orthognathic articulators.

The Bland Altman plot (Graph 5.6a&b) confirmed the results shown in the histograms. The Orthognathic articulator showed (Graph 5.6b.) smaller errors, the mean being closer to zero than for the Standard articulator (Graph 5.6a.), which also displayed a much greater variability, as shown by the separation of the 95% confidence limits. It was not clear from the plots that the points fell into the five separate groups related to the angulations of the plastic skull.

The plot of the absolute errors (Graph 5.6b.) confirmed the results shown in the histograms. The Orthognathic articulator showed smaller errors, the mean being closer to zero than the Standard articulator. There was, however a plotted error for the Orthognathic articulator, which was 4mm, which would be certainly clinically be significant.

The Wilcoxon comparison of the absolute measures indicated that the Orthognathic articulator showed a larger error in 2 of the 30 paired comparisons, the Standard articulator showed larger errors in 20 comparisons, with 8 showing no difference. The value of the Wilcoxon parameter, z, was –3.963. The difference in the errors of the two articulators was highly significant, P<0.000.

5.2.1. Other vertical errors.

The statistics descriptive of the other vertical errors are given in Table 5.1.

	Standard (mm) Range Mean (SD)	**Orthognathic (mm)** Range Mean (SD)	**Abs. Standard (mm)** Range Mean (SD)	**Abs. Orthognathic(mm)** Range Mean (SD)
Anterior Right	-4.0 → 6.0 0.07 (2.79)	-2.0 → 3.5 0.17 (1.00)	0 → 6.0 2.1 (1.79)	0 → 3.5 0.73 (0.69)
Anterior Left	-2.5 → 7.0 0.52 (2.46)	-1.0 → 2.75 0.47 (0.85)	0 → 7.0 1.72 (1.82)	0 → 3.0 0.63 (0.73)
Posterior Right	-5.0 → 5.0 -0.08 (2.85)	-2.5 → 1.75 0.03 (0.82)	0 → 5.75 2.28 (1.66)	0 → 2.75 0.53 (0.62)
Posterior Left	-3.0 → 6.0 0.5 (2.45)	-1.75 → 3.0 0.55 (0.94)	0 → 5.75 1.93 (1.54)	0 → 3.0 0.82 (0.71)

Table 5.1. Vertical errors, mm, measured at 4 reference points.

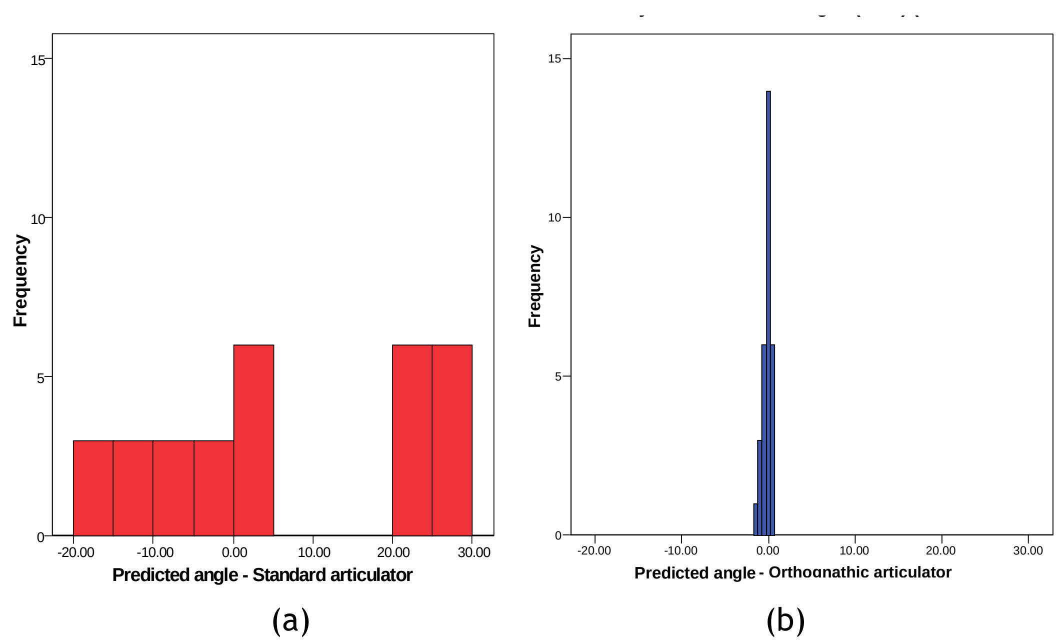
The values of the parameters in Table 5.1 were consistent with the vertical errors measured at the central incisor. The range of errors for the Standard articulator is consistently wider than for the Orthognathic articulator and this difference is also apparent in the value of the standard deviation. The value of the mean error was, with one exception, smaller for the Orthognathic articulator than the Standard articulator.

The Wilcoxon comparisons using the absolute errors are shown in Table 5.2. At all sites the comparisons showed that the Orthognathic articulator was consistently better than the standard articulator, the differences being statistically highly significant.

Site	Orthognathic Artic better	Standard Artic better	No difference	z	P<
Ant. Right	22	2	6	-4.028	0.000
Ant.Left	20	2	8	-3.827	0.000
Post. Right	24	1	5	-4.315	0.000
Post. left	22	4	4	-3.700	0.000

Table 5.2. Wilcoxon comparison of vertical errors measured at 4 reference points.

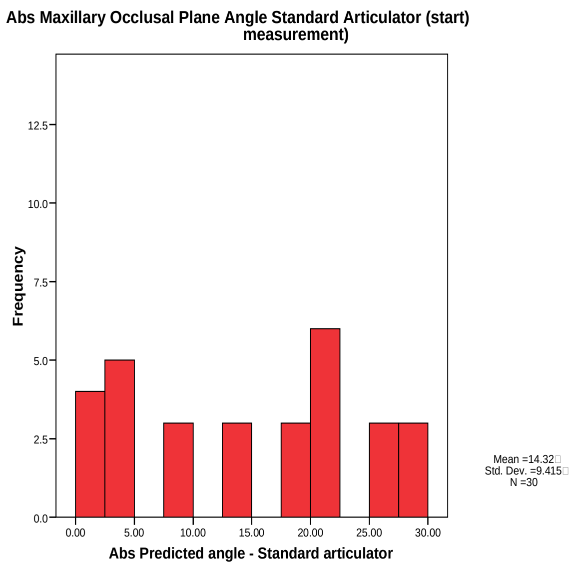
5.2.4. Maxillary occlusal plane angle.

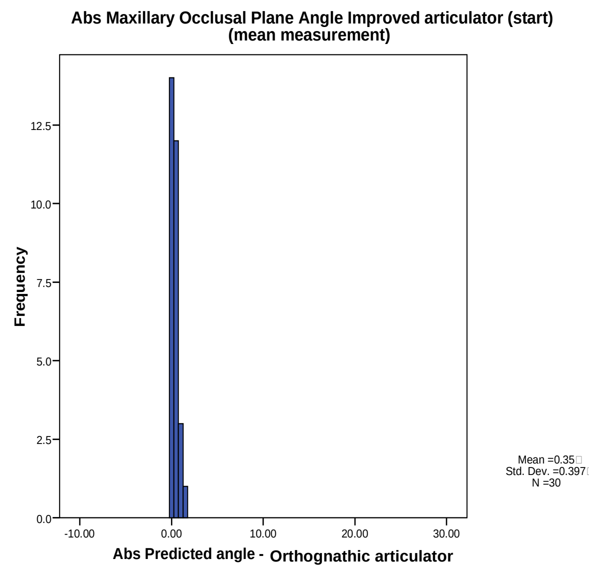


Graph 5.7a&b. Maxillary Occlusal Plane Angle errors, in degrees. Standard and Orthognathic articulators.

The histograms showed that the errors for the Standard articulator (Graph 5.7a) ranged from -19° to 28°, mean = -5.62° and the standard deviation = 16.37°; the errors for the Orthognathic articulator (Graph 5.7b) ranged from -0.75° to 0°, mean = -0.15° and the standard deviation = -0.51°.

The Standard articulator again showed the larger error of the two articulators, with a larger standard deviation. The errors of the Orthognathic articulator were very much smaller and more consistent.



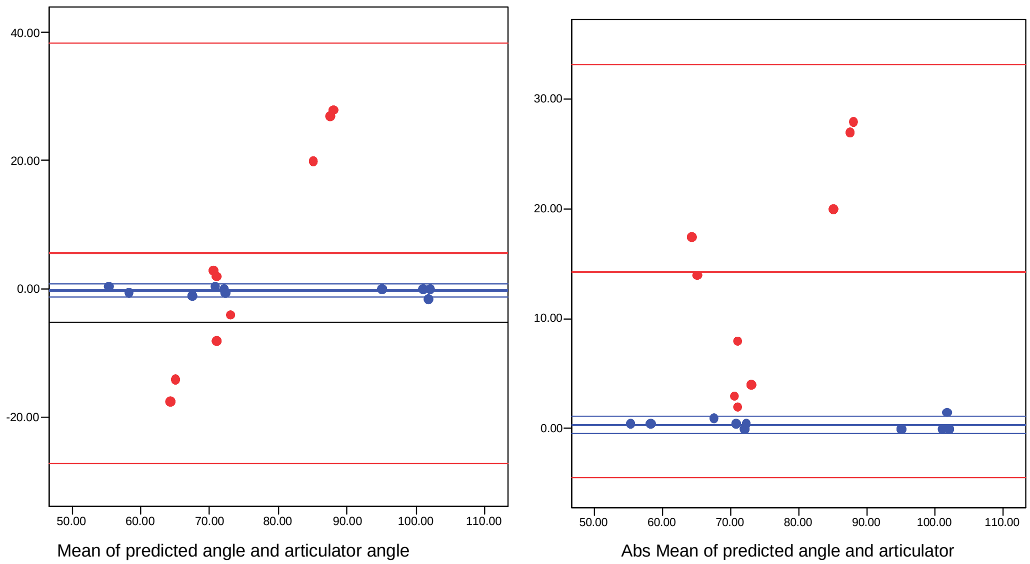


(a) **(b)**

Graph 5.8a&b. Maxillary Occlusal Plane Angle absolute errors in degrees. Standard and Orthognathic articulators.

Graph 5.8a showed that the absolute errors for the Standard articulator ranged from 0° to 28°, mean = 14.32°, with a standard deviation = 9.415°; the errors for the Orthognathic articulator (Graph 5.8b) ranged from 0mm to 0.5° mean = 0.35°, with a standard deviation = 0.397°.

There was still a marked difference between the mean and standard deviation of the errors for the Standard articulator and the Orthognathic articulator, which was in favour of the Orthognathic articulator.



Signed Errors (a) **Absolute errors (b)**

Graph 5.9a&b. Bland Altman plot showing Maxillary Occlusal Plane Angle errors, in degrees. Standard and Orthognathic articulators.

