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The University of Texas Graduate School of Biomedical Sciences

At San Antonio

In Partial Fulfillment

Of the Requirements

For the Degree of

MASTER OF SCIENCE

By

Jay Douglas Graver, D.M.D.

San Antonio, Texas

May, 2001

AN IN VITRO COMPARISON OF PANTOGRAPHIC TECHNIQUES

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DEDICATION

This thesis is the culmination of many grueling hours of work, study, and blank stares into an empty computer screen. This work is not only a product of my efforts but also my family's many hours of support and overwhelming sacrifices.

To my children, Hunter, Bethie, Tyler and Ethan for their patience, understanding and ability to help me smile through this entire project. Their ability to keep me grounded, inspired and task oriented was truly special. I am forever grateful.

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AN IN VITRO COMPARISON OF PANTOGRAPHIC TECHNIQUES

Publication No._________

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The primary use of pantography is to program an articulator so the articulator movements will more closely harmonize with the patient's mandibular movements. The objective of this four-part investigation was to assess and compare the accuracy, repeatability, and procedure time of the optoelectronic computerized pantograph, the electronic stylus computerized pantograph, the mechanical pantograph, and the kinematic face-bow. This study was performed in vitro on three identical semi-adjustable articulators (Denar Mark II, Teledyne Water Pik). A kinematic face-bow (Denar Axis Locator, Teledyne Water Pik) and optoelectronic pantograph (Condylocomp, Dentron) performed the transverse horizontal axis investigations. A

mechanical (Denar, Teledyne Water Pik), electronic-stylus (Pantronic, Teledyne Water Pik), and optoelectronic (Condylocomp, Dentron) pantograph performed protrusive condylar path, progressive mandibular lateral translation, and immediate mandibular lateral translation determinations. The experimental design restricted the patient variables associated with these methods.

An initial evaluation was performed to identify the measured mid-point of the articulator condyles. Next, the Stuart axis locator (Stuart Gnathologic Instruments) was used to determine the transverse horizontal axis of each articulator. The kinematically located transverse horizontal axis and the measured center of the condylar ball were identical.

Results of this investigation showed that:

In Aim 1, the kinematic face-bow was better (p=0.0001) than the optoelectronic pantograph in verifying the transverse horizontal axis.

In Aim 2, the kinematic face-bow was better (p=0.0001) at locating and correcting to the transverse horizontal axis than the optoelectronic pantograph. However, it was slower (p=0.0001) than the optoelectronic location.

In Aim 3, the electronic-stylus pantograph was better (p=0.0690) when determining preset values for progressive mandibular lateral translation angles. The electronic-stylus pantograph performed better (p=0.0001) when determining the protrusive condylar path angles. The electronic-stylus determinations were faster (p=0.0001) than the other instruments.

In Aim 4, the electronic-stylus pantograph was better (p=0.0019) when determining preset values for progressive mandibular lateral translation angles. The mechanical pantograph was better (p=0.0891) when determining preset values for immediate mandibular lateral translation. The electronic-stylus pantograph performed better (p=0.0001) when determining the protrusive condylar path angle. The electronic-stylus computerized pantograph was fastest (p=0.0001) instrument for this set of determinations.

This investigation showed: 1) the kinematic face-bow was better at locating the transverse horizontal axis, however it was slower than the optoelectronic pantograph, 2) electronic-stylus pantograph was superior when determining progressive mandibular lateral translation and protrusive condylar path angle values, 3) the mechanical pantograph was better when determining immediate mandibular lateral translation values, and 4) the electronic-stylus computerized pantograph was the fastest instrument when determining progressive mandibular lateral translation angles, immediate mandibular lateral translation amounts and protrusive condylar path angle values.

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I. INTRODUCTION

McCollum and Stallard coined the term "gnathology" to describe the science that encompasses the study and treatment of the stomatognathic system based on examination, diagnosis, and treatment planning. The teeth, supporting tissues, temporomandibular joints, and associated hard and soft tissues can collectively be described as the stomatognathic system (Bauer 1976, GPT-7).

The structures of the stomatognathic system function as a unit. Therefore, understanding and treating this system require knowledge of the component parts and their relationships (McCollum 1955, Aull 1963, Weinberg 1963, Aull 1965, Bauer 1976, Friedman 1985, and Solnit 1988). However, the complete study and treatment of the stomatognathic system can not be accomplished intraorally (Gysi 1910, McCollum 1955, Bauer 1976, Solnit 1988). To this end, dental professionals have long recognized the need for extraoral duplication of the oral structures and their function (Gysi 1910, McCollum 1955, Payne 1997). Advances in the study of the stomatognathic system have closely paralleled the development of improved instrumentation and techniques designed to accurately simulate function, and precisely record jaw position and movement. The most notable advances include the development of articulators and mandibular movement recording devices, including the pantograph (Bauer 1976, Solnit 1988).

A pantograph, in dentistry, is an instrument used to graphically record, in one or more planes, paths of mandibular movement and to provide information for the programming of an articulator. Pantography is the most accurate and complete means of recording jaw movement and border positions available (Clayton 1971, Lucia 1983).

Pantography provides information about the temporomandibular joints and surrounding tissues and can record the mandible's border movements (Clayton 1971, McCollum 1955). The primary clinical application of pantography is to program an articulator so that articulator movements will be in harmony with the patient's mandibular movements (Curtis 1986). Restorations fabricated on articulators programmed using pantography should function in the patient's mouth without interference (Anderson 1987). Types of pantography include mechanical, electronic-stylus, and optoelectronic.

Mechanical pantography is accurate and reliable (McCollum 1955, Beard 1986, Donaldson 1986, Pelletier 1991), but the time and complexity involved in recording movements and setting the articulator from the tracings are major shortcomings (Coye 1977, Price 1989).

An electronic-stylus, computerized pantograph was developed to quickly analyze patient movements and minimize articulator-programming errors by generating numerical condylar values. In vivo and in vitro investigations have shown the electronic pantograph to be an acceptable, practical alternative to mechanical pantography (Clayton 1983, Beard 1986, Anderson 1987, Price 1989, Pelletier 1991). Unfortunately, the electronic stylus, computerized pantograph is no longer manufactured.

New optoelectronic, computerized pantographs have been developed. However, the accuracy and reliability of the optoelectronic pantograph have not been investigated.

The objective of this investigation is to assess and compare the accuracy, repeatability, and procedure time of the opto-electrical computerized pantograph, the electronic-stylus computerized pantograph, the mechanical pantograph, and the kinematic face-bow. Analysis of the results will determine if optoelectronic computerized pantography can quickly, accurately and reliably determine the transverse horizontal axis (THA), posterior condylar settings, and permit its use as a practical clinical alternative to the kinematic face-bow, mechanical pantography, and electronic-stylus pantography.

This investigation utilizes a bench top approach. Beard (1986) and Pelletier (1991) advocate the bench top investigations for pantograph testing to minimize variables and eliminate patient-induced error. Additionally, comparative analysis of different pantographic instruments and techniques is difficult due to a lack of standardization (Van Putten 1987). This investigation is designed to make comparisons of the appropriate instrument capabilities, and generate articulator-programming data for a common articulator.

In a preliminary study, an apparatus was fabricated that securely suspends an articulator. This holder allowed movement of only the articulator's mandibular element. Consequently, the function of the attached articulator more accurately represented patient mandibular motion.

Test instruments were attached to the articulator and holding apparatus in a manner similar to patient treatment. The test instruments recorded articulator movement in a clinically relevant fashion while attached to the articulator and holding apparatus. The apparatus-articulator-instrument arrangement allowed in vitro analysis of the test instruments.

Three identical Denar Mark II semi-adjustable articulators were used in this investigation. The rationale for using multiple articulators was to rule out investigation instrument/articulator bias. The beneficial features of the Denar Mark II articulator include a centric holding latch to aid in the THA determinations (Celenza 1979, Heartwell 1980, Pelletier 1991), adjustable protrusive condylar paths (PrCp), progressive mandibular lateral translation (PMLT) angles, adjustable immediate mandibular lateral translation (IMLT) (Heartwell 1980), and straight-line protrusive, progressive and immediate mandibular lateral translation movement (Stern 1988, Hatano 1989, Shillingburg 1997).

The Denar kinematic face-bow and Condylocomp optoelectronic pantograph performed transverse horizontal axis investigations. The Denar mechanical, Denar Pantronic electronic stylus and Condylocomp optoelectronic pantographs were used to determine the protrusive condylar path (PrCp), progressive mandibular lateral translation (PMLT) angle, and amount of immediate mandibular lateral translation (IMLT).

The centers of the articulator condyles may not be the true THA of the articulator (Beard 1981). Therefore, the coincidence of the THA and measured condylar midpoints of each articulator was initially determined (Beard 1981). This was accomplished using the industry standard, the Stuart Axis Locator. Following the Stuart Gnathologic Instrument Instruction Manual (Stuart 1979), the THA of each articulator was analyzed. The kinematically located THA and the measured centers of the condylar balls were identical.

The main part of the investigation consists of four specific aims. Specific Aim One investigated the ability of the kinematic face-bow and optoelectronic pantograph to accurately and reliably determine the THA. Distances from the test-located THA determinations and the articulator THA were measured to the nearest 0.1mm using a digital caliper and 15x magnification.

Statistical analysis of the results indicated the kinematic face-bow was better than the optoelectronic pantograph in verifying the identified THA. The combined mean error was 0.2 mm (kinematic) versus 0.6 mm (optoelectronic).

Specific Aim Two investigated the procedure time and ability of the kinematic face-bow and optoelectronic pantograph to accurately and reliably correct to the THA. The axis location and correction to the axis procedures were timed and the distances from the test-located THA determinations and the articulator THA were measured to the nearest 0.1mm using a digital caliper and 15x magnification.

Aim Two indicated the kinematic face-bow was better at locating and correcting to the THA. The combined mean error was 0.2 mm (kinematic) versus 1.0 mm (optoelectronic). The kinematic procedure time was slower than the optoelectronic, 437 seconds versus 204 seconds.

Specific Aim Three investigated the procedure time and ability of the mechanical pantograph (MP), electronic stylus computerized pantograph (EP), and optoelectronic pantograph (OP) to accurately and reliably determine preset values for the PrCp and the PMLT angles. The determinations were timed. The test determined PrCp and PMLT angles were recorded, compared to the true articulator settings and error determined.

Aim Three suggested the electronic-stylus pantograph was better when determining preset values for PMLT angles. The mean error was 2.3° MP, 2.1° OP and 1.3° EP. The electronic-stylus pantograph performed better than the optoelectronic pantograph in PrCp determinations. The mean error was 3.2° MP, 9.4° OP, and 2.0° EP. The electronic-stylus pantograph determined the test values faster than the other pantographs. The mean procedure time was 752 seconds MP, 136 seconds OP, and 30 seconds EP.

Specific Aim Four evaluated the procedure time and ability of the mechanical pantograph, electronic-stylus computerized pantograph, and optoelectronic pantograph to accurately and reliably determine preset values for the PrCp, the PMLT angles, and the amount of IMLT. The determinations were timed. The test determined PrCps, PMLT angles, and amount of IMLT were recorded and the error determined.

Aim Four revealed the electronic-stylus pantograph was superior when determining preset values for PMLT angles. The mean error for PMLT was 2.0° MP, 1.85° OP and 1.35° EP. The mechanical pantograph was superior when determining preset values for IMLT. The mean error for IMLT was 0.2 mm MP, 0.4 mm OP and 0.4 mm EP. The electronic-stylus pantograph determined the PrCp better than the other test pantographs. The mean error was 2.8° MP, 8.5° OP and 0.8° EP. The electronic-stylus computerized pantograph performed determinations faster than the other pantographs. The mean procedure time was 824 seconds MP, 137 seconds OP, and 31 seconds EP.

This investigation compared the accuracy, repeatability, and procedure time of three pantographic and two THA location systems. The results of this investigation indicate that statistically significant differences exist among the instrument capabilities.

The results indicated: 1) the kinematic face-bow was better at locating the THA, however it was slower than the optoelectronic pantograph, 2) electronic-stylus pantograph was superior when determining PMLT and PrCp values, 3) the mechanical pantograph was better when determining IMLT values and 4) the electronic-stylus computerized pantograph was the fastest instrument when determining PMLT, IMLT and PrCp values.

In summary, the optoelectronic method may not be a practical alternative to the kinematic, mechanical and electronic stylus methods for quick, accurate, and reliable transverse horizontal axis location and posterior condylar setting determination.

II. LITERATURE REVIEW

The movements of the mandible in relation to the maxilla are of prime importance for mastication, deglutition and phonetics (Chance 1982). Therefore, it follows that the functional aspects of the stomatognathic system should be one of the primary areas of dental research. Understanding and treatment of this system requires knowledge of the component parts and their relationships (McCollum 1955, Aull 1963, Weinberg 1963, Aull 1965, Bauer 1976, Friedman 1985, and Solnit 1988). To this end, dental professionals have long recognized the need for extraoral duplication of the oral structures and their function (Gysi 1910, McCollum 1955, and Payne 1997). Dental researchers and clinicians have employed many methods to analyze and record the movements of the mandible. It follows that advances in the study of the stomatognathic system closely paralleled the development of improved instrumentation and techniques designed to accurately duplicate function, and precisely record jaw position and movement. The most notable advances include the development of articulators, face-bows and mandibular movement recording devices (Bauer 1976, Solnit 1988).

A. Developments: 1750 - 1850

The early history of articulator development and the study of mandibular movement are based on anecdotal information, inadequate historical records, and little early scientific research (Starcke1999). Traditionally, around 1750 Philip Pfaff is credited with making the first copies of edentulous maxillary and mandibular dental arches using beeswax impressions that were poured with plaster. In 1756, Pfaff has also been credited with creating a device, Pfaff's slab articulator. This device was described as a static relator of dental casts that lacked the ability to duplicate patient mandibular movement (Bauer 1976, Mitchell 1978).

Gariot is credited in 1805 with the developing the first articulator with movement. Garriot's articulator design is described as based on a metallic hinge, which was restricted to simple rotational movement (Hall 1930, Bauer 1976, and Mitchell 1978).

Recently published articles (Starcke 1999, Starcke 1999, Starcke 2000) question the credit given to Pfaff and Gariot. Starcke credits Pfaff in 1756 with describing a method of making plaster casts. If the patient had teeth, he had the patient bite into wax so the relationship of the teeth could be recorded. However, Starcke states "Pfaff never described using this registration to preserve the relationship of the casts."

Starcke credits Gariot, in 1805, with describing a method of making plaster casts and extending them posteriorly to provide an indexing mechanism for preserving the relationship of the casts. Therefore, Gariot was the first to describe a plaster articulator. The plaster articulator was a simple indexing device, which became known as the "oiled board" articulator (House 1970).

Starcke (1999) states, "Very little is known about the origins of dental articulators. All that can be said with assurance is two documented facts: 1) Pfaff was the first to describe a wax impression procedure and a method for making plaster casts; and 2) Gariot was the first to describe a method for mounting casts and preserving their relationship with a plaster index."

Starcke (1999) contends the exact origins of the first mechanical hinge articulator may never be known. However, some time before 1840 mechanical hinge articulators became the preferred type of articulator. The term "articulator" was not the preferred term for these instruments. Among the more common terms were "antagonizing frames," occluding frames," occlusion frames," and "antagonizers."

The first published reference to mechanical hinge articulators was Fairhurst's article on Hovarth's and Ladmore's articulators of the 1830's. Fairhurst described these early instruments as two wooden or metal blocks or slabs hinged together with a simple hinge. These early instruments resembled what is now referred to the "barn door hinge" (Starcke 1999).

The exact origins of these early instruments may never be elucidated. However, certain facts concerning the advances of this period must be understood. The device described as a plaster articulator was a static relator of the casts that lacked the ability to duplicate any patient mandibular movement. Additionally, the development of the first articulator with movement, those described as based on a metallic hinge, were restricted to simple non-anatomical rotational movement (Bauer 1976, Mitchell 1978).

B. Developments: 1850 - 1900

In 1859, Bonwill developed, on the basis of morphological studies, an articulator that he thought closely mimicked the anatomy and movement of the temporomandibular joint. His articulator had horizontal condylar paths and the distance between the condyles, the intercondylar distance, was established at an anatomical distance of 100 mm (McCollum 1960, Sonstebo 1961, Bauer 1976). This articulator allowed the mounted casts to make centric opening and closing, left lateral, right lateral and protrusive movements (Chance 1982). Bonwill arbitrarily located the casts in the articulator by means of dividers, setting the mesial line of the trial plate at four inches from the condyles or joints of the articulator, this being the average measurement as he found it in his investigations (Hall 1930, Brandrup-Wognsen 1953).

In 1866, Balkwill used anatomical investigations to describe mandibular movements. He first described an opening and closing axis that ran through the mandibular condyles. He also noted downward, forward, and lateral glide movement of the mandibular condyles (Isaacson 1959, McCollum 1960, and Bauer 1976). Balkwill is also noteworthy for having an illustration in his article showing a Gothic arch tracing; however, he does not mention this illustration in the text (Chance 1982, House 1970).

In 1889, Luce was the first investigator to make a photographic recording of mandibular motion. Photographic analysis was an early methods used to analyze mandibular movement. Luce's subject sat in a brightly-lit area; a small reflective sphere attached to the end of a wooden rod, was placed between the subjects mandibular incisors. The ball would reflect the light onto a photographic plate in the sagittal plane, allowing a record of the path of the ball on opening to be recorded. Later he fabricated an improved reflecting device. It consisted of a framework with reflectors extending to the condyle and mandibular angle areas. Luce analyzed the recordings and concluded that the condyle traveled in a curved path, the mandible moved downward and forward motion during anterior thrust movement, and the concave portion of the curved path is located superiorly. Luce's investigations confirmed Balkwill's findings that the condylar path is downward and forward (Sonstebo 1961, Bauer 1976, Van Putten 1987, Chance 1982).

Hayes, in 1889, received a patent for an articulator that was the first to incorporate a fixed descending condylar path (Starcke 1999). The design of his articulator reflected Hayes' concept of condylar movement. It featured fixed curved condylar paths and individual condylar tension springs. Having nonadjustable condylar elements, his articulator can be classified as a "fixed condylar guide" articulator. It is interesting to note that the Hayes' design is most likely the first example of an articulator that can be identified as an "arcon articulator" (Starcke 1999). Hayes also invented the "articulating caliper." The caliper is the first instrument on record that attempted to locate the casts in an anatomically correct position in the articulator. Unfortunately, it simply enabled him to set the median incisal point in relation to its distance from the two condyles. There was no orientation of the occlusal plane, and if there was any lateral deviation, it was not taken into account (Hall 1930, Brandrup-Wognsen 1953).

In 1892, Warnekros introduced an engraving method for recording mandibular movement. This was the first attempt at a stereographic system of jaw-movement recording. He used his recording to adjust the individual lateral movement in his articulator (House 1970, Van Putten 1987).

In 1896, Walker developed the first articulator with adjustable condylar paths and a provision for adjustable lateral movement. His articulator permitted a greater range of motion and closer approximation of individual patient function (Bauer 1976, Chance 1982). Walker stated that the curvature of the roof of the glenoid fossa caused the condyle to move forward and downward on the orbiting side and slightly upward and backward on the rotating side. Initially, he used facets on mounted casts to adjust the condylar inclination on his articulator. Later he was one of the first investigators to develop an extraoral recording device from which measurements could be taken to set his adjustable articulator. The Walker "Facial Clinometer" was a mechanical apparatus consisting of a frame-like headpiece and separate jaw-piece. It could measure condylar inclination in lateral or protrusive excursions, the angulation of the occlusal plane, the relative amount of movement of the orbiting condyles in lateral excursion, and several facial angles that were of interest at the time. Measurements were taken directly from protractor-like scales on the sides of the device (Chance 1982). Unfortunately Walker's device was exceedingly complicated and never gained widespread acceptance. Additionally, in accordance with Bonwill's method, Walker arbitrarily mounted patients' casts in his articulator (Brandrup-Wognsen 1953).

Ulrich, in 1896, used a photographic technique to analyze mandibular movement. Initially he marked seven facial recording points. He then used a celluloid plate to record the initial position for all the points. Next, photographs of the occlusal position, opening, protrusive and retrusive movements were made in the sagittal plane. The celluloid plate was then used as an overlay to determine subsequent positions relative to initial positions. From his recordings he concluded that the action of muscles governed movements, not the shape of the temporomandibular joint (Chance 1982, Van Putten 1987).

In 1899, Snow introduced an improved face-bow that allowed casts to be attached to an articulator in a more anatomically correct position. The position of the casts was determined by using the temporomandibular joint as a point of reference (Hall 1930, Bauer 1976, Mitchell 1978, and Van Putten 1987). Bonwill's arbitrary method of mounting casts prevailed until Snow devised and introduced his face-bow and technique. Brandrup-Wognsen (1953) stated that "in spite of its very simple construction, Snow's face-bow was epoch-making in prosthetic dentistry. Since the introduction of Snow's apparatus, no fundamental changes have been made in the face-bow." Snow's face-bow is the prototype of the face-bows in use today (Hall 1930, Brandrup-Wognsen 1953).