The Bland Altman plot of the signed and absolute errors (Graph 5.9a&b) confirmed the results shown in the histograms. The Orthognathic articulator showed significantly smaller errors, the mean being closer to zero than the Standard articulator. The Standard articulator also had very large errors occurring. This would certainly be clinically significant.

The Wilcoxon comparison of the absolute measures (See Appendices) showed that the Orthognathic articulator showed smaller error in all of the 30 paired comparisons and that the difference was highly significant, $P<0.000$.

6

DISCUSSION AND CONCLUSIONS

6.1. Discussion.

Commercially available semi-adjustable articulators manufactured for prosthetic and occlusal analysis purposes have been used worldwide for orthognathic planning, but the literature identifies inaccuracies that arise from using these systems.

There has been compelling evidence that casts mounted on semi-adjustable articulators using the conventional face bow technique have systematic errors of cast orientation. The angle between the maxillary occlusal plane angle of the cast and the articulator cross member replicates neither the angle between the occlusal plane and the Frankfort horizontal plane nor horizontal plane with the patient in the natural head position. The discrepancy may be as much as 20º **(Walker et al (2008a).**

There is also been strong evidence that the final surgical outcome may differ from the prediction plan using commercially available articulators. These issues were reviewed and discussed in chapter 1 and 2.

Within the literature there have been suggestions that there is a causal connection between misalignment of the casts used for model surgery and inaccurate surgical outcomes. **Ellis (2001)** suggested that errors of surgical outcome were both more common and more severe than the literature suggested and that surgeons evaluating the accuracy of the outcome of orthognathic surgery "will often face a surprise, if not be shocked". He was explicit about the cause of errors-"accurate mounting of the casts on an articulator is an *essential* (sic) component of planning surgery”. By accurate mounting he meant “orientating the casts on the articulator in the same spatial relationship as the teeth are oriented to the facial bones”. He offered no evidence, other than clinical experience, for his statements.

Sharifi et al (2008) identified the well-established discrepancy in the orientation of models mounted on articulators using conventional face bows as a possible source of error in surgical outcome. There was, once again, no objective evidence to support this suggestion.

Gateno et al (2001) investigated the effect of the occlusal plane misalignment on the surgical outcome for a single case in which the axis-orbital plane was 12° steeper than the patient’s value. Analysis of tracings suggested that a 10mm maxillary advancement relative to the articulator would result in a surgical under advancement of 1.5mm. The findings in this study also show a vertical error that was overlooked by the authors.

Natterstad and Vedtofte (1994) presented a mathematical analysis of the surgery effect of an angular error in the mounted casts, which was equivalent to a discrepancy in the orientation of the reference and articulator axes. Only the vertical position was analysed, but the equations used were incorrect and contained only the tangent of the angle. This resulted in the vertical discrepancy depending only on the horizontal displacement and an underestimate of the magnitude of the errors.

There was clearly a need for convincing evidence of the effect of incorrect cast orientation on surgical outcome compared with the prediction plan. This gave the motivation to undertake this study. Firstly to demonstrate the effect of incorrect cast orientation on the maxillary cast movements in model surgery, to mathematically quantify the errors and to experimentally validate the mathematical analysis, all of which have been presented in this thesis.

Methods of improving the mounting of casts on semi-adjustable articulators using conventional face bows have been suggested, despite the lack of evidence of the connection between cast misorientation and surgical outcomes. It is necessary to decide whether the mounted cast should reproduce the angle between the occlusal plane and either the Frankfort plane or the horizontal plane in the natural head position.

The Frankfort horizontal plane is a widely recognised anatomical reference plane. It is relatively easy to identify on the patient and from lateral radiographs. Downs (1956), however, showed that the Frankfort horizontal plane is commonly not horizontal. (Fig. 6.1).

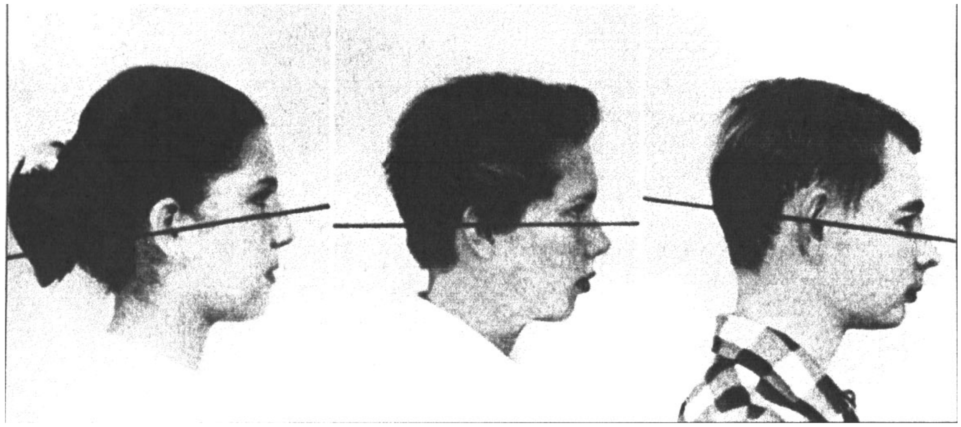


Fig.6.1. Variations of the cant of the Frankfort horizontal plane. (Illustration from Downs WB. Angle Orthod.1956;26:)

Thus casts mounted with the articulator's cross member representing the Frankfort plane may give a false impression of the clinical orientation of the maxillary occlusal plane.

Patients can repeatedly and accurately assume their natural head position **(Moorrees and Kean,1958 ; Walker et al 2008 A)** and the horizontal plane is easily and repeatably identified. Apart from being easily reproducible the natural head position can be seen by a trained eye and adjusted accordingly if the patient has postured. Casts mounted relative to the horizontal natural head position reproduce the natural appearance of the teeth relative to the head.

The angular difference between the two planes is variable. **Allport (2002)** presented data from 10 patients that showed that the mean angle between the planes was 7.65° but varied between -1.5° and + 18.5°. **Pitchford (1991)** reported an average discrepancy of 8° between the natural head position and the Frankfort horizontal plane, but gave no details of the range of values.

Various methods of correcting the inaccurate orientation of casts mounted using conventional face bow have been suggested. **Gonzalez & Kingery (1968)** devised an arbitrary adjustment to align the articulator cross member with the Frankfort plane that consisted of either placing the orbital pointer 7mm lower than the orbital border of the patient or raising the orbital pin of the face bow by 7mm once transferred to the articulator. The correction was equivalent to a 5.9º realignment of the cast. **Stade et al (1982)** suggested a correction of 16.4mm, equivalent to a 10º realignment, to align the cross member with the horizontal of the natural head position. Such mean value corrections are unlikely to suit all patients, particularly candidates for orthognathic surgery, who may be particularly variable.

Ellis et al (1992) suggested individual corrections could be made by rotating the face bow attached to the articulator to reproduce the angle between the maxillary occlusal plane and Frankfort plane measured on a lateral cephalograms. The corrections were time consuming and depended on the operator measuring the lateral cephalogram accurately. A similar method was suggested by **Gateno et al (2001),** but required an additional lateral cephalograms. This made this method unsuitable for routine use because it would not be ethical to subject patients to an additional lateral cephalogram.

There appears to be only one articulator system specifically designed for orthognathic model surgery planning. **Walker et al (2008 A and B)** took into consideration all the limitations of commercially available articulator systems and devised a system that addressed these shortcomings. The natural head position was used to reproduce the maxillary occlusal plane angle seen in the patient on the articulator. Although the accuracy of the orientation of mounted casts was established, the accuracy of the perioperative wafers constructed on the orthognathic articulator was not investigated. This fuelled the motivation to undertake this study to evaluate Walker's orthognathic articulator.

6.1.1. Errors produced by cast misalignment.

The qualitative example showed that a horizontal movement of a model relative to axes based on the articulator on which it is mounted also produced movements of the model relative to the reference axes based on the patient's natural head position. Relative to the reference axis the model was under-advanced and displaced inferiorly.

In this study the mathematical analysis is presented, it quantified the errors produced by discrepancies between the reference and articulator axes. The mathematical analysis produced equations, which showed that movements of a maxillary model relative to the articulator axes produced errors in the movements of the model relative to the reference axes. The magnitude of the resulting errors depended on three variables these were: the magnitudes of the horizontal and vertical movements made relative to the articulator and the angle between the upper cross member of the articulator and the reference horizontal. This dependence was not surprising, but quantification of the errors produces surprisingly large values. When the angular discrepancy was 20º a 10 mm advancement and down graft produced a 4mm horizontal error and the equations showed that even a 5 mm movement would produce an error of more than 3 mm horizontally. A smaller angular discrepancy reduced the errors, but a 10º difference produced an error of more than 2 mm in a 10 mm displacement (See Chapter 4, Table 4.1).

The practical study based on photographs of specific movements of a maxillary model mounted on an articulator followed by image analysis validated the results of the analysis, there being no significant difference between the practical results and the theoretical predictions from the equations.

The movement of the casts for the photographic study used aluminium spacers for vertical displacements and pre-drilled holes in the articulator's cross bar for forward displacements. The choice of a disc of a standard size and standard hole positions produced accurate and reproducible movements without the need for measurement. The method was simple and convenient and eliminated the need to detach the casts from the mounting disc before the casts were measured and marked, trimmed and remounted.

6.1.2. Evaluation of a new orthognathic articulator.

The errors identified above would be incorporated into the inter-occlusal wafer prepared for the surgeon and used as a template for positioning the maxilla, and would have a seriously deleterious effect on the surgical outcome.

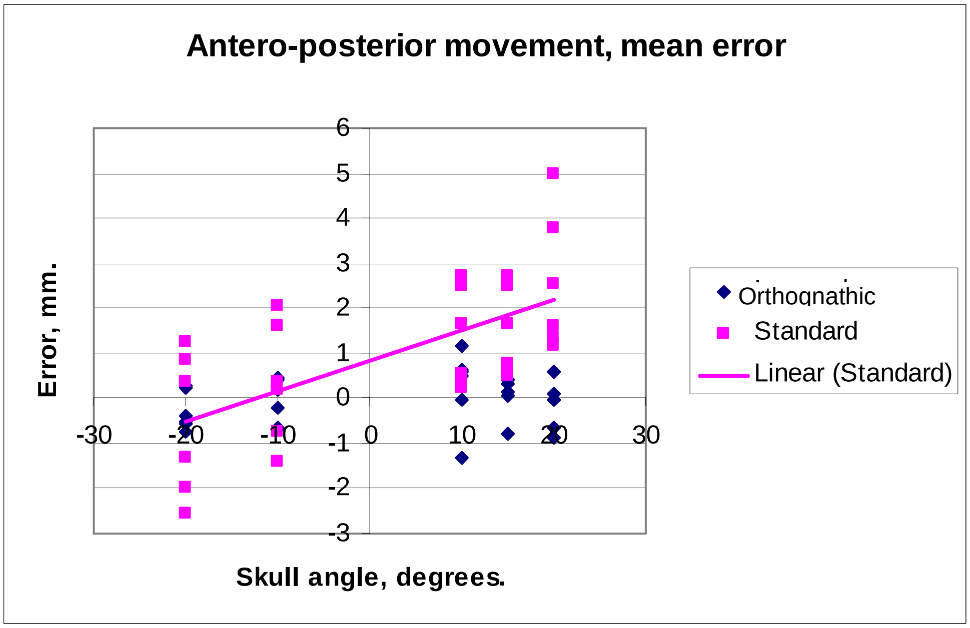
The second stage of the study was to take this concept further by simulating orthognathic surgery using plastic model skulls to validate the analysis and clarify the clinical significance relative to the first stage of the study.

The study was run as a parallel study with a Standard articulator and an Orthognathic articulator where appropriate face bow recordings were taken and dental casts were mounted on each articulator. Orthognathic model surgery on the maxilla was carried out and surgical wafers constructed. Measurements from anatomical reference points were recorded before and after orthognathic surgery was simulated on the plastic model skulls in five predetermined head positions using a custom made measuring device. This process was documented in the materials and methods (chapter 5). It may have been more advantageous to use natural skulls, as they would have given more variety of maxillary and mandibular relationship, as all the plastic skulls, were in a class I occlusion before simulated surgery was carried out. Thus, carrying out a Le Fort I osteotomy and autorotating or de-rotating the mandible into occlusion would be more realistic approach. However, this is irrelevant as it was only maxillary surgery that was carried out in this study and the mandible remained in a fixed position. It proved to be necessary to have a fixed reference point using the mandible to achieve the required measurements on the maxilla. When carrying out a Le Fort I osteotomy, any height change of the maxilla is measured from a pin placed into the bone at nasion. This was not applied in this study.

The measurements were carried out using a digital vernier gauge for the antero-posterior movements, which was accurate to a hundredth of a mm. Vertical measurements were recorded using a vertical height calliper (Chesterman, Sheffield) with an analogue vernier scale with a resolution of 0.5mm accuracy. The measurements could have been carried out using 3D imaging, which would have given more accurate recordings. However this would have been of little benefit as the surgeon is only able to perform orthognathic surgery to 0.5 mm, this is because of the saw blades that they use being 0.5mm or more in width. The measurements produced were as accurate as required for this type of study.

With the method devised, the maxilla had to be detached and replaced back into its original position on the skull before surgery was carried out. The most simple and practical method was by using custom made bone plates (documented in chapter 5). After the surgery was carried out the maxilla was located and fixed in place using sticky wax. The wax could have expanded or contracted, this was eliminated by using the fixed mandible and a bite registration to ensure no unwanted height changes occurred.

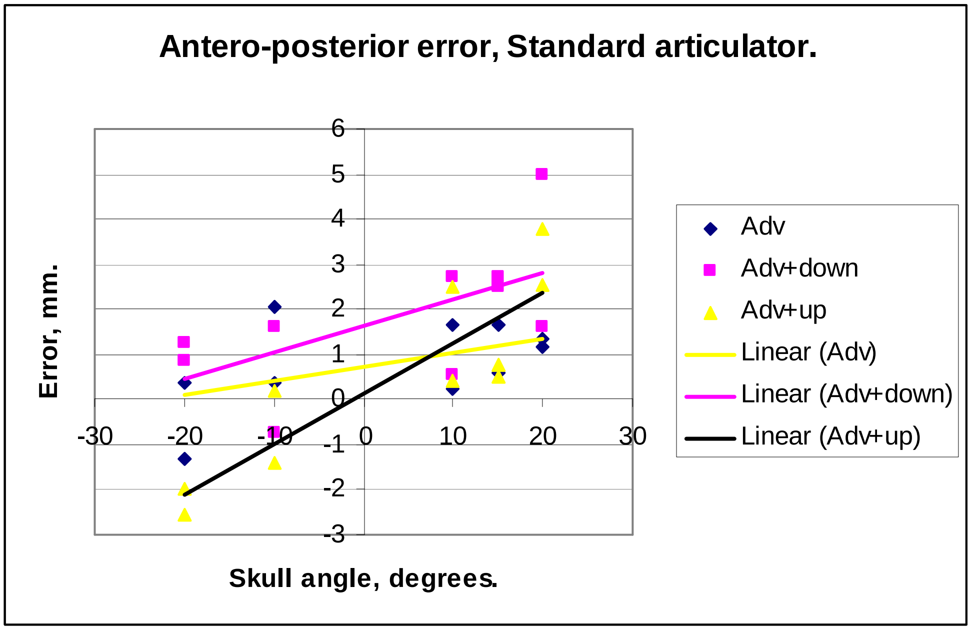
The Bland Altman plot of the errors of antero-posterior movement (Chapter 5 Fig.5.3a) showed grouping of the data that appeared to be related to the different skull angles. The x-axis of the Bland Altman plot in (Fig.5.3a.), was arbitrary and the grouping was investigated by plotting the error against the skull angle (Fig.6.1.), which showed that the grouping is clearly a function of skull angle. The errors produced by the Standard articulator were systematically dependent on the angles. The errors for -20° and -10° being both negative and positive, but for the positive angle the errors were only positive. No such asymmetry or systematic variations were shown for the results of the Orthognathic articulator and the errors appeared to be random.



Graph 6.1. Error of antero-posterior movement as a function of skull angle.

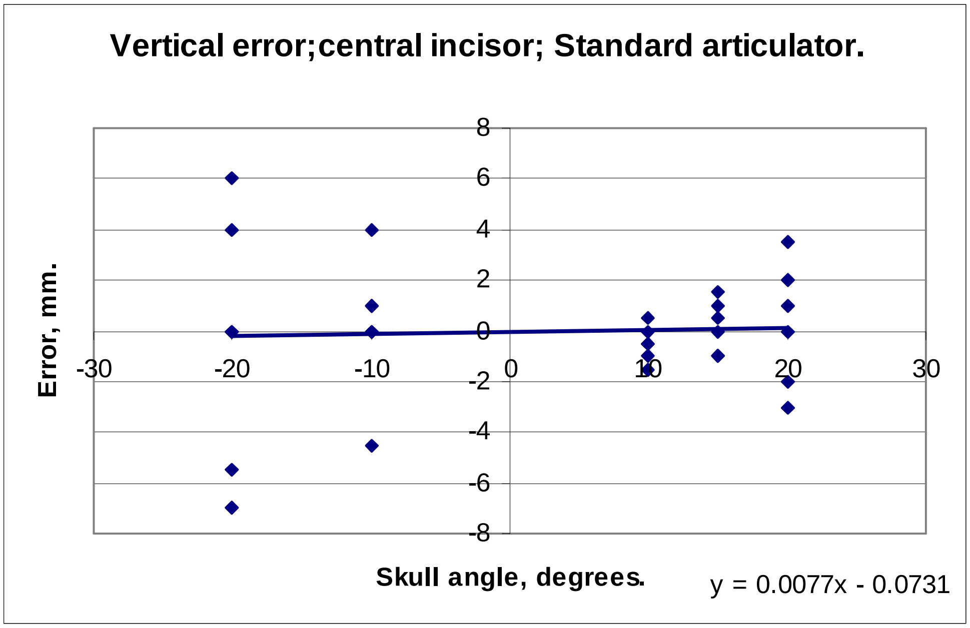
The best straight line fitting the Standard articulator data was calculated and added to Graph 6.1., showing that the asymmetry of the results was caused by the skewed distribution of the data; the line did not pass through the origin of the graph, but cut the error axis at a skull angle of -12°. This implied that mounting the casts using the conventional face bow technique introduced an added misalignment of 12°, a value similar to the 10.75° discrepancy reported for similarly mounted casts by **Walker et al (2008a).**

The mathematical analysis predicted that the error produced by cast misalignment would depend on angle and the magnitude of the movements of the cast. The dependence on angle was confirmed by Graph 6.1. The dependence on movement was more difficult to demonstrate, because the movements were combined. Replotting Graph 6.1. for each of the movements, Graph 6.2. showed that the results for each movement displayed a consistent pattern, suggesting a dependence of error on cast movement. Each of the best straight lines showed a positive gradient which, when combined gave the clear dependence on angle shown in Graph 6.1.



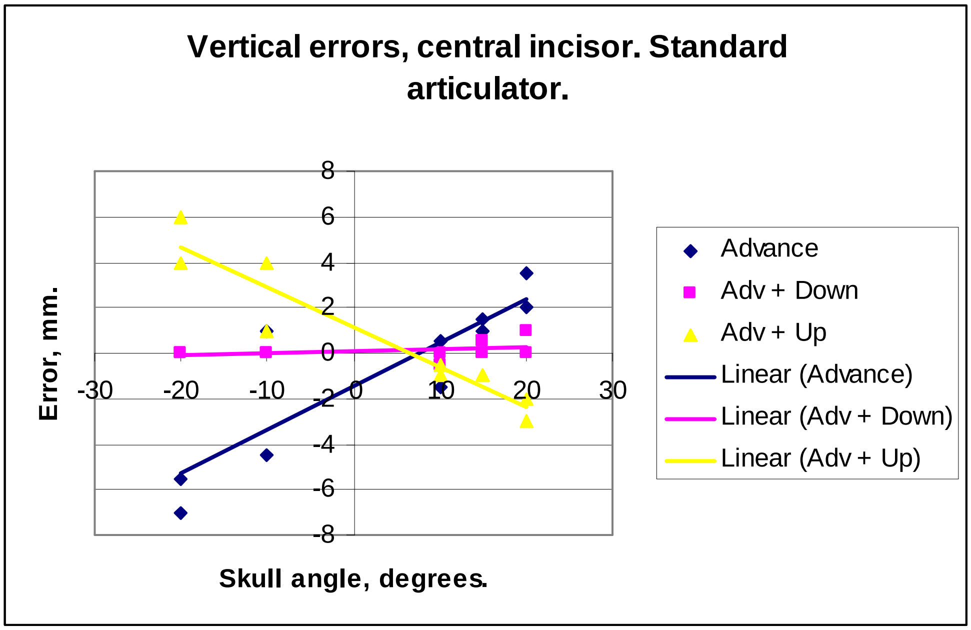
Graph 6.2. Error of antero-posterior movement as a function of skull angle for each movement advance, advance down and advance up.

The Bland Altman plots for the vertical errors did not show the grouping shown by the antero-posterior errors. The vertical errors measured from the central incisor were plotted against the skull angle, Fig.6.3, which showed the grouping of the data. Neither the gradient nor the intercept of the best straight line shown on the graph were significantly different from zero, reflecting the variability of the data, and this may account for the lack of grouping in the Bland Altman plots of the vertical errors.



Graph 6.3. Error of vertical movement measured at central incisor as a function of skull angle. Compare with Chapter 5 Graph 5.9a.

Replotting Graph 6.3. for each of the movements, Graph 6.4., showed that the results for each movement displayed a consistent pattern, suggesting a dependence of error on cast movement. One of the best straight lines showed a zero gradient, one a positive gradient the third a negative gradient; the two latter lines were widely spaced at -20º, which accounted for the wide range of points shown for -20º in Graph 6.3.