C. Developments: 1900 - 1950

In 1901, Christensen presented a method for intraoral registration of jaw movement. Using wax rims applied to vulcanized rubber based, he recorded the forward and downward movement of the mandible and condylar path slopes. In addition to recording the protrusive movement, Christensen used this method to record the full range of mandibular movements. In essence this method was the first functionally generated path recording. Christensen also developed an articulator with adjustable condylar paths to utilize his registrations and improve prosthesis fabrication (Bauer 1976, House 1970, Chance 1982, Van Putten 1987).

In 1901, Tomes and Dolamore utilized a photographic technique to investigate mandibular movement. Their technique utilized reflected light and reference points. A series of still photographs allowed them to capture and analyze various mandibular movements (Van Putten1987).

In 1902, Campion demonstrated two phases of mandibular opening motion: an initial rotational movement around an axis that ran through both condyles followed by a translational motion downward and forward. He used a recorder attached to a tray that was cemented to the mandible. The instrument recorded jaw movements by a series of dots on the skin. The dots consisted of a rouge and oil mixture. Paper was applied to the facial dots, transferring the dots to paper for study. The recordings were made at extreme left, extreme right, and maximal opening positions. Campion also concluded that casts should be mounted in articulators in such a way that the rotational axis of the articulator coincides with the opening and closing axis of the mandible (House 1970, Bauer 1976, Chance 1982, Van Putten 1987).

In 1903, Parfitt described three types of mandibular motion: a rotational movement around a horizontal axis running through the condyles, a translational motion forward and down, and a rotational motion around a vertical axis when the mandible is displaced laterally.

In 1907, Bennett discussed the rotational and lateral movement of the mandible and condyles. He attached small lights to a mandibular framework, one over the condyle and another at the symphysis. The lights were focused with a lens onto a sheet of paper placed in the sagittal plane, and the focused spots were marked at several intervals. Bennett's conclusions were that there was an instantaneous center of rotation that varied with different condylar movements and position, rather than a solitary, fixed center of rotation. Bennett made a secondary observation when spots were recorded in the frontal plane. He noticed a lateral shift in the position of the working condyle towards the side to which the movement was being made. In summary, he noted that when the mandible was moved bodily to one side, the condyle on the side of the movement rotated in place or moved slightly, and the opposite condyle, the side away from the movement, moved downward and forward (Bennett 1907, McCollum 1955, Bauer 1976).

Using a modified Snow face-bow, Gysi (1910), is credited with the invention of the first pantograph. His instrument utilized a pantograph style framework to make registrations of the orbiting movement of each condyle in the posterior horizontal plane. Gysi was the first investigator to make continuous-line graphic illustrations of mandibular movements. Additionally, he recorded the curvature of the condylar path and the angulation of the path to the occlusal plane. Gysi also made graphic recordings of the path of an incisor point in the horizontal plane, using an extraoral tracer with a stylus attached to the maxillary arch and the recording plate on the mandibular arch. The results were classic "Gothic arch" tracings. Gysi's pantograph is considered a major improvement in mandibular motion analyzers (Bauer 1976, Van Putten 1987)

Luce (1911) developed a technique (based on Warnekros' method) to register the paths of motion of the edentulous mandible. His intraoral registration technique used five roundhead nails mounted in a mandibular occlusal rim to scribe the paths of mandibular motion on a rim of softened impression compound on a maxillary record base. His three-dimensional recordings produced Gothic arch tracings, which captured centric relation, lateral and protrusive pathways. These recordings could then be used to program an articulator.

During this period, Height (1911) contributed to the development of simple graphic motion analyzers. Using a system similar to Luce's, his technique utilized an intraoral device with styli connected to the maxilla to scribe paths on a mandibular plate. His tracings provided a representation of the position and movement of the mandible in two dimensions (Bauer 1976, Van Putten 1987).

Further development of photographic techniques led to the first crude motion picture cameras in this period. Dental researchers began incorporating the science of motion pictures into the science of mandibular movement. In 1914, Thouren is credited with the first cinephotographic registration of mandibular motion. His motion pictures recorded mandibular movement in the horizontal and sagittal planes (Van Putten 1987).

In 1921, Harlan and McCollum developed a practical method for determining the pure rotational axis of the mandible. McCollum noted the hinge axis points on the skin along with an anterior third point of reference on the face defined a reproducible plane that should be used with face-bows to orient casts in an articulator (McCollum 1955, McCollum 1960, Stuart 1964, Bauer 1976,Van Putten 1987). This allowed the relationship of the maxillary cast to the articulator condyle to mimic the relationship of the maxilla to the temporomandibular joint.

Needles (1922) adapted Luce's intraoral recording technique. First, he shaped the maxillary and mandibular occlusal rims with a section of four-inch radius sphere to establish the occlusal curvature. Next, he embedded four wires into the maxillary occlusion rim. Small projections of the wires extended above the rim and served as styli. These wires were used to carve four Gothic arch stereographs into the lower wax occlusion rim (House 1970, Chance 1982).

Wadsworth in (1924) introduced an articulator with adjustable condylar path slopes, adjustable intercondylar distances and an adjustable incisal table. He also developed a face-bow and an attachment for the face-bow that permitted the orientation of the maxillary teeth in a defined plane (Wadsworth 1925, Bauer 1976). McCollum (1960) credits Wadsworth as being the first dentist to call attention to the necessity for definitely orienting the casts in an articulator by using a third point of reference.

Simultaneous improvement of the pantograph by McCollum (1927) and Needles (1927) saw the development of instruments capable of recording patient movement in three dimensions (McCollum 1939a, Isaacson 1959, Bauer 1976, Van Putten 1987). These prototype extraoral graphic devices recorded left, right, anterior and posterior jaw movements simultaneously. As described earlier, Needles' first recording device was based on an intraoral technique. Unlike Needles' intraoral device, his extraoral recorder featured four recording plates, all in the horizontal plane with two positioned anteriorly and two posteriorly. This pantograph was capable of transfer to an articulator. McCollum's first graphic recording instrument had four styli on a single glass plate positioned around a subject and oriented to the axis-orbital plane. This system also used removable intraoral clutches with separate detachable maxillary and mandibular frames. Tracings of horizontal, vertical and sagittal movement were recorded on smoked glass plates and then etched to produce a permanent record.

Stansbery (1929) used a central bearing device with his recording instrument. His design was an improvement on Gysi's method of Gothic arch registration by incorporating the bearing device with an extraoral Gothic arch tracer. His technique eliminated the influence of the record base on the Gothic arch tracer and allowed for adjustment of vertical dimension.

House (1931) used a system similar to Needles' and Luce's intraoral technique. He created intraoral stereographs (functional chew-in) using three cutting styli on a vulcanite central bearing device. The styli cut three Gothic arch stereographs simultaneously as the patient made jaw movements. His tracings provided a representation of the position and movement of the mandible in two dimensions (Bauer 1976, Van Putten 1987).

Hildebrand reported on the mechanism and kinematics of masticatory function using motion pictures in 1931. He also introduced a cineradiographic method of recording mandibular movements. This helped Klatsky to utilize cineradiographic techniques to record mandibular movements in 1939 (Van Putten 1987).

McCollum (1939b) began development of a new pantograph (the Gnathograph), with two posterior vertical recording plates and two anterior horizontal recording plates, to study the effects of intraoral guidance on the recordings or pantograms. It also featured removable maxillary and mandibular removable clutches, attached frames with adjustable arms, and a central bearing device. He credits Phillips (McCollum 1960), as does Stansbery 1929), with the development of the central bearing device. The design featured a curved metal plate in the center of the maxillary record base and a metal plate with an adjustable screw in the center of the mandibular record base. McCollum found that using the central bearing device helped to eliminate cuspal interferences and had no effect upon the mandibular recordings. Tracings made with this pantograph could be mounted on McCollum's highly adjustable articulator (the Gnathoscope) and manually retraced. When programmed with pantographic tracings, the Gnathoscope allowed a better mechanical representation of patient function compared to all other available methods (McCollum 1955, Bauer 1976,and Van Putten 1987).

Kurth (1942) studied the chronology of mandibular movements. He attached a polished steel ball to the mandibular incisors. The ball was illuminated with a strobe light set at twenty-five flashes per second. Photographic plates in the frontal, sagittal and horizontal planes recorded the images. He used the results to measure directions of mandibular movement. He noted that only lateral and opening movements were made during mastication.

D. Developments: 1950 – Present

Sears (1952) measured condylar displacement with his mechanical instrument. Using mounted casts his "condyle migration recorder" measured three-dimensional changes in condyle position. The changes in position were noted on adjustable graphs for study and analysis.

Posselt (1952), using a simple sagittal recording plate and stylus attached to intraoral clutches studied incisal movement. His study demonstrated that mandibular motion was not unlimited, and the maximum amount of movement in any plane or direction is termed a border movement. Using the data gathered from the study of the incisal point he made and labeled diagrams and outlined the anatomical factors involved at each segment of the border movement. The sagittal incisal tracing is now classically known as "Posselt's diagram." He also demonstrated that border movements are unique and reproducible (Posselt 1952, Solnit 1988).

Jankelson (1953), Berry and Hofman (1956), Linblom (1957) and Lundberg (1963) utilized cineradiographic techniques to analyze mandibular movement and function of the stomatognathic system. This method is useful for analysis of intra-oral functions such as denture movement, bolus position, phonetics, and velopharyngeal functions. It is limited to a two-dimensional presentation of the movements, and cannot be compensated for by subsequent recordings in different positions.

McCollum's and Stuart's (1955) developments produced the fully adjustable Stuart Gnathologic Computer (Stuart Articulator-Occlusal Analytical Computer) which, when programmed with their pantograph, allowed an accurate mechanical representation of the functioning stomatognathic system (Donaldson 1986, Van Putten 1987). Their final pantograph was composed of six graphic tracings, two vertical and two horizontal tracings in the condylar region, and two horizontal tracings in the incisal region. The use of a standard cranial reference plane, the axis-orbitale, in defining the condylar angle made consecutive recordings more comparable.

Atkinson and Shepard (1955) filmed the motion of two indicator balls positioned anterior to the maxillary and mandibular incisors. A mirror was positioned so that movement of the mandibular ball was seen in the sagittal and frontal planes. A reference grid was placed in front of the ball during filming. A frame-by-frame analysis of the sequence of masticatory function was made.

Cohen (1956) investigated the relationship of anterior guidance in mandibular movement and pantographic recordings. He noted changes in vertical dimension and clutch-bearing surfaces had no effect on posterior tracings. The anterior tracings in Cohen's study changed with vertical dimension due to the orientation of the straight anterior styli.

Posselt (1957a) developed a mechanical instrument similar to Sears' Condyle Migration Recorder, which he called the "Gnatho-Thesiometer." It was used to record the various positions of the dentition and measure the differences between them. He included an anterior reference point adjustable in three dimensions. The device did not measure jaw movements, but evaluated positional changes as a result of movements.

Measurements were made of three points on a mandibular cast in each of the three spatial planes. He used it to evaluate Bennett movement and condylar path inclination. In another study, Posselt (1957b) used the same instrument to measure the three-dimensional contact area of an incisal point. The resultant information was used to construct three-dimensional models of movement at the incisal point, which were facsimiles of border movements at this point.

Shanahan and Leff (1959) used a small light bulb attached to the chin as a recording point in measuring opening and closing path differences between humans and articulators. The bulb was coated with black paint and a small hole was made in the coating to produce a pinpoint light source. Time exposure photographs captured the movement of the recording point. They found that humans and articulators opened and closed on different paths. This technique was the basis for six additional articles. In Part II, Shanahan and Leff (1962a) modified their device by attaching the bulb to a rod connected to the mandibular anterior teeth. A second bulb attached to the maxillary anterior teeth was used as a reference. They found that photographs of projected tracings of mandibular movements did not necessarily reveal the true nature of mandibular movements. In Part III, Shanahan and Leff (1962b) placed a mirror adjacent to the lights so that a side view could be recorded. Observations on the mandibular axis were made. The same apparatus was used in Part IV by Shanahan and Leff (1962c) to interpolate condylar movements in three dimensions. In Part V, Shanahan and Leff (1963) used the mirror superior to the device to make observations of movement in the horizontal plane. In Part VII, Shanahan and Leff (1964b) added a condylar light to their device. Sagittal photographs were used to compare condylar movements with intraoral anatomic landmarks that could affect the condylar path.

Using a stroboscopic method, Lundeen (1959) made multiple exposures of mandibular recording points. Small steel balls were attached to a mandibular framework and were positioned at the condylar area near the mandibular premolars and midway between these two. Two bearings were attached to the maxillary arch as a reference. A strobe light set at ten flashes per second reflected off the steel balls and onto a recording photographic plate in the sagittal plane. He stated that his technique could measure the angle of rotation of the mandible and allow for calculation of the motion of other points in addition to those measured.

Zola and Rothschild (1961) fabricated a "mechanical condylar thesiograph" that they used to trace and record condylar positions. This instrument was similar to a conventional face-bow except it had separate left and right sections that were cemented to the mandibular buccal surfaces. The condylar-marking element could record the positions of each condyle. They concluded that the rest position of the mandible had no predictable relationship to the hinge axis position.

Boucher (1961) used extraoral Gothic arch tracings to study the limiting factors of mandibular retrusion. The temporomandibular and capsular ligaments were severed on cadavers and on live subjects requiring this therapy. Neither ligament was found to limit mandibular retrusion. A subsequent study by Boucher and Jacoby (1961) used extraoral Gothic arch tracings to show that the mandibles of unconscious subjects could be retruded further posteriorly than when the subjects were conscious.

Woelfel, Hickey, and Allison (1962) used a technique where indicators were attached to maxillary and mandibular complete dentures. Left anterior, center and right anterior balls were attached to each denture. Motion pictures were made while subjects performed border movements and masticatory functions with various occlusal forms. Each frame of the film was analyzed and projected on an electronic device that plotted the positions of the recording points. Simultaneous observation of selected points allowed examination of individual cyclic mandibular movements.

Beck and Morrison (1962) recorded functional mandibular motions with teeth in contact using a transducer/recorder system. Their work was some of the earliest research with an electronic, computerized system. The transducers were attached to a rigid framework around the patient's head and measured movement of three brass spheres that were attached to a mandibular clutch via ball bearings and raceways. Mandibular movement caused a change in the signal transmitted to the transducer. This signal was then fed into a recorder and stored. The recorded signal was then fed into a duplicator that translated the data and programmed the movement on casts mounted on a motion simulator with six pen motors.

Hickey (1963) made motion pictures of functional masticatory movements using three small light sources as the recording points. A pin was surgically inserted into each condyle and was used as a light support. The third light was attached to the mandibular anterior teeth. Three reference grids were placed around each light and three cameras were positioned in different planes to record all lights simultaneously. Analysis was made with a frame-by-frame projection onto graph paper.

Griffin (1963) designed a mandibular movement-recording device he called a "mandibular kinematograph." This instrument measured the three-dimensional displacement of a rod projecting horizontally form the subject's chin. The rod was attached to the chin by a chin cap and a neck strap. There were no intraoral attachments. Several recording styli were attached by means of ball joints to the other end of the rod and positioned to make tracings in three dimensions. Mandibular movements were recorded on moving graph paper adjacent to the styli. The subject would press his head forward against nasion and philtrum rests to stabilize the maxilla during recordings.

Weinberg (1964) made motion pictures of dentate patients in left lateral, right lateral, opening and closing movements, and in centric relation. He used no reference points in comparing facial landmarks with positions on diagnostic casts.

Martone (1964) made motion pictures in the frontal planes of subjects wearing complete dentures. Reference grids were projected onto the subjects from the left and right sides. This provided bilateral contour lines with which to assess any long-term changes in functional facial contours of completed denture wearers.

Beyron (1964) also investigated mandibular function using cinematographic records. The mandibular movements were recorded using an indicator placed directly on the mandibular incisors. The movements were recorded during chewing with the lips apart.

Swanson (1966) introduced a recording system based on a modification of the Luce, Needles and House technique. This technique used custom-fabricated, intra-oral maxillary and mandibular clutches with a central bearing device. The maxillary clutch had four triangular-shaped cutting styli. The styli carved Gothic arch tracings into chemically-activated, acrylic resin before it polymerized. Swanson's system also included an articulator capable of accepting the recorded stereograph. The stereograph was used to manually program the articulator. When manually retraced, plastic fossa boxes were filled with a chemically-activated, acrylic resin on the maxillary member, then the mandibular condylar elements were used to create acrylic resin replicas of the temporomandibular fossa. These fossa replicas captured the recorded movements from the intraoral record and transferred it to the articulator, and permitted the articulator to closely mimic patient function.

Hodge and Mahan (1967) designed a position-gnathometer to measure mandibular movement in specified closure paths at the mandibular incisors. This mechanical instrument was designed so that a pointer could be moved in any direction in three dimensions to measure a mandibular incisor point relative to the maxillary anterior teeth and the Frankfort horizontal plane. They specifically measured deviations between centric relation occlusion and centric occlusion.

Rudd (1967) used two anterior reference spheres; one attached to the maxillary arch and one to the mandibular arch, to illustrate functional masticatory movements. The spheres were coated with fluorescent paint and illuminated with an ultraviolet light. Mirrors were positioned so that movement of the spheres could be seen in three planes. Time-exposure photography was used to make a permanent record of the movements.

Messerman (1967) developed a computer-pantograph system at the Case Institute of Technology. Six linear transducers connected to maxillary and mandibular face-bows measured jaw movements. The clutches were attached to the buccal surfaces of the maxillary and mandibular teeth. The intraoral clutches were designed to allow occlusal contact. The recorder weighed less than two ounces and allowed the patient's head freedom of movement. Electronic sensor output was fed into a multi-channel tape recorder. Recorded information was fed into a device called the Case Gnathic Replicator. This mechanism contained six motors that drove rods to which diagnostic casts were attached. The mechanism permitted the casts to mimic the recorded movements that were fed into the Case Gnathic Replicator.

Schmidt (1967) developed an instrument to measure six angles of jaw movement in inches and degrees of rotation. The device consisted of six potentiometers arranged in a precision linkage that was attached to the maxillary and mandibular teeth. Intraoral clutches were used, which allowed for occlusal function. The twenty-ounce recorder was positioned anterior to the patient in the midline and provided electrical signals that could be coupled to an analog computer.

Gillings (1967) developed an instrument he called a Photoelectric Mandibulograph. This device used a mandibular rod and light that attached to the labial surfaces of the mandibular incisors with cyanoacrylate cement. A headframe was rigidly attached to the head without restricting head movements. Three sets of photocell detectors were positioned in the frame in three different planes. Mandibular movement caused the light to move in relationship to the photocells, changing their electrical output. These signals were recorded and displayed on a moving-paper oscillograph.

Oishi (1968) developed a device that measured and recorded mandibular movements in three dimensions by means of variable air condensers connected to a mechanical linkage. The motion of a point attached to the condensers caused a variation in capacitance that was detected by an oscillation circuit. Amplified voltage changes were then displayed on an oscilloscope as border movement tracings. The air condensers were positioned so that the motion was recorded in three planes.

Lee (1969) developed an extraoral stereographic research instrument. Condylar movements were engraved into clear plastic blocks by means of high-speed air turbines. An upper face-bow was attached to the maxillary arch with housed three plastic blocks. Lateral and protrusive movements of the mandible were captured in the sagittal plane. Once the records were engraved, the plastic blocks could be used as condylar guides for an articulator.

Rudd, Morrow and Jendresen (1969) developed a computerized photoanthropometry system composed of fluorescent-coated, ultraviolet-illuminated indicator balls attached to the maxillary and mandibular teeth by wire frameworks. The camera had a beam splitter attached to the lens so that it simultaneously recorded masticatory functions and a reference grid. Motion picture cameras in the frontal, horizontal and sagittal planes recorded the functional envelopes of motion. A film motion analyzer was used to transpose the images onto computer data sheets. The data was plotted and the various envelopes of motion could be visualized.

Guichet (1970) developed a pantographic system similar to McCollum's and Stuart's. His pantograph utilized six recording tables and six tracing styli. There were four condylar tables: one vertical and one horizontal table on each side, and two horizontal tables in the anterior incisal region. A compressed carbon dioxide cartridge powered the tracing styli. This permitted a single person to control the release of the six styli during the recording of lateral and protrusive movements and perform the pantographic recording (Van Putten 1987). Like the pantographs of McCollum and Stuart, the condylar characteristics of the patient were defined after the pantograph was mounted on an articulator and the record retraced.