Graph 6.4. Error of vertical movement measured at central incisor as a function of skull angle.

The difference between the results of the Wilcoxon tests on signed and absolute data was very striking. The tests were initially carried out on the signed data. The histograms and Bland Altman plots showed that the errors of the Orthognathic articulator were consistently smaller than the Standard articulator; it came as no surprise the Wilcoxon test showed the difference to be statistically significant at P< 0.001. Although the vertical errors using the orthognathic articulator were also consistently smaller than the Standard articulator, none of the Wilcoxon comparisons were statistically significant, with P value ranging from 0.534 to 0.963. The reason was outlined in chapter 5.2. Using the Wilcoxon test to compare the absolute values of the errors showed that the errors of the Orthognathic articulator were consistently highly significantly smaller than the errors of the Standard articulator.

Casts repositioned using the Standard articulator showed significant antero-posterior and vertical errors. It is common surgical practice to check the post-operative vertical position of the maxilla with dividers and move the maxilla vertically to achieve the prescribed vertical position. An initial assessment of this adjustment was carried out on casts repositioned on the standard articulator. Five casts that had undergone a 10mm advancement and a 5mm impaction were investigated, one at each skull angle. After the measurements with the mandible in the fixed position were completed, the maxilla was detached from the skull and relocated in the wafer supported on the mandibular teeth. The mandible and the supported maxilla were raised by autorotation while measuring the vertical position of the reference point on the central incisor until the vertical error was eliminated. The maxilla was then fixed using sticky wax and the displacements of the other reference points determined.

The results (Table 6.1) showed that correcting the vertical error made the horizontal error worse. The consistency of the increase in error made the results statistically significant although there are only five paired results (Binomial test, $P < 0.005$).**(Zar 2010)**.

Angle°	Fixed, mm	Autorotated, mm	Difference, mm
-20	-2.00	-2.66	0.66
-10	-1.39	-2.17	0.82
10	0.43	1.51	-1.08
15	0.51	1.58	-1.07
20	2.55	6.19	-3.54

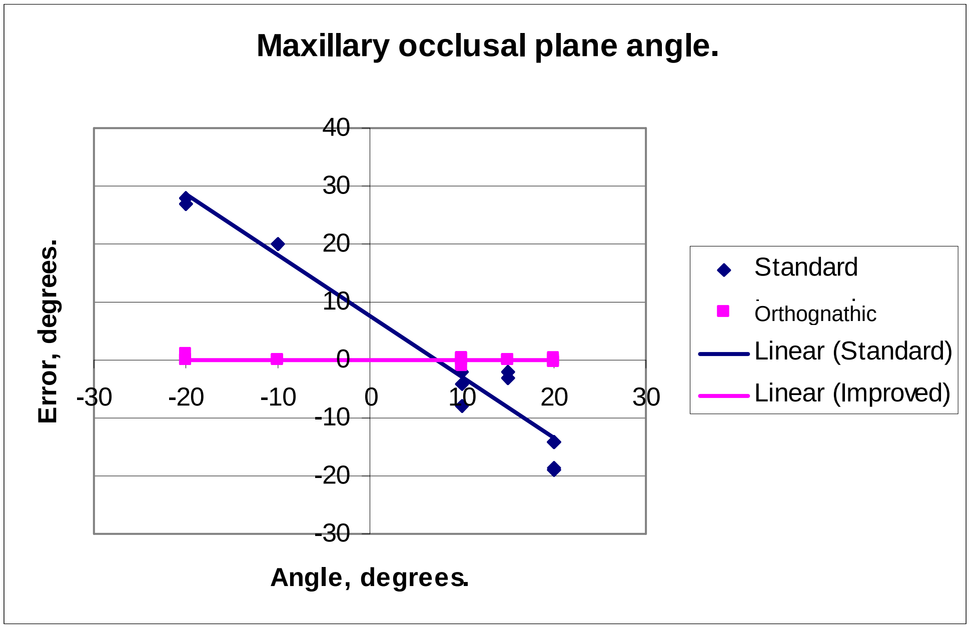
Table 6.1. Antero posterior errors, mm. Difference between fixed and autorotated mandible.

The Wilcoxon test of the absolute values (Table 6.2) was also significant at $P<0.005$.

Angle°	Fixed,mm	Autorotated,mm	Difference, mm
-20	2.00	2.66	-0.66
-10	1.39	2.17	-0.82
10	0.43	1.51	-1.08
15	0.51	1.58	-1.07
20	2.55	6.19	-3.54

Table 6.2. Absolute antero posterior errors, mm. Difference between fixed and autorotated mandible.

It was suggested that one of the advantages of using the natural head position was that the mounted cast more accurately replicated the appearance of the natural relationship between the teeth and skull. Graph 6.5. showed the angle between the pre-operative maxillary occlusal plane angle for the skulls and the mounted casts for both the Standard and Orthognathic articulator.



Graph 6.5. Difference between the pre-operative maxillary occlusal plane angle of the skull and of the mounted casts.

Casts mounted on the Standard articulator showed a large systematic difference from the skull angle, whereas the casts mounted on the Orthognathic articulator consistently and accurately replicated the natural skull angle. The difference between the articulators was shown to be statistically significantly at $P< 0.05$.

6.1.3. Development of the orthognathic articulator system and suggestions for further work.

The orthognathic articulator system has proved without a doubt a more accurate way to plan orthognathic surgery, but there are problems that arise when using the device. The face bow and articulator can be difficult to apply, because the adjustable components are rather difficult to set. This could be easily overcome with commercially machined adjustable components, so that adjustments can be made to the devices with ease. It is possible to adjust the lateral position of each condyle independently and this is necessary to relate the position of the jaws and teeth to each condyle. It is also possible to independently adjust the antero-posterior and vertical position of each condyle. This adjustment would seem to be redundant because the related position of the condyles would be sufficient. Making only one condyle adjustable in the lateral plane would be sufficiently accurate and simplify the setting up of the articulator for orthognathic surgery but not for asymmetric cases. Fully adjustable condylar components would be required for such cases.

Once the mandibular cast is mounted on the articulator, removing it and fixing it in the correct predetermined position can be difficult in some cases i.e. mandibular set-backs. The development of an additional adjustable mandibular mounting base for these cases would be the way forward. Using the disc and hole system simplified the movement of the maxillary casts eliminating the need to mark up the cast, detach, trim and then replace and fix it in position. This saved time and was also likely to be more accurate.

Adjustable predetermined vertical movements could be achieved by providing a set of discs with thickness of 1 to 10mm or by build up sets of thinner discs covering the same range. Further development of the hole system could be used for horizontal movement. The incorporation of rotation into the adjustable positioning system to allow for lateral rotations where occlusal canting is present and horizontal rotation is required to correct the maxillary and mandibular midlines would be slightly more difficult, but entirely possible. The adjustable system could be used with some effect on semi-adjustable articulators as well as the orthognathic articulator. The use of magnetic articulating discs would allow easier fixation and removal of casts from the articulator.

Five plastic model skulls were used and the process duplicated, but the whole process took a considerable amount of time to execute for each articulator system allowing time only for the ten cases to be undertaken. It would have been advantageous to undertake this study, particularly the effect of autorotation, on a larger number of skulls. This would have produced more robust conclusions.

The ultimate test of the Orthognathic articulator system would be a clinical study carried out on patients undergoing orthognathic surgery using pre and post-operative cephalograms to compare the predicted movement and the actual outcome of treatment. This has been undertaken in a previous study where the post-operative results using the two articulator systems were compared and evaluated **(Walker at al 2008b).** A more robust clinical study would be the logical conclusion to the evaluation of the orthognathic model surgery system.

6.1.5. The future of orthognathic surgery planning, the use of 3D models.

Using cone beam computed tomographic scans as the input to 3D rapid prototyping systems is a useful means for the production of 3D models of the human skull. There is considerable interest in using such models for orthognathic surgery planning. However, there are problems of producing the dentition from CT data due to magnification and streak artifacts produced by the presence of metal, such as fillings or orthodontic brackets in or on the teeth. An accurate perioperative wafer could not be constructed on the present generation rapid prototyped skull models. Studies have been undertaken to replace the distorted dentition of 3D model skulls. Replacement of the model teeth with an accurate plaster dentition from dental impressions has been successfully achieved with an accuracy of 0.5mm **[O'Neil et al (2010)]. Swennen et al (2009)** replaced the inaccurate occlusal detail of models with the accurate dentition using a double cone-beam CT scan. Cone-beam scans deliver less radiation than the original CT scans, but it would still be unethical to subject patients to the extra radiation of a double scan. Other studies are underway to replace the distorted model dentition using an intra-oral technique. The findings on these have yet to be published.

Technology is moving forward all the time and the use of plaster dental casts mounted on an articulator when planning orthognathic surgery will slowly become obsolete. This will not happen overnight and it could take some years. For the meantime the Orthognathic articulator will facilitate more accurate model surgery. Even when the use of models for orthognathic treatment becomes established, some form of articulator to simplify accurate positioning of dental segments, perhaps using the disc and hole system pioneered in this thesis, will still be needed.

6.2. Conclusions.

6.2.1. Errors produced by cast misalignment.

1. The literature provides convincing evidence that the outcome of orthognathic surgery may differ from the planned outcome, although inappropriate statistical testing confuses the situation.
2. The misalignment of casts mounted on semi-adjustable articulators may cause or contribute to the errors of surgical outcomes.
3. An illustrative example showed that movements of casts parallel to the articulator cross member produced erroneous movements relative to axes representing the patient's natural head position (reference axes).
4. A detailed mathematical analysis confirmed the errors in the example. The relationship of movements relative to the articulator and reference axes showed that the latter, and hence the errors, depended on the magnitude of the movements made relative to the articulator and the angle between the cross member and reference axes.
5. The accuracy of the theoretical analysis was confirmed by an experimental study using image analysis.

6.2.2. Evaluation of a new orthognathic articulator.

1. The maxillary occlusal plane angles of the skulls were accurately reproduced by casts mounted using the Orthognathic articulator system, but casts mounted using the Standard articulator showed systematic errors of up to 28º.
2. The post-operative position of the maxilla after simulated orthognathic surgery demonstrated that the Orthognathic articulator system produced more accurate model surgery. The differences between the actual and predicted movements were significantly smaller for the Orthognathic articulator system than for the standard articulator system.
3. The results justify further research, development and evaluation of the Orthognathic articulator system.

7

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Appendices

ERRORS PRODUCED BY CAST MISALIGNMENT STUDY (Mathematical study was carried out by Professor J.C.Barbenel (University of Strathclyde).

A model is displaced from its initial position O relative to orthogonal axes based on the articulator, with horizontal axis H_a and vertical axis V_a. The model is moved by the horizontal and vertical distances h_a and v_a, which can be represented in Figure A1 by the line r at an angle θ to the H_a axis and:

$$h_a = r \cos \varepsilon \quad \text{and} \quad v_a = r \sin \varepsilon \qquad \text{Eqn A.1}$$

The displacements relative to the orthogonal reference axes H_r and V_r at an angle ε to the articulator axes H_a and V_a are h_r and v_r with r being at an angle α to the H_r axis. And:

$$h_r = r \cos \alpha \quad \text{and} \quad v_r = r \sin \alpha \qquad \text{Eqn A.2}$$

From Fig A.1

$$h_r = r \cos (\varepsilon - \theta) \quad \text{and} \quad v_r = r \sin (\varepsilon - \theta) \qquad \text{Eqn A.3}$$

But

$$\cos (\varepsilon - \theta) = \cos \theta \cos \varepsilon + \sin \theta \sin \varepsilon \qquad \text{Eqn. A.4}$$

and $\sin(\varepsilon-\theta) = \sin\theta \cos\varepsilon - \cos\theta \sin\varepsilon$ Eqn. A.5

Substituting Eqn A.4 into Eqn A.3 and Eqn A.5 andEqn. A.1 into Eqn. A.3 yields:

$$h_r = r(\cos\theta \cos\varepsilon + \sin\theta \sin\varepsilon)$$

$$= r\cos\theta \cos\varepsilon + r\sin\theta \sin\varepsilon \qquad \text{Eqn A.6}$$

and

$$v_r = r(\sin\theta \cos\varepsilon - \cos\theta \sin\varepsilon)$$

$$= r\sin\theta \cos\varepsilon - r\cos\theta \sin\varepsilon \qquad \text{Eqn A.7}$$

Eliminating $r\cos\varepsilon$ and $r\sin\varepsilon$ in Eqn A.6 and A.7 using Eqn A.1 yields:

$$h_r = h_a \cos\theta + v_a \sin\theta$$

and $v_r = v_r \cos\theta - h_a \sin\theta$.

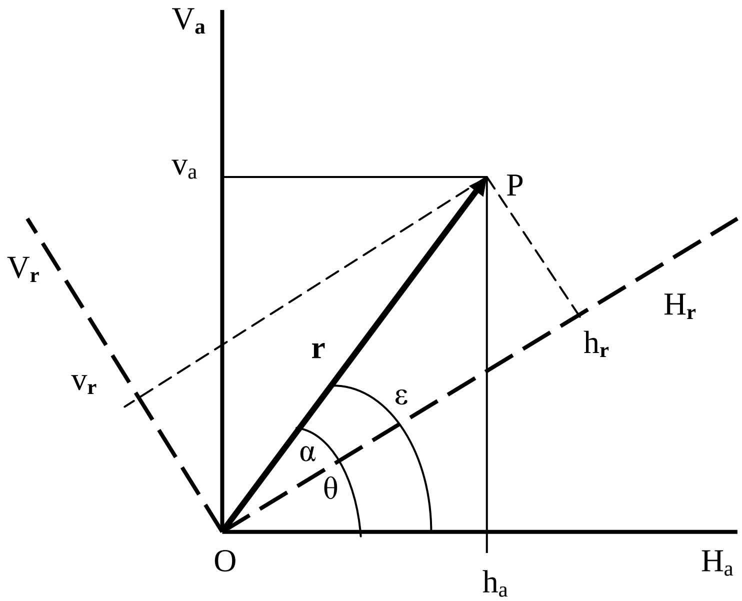
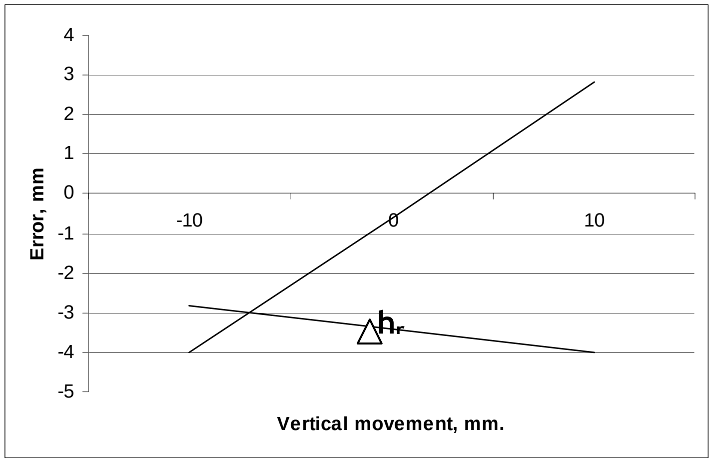
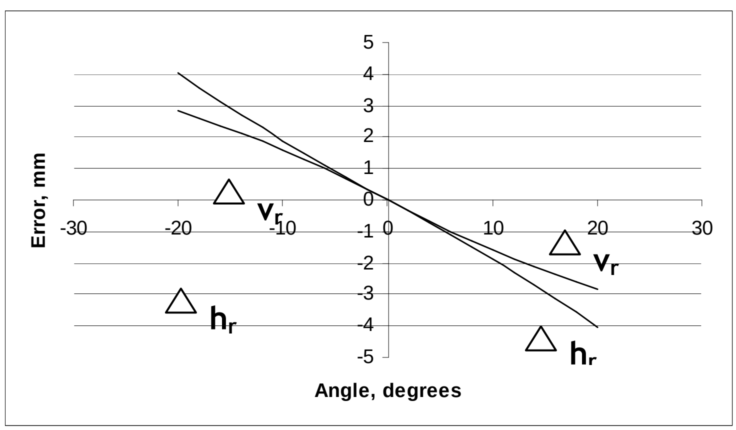


Figure A1. Displacement of model referred to articulator and reference axes.



Graph 4.1. The dependence of the vertical and horizontal errors, Δv_r and Δh_r, on the vertical movement, v_a. The horizontal movement, h_a, is an advancement of 10mm. θ is 20°.



Graph 4.2. The dependence of the vertical and horizontal errors, Δv_r and Δh_r, on θ. The horizontal movement, h_a, is an advancement of 10 mm and the vertical movement, v_a, is a downgraft of 10 mm.

Qualitative illustration.

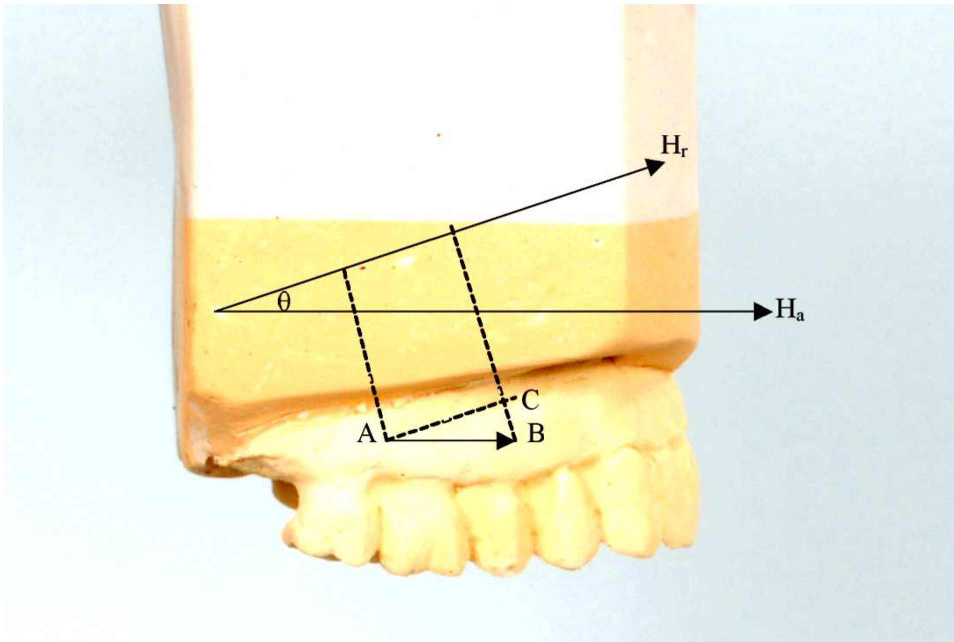
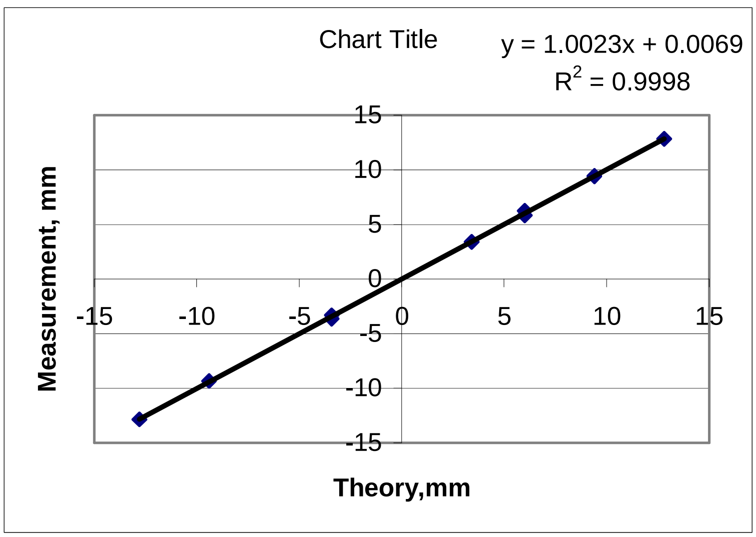


Figure 2. Model displaced by a distance AB parallel to the axis H_a parallel to the articulator cross bar produces displacements relative to the reference axes H_r and V_r.

Direction and distance, mm, of movement relative to articulator axis.	Direction and distance, mm, of movement relative to reference axis.		
Up	Movement	Measurement	Theory
$h_a = 0.0$	h_{20}	3.40	3.42
$v_a = 10.0$	v_{20}	9.43	9.40
Down			
$h_a = 0.0$	h_{20}	-3.62	-3.42
$v_a = -10.0$	v_{20}	-9.34	-9.40
Forward			
$h_a = 10.0$	h_{20}	9.46	9.40
$v_a = 0.0$	v_{20}	-3.30	-3.42
Forward +Up			
$h_a = 10.0$	h_{20}	12.84	12.82
$v_a = 10.0$	v_{20}	5.83	6.00
Forward+down			
$h_a = 10.0$	h_{20}	6.25	6.00
$v_a = -10.0$	v_{20}	-12.84	-12.82

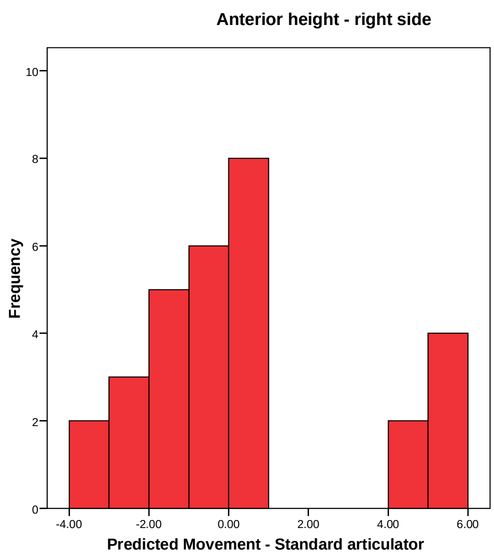
Table 4.1. Comparison of theoretical predictions and experimental measurements.