Commercially-produced pantographs are generally based on McCollum's Gnathograph. Two pantographs that are presently available and are widely used in clinical practice and research are the Stuart and Denar pantographs. Stuart's association with McCollum led to the development of his pantograph as a successor to the Gnathograph. The Stuart pantograph differed in that it had magnetic assisted styli and used chalked Formica recording plates. The Denar pantograph differs in that it has the posterior recording plates mounted on the mandibular frame, uses pressure-sensitive recording paper and has spring-loaded styli. Both have been applied extensively to research in analyzing various aspects of border movements.

Knap (1970) reported a study which used a sensing device consisting of six potentiometers housed on two face-bows that were connected to maxillary and mandibular clutches. The device weighed 200 ounces, and was supported above by a constant-tension spring suspended from the ceiling. Movement around each axis of the potentiometers was recorded in six degrees of freedom. This information was processed into a computer that converted the signals into mathematical values that could be graphed.

Clayton (1971) noted; "A pantograph graphically reflects individual anatomic characteristics of the temporomandibular joints which influence mandibular paths of movement or paths of movements of cusps. An articulator is used to interpret the information recorded by the pantograph. The articulator is then used to produce motions, which determine occlusal anatomy."

Honee and Meijer (1974) attached a light-sensitive element to a maxillary incisor, and another to a mandibular incisor. An adjacent oscilloscope screen was used to generate a bright, triangular-shaped light source that was focused by a lens onto the place of the photoelements. As the mandible moved, the light passed the photocells and signals were generated. The time interval between electrical pulses of the two photocells was a measure of the distance between the two elements and therefore measured jaw displacement. Electrical signals were also used to generate the pattern of movement of a second oscilloscope.

Knap (1975) combined optical sensors with a mechanical linkage to record mandibular movement. The device consisted of six optical incremental encoders connected to each other and the intraoral clutches by a linkage that allowed freedom of movement in all directions. Angular displacement about each axis was measured by the encoders, and converted to electrical output. Optical sensor signals were amplified and recorded in a recorder. A motion duplicator was designed identically to the mandibular recorder except that electric motors were used in place of optical encoders. The motion duplicator, with mounted casts, mimicked mandibular movements when programmed with recorded data. A digital platter provided a graphic display of mandibular motion.

Waysenson (1977) devised an optoelectronic-recording device that did not attach to or interfere with the subject. The apparatus consisted of three photoelectric cells; two of the cells were placed at right angles to each other in a light tight box. A horizontal light beam struck both cells simultaneously after passing through narrow windows in the box. Opening, closing, and anterior-posterior movements were detected by the sensors. A third sensor used a vertical beam of light to measure lateral movements. Electrical signals from the photocells provided input for an oscilloscope, providing visualization of mandibular movements.

Karlsson (1977) developed a mandibular movement monitor using light-emitting diodes (LED's) and a photodetector system. Light form the LED's was focused onto semiconductor photodetectors placed in two cameras at right angles to each other. Digital output from the cameras was used to drive recording pens on an oscillograph. Karlsson concluded that mandibular movements in three dimensions could be measured with precision and reproducibility.

Joire (1978) used a single mandibular anterior light source to record Posselt's envelope of motion in the frontal and sagittal planes. The light was strobed so the photographic recordings incorporated a chronological component in the border tracings. It was then possible to see the relative length of time the mandible stayed in a particular border position.

Joss and Graf (1979) developed an optoelectronic system to study Posselt's envelope of motion. Mandibular movements were tracked by infrared-light emitters attached to splints that were cemented to the labial surfaces of the maxillary and mandibular teeth. Karlsson's camera-sensing system was used to track the lights. Data was computer-enhanced and printed in a three-dimensional format.

Jemt and Karlsson (1982) reported on the development and use of an optoelectronic system (Selspot System) that utilized three reference diodes attached to glass frames and a fourth mobile diode attached to a mandibular incisor. Two cameras that processed the information into a computer recorded light impulse signals. The computer calculated the magnitude of the registered movements.

Chance (1982) designed an optical pantograph to determine the chronology of mandibular border movements. He modified a Stuart pantograph to use styli that transmitted a beam of light rather than the pointed metal styli. The light was pulsed at 100-millisecond intervals. The recording medium was ultraspeed radiographic film. The result was a pantographic tracing that appeared as dotted lines on the radiographic film plates. He found the time-based optical pantograph to be a viable method of incorporating a time interval directly into recordings of mandibular border movements.

Lucia (1983) stated that the pantograph is the most accurate and practical method of recording jaw movements. He stated that interocclusal lateral and protrusive records provide limited information about the patient's condylar movements because the record captures only one position of the patient's lateral border movement. On the other hand a pantograph records the entire border movement and the information obtained equals an infinite number of lateral interocclusal records.

Hobo and Mochizuki (1983) developed a computer-based pantograph-articulator system, "the Cyber-Hoby." Three identical sensors were developed that could measure motion in two spatial dimensions. In addition, three styli were developed that would send a signal to the sensor. The styli were attached to the mandible, while the sensors were attached to the maxilla on the sagittal and frontal planes. By recording in two directions for each stylus, six independent measurements could be continuously generated during mandibular movement. The measuring system consisted of the sensor, voltage generator, voltage detector, data recorder, computer, and graphic plotter.

In 1983, Clayton described a new electronic pantograph. This system used four electronic sensors placed in the condylar region. The system produced numerical printouts used to program an articulator. It also produced a graphical printout that could be used to study the nature of the mandibular movements. Two anterior recording tables and styli simultaneously graphically recorded the mandibular motion.

Clayton (1983) in an in vivo study of 20 subjects compared a mechanical and electronic stylus pantograph. He found the recordings made by the electronic pantograph were comparable to those of the mechanical pantograph. He also found the recordings to be consistent over time and between operators.

Donaldson (1986) studied the ability of the two widely used and commercially available mechanical pantographs (Stuart and Denar) to record the same mandibular movements. He determined that the two pantographs recorded mandibular movements within a mean difference of less than 0.1mm.

Beard (1986) studied the same electronic pantograph that Clayton investigated. His studies found electronic pantography to be accurate and reliable. He found the electronic pantograph's ability to consistently record articulator settings was comparable to that of the mechanical pantograph. He noted the electronic pantograph was able to quickly analyze patient movements and generate numerical printouts of posterior condylar setting values. These numerical printouts reduced the potential of articulator setting error.

Anderson (1987) in his in vitro investigation noted the electronic pantograph provided an accurate and reliable means of recording immediate mandibular lateral translation, progressive mandibular lateral translation, and protrusive condylar inclination. Additionally, the electronic pantograph exhibited intra-instrument and inter-instrument reliability in recording the same movements.

Price (1988) compared the articulator settings obtained using the electronic pantograph and those obtained with lateral bite recordings. Over a two-week period he noted that two operators consistently obtained the same articulator settings using an electronic pantograph. The settings obtained using lateral records had a large ranges and large coefficients of variation. He stated that the lateral record technique is too unreliable to be used to accurately set an articulator.

Pelletier (1991) in his bench-top study compared the condylar control settings obtained using a variety of methods. He stated the both electronic and mechanical pantography recorded reproducible and accurate measurements. His final conclusion was the electronic method was the most accurate and reliable method.

Catic (1999) used an optoelectronic jaw-movement recording system to record opening and closing movements in symptomatic and asymptomatic patients. Movement paths of the hinge axis and the kinematic axis were calculated. He found significant differences in the axis location and repeatability of the axis location of both groups.

Olthoff (2000) used an optoelectronic pantographic system in conjunction with a CAD/CAM system to model functional occlusal surface of posterior teeth. His study investigated the differences in crown structure and occlusal morphology of a crown designed in a static occlusion and one in which an individual pattern of dynamic movement was considered. He also demonstrated that, in the near future, computer techniques might help to monitor the ideal articulation in restorative dentistry. Electronic registration devices will be an essential part of these new techniques.

III. MATERIALS AND METHODS

A. Materials and Equipment

The materials and equipment used in this investigation were as follows:

Semi-adjustable articulators:

Denar Mark II articulator (Teledyne Water Pik, Fort Collins CO, Figure 1)

Standardized initial THA location:

Stuart axis locator (CE Stuart Gnathologic Instruments, Ventura CA, Figures 2 and 3)

Reference plates:

Stuart maxillary and mandibular pantographic reference plates (CE Stuart Gnathologic Instruments, Ventura CA, Figure 4)

Test THA instruments:

Kinematic face-bow (Denar, Teledyne, Fort Collins CO, Figures 5 and 6)

Optoelectronic computerized pantograph (Condylocomp, Dentron, Germany, Figures 7 and 8)

Test pantographic systems:

Mechanical pantograph (Denar, Teledyne Water Pik, Fort Collins CO, Figure 9)

Optoelectronic computerized pantograph (Condylocomp, Dentron, Germany, Figure 7)

Electronic stylus computer pantograph (Pantronic, Teledyne Water Pik, Fort Collins CO, Figure 10)

Figure 1: The three semi-adjustable articulators, Denar Mark II articulators.

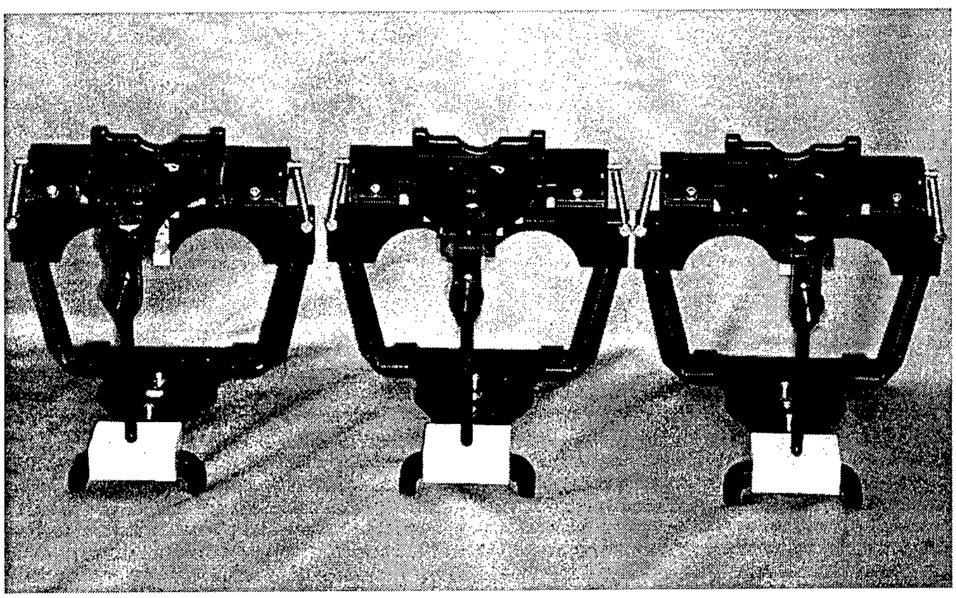


Figure 2: The standardized initial transverse horizontal axis location instrument. Stuart kinematic face-bow, transverse horizontal axis location instrument, lateral view.

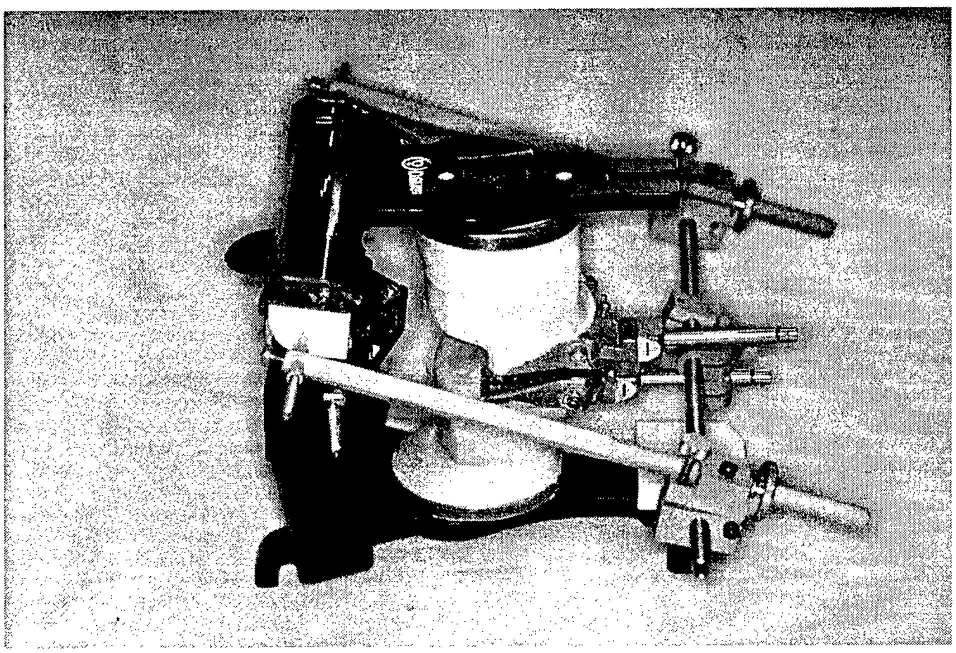


Figure 3: The standardized initial transverse horizontal axis location instrument. Stuart kinematic face-bow, transverse horizontal axis location instrument, frontal view.

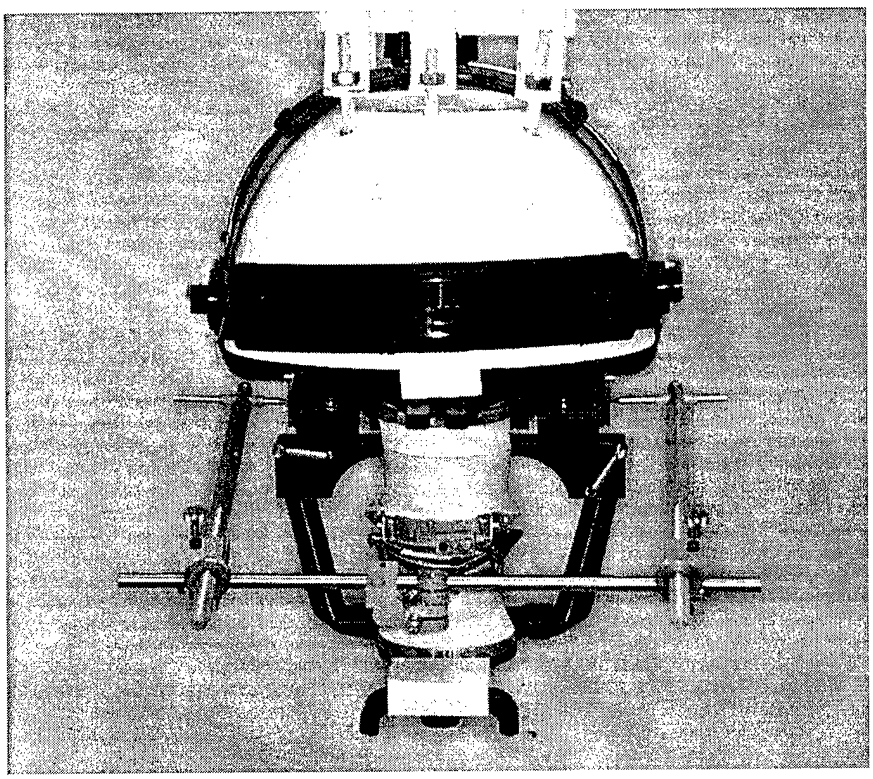


Figure 4: The maxillary and mandibular pantographic reference plates, Stuart reference pantographic reference plates.

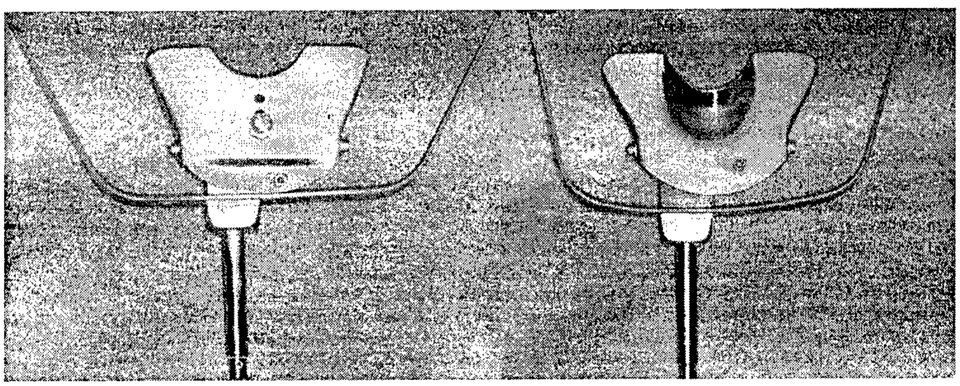


Figure 5: The investigation transverse horizontal axis location instrument. Denar kinematic face-bow, transverse horizontal axis location instrument , lateral view.

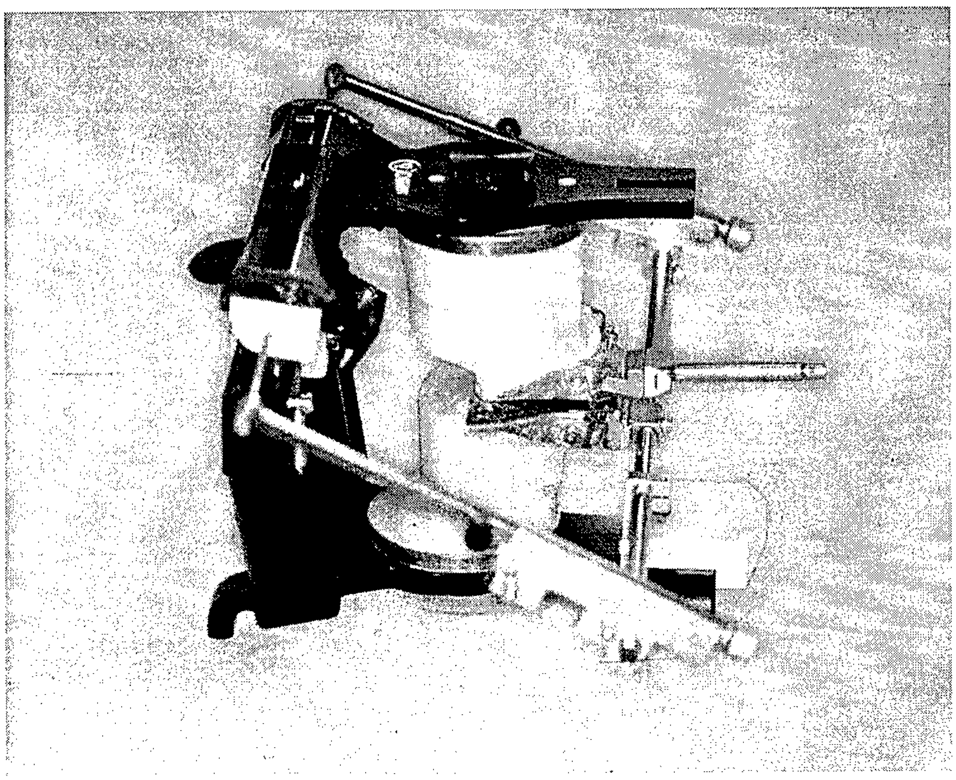


Figure 6: The investigation transverse horizontal axis location instrument. Denar kinematic face-bow, transverse horizontal axis location instrument, frontal view.

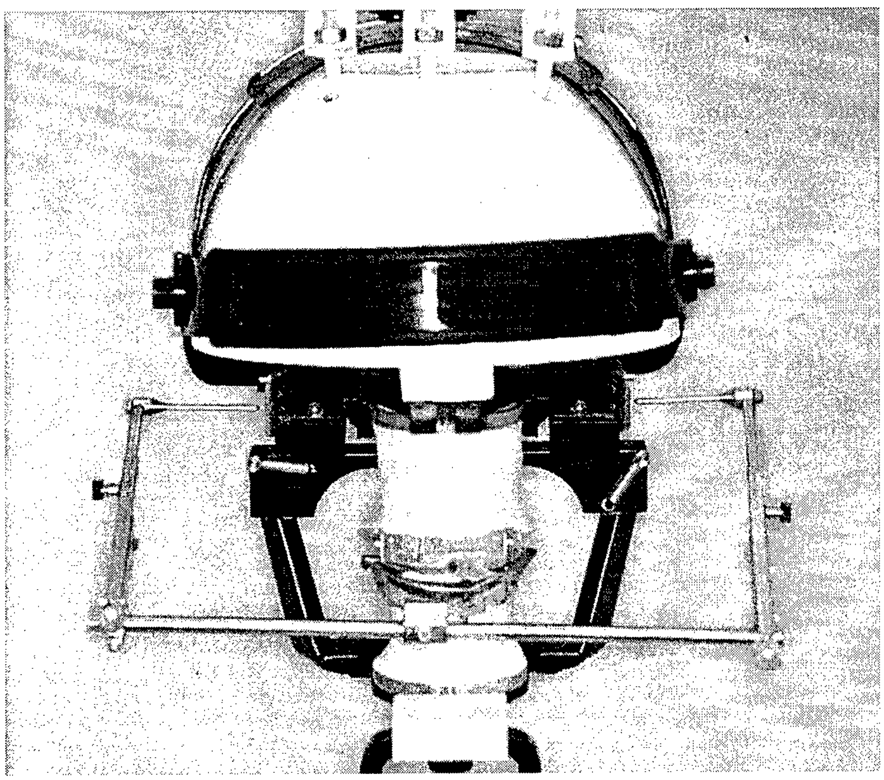


Figure 7: The investigation transverse horizontal axis location instrument, Condylocomp optoelectronic computerized pantograph, frontal view.

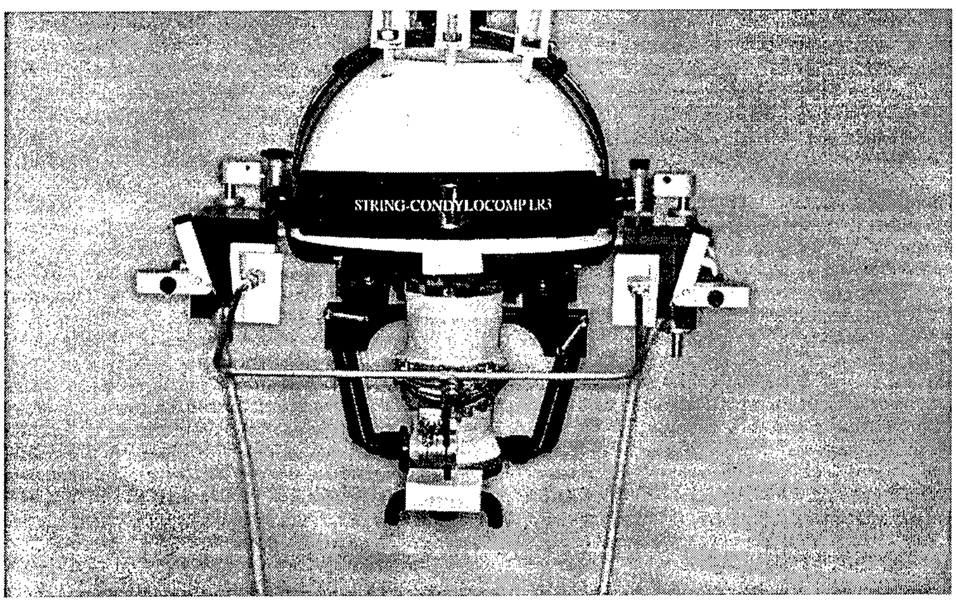

STRING-CONDYLOCOMP LR3

Figure 8: The investigation transverse horizontal axis location instrument, Condylocomp optoelectronic computerized pantograph, transverse, horizontal axis location headframe, frontal view.

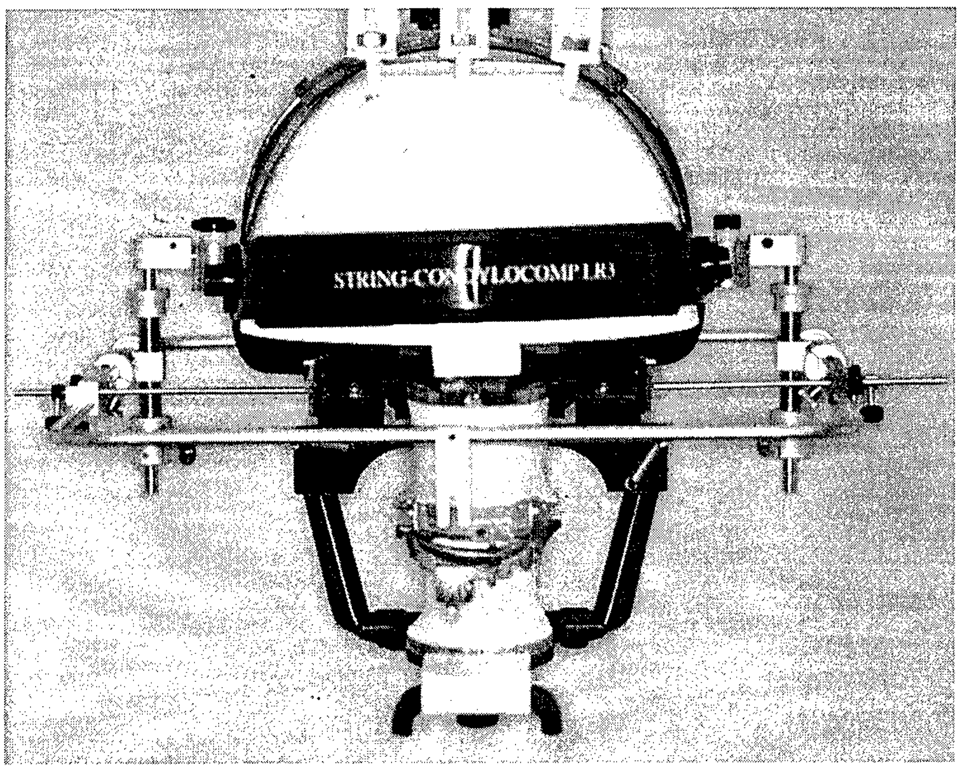

STRING-CONDYLOCOMP LR3

Figure 9: The mechanical pantograph, Denar mechanical pantograph.

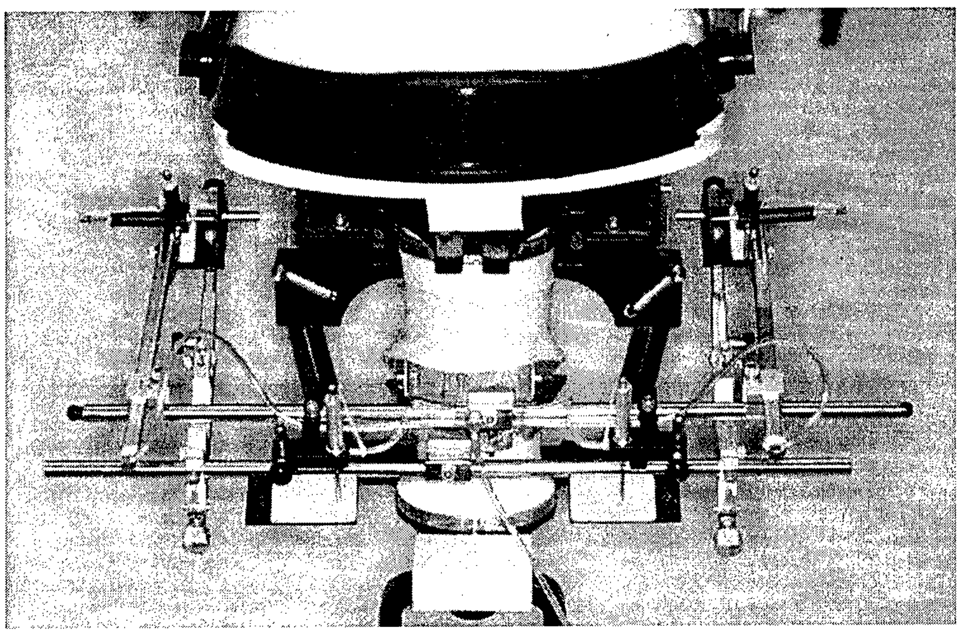
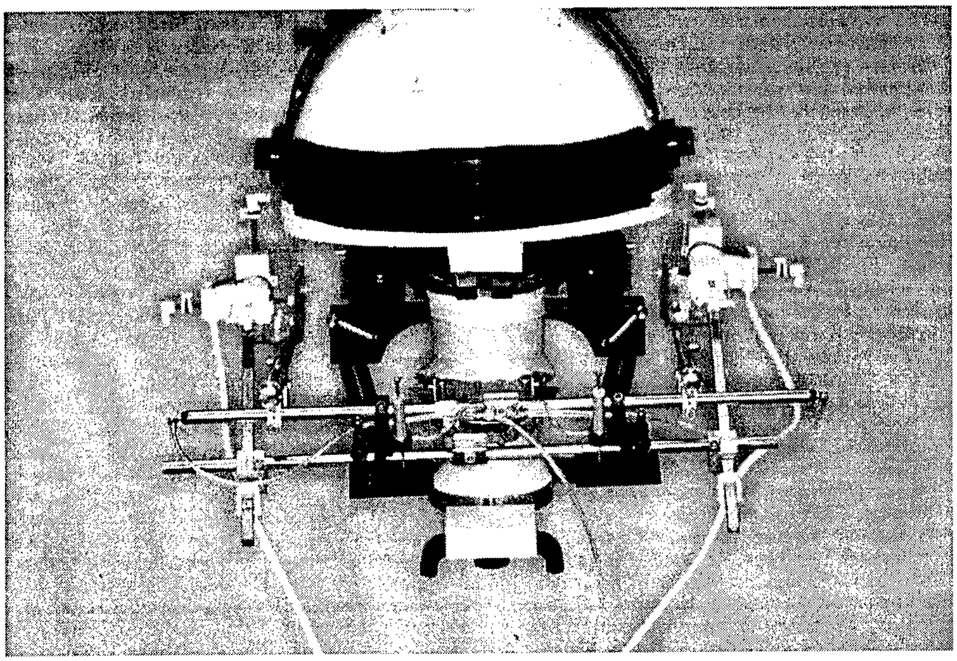


Figure 10: The electronic stylus computerized pantograph, Pantronic electronic stylus, computerized pantograph.



Measurement device:

Electronic vernier caliper (#6425, Central Tools, Cranston RI, Figure 11)

Magnification:

Binocular microscope 15x magnification (Nikon SMZ-1B, Nikon Ind., Japan, Figure 12)

Through-the-lens, 4.3x magnification (Prismatic TTL, Orascoptic Research, Madison WI, Figure 13)

Apparatus fabricated for the investigation:

Fine-lined graph paper holding and repositioning device (Figure 14)

Articulator holding and suspending apparatus (Figure 15)

The features of the Denar Mark II instrument include a centric holding latch (Figure 16), adjustable protrusive condylar path (PrCp) angle (Figure 16), adjustable progressive mandibular lateral translation (PMLT) angles (Figure 17), adjustable immediate mandibular lateral translation (IMLT, Figure 18) and straight-line PrCp, PMLT and IMLT movement.

The Stuart axis locator and Denar axis locator are kinematic face-bows designed to locate the THA of the mandible. Each apparatus has a mandibular element which consists of a mandibular reference plate to secure the instrument to the mandibular arch, a cross arm attached to the reference plate and right and left micro-adjustable arms with axis pins or styli attached to the cross arm. Traditionally, recording flags using fine-lined graph paper (Figure 19, Stuart) or micro-dot paper (Denar) are secured to the patient in the area of the THA either using a head harness or a clutch, cross-arm

Figure 11: The measurement device, Central Tools electronic vernier caliper #6452.

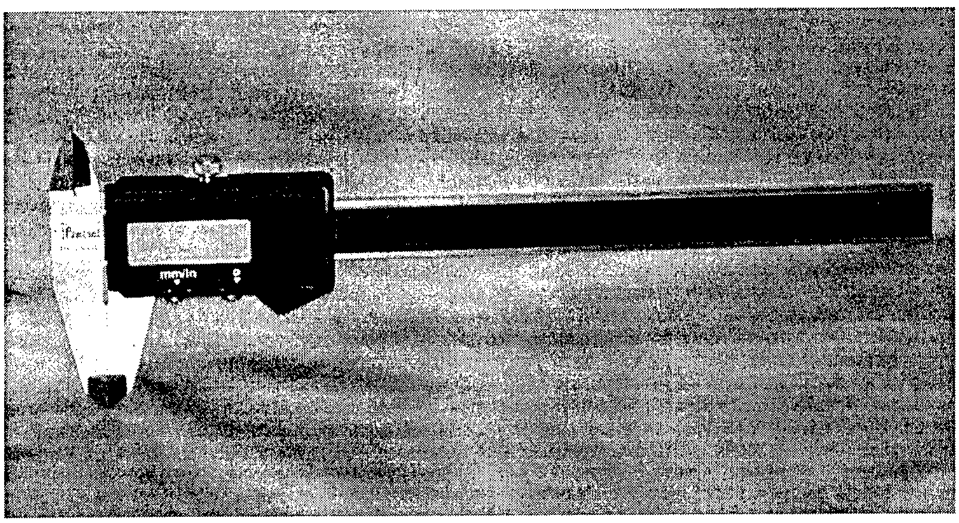

mm/in

Figure 12: The binocular microscope, Nikon SMZ-1B 15x magnification microscope.

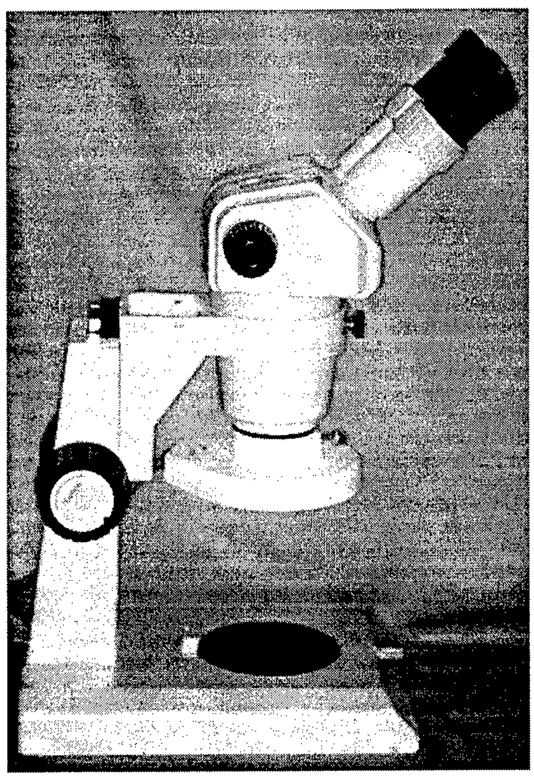


Figure 13: The through-the-lens Prismatic TTL 4.3x magnification.

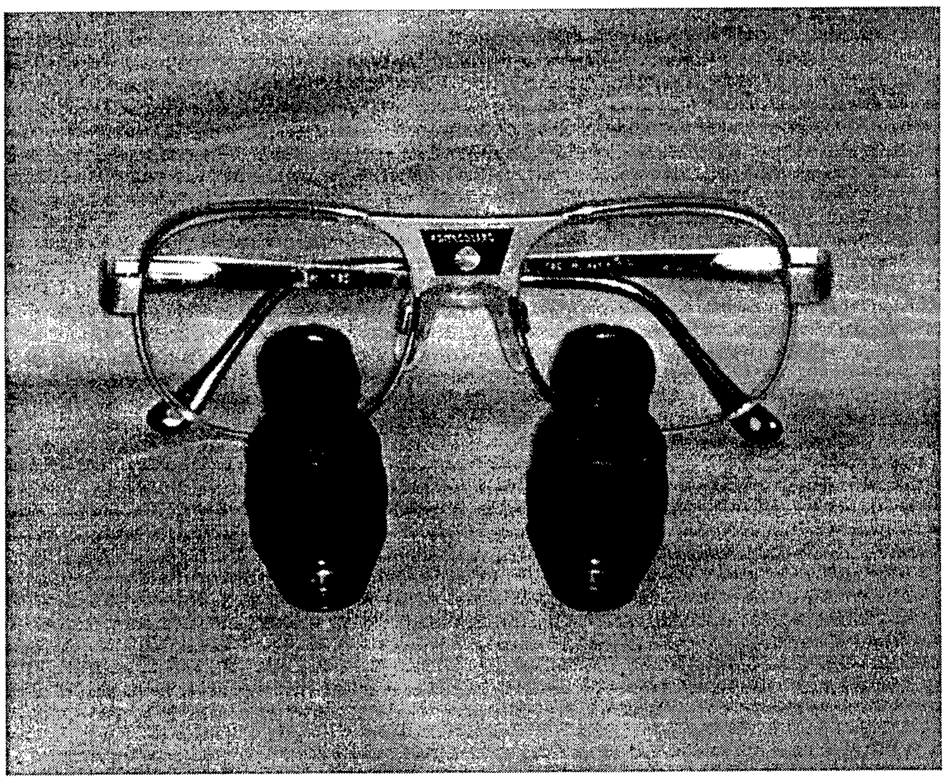


Figure 14: The fine-lined graph paper holding and repositioning device.

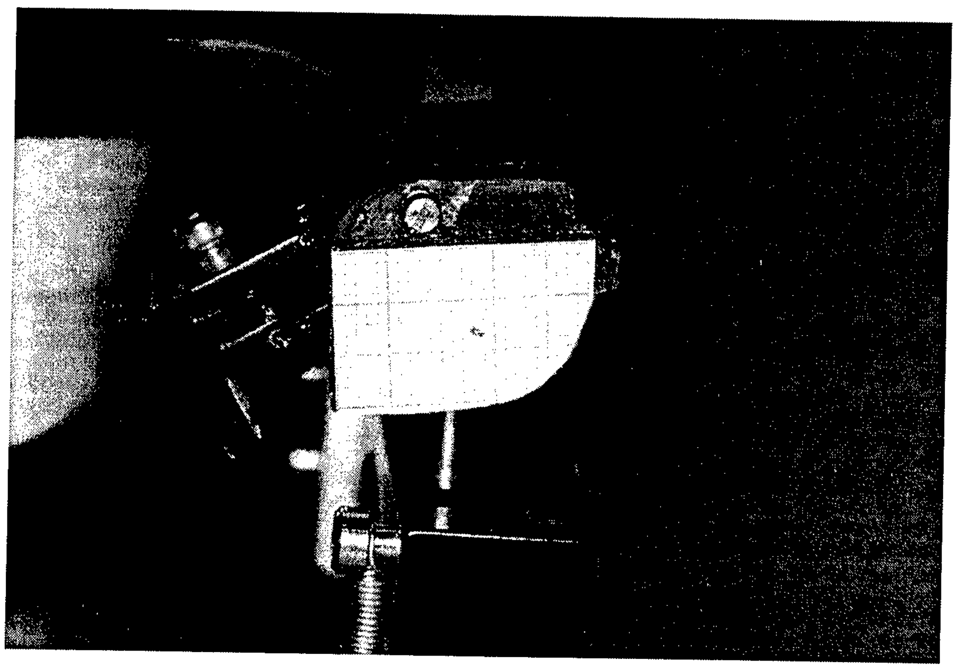


Figure 15: The articulator holding and suspending apparatus.

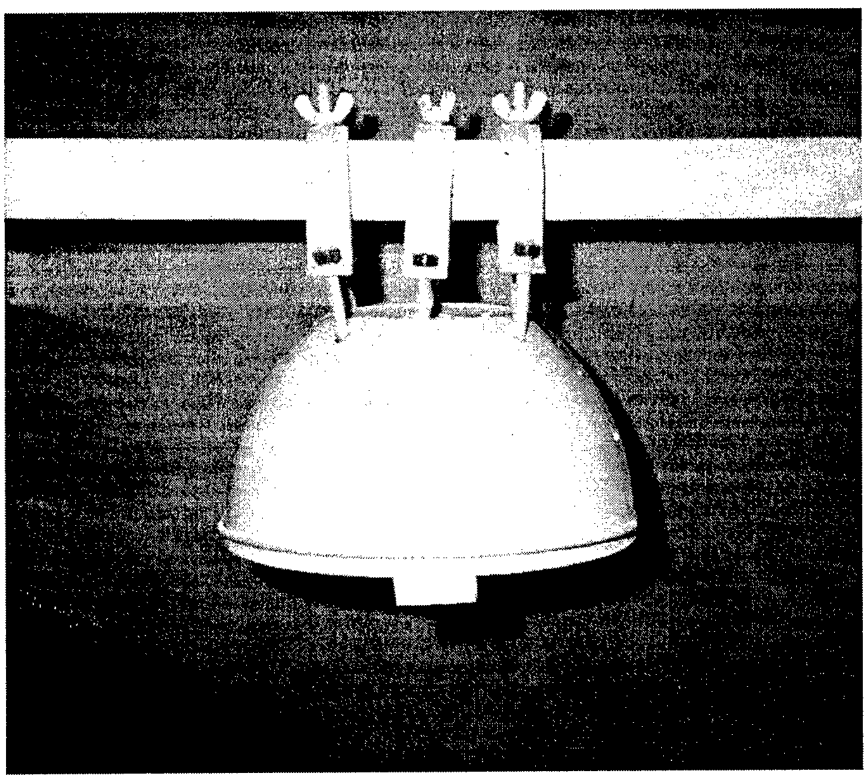


Figure 16: The Denar Mark II centric-holding latch, and protrusive condylar path adjustment.