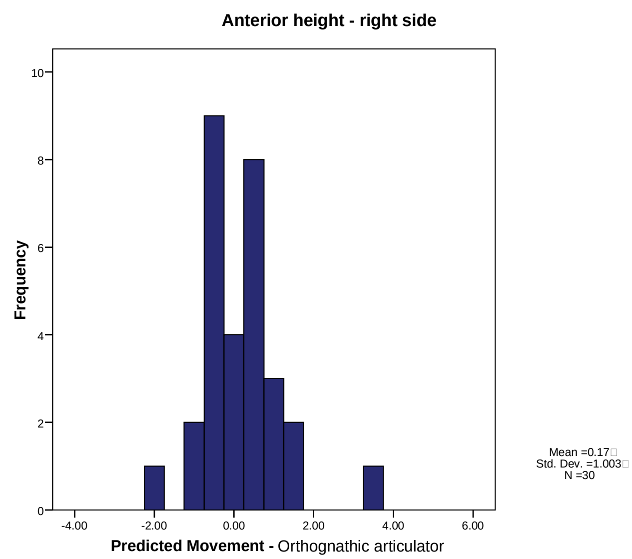


Graph 4.3: A statistical representation of the correction between the predicted theoretical values of the displacement and experimental values obtained. Data from table 4.1.

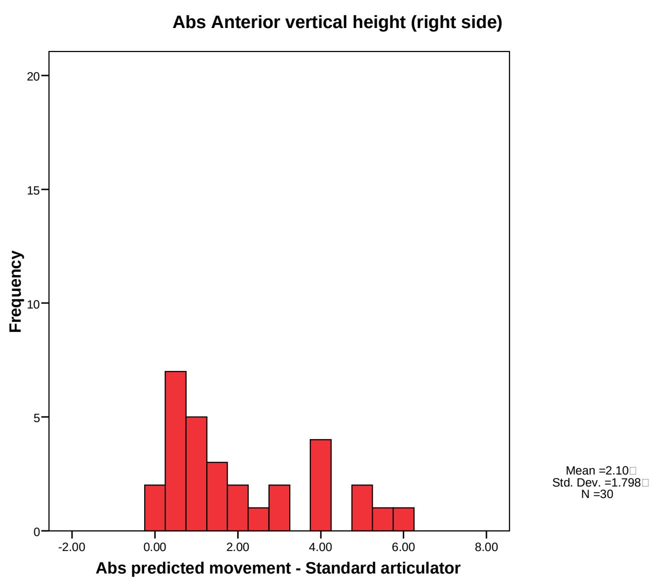
Evaluation of an Improved orthognathic articulator system results relating to chapter 5:

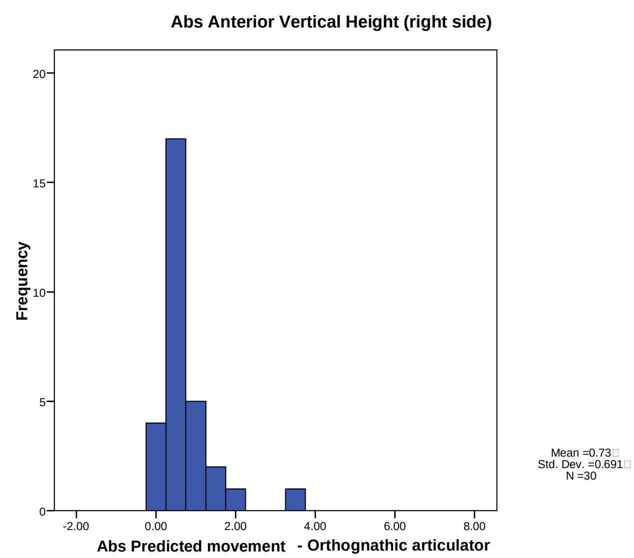
1a. Anterior vertical height - right side:



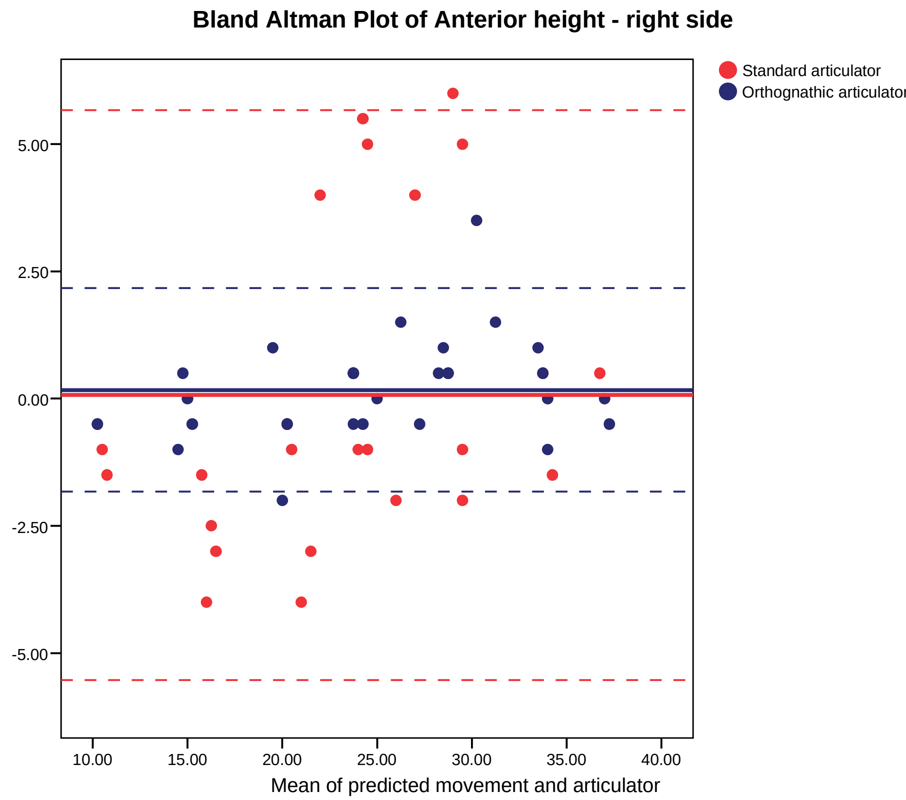


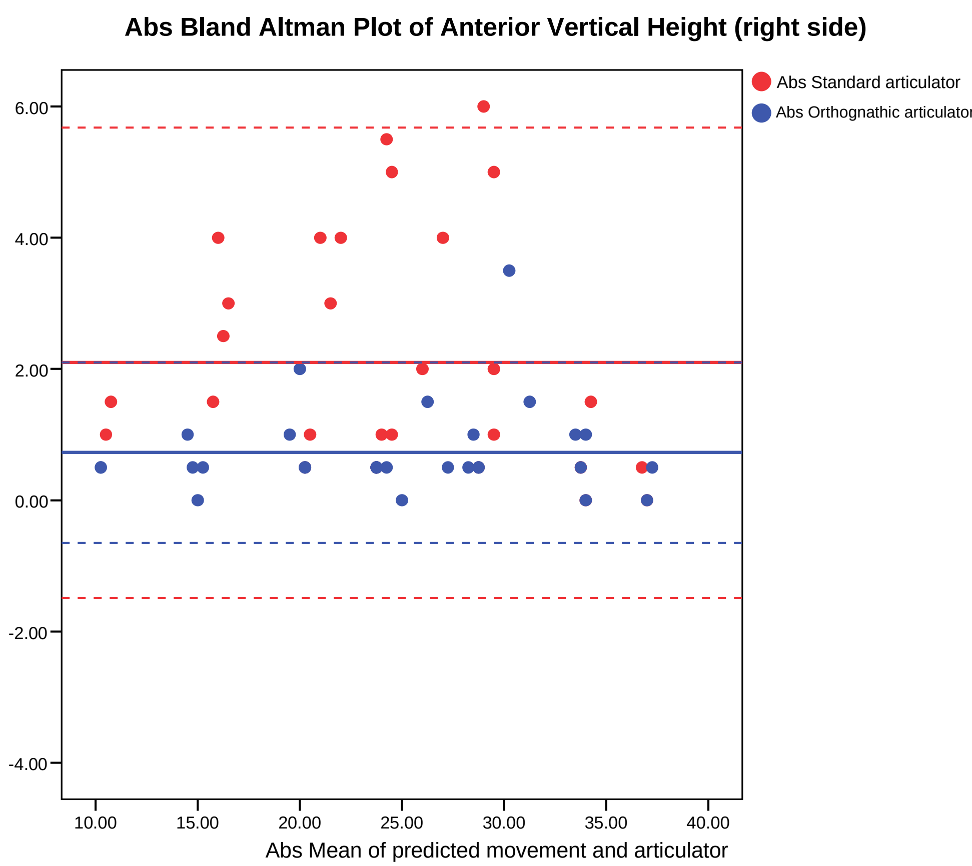
1b. Anterior vertical height - right side absolute measure:





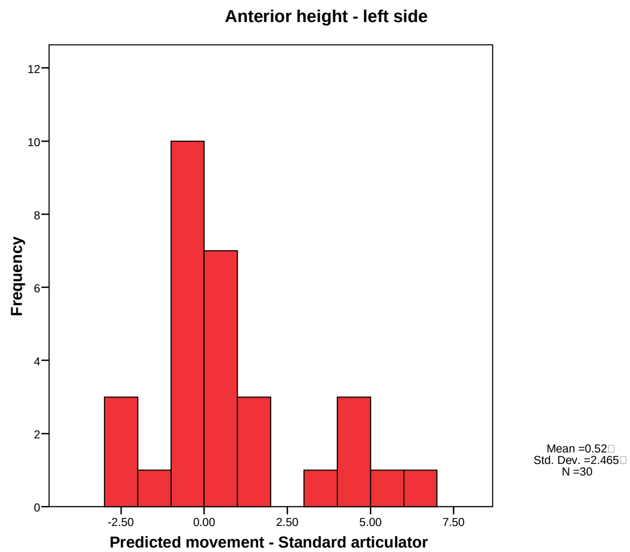
1c&d. Anterior vertical height – right side measure: Real and absolute