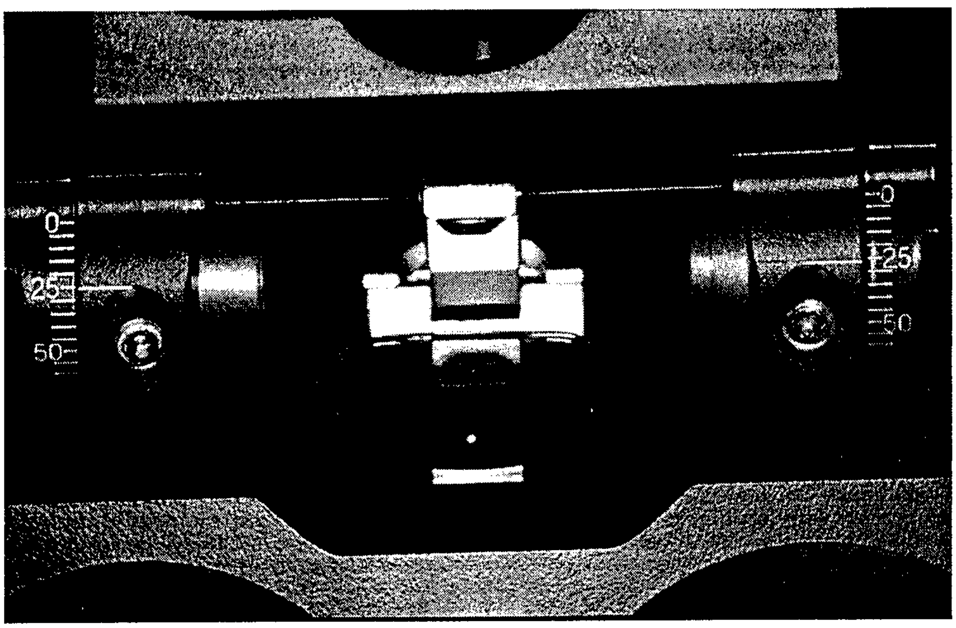

0
25
50
0
25
50

Figure 17: The Denar Mark II progressive mandibular lateral translation adjustment.

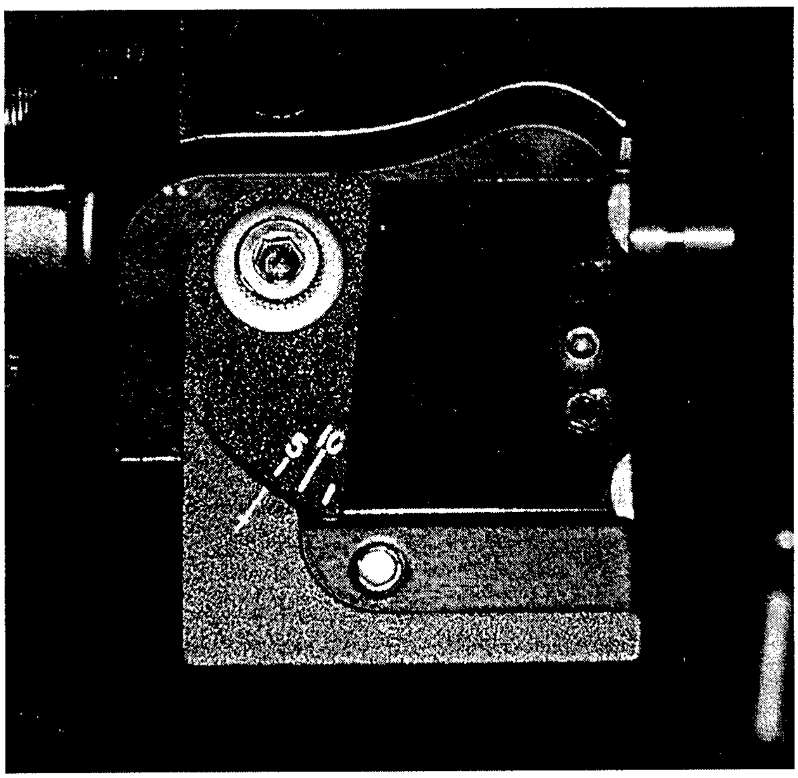


Figure 18: The Denar Mark II immediate mandibular lateral translation adjustment.

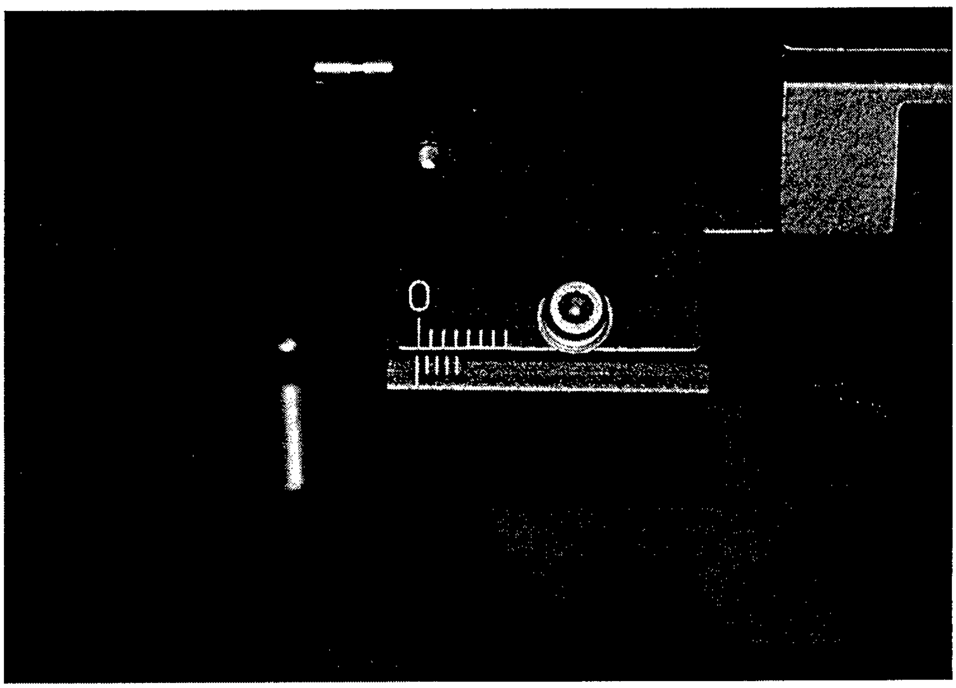
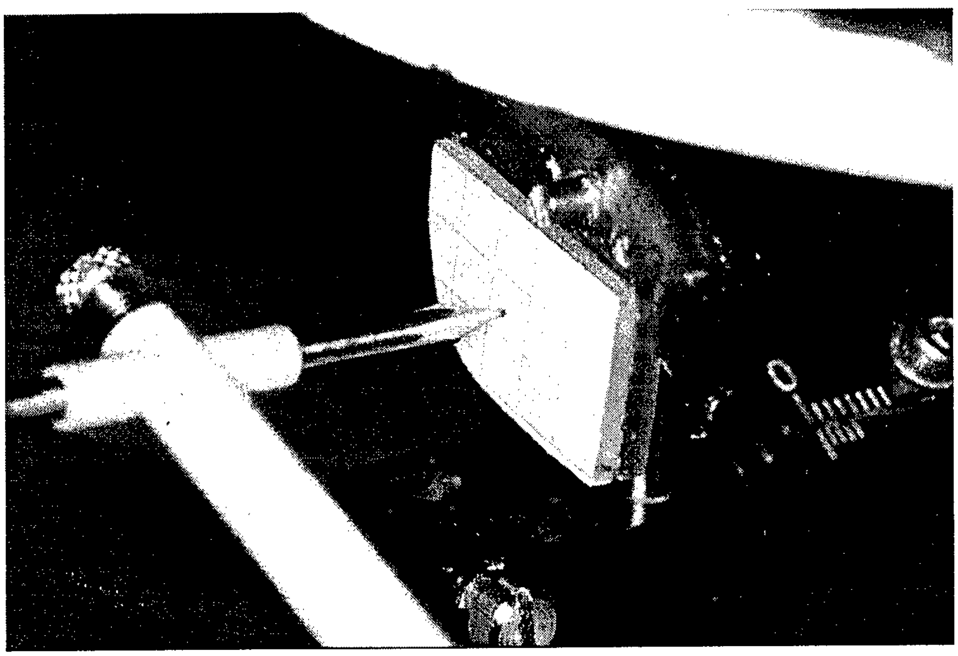


Figure 19: Fine-lined, one millimeter square, graph paper pictured with the Stuart kinematic face-bow, transverse horizontal axis location instrument.



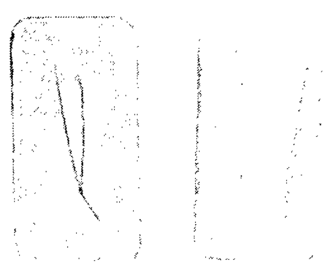
assembly. The mandibular element is permitted free rotational movement. Through a series of adjustments of the side arms, a position will ultimately be located by trial and error where the tips of the styli do not translate on an arc, but remain fixed in that position during small opening and closing movements of the mandible.

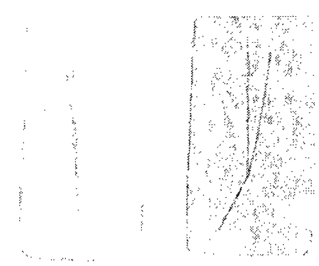
The mechanical pantograph is an instrument consisting of a series of rods arranged in a parallelogram-like configuration that is used to duplicate a map or drawing on the same or different scale. The dental pantograph, or mandibular recorder, is used to record the condylar pathways of lateral border movements, the topography of the fossa in these pathways, and the lines for the resulting three-dimensional simultaneous movement that occurs in each of the three coordinate planes. Protrusive movement, although not a border movement, is also recorded. The pantographic recordings or pantograms may then be used to program articulators capable of accepting these recordings.

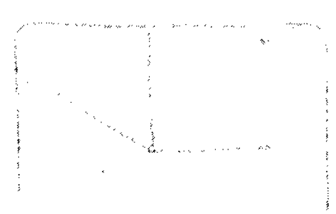
It is believed if an instrument can duplicate border movements, the functional movements within these borders would also be captured. It is then possible to construct occlusal restorations and prosthesis on this instrument. These restorations will then function properly in the mouth without interference. (Lucia 1983, Stuart 1979)

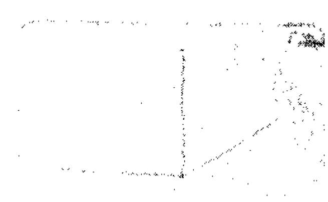
The Denar pantograph consists of micro-adjustable, recording side arms, recording plates that accept the Denar recording pads, and air and elastic controlled styli that are used to generate the extraoral graphic record of mandibular movements (Figure 20). Once these movements are recorded, the pantograph is transferred to an articulator (Denar fully or semi- adjustable) to program the articulator.

Figure 20 Example of extraoral graphic record of articulator movements recorded by the mechanical pantograph, Denar mechanical pantograph.









The Pantronic pantograph is a micro-processor-assisted electronic stylus measuring system. A conventional Denar mechanical pantograph is converted by replacing the posterior horizontal and vertical recording tables and styli with Pantronic recording tables, electronic styli and sensors. The converted mechanical Denar pantograph is joined to the Pantronic computer via a foot control and data cable. This system records mandibular movement at 4 different points by means of a lightly contacting, electronic-stylus sensor system (Figure 21) with a resolution of 0.1mm. Anterior graphic recording tables are also available for immediate graphic recording. Measurement data is recorded and processed by the Pantronic computer (Figure 22). The data is then presented in a printout from the Pantronic computer (Figures 23 and 24). Numeric and graphic readouts may be obtained.

The Pantronic numeric printouts can be used to program fully or semi- adjustable Denar articulators. The graphic readouts can be used to evaluate patient movement. Each increment of the plotted graphs represent 0.1mm. The information may be stored through programming of the articulator or the readout hard copy.

The Condylocomp LR3 is a microprocessor-assisted measuring system for operation with IBM compatible computers. It is an optoelectronic measuring device for recording all mandibular movements (translations and rotations). A rigid, adjustable head-frame holds the adjustment portions of the apparatus as well as the infrared light-emitting and receiving sensors. A rigid, lightweight (approximately 50g) bow containing the light reflectors is attached to the mandible via a para-occlusal clutch or occlusal reference plate.

Figure 21: The electronic-stylus computerized pantograph, Pantronic, lightly contacting electronic-stylus sensor system.

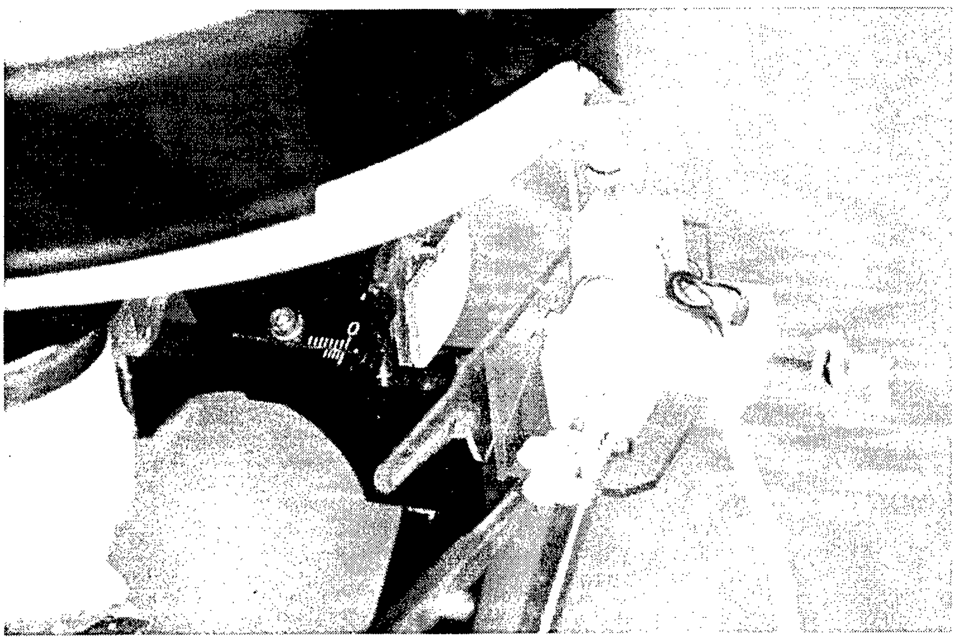


Figure 22: The electronic-stylus computerized pantograph, Pantronic computer.

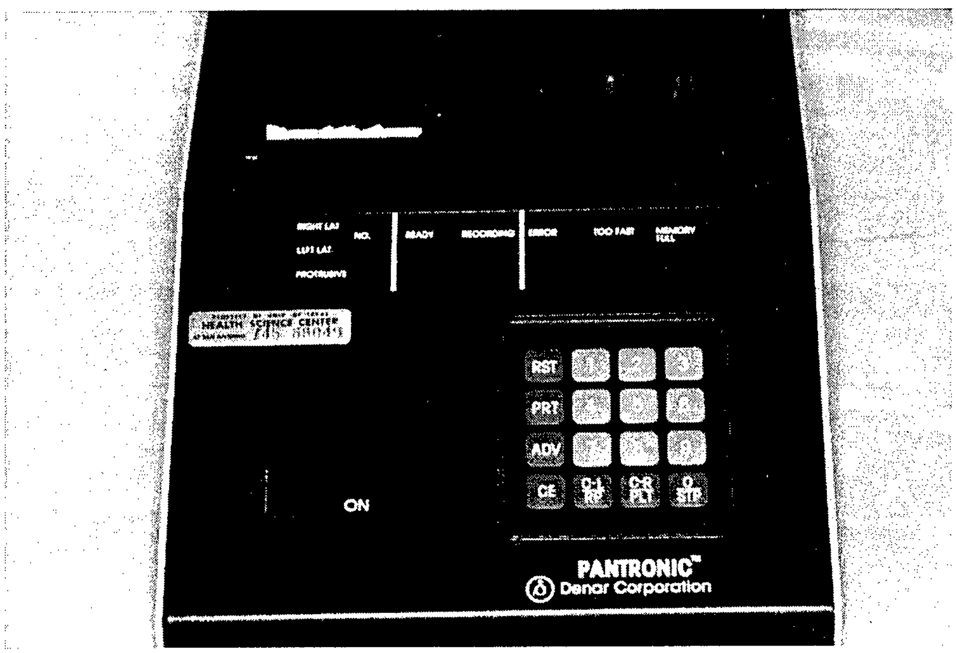

RST
PRT
ADV
CE
ON
PANTRONIC™
Denar Corporation

Figure 23: Example of the electronic-stylus computerized pantograph, Pantronic print-out.

Pantronic Print-out

Numeric Readouts

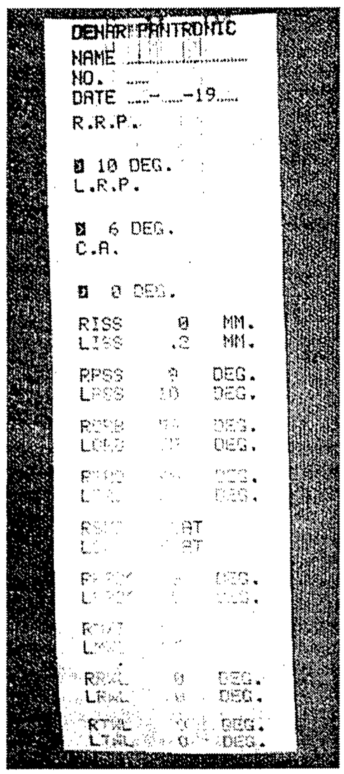
Note: The "R" and "L" preceding each abbreviation below stand for the patient's right and left condylar paths of movement.

Medial Wall Insert Abbreviations

ST Straight
DI Distributed
EL Early

A [illegible]
B [illegible]
C [illegible]
D [illegible]
E [illegible]
F [illegible]
G [illegible]
H [illegible]

Figure 24: Example of the electronic-stylus computerized pantograph, Pantronic, print-out from investigation.


DENAR PANTRONIC
NAME
NO.
DATE -19
R.R.P.
10 DEG.
L.R.P.
6 DEG.
C.A.
0 DEG.
RISS 0 MM.
LISS .2 MM.
RPSS 0 DEG.
LPSS 10 DEG.

The Condylocomp optoelectronic system records mandibular movement at 10 different points by means of a non-contact, disturbing-light, compensated-light reflection principle with a resolution of 0.01mm (Figures 25 and 26). Measurement data is processed by the Condylocomp microprocessor (Figure 27), and then passed on to the IBM compatible computer (Figure 28). The JAWS program makes evaluation of the recorded data for Windows®. Recorded movements are shown on a computer screen in real-time or slow motion. The patient's sagittal, vertical and transverse planes on both sides are viewed simultaneously.

In addition to viewing the recorded mandibular movements (Figures 29,30 and 31), the system can determine THA location (Figure 32), and calculate articulator-specific settings (including IMLT, PMLT and PrCp) for several articulator systems. This information can be displayed on the monitor, printed, or stored.

B. Rationale

This investigation consisted of four specific aims. These specific aims were designed to address the main objective of the project: to assess and compare the accuracy, repeatability, and procedure time of the optoelectronic computerized pantograph, the electronic stylus computerized pantograph, the mechanical pantograph, and the kinematic face-bow.

The constants were PrCp, PMLT and IMLT. The variables were the axis-location instruments and the pantographs. The electronic-stylus computerized pantograph and mechanical pantograph can not locate the THA, but instead utilize kinematic face-bow THA location. The optoelectronic pantograph does have THA location abilities. The

Figure 25: The optoelectronic pantograph non-contact, Condylocomp, infra-red light emitters and reflectors.

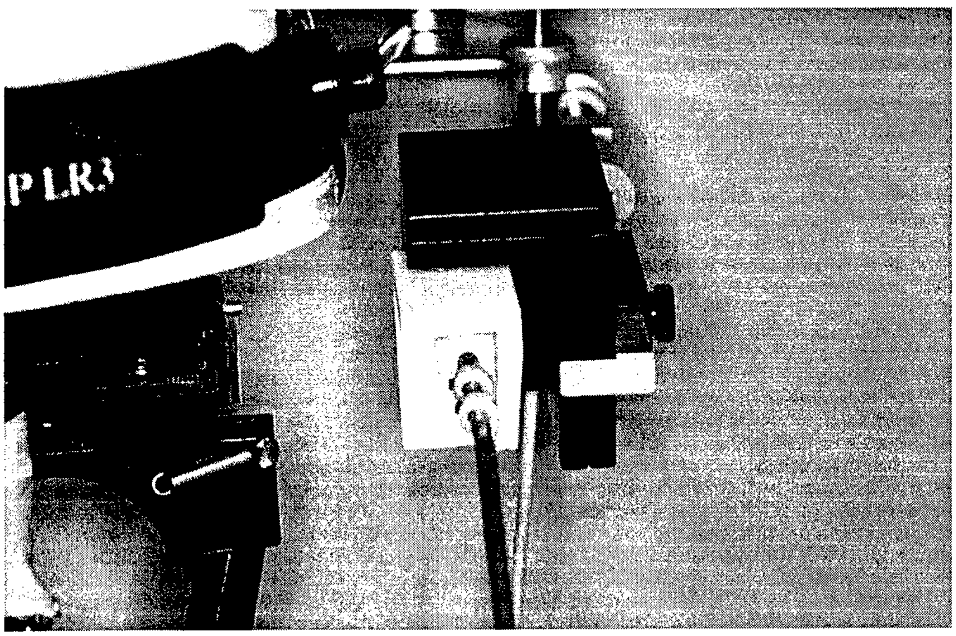

P LR3

Figure 26: The optoelectronic pantograph non-contact, Condylocomp, infra-red light emitters and reflectors.

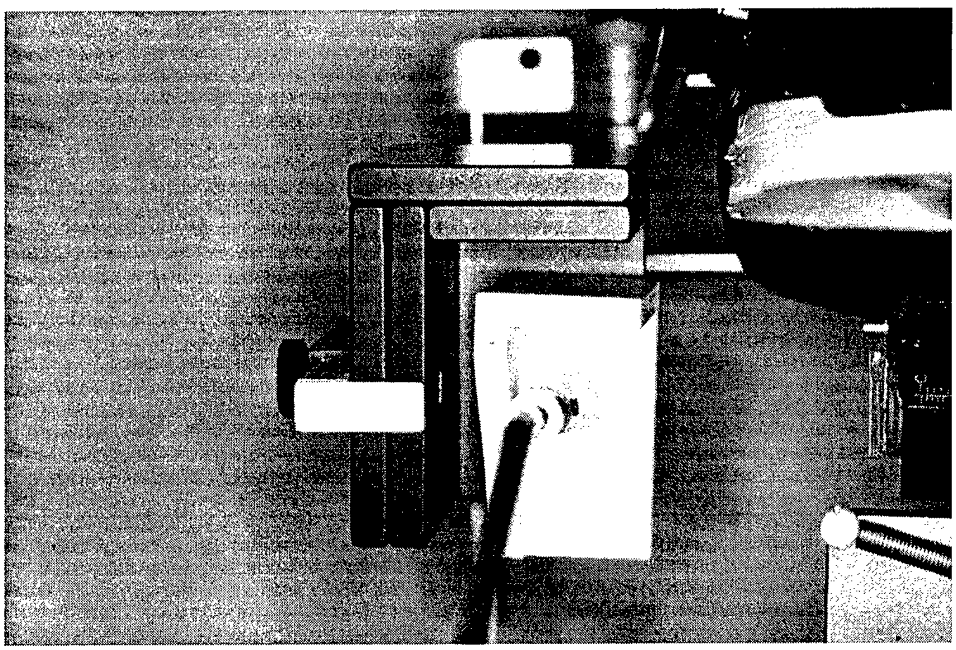


Figure 27: The optoelectronic pantograph, Condylocomp, microprocessor.

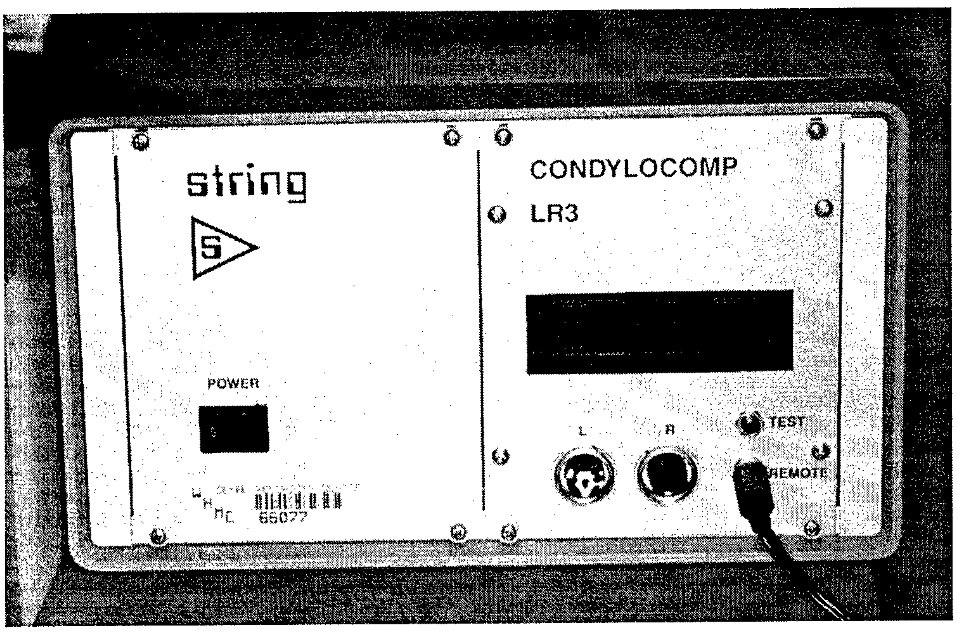

string
CONDYLOCOMP
LR3
POWER
L
R
TEST
REMOTE
65077

Figure 28: The optoelectronic pantograph, Condylocomp, microprocessor IBM compatible computer and monitor.

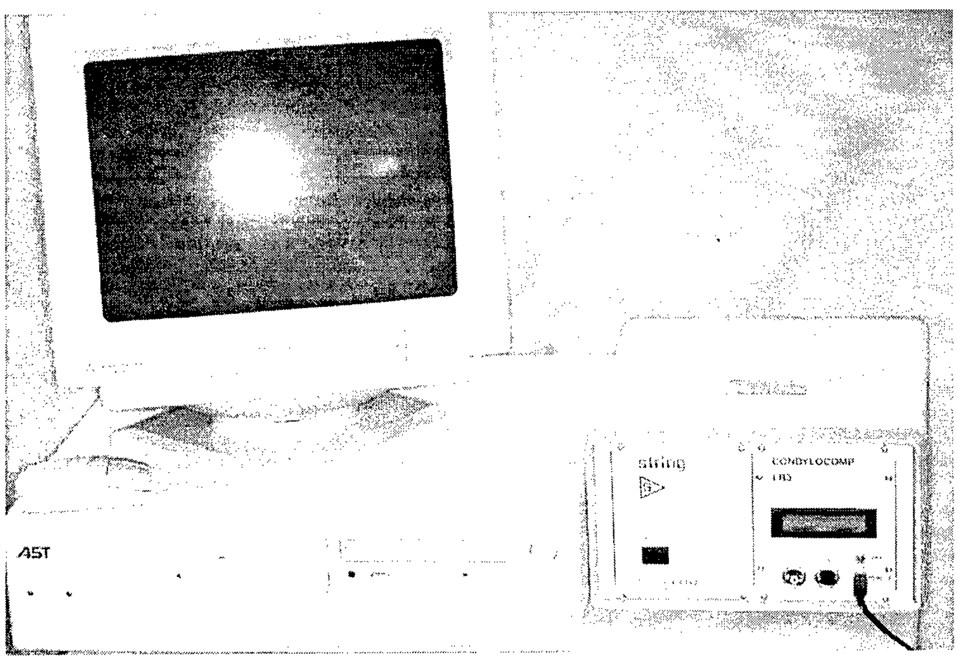

AST
CONDYLOCOMP

Figure 29: Example of the optoelectronic pantograph, Condylocomp, real time recording of protrusive condylar path movement from the investigation.

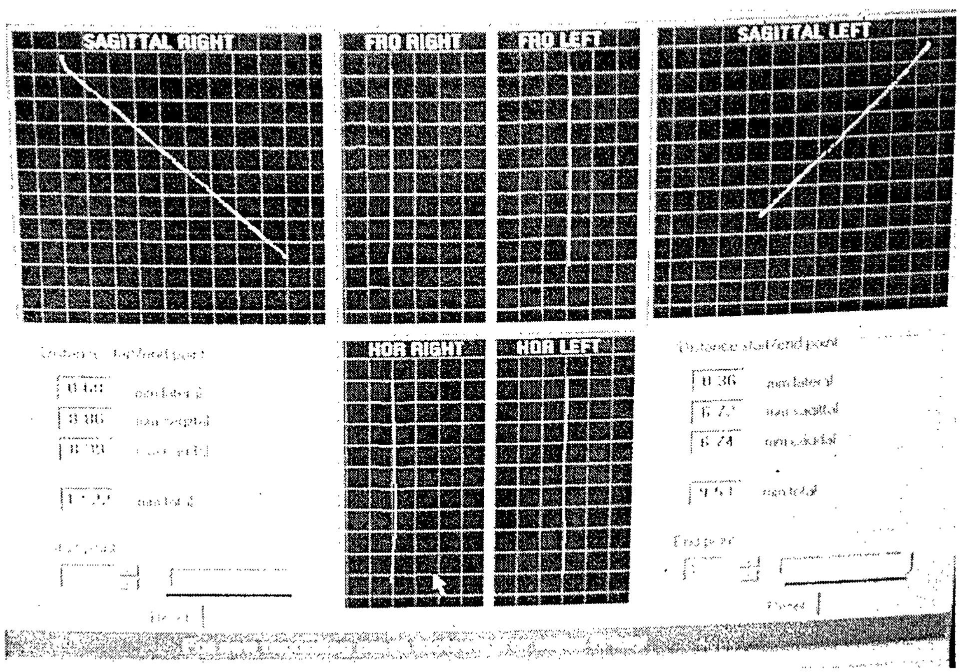

SAGITTAL RIGHT
FRO RIGHT
FRO LEFT
SAGITTAL LEFT
HOR RIGHT
HOR LEFT

Figure 30: Example of the optoelectronic pantograph, Condylocomp, real time recording of left mediotrusion, right progressive mandibular lateral translation movement from the investigation.

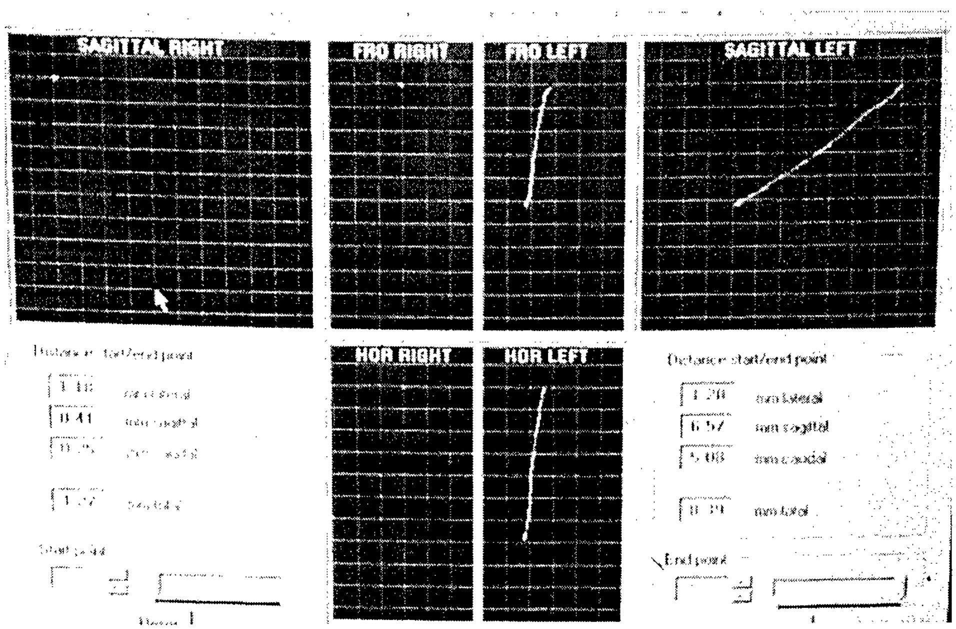

SAGITTAL RIGHT
FRO RIGHT
FRO LEFT
SAGITTAL LEFT
HOR RIGHT
HOR LEFT
Distance start/end point
6.57
mm lateral
mm sagittal
mm caudal
mm total
End point

Figure 31: Example of the optoelectronic pantograph, Condylocomp, real time recording of right mediotrusion, left progressive mandibular lateral translation movement from the investigation.

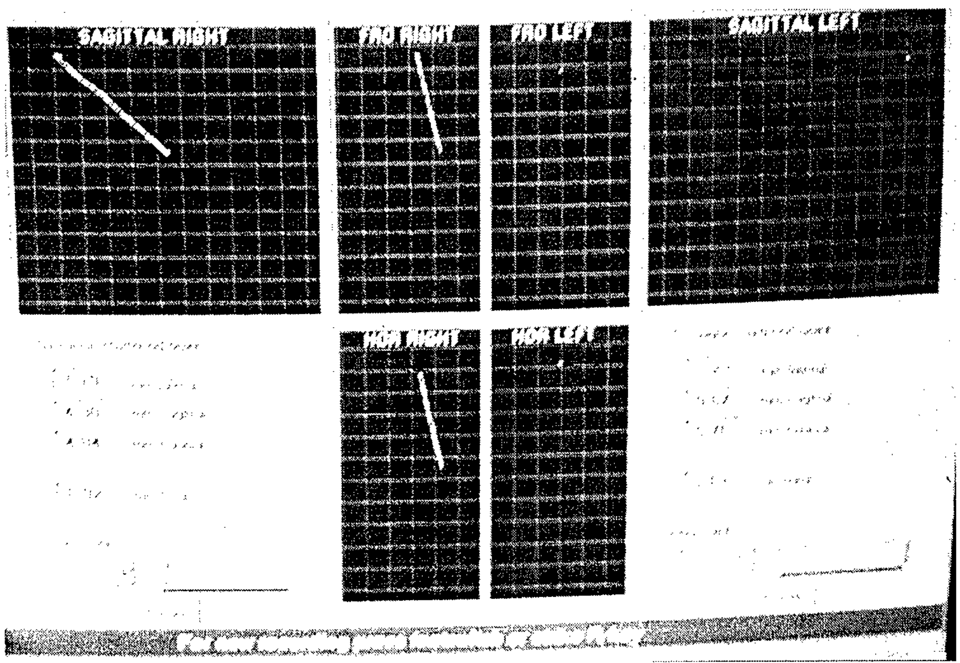
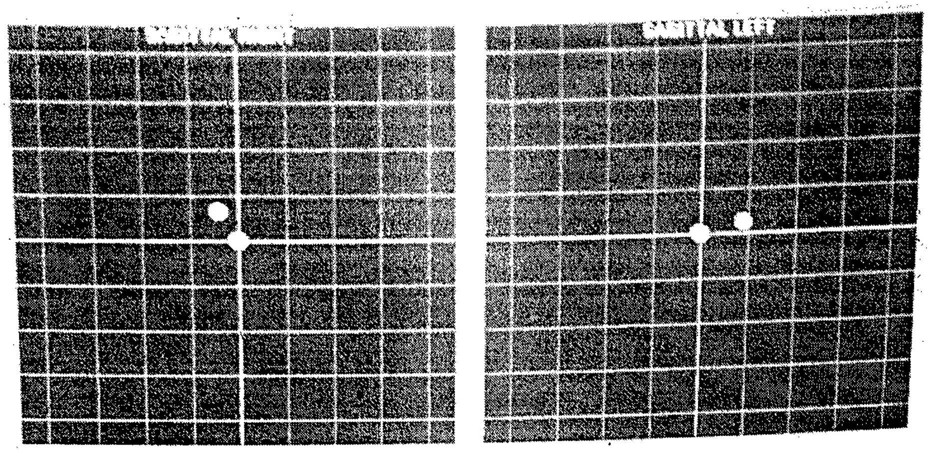

SAGITTAL RIGHT
FRO RIGHT
FRO LEFT
SAGITTAL LEFT
HOR RIGHT
HOR LEFT

Figure32: Example of the optoelectronic pantograph, Condylocomp, real time recording of transverse horizontal axis movement and location from the investigation.


SAGITTAL LEFT

mechanical, optoelectronic and electronic stylus pantographs are able to perform PrCp, PMLT and IMLT determinations. This investigation was designed to make comparisons of the appropriate instrument capabilities.

The specific aims were:

Specific Aim 1: Determine the ability of the kinematic face-bow and optoelectronic pantograph to accurately and reliably determine THA.

Specific Aim 2: Determine the procedure time and ability of the kinematic face-bow and optoelectronic pantograph to accurately and reliably correct to the THA.

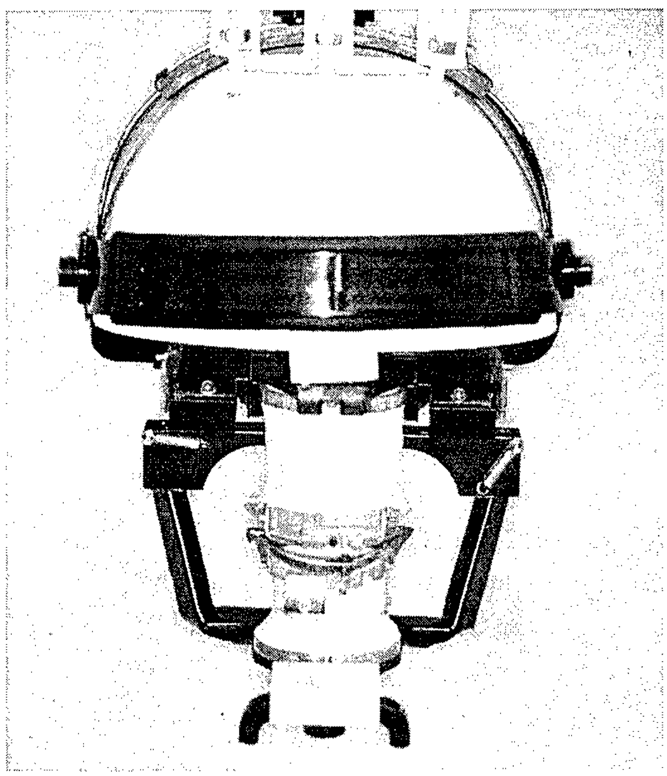
Specific Aim 3: Determine the procedure time and ability of the mechanical pantograph, electronic stylus computerized pantograph, and optoelectronic pantograph to accurately and reliably determine preset values for the PrCp and the PMLT angles.

Specific Aim 4: Determine the procedure time and ability of the mechanical pantograph, electronic stylus computerized pantograph, and optoelectronic pantograph to accurately and reliably determine preset values for the PrCp, the PMLT angles, and the amount of IMLT.

C. Preliminary Studies

An apparatus was fabricated that securely suspended the test articulator (Figure 33). This holder allowed movement of only the articulator mandibular element. Therefore, the articulators functioned, while attached to the holding apparatus, more accurately represented patient mandibular motion.

Figure 33: Articulator suspending apparatus. Pictured holding the semi-adjustable Denar Mark II articulator.



Each test pantograph was attached to the articulator and holding apparatus in a manner similar to patient treatment. The test pantographs recorded articulator movement in a clinically relevant fashion while attached to the articulator and holding apparatus. This permitted the in vitro THA determination, correction to the known THA, PrCp, PMLT and IMLT determinations to be performed in a clinically relevant manner.

Traditionally, recording flags using contrast paper have been secured to the patient in the area of the axis. To facilitate consistent location and measurement of the THA, a fine-lined, graph paper holding and repositioning device was fabricated. The graph paper was securely held in place on the right and left side of the articulator in the area of the articulator THA (Figures 34 and 35). This device permitted repeatable marking of the actual axis and coverage with additional graph paper for the investigation, and it facilitated investigation measurement (Figures 36 and 37). Additionally, the device did not interfere with movement of the mandibular element of the articulator or THA location in a traditional manner.

Investigation casts for the upper and lower elements of the articulator were fabricated using Silky Rock (Whip-Mix Corp., Louisville, KY) improved dental stone. The casts were mounted on the articulators using Blue Mounting Stone (Whip-Mix Corp., Louisville, KY) in accordance with the manufacturer's instructions. The casts were fabricated to allow secure placement of the Stuart reference plates in the mid-position of the articulator. The reference plates were secured to the maxillary and mandibular casts using Silky Rock Stone to prevent loosening or inappropriate movement during the investigation. The central bearing screw was elevated to allow the reference plates to move past each other in functional movements without interference. The casts,

Figure 34: Graph paper holder positioned over the articulator condyle.

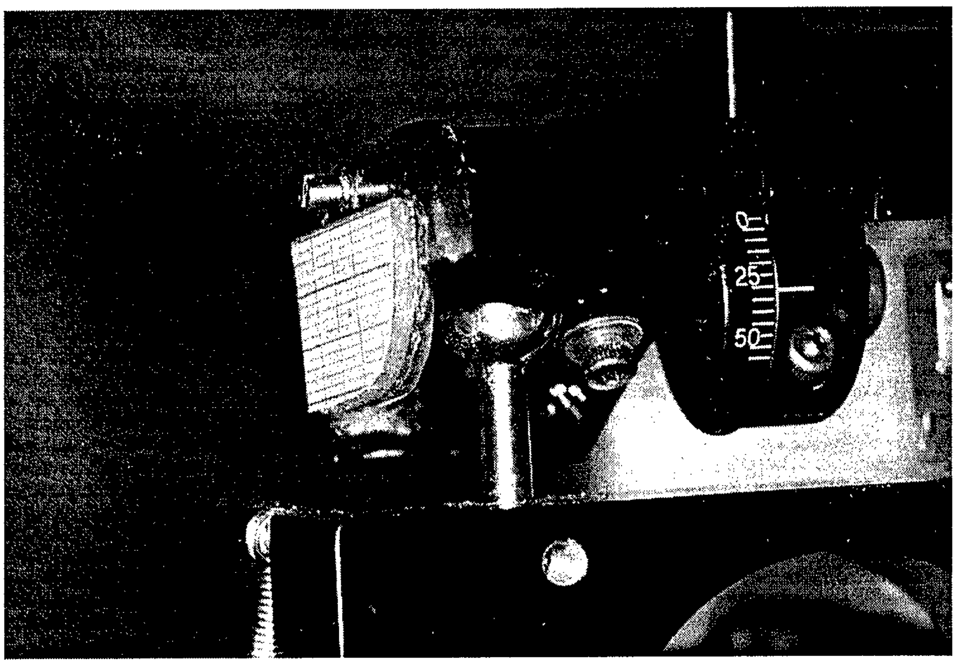

25
50

Figure 35: Graph paper holder positioned over the articulator condyle.