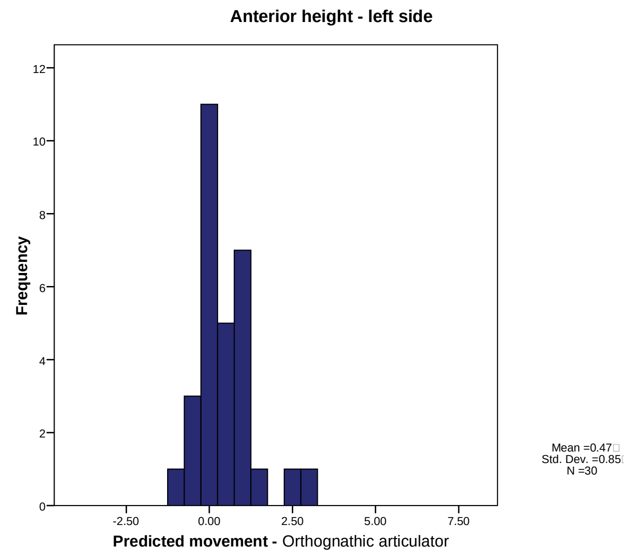




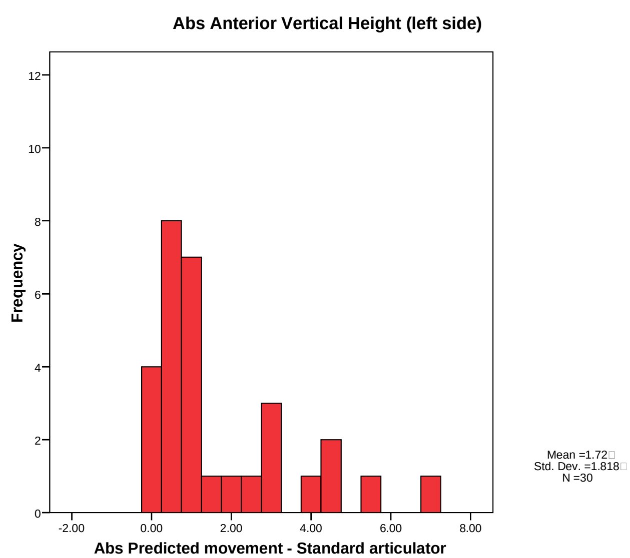
2a.

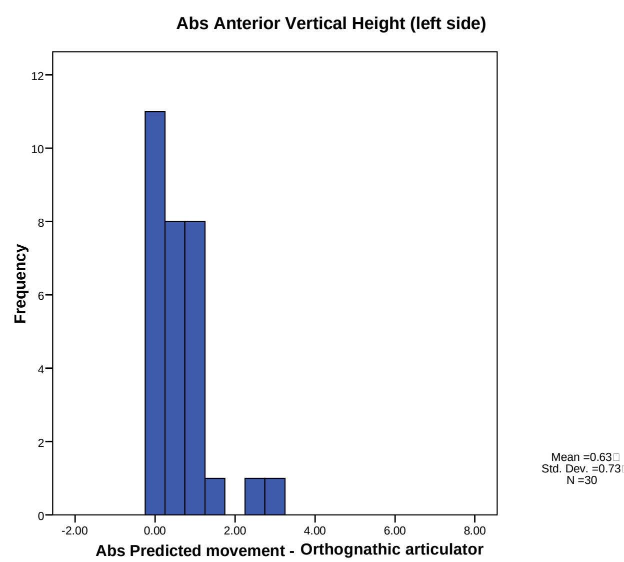
Anterior vertical height - left side:



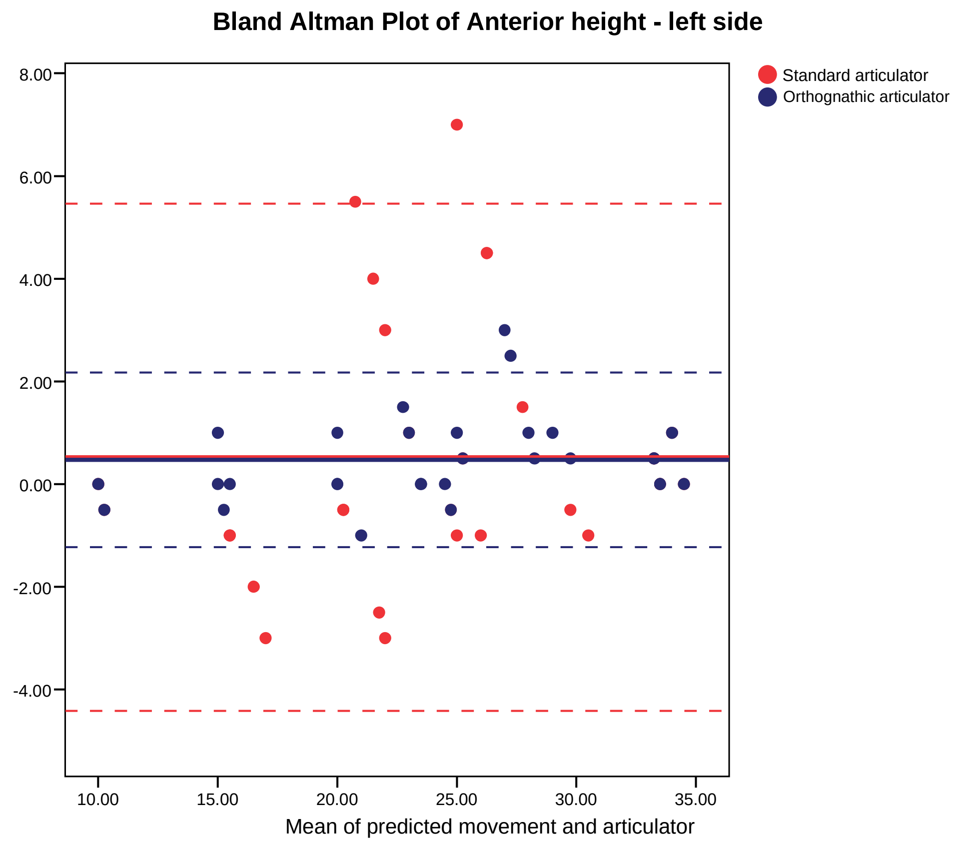


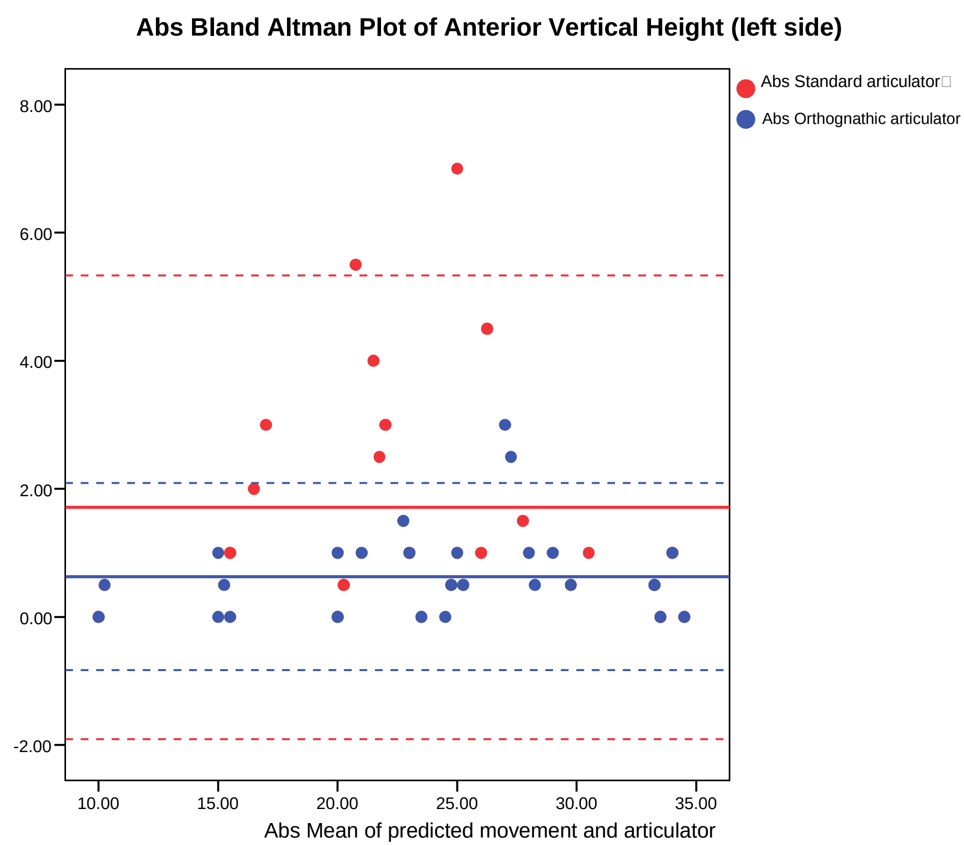
2b. Anterior vertical height - left side absolute measure:



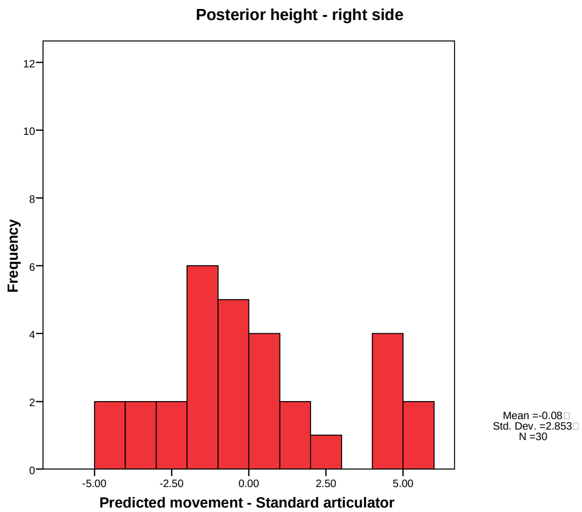


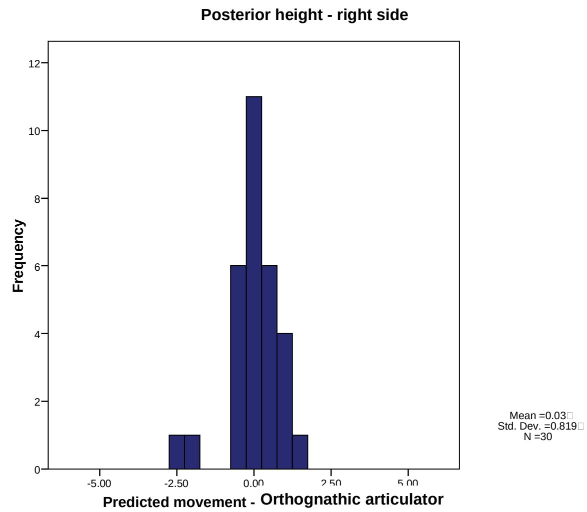
2c&d. Anterior vertical height - left side: real and absolute