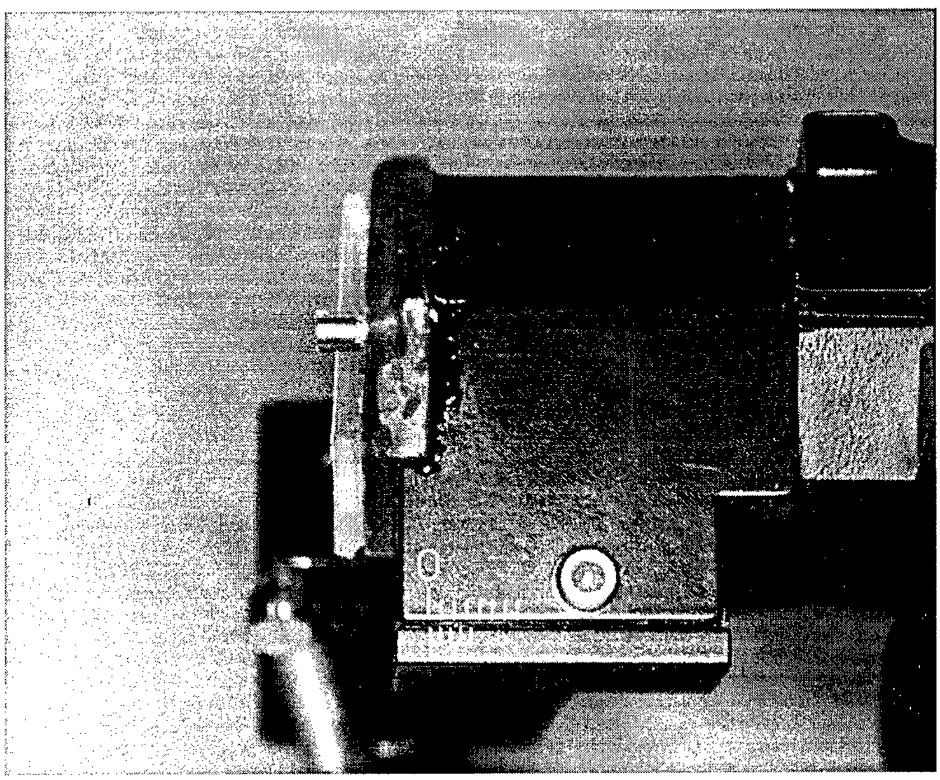


Figure 36: Graph paper holder positioned over the articulator condyle, optoelectronic transverse horizontal axis indicator marking the located transverse horizontal axis.

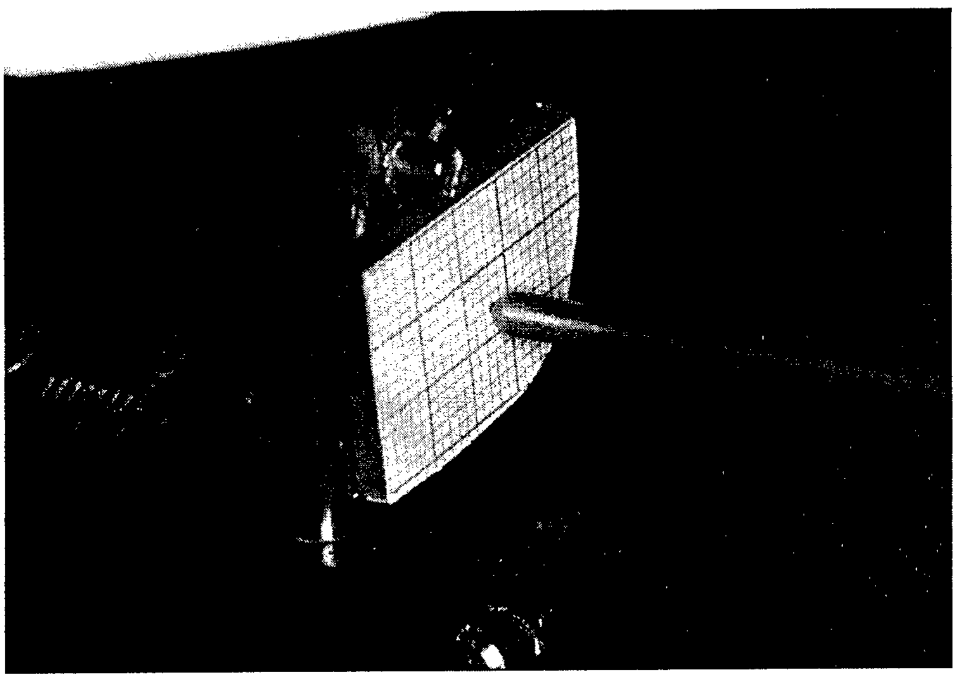
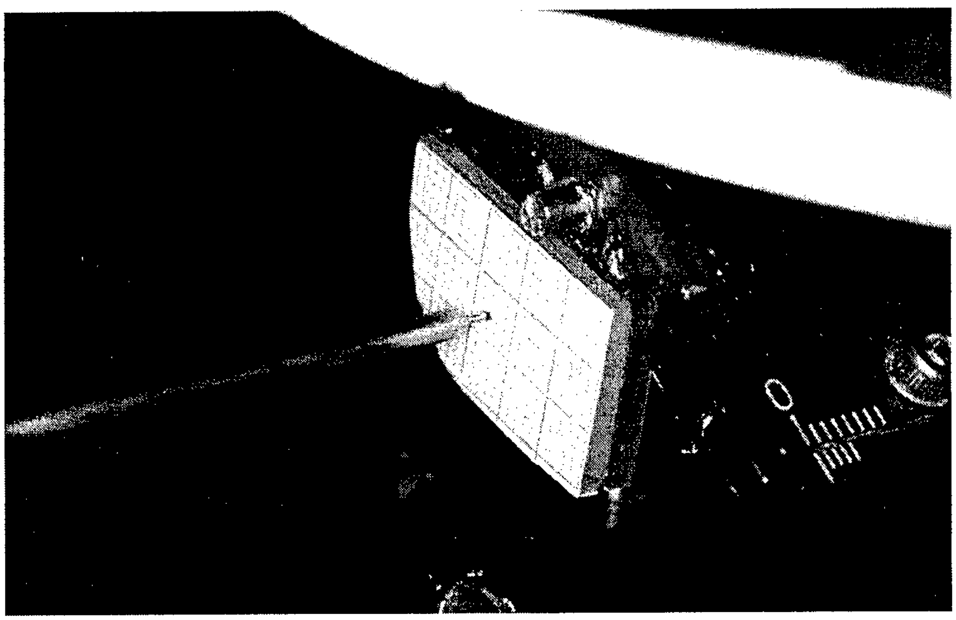


Figure 37: Graph paper holder positioned over the articulator condyle, kinematic face-bow transverse horizontal axis indicator marking the located transverse horizontal axis.



reference plates and central bearing screw were all secured to maintain the horizontal plane of reference of the articulator and reference plates throughout the investigation.

The coincidence of the articulator THA and measured condylar midpoint was determined. This was accomplished first by determining the measured center of the condylar ball. Second, the THA was located using the Stuart Axis Locator by following the Stuart Gnathologic Instrument Instruction Manual (Stuart 1979). The kinematically located THA and the measured centers of the condylar balls were identical (Figures 38 and 39).

D. Methods

Three Denar Mark II articulators were calibrated with an optical inspection gauge (Denar, Teledyne Water Pik, Fort Collins, CO) to ensure the accurate transfer of mounted casts and cross accuracy of the articulators.

The maxillary and mandibular casts and reference plate assemblies were securely attached to their respective articulator members. All connections and joints were checked to ensure proper orientation and rigidity.

The graph paper holding and repositioning devices were securely attached on the right and left sides of the articulators. This was accomplished for all three Mark II articulators.

1. Specific Aim 1

Three determinations were performed on three, separate Mark II articulators for each test THA location instrument.

Figure 38: The condyle of the semi-adjustable articulator, lateral view.

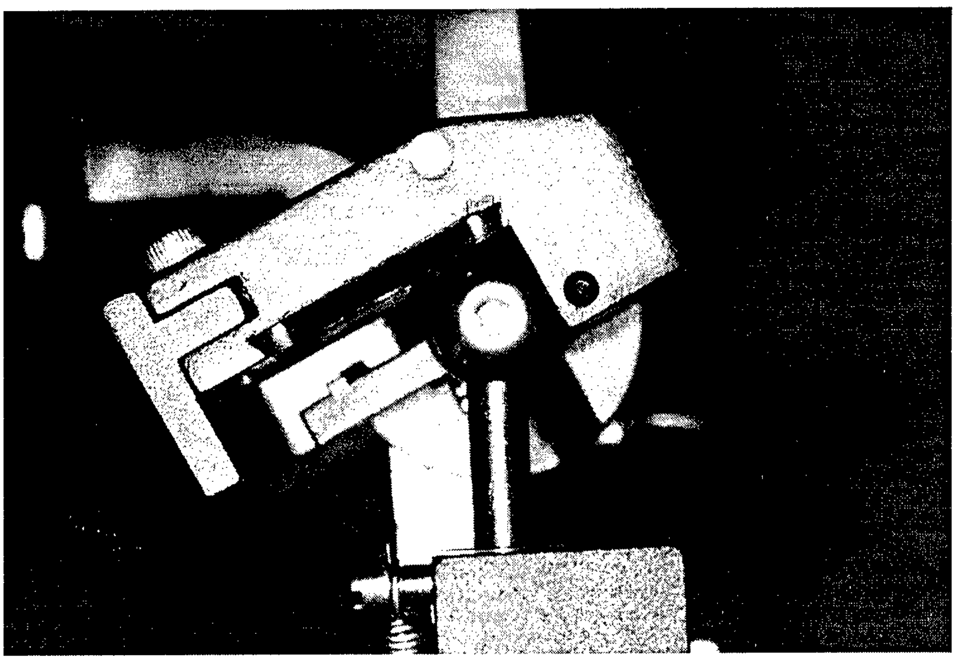
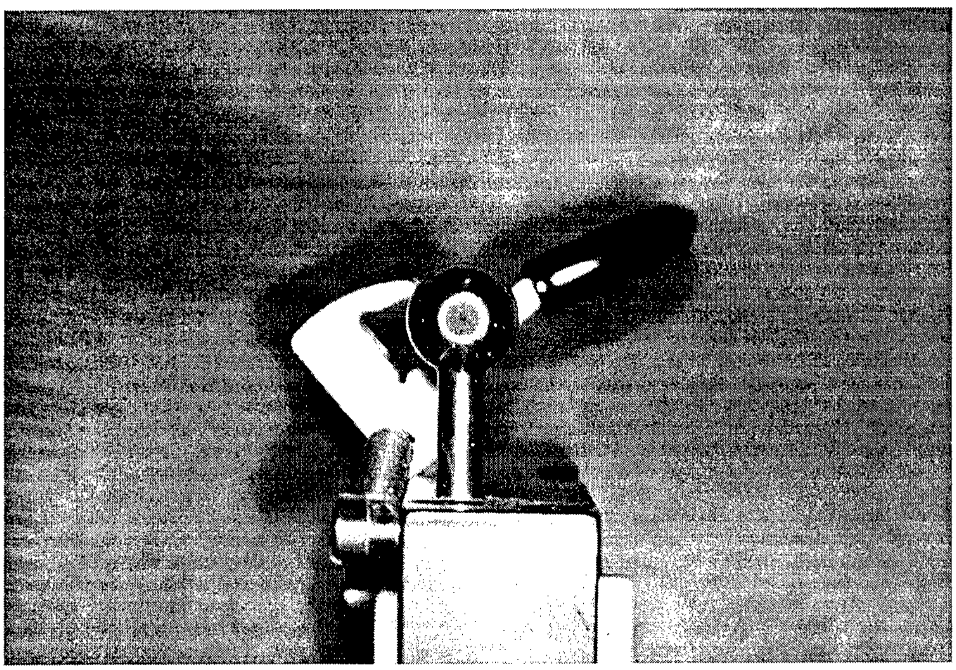


Figure 39: The condyle of the semi-adjustable articulator with measured mid-point and kinematically-located, transverse horizontal axis, lateral view.



Initially the THA was marked on the graph paper device that was located over the articulator condyles. The test instruments were attached sequentially and located to the THA. The THA marked graph paper was covered with a second sheet of graph paper, therefore blinding the operator prior to THA determinations. THA determinations were performed following instruction manual techniques (Ingraham 1972 and Denar Fully Adjustable Procedure Manual 1986, Dentron 1995).

The kinematic bow axis location was accomplished by trial-and-error method with illumination and 4.3 x TTL Orascoptic magnification. Adjustments were made until the tips of the styli did not translate on an arc, but remain fixed in that position during controlled opening and closing movements. The test-located THA was marked on the second layer of graph paper.

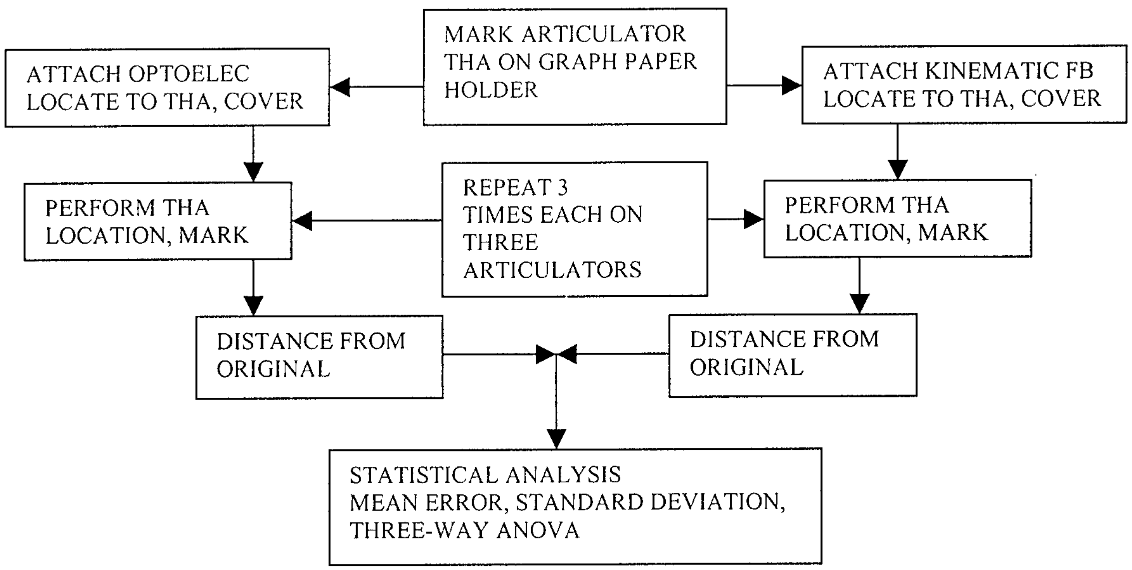
The optoelectronic axis location was accomplished by selecting the axis location function from the program menu. At the computer prompt, initiated by depressing the unit foot pedal, a 10 mm opening movement of the mandibular element of the articulator was accomplished. At the appropriate opening, the program noted the recorded axis and listed any corrections to be made to the adjustable head frame in order to place the axis styli over the THA. The test-located THA was marked on the second layer of graph paper.

Distances from the test-located THA determinations and the articulator THA were measured to the nearest 0.1mm using a digital caliper and 15x magnification.

The data was recorded the mean errors and standard deviations were determined. A three-way ANOVA was accomplished to determine if a significant difference existed between any of the investigated factors (Figure 40).

Figure 40: Specific Aim One Flow Chart.

Specific Aim 1: Flow Chart



2. Specific Aim 2

Three determinations were performed on three separate Mark II articulators for each test THA location instrument. Each determination was timed.

Initially the THA was marked on the graph paper device located over the articulator condyles. The test instruments were attached sequentially and positioned to the articulator THA. The test instruments were reoriented to a specific non-THA test position by a second individual (I-2).

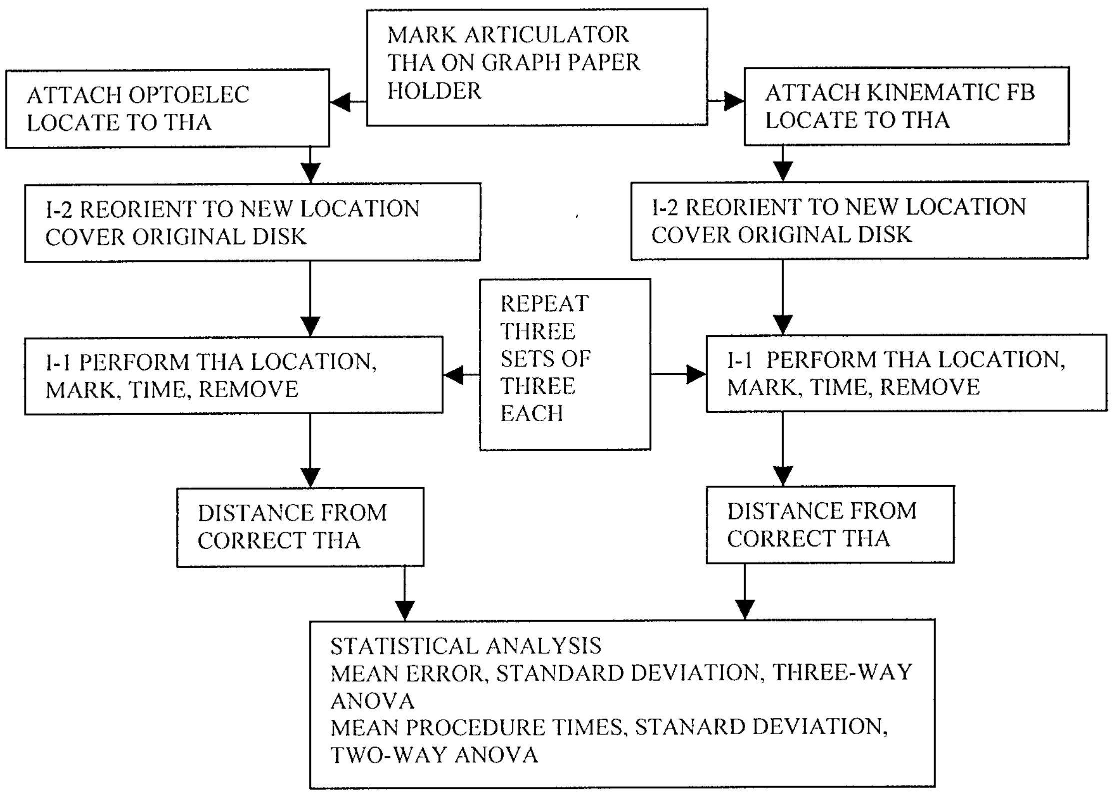
I-2 was trained to perform this function in a similar, consistent, and calibrated manner. I-2 selected the test position from several predetermined options. The selected test position remained the same for all determinations (9 per instrument) in Specific Aim 2. I-2 moved the axis locators to the test position, covered the articulator condyles, and covered the graph paper on the repositioning device with another piece of graph paper.

Selecting the test position and covering the condyles blinded the test operator (I-1) to the exact location of the actual THA. The THA determinations were performed as in Specific Aim 1 and the covering graph paper was marked. After each THA determination, I-2 removed the marked location disks. After all determinations were completed, the distances from the test-located THA and the articulator THA were measured to the nearest 0.1mm using a digital caliper and 15x magnification.

The location data and procedure times were recorded. The mean errors, mean procedure times and standard deviations were determined. A three-way ANOVA was accomplished to determine if a significant difference existed between the instrument THA location ability. A two-way ANOVA was employed to investigate if a significant difference existed between the instrument THA location procedure times (Figure 41).

Figure 41: Specific Aim Two Flow Chart.

Specific Aim 2: Flow Chart



3. Specific Aim 3

Each pantograph performed three determinations of the PrCp and PMLT angles on each of the three, separate Mark II articulators. Determinations were timed.