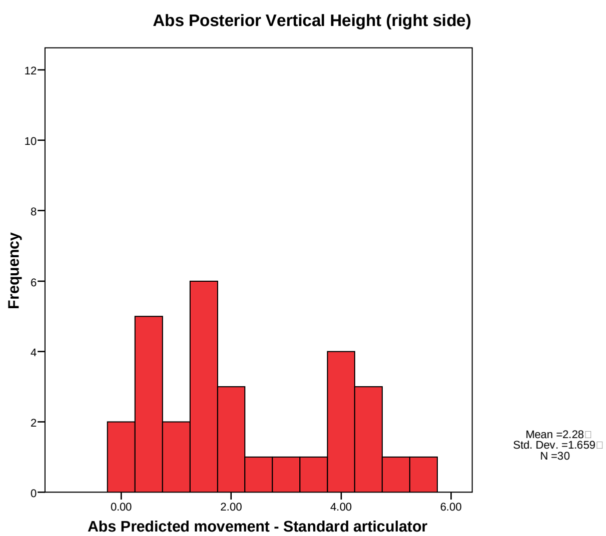


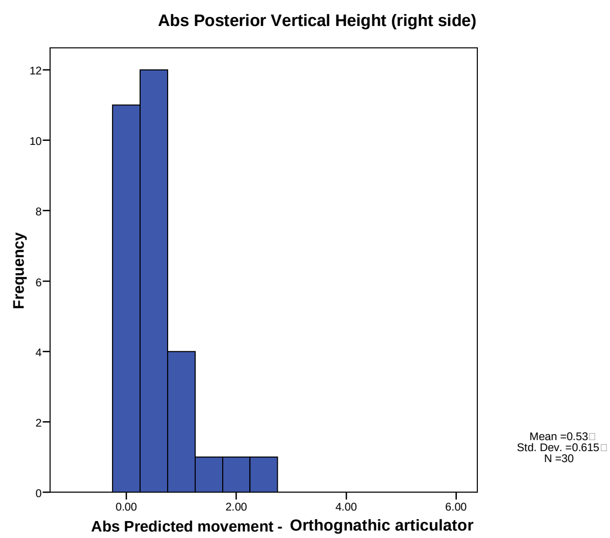
3a. Posterior vertical height – right side:



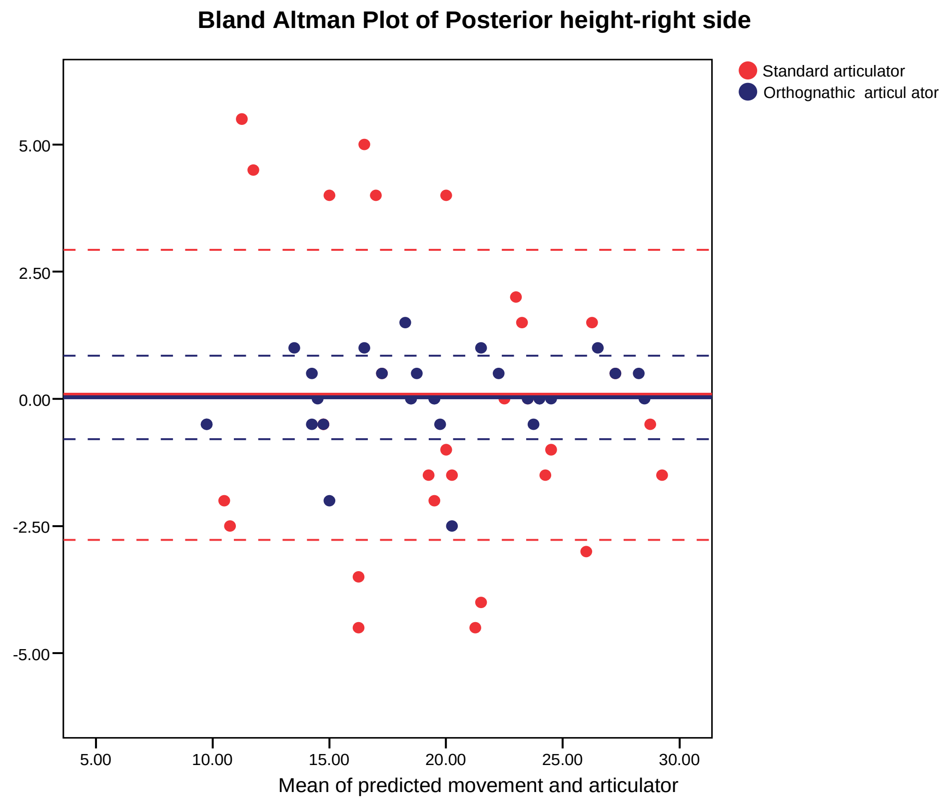


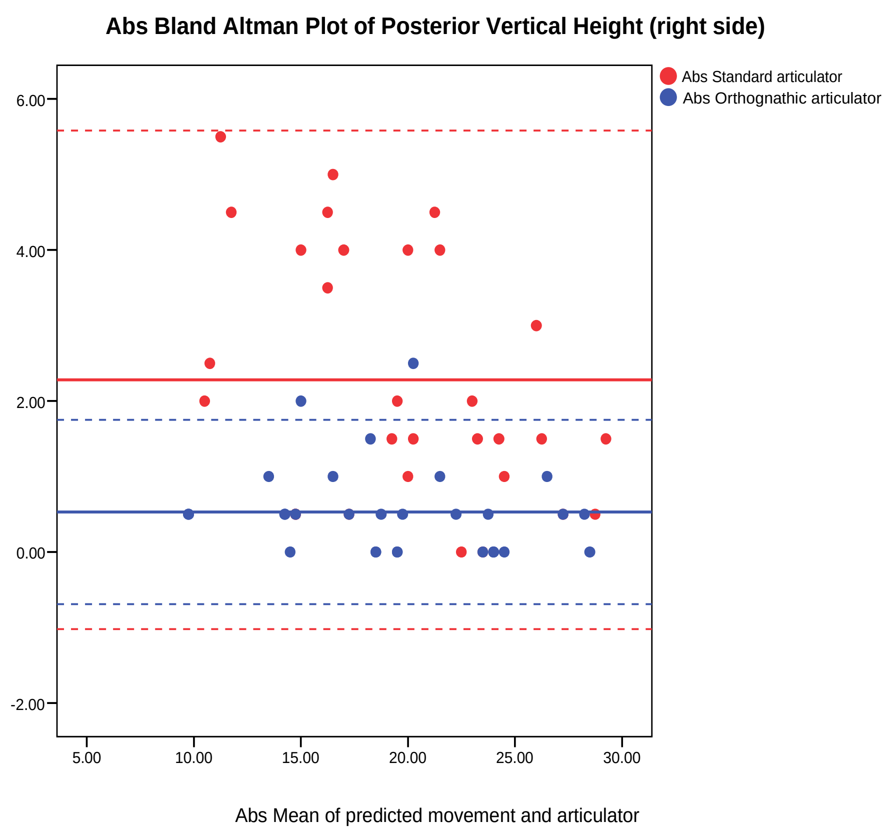
3b. Posterior vertical height – right side absolute measure:



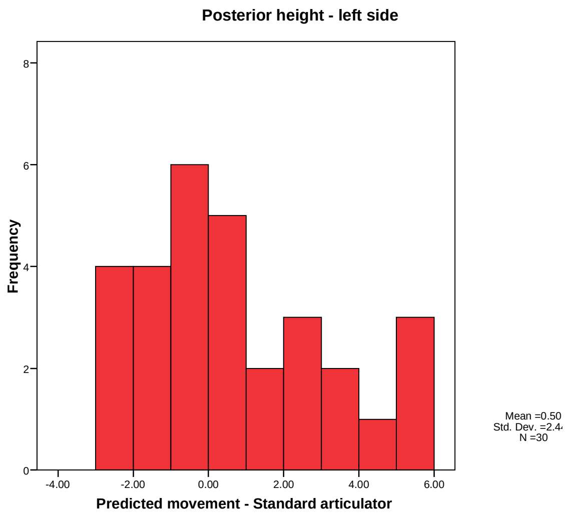


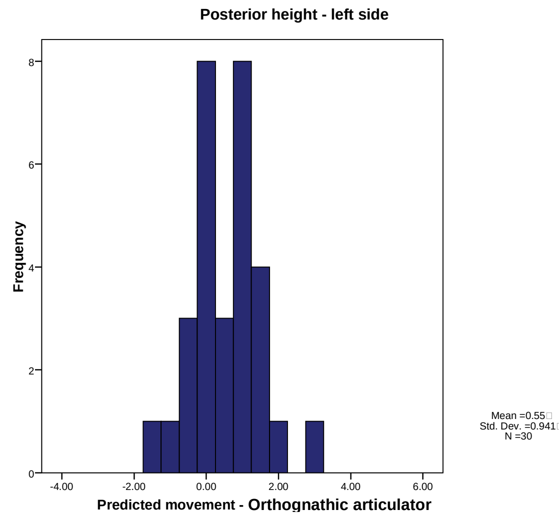
3c&d. Posterior vertical height - right side: real and absolute



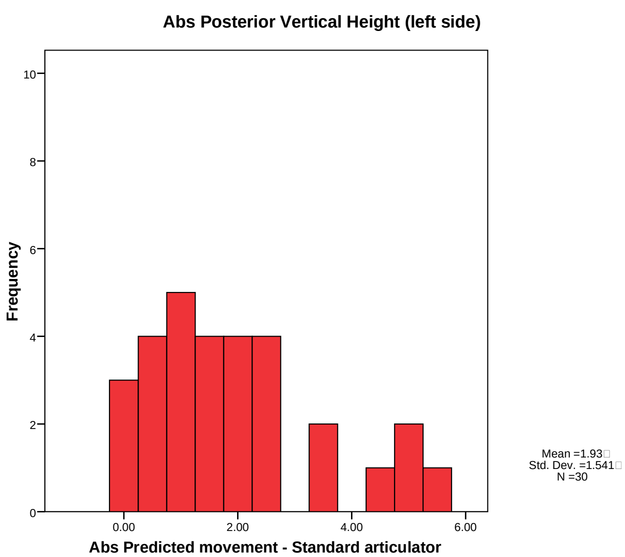


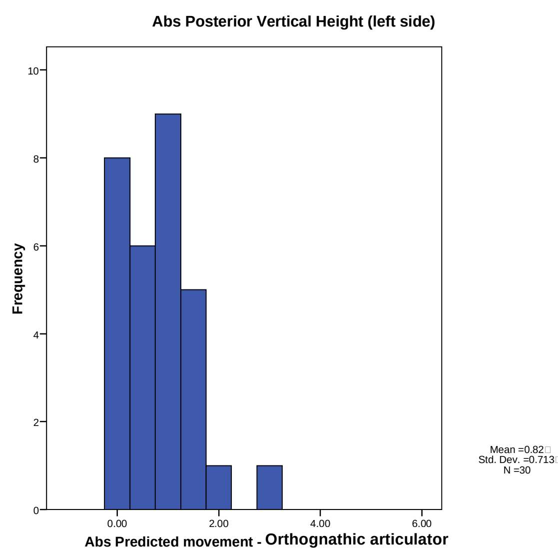
4a. Posterior vertical height – left side:





4b. Posterior vertical height – left side absolute measure:





4c&d. Posterior vertical height - left side: real and absolute measure