Initially, the test instruments were attached and sequentially positioned to the articulator THA. Next, the articulator PMLT and PrCp condylar settings were adjusted and covered by I-2. I-2 selected the test settings from several predetermined options. The selected test settings remained the same for all 27 determinations (9 per instrument) in Specific Aim 3.

I-2 was trained to perform this function in a similar, consistent, and calibrated fashion. Selecting the test condylar settings and covering the settings blinded the pantograph operator (I-1) to the exact values.

The pantographs were attached to the articulators and determinations performed following the instruction manual techniques (Ingraham 1972 and Denar Fully Adjustable Procedure Manual 1986, Denar Pantronic Technique Manual 1983, Dentron 1995). I-1 moved the articulator with the attached pantograph through the functional range of PrCp and PMLT. I-2 then zeroed the condylar settings. The optoelectronic and electronic stylus pantographs provided PrCp and PMLT articulator settings. For the mechanical pantograph I-1 determined PrCp and PMLT values by manually retracing the pantographic tracing and programming the articulator.

The PrCp and PMLT data and procedure times were recorded. The mean errors, mean procedure times and standard deviations were determined. Three-way ANOVAs were accomplished to determine if significant differences existed between the instrument PrCp and PMLT location abilities, followed by a Bonferroni post hoc analysis.

A two-way ANOVA was employed to investigate if a significant difference existed between the instruments THA location procedure times (Figure 42).

4. Specific Aim 4

Each pantograph performed three determinations of the PrCp, the PMLT angles, and the amount of IMLT on three separate Mark II articulators. The determinations were timed.

Initially, the test instruments were attached and sequentially positioned to the articulator THA. The articulator condylar settings selected in Aim 3 remained the same in Aim 4. I-2 selected the immediate lateral translation settings for the test from several predetermined options. Next, the articulator condylar settings were adjusted and covered by I-2. The selected test settings remained the same for all 27 determinations (9 per instrument) in Specific Aim 4.

I-2 was trained to perform this function in a similar, consistent, and calibrated fashion. Selecting the test condylar settings and covering the settings blinded the pantograph operator (I-1) to the articulator condylar values.

The pantographs were attached to the articulators and determinations performed by I-1 following the instruction manual techniques (Ingraham 1972 and Denar Fully Adjustable Procedure Manual 1986, Denar Pantronic Technique Manual 1983 and Dentron 1995). I-1 moved the articulator with the attached pantograph through the functional range of PrCp, PMLT and IMLT. I-2 then zeroed the condylar settings. The optoelectronic and electronic stylus pantographs provided PrCp, PMLT and IMLT articulator settings. For the mechanical pantograph I-1 determined PrCp, PMLT and

IMLT values by manually retracing the pantographic tracing and programming the articulator.

The PrCp, PMLT, and IMLT data and procedure times were recorded. The mean errors, mean procedure times and standard deviations were determined. Three-way ANOVAs were accomplished to determine if significant differences existed between the instrument PrCp, PMLT and IMLT determination abilities, followed by a Bonferroni post hoc analysis. A two-way ANOVA was employed to investigate if a significant difference existed between the instruments THA location procedure times (Figure 43).

Figure 42: Specific Aim Three Flow Chart.

Specific Aim 3: Flow Chart

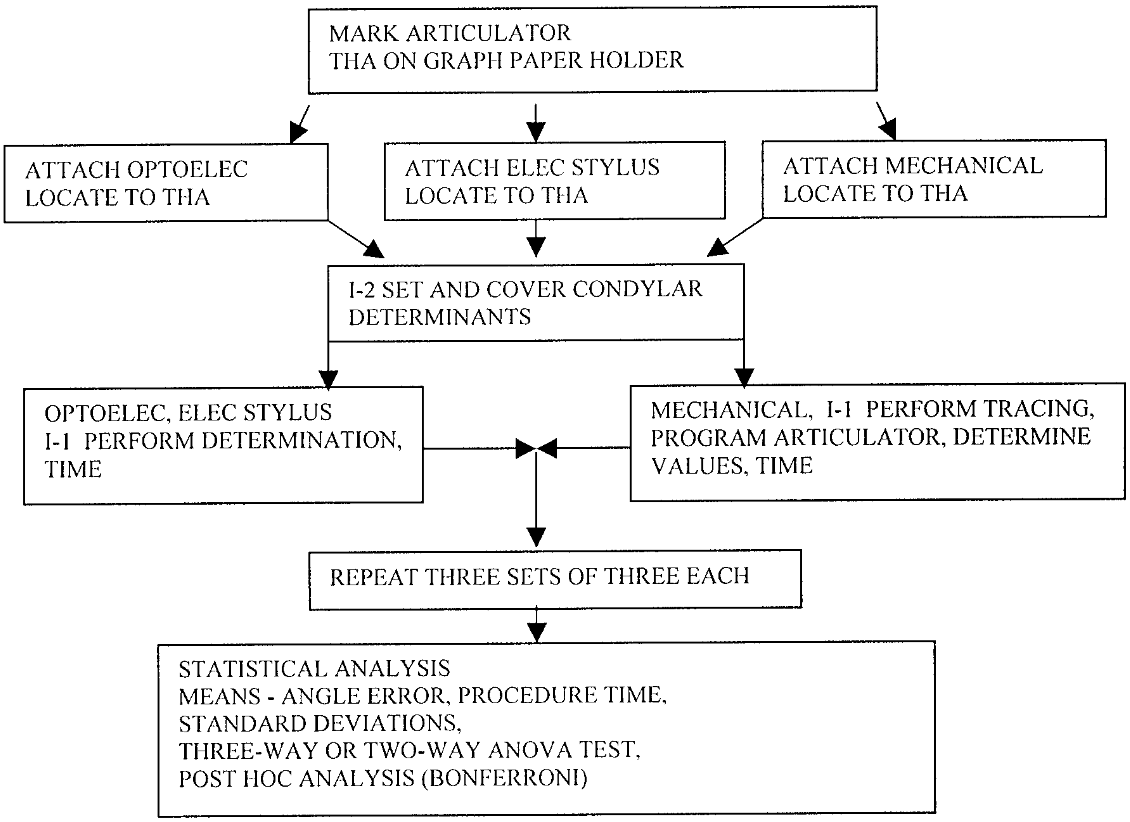
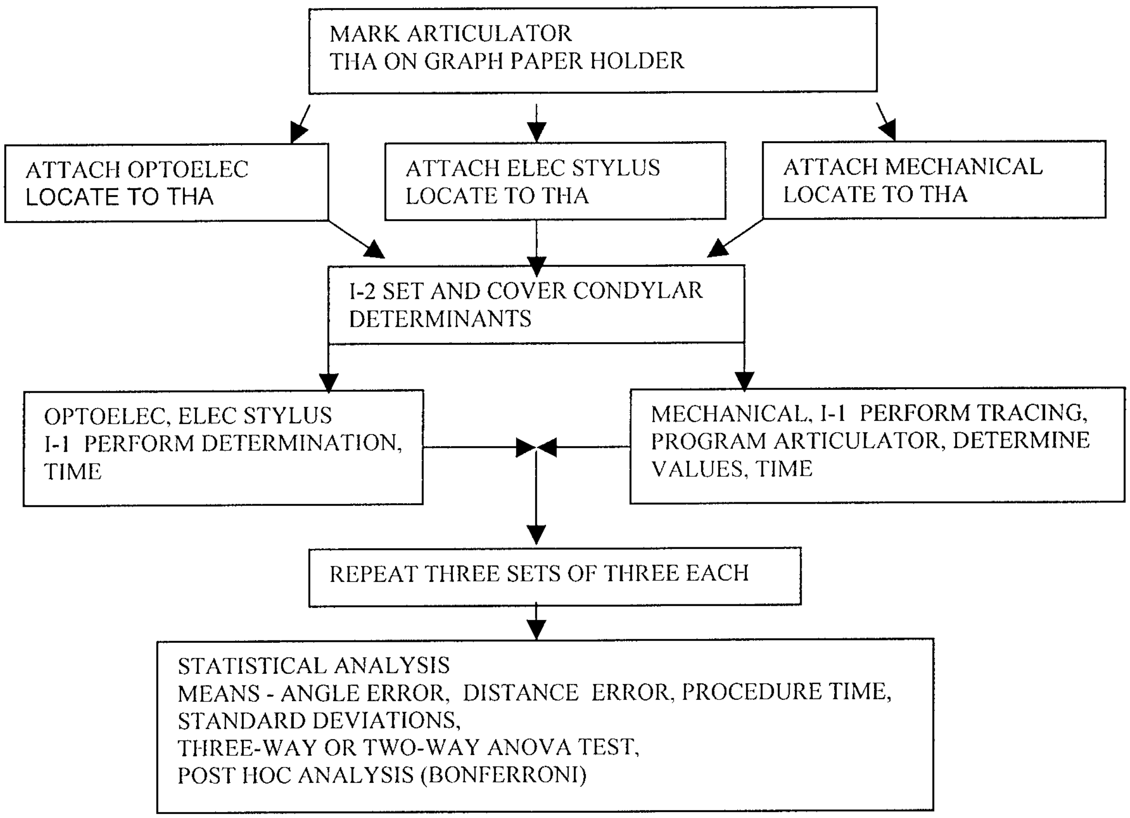


Figure 43: Specific Aim Four Flow Chart.

Specific Aim 4: Flow Chart



IV. RESULTS

A. Specific Aim 1

Specific Aim 1 investigated the ability of the kinematic face-bow and optoelectronic pantograph to confirm the THA. Distances from the test-located THA determinations and the articulator THA were measured to the nearest 0.1 mm using a digital caliper and 15x magnification.

The data was entered on a spreadsheet. Means, standard deviations and variances were then calculated (Table 1). A three-way analysis of variance (ANOVA) was performed. The three-way ANOVA showed: no significant difference existed between the determinations performed on the right and left sides of the articulators, no significant difference existed between the determinations performed on the three individual articulators, and the kinematic face-bow was statistically significantly (p=0. 0001) better than the optoelectronic pantograph in verifying the THA.

Specific Aim 1 right and left side data for each instrument were combined to give an overall mean error for each instrument. The combined number of trials was 18 per instrument. The mean error was 0.2 mm (kinematic) versus 0.6 mm (optoelectronic). See Bar Graph Specific Aim One, Figure 44.

B. Specific Aim 2

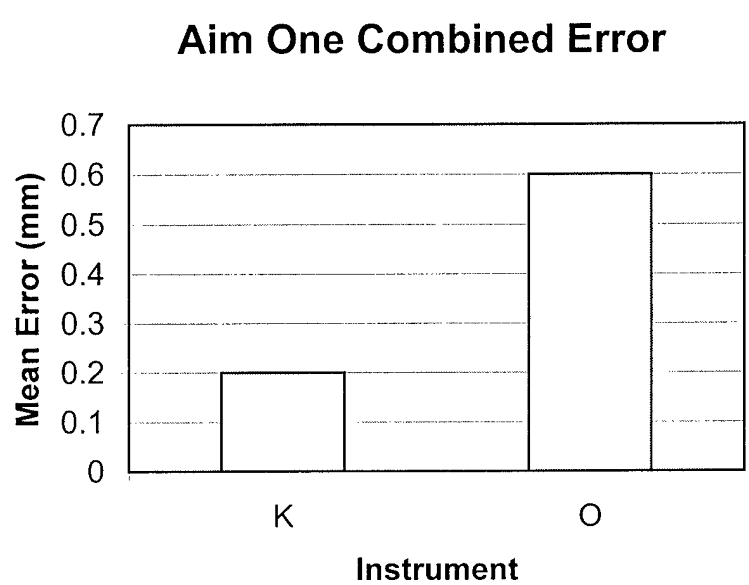
Aim 2 investigated the procedure time and ability of the kinematic face-bow and optoelectronic pantograph to accurately and reliably correct to the THA. The procedures were timed and the distances from the test-located THA determinations and the articulator THA were measured to the nearest 0.1 mm using a digital caliper and 15x magnification.

Table 1: Specific Aim One Data: error, mean error, standard deviation and variance.

Specific Aim 1

	Kinematic Face Bow		Optoelectronic		
	Right	**Left**	**Right**	**Left**	
	0	0.2	0.5	0.7	
	0.2	0.4	0.3	0.5	**Articulator 1**
	0.3	0	0.8	0	
Mean	0.1667	0.2	0.5333	0.4	
Std Dev	0.1528	0.2	0.2517	0.3606	
Var	0.0233	0.04	0.0633	0.13	
	0.4	0.2	0.8	0.5	
	0.2	0.1	0.7	0.4	**Articulator 2**
	0	0.3	0	0.6	
Mean	0.2	0.2	0.5	0.5	
Std Dev	0.2	0.1	0.4359	0.1	
Var	0.04	0.01	0.19	0.01	
	0	0	1	0.7	
	0.5	0	0.8	0.6	**Articulator 3**
	0.1	0.4	0.5	0.8	
Mean	0.2	0.1333	0.7667	0.7	
Std Dev	0.2646	0.2309	0.2517	0.1	
Var	0.07	0.0533	0.0633	0.01	
Mean	0.188	0.1778	0.6	0.5333	
Std Dev	0.183	0.1641	0.3082	0.2345	**Combined**
Var	0.0336	0.0269	0.095	0.055	

Figure 44: Specific Aim One Mean Error Bar Graph.



Aim One Combined Error
Mean Error (mm)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
K
O
Instrument

The data was entered on a spreadsheet. Means, standard deviations and variances were then calculated (Table 2). A three-way ANOVA was performed. The three-way ANOVA showed: no significant difference existed between the determinations performed on the right and left sides of the articulators, no significant difference existed between determinations performed on the three individual articulators, and the kinematic face-bow was significantly (p=0.0001) better than the optoelectronic pantograph in verifying the THA. Next, a two-way analysis of variance of procedure time was performed. This statistical test showed the optoelectronic THA location was significantly (p=0.0001) faster than the kinematic face-bow.

The data for each instrument was combined to give an overall mean error and mean procedure time for each instrument. The combined number of trials was 18 per instrument. The mean error was 0.2 mm (kinematic) versus 1.0 mm (optoelectronic). The mean procedure time was 437 seconds (kinematic) versus 204 seconds (optoelectronic). See Specific Aim Two Bar Graphs, Figures 45 and 46.

C. Specific Aim 3

Aim 3 studied the procedure time and ability of the mechanical pantograph, electronic-stylus computerized pantograph, and optoelectronic pantograph to accurately and reliably determine preset values for the PrCp and the PMLT angles. The determinations were timed, the test determined PrCp angles and PMLT angles were recorded and compared to the true articulator settings, and error determined.

The data was entered on a spreadsheet. Means, standard deviations and variances were then calculated (Tables 3-6). A three-way ANOVA was performed. The three-way ANOVA showed: no significant difference existed between the determinations performed on the right and left sides of the articulators and no significant difference existed between determinations performed on the three individual articulators. The results of the three-way ANOVA (p=0.0690) followed by the Bonferroni post hoc analysis suggested the electronic-stylus pantograph was superior when determining preset values for PMLT angles. The results of the three-way ANOVA (p=0.0001) followed the Bonferroni post hoc analysis indicated the electronic-stylus pantograph performed statistically significantly better when determining the PrCp angles. The electronic-stylus determinations were significantly (two-way ANOVA, p=0.0001 faster than that of the other instruments.

The investigation results revealed the electronic stylus (EP) pantograph performed better in determining preset values for PMLT angles. The mean error was 2.3° (MP), 2.1° (OP) and 1.3° (EP). The electronic stylus pantograph performed significantly better than the mechanical and optoelectronic pantographs in PrCp determinations. 3.2° (MP), 9.4° (OP), 2.0° (EP). The electronic stylus pantograph determined the test values significantly faster than the other pantographs. The mean procedure time was 752 seconds (MP), 136 seconds (OP), and 30 seconds (EP). See Specific Aim Three Bar Graphs, Figures 47 and 48.

D. Specific Aim 4

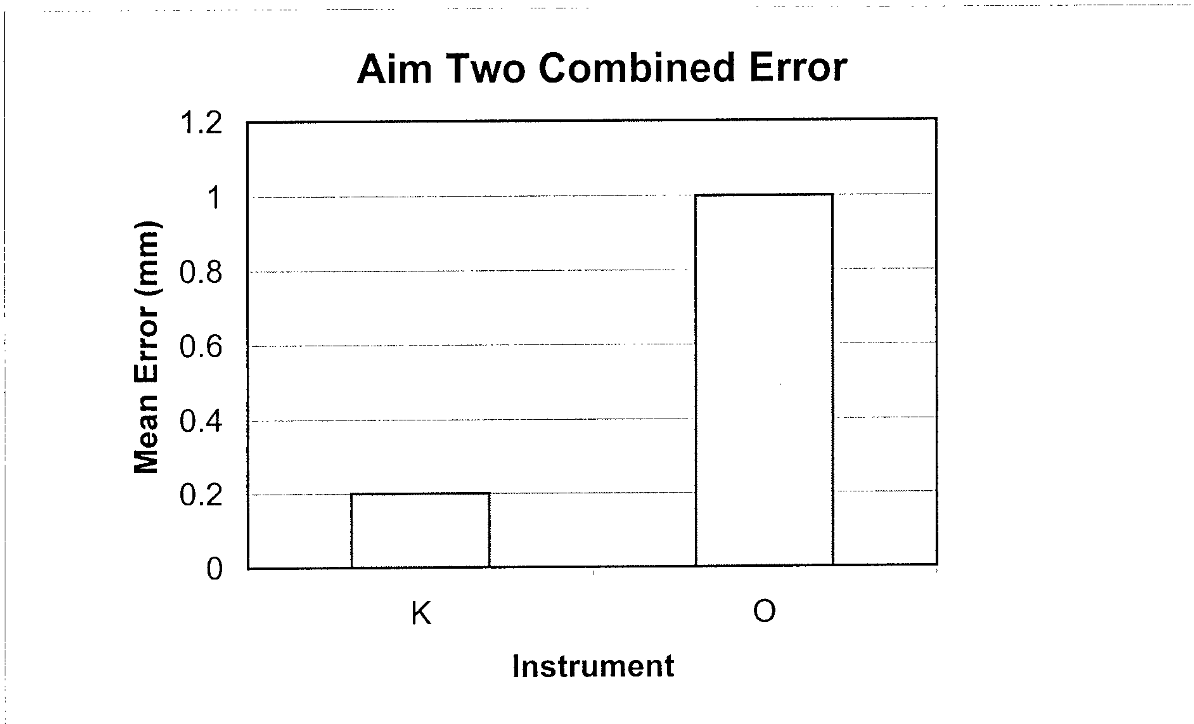
Aim 4 evaluated the procedure time and ability of the mechanical pantograph, electronic stylus computerized pantograph, and optoelectronic pantograph to accurately and reliably determine preset values for the PrCp, the PMLT angles, and the amount of IMLT. The determinations were timed. Test determined PrCp angles, PMLT angles, and amount of IMLT were recorded and error determined.

Table 2: Specific Aim Two Data: error (mm), mean error, standard deviation, variance, time (seconds) and mean time.

Specific Aim 2

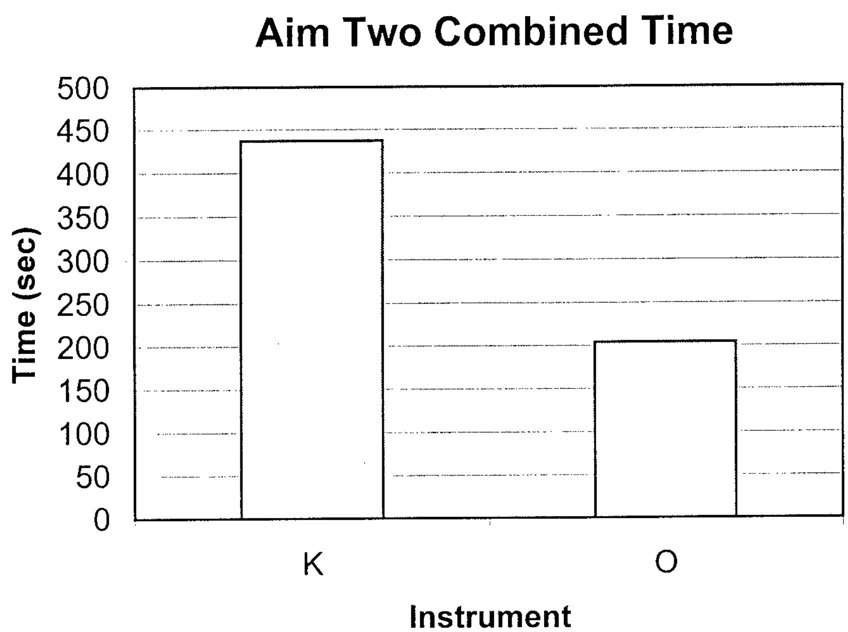
	Kinematic Face Bow			Optoelectronic			
	Right	**Left**	**Time**	**Right**	**Left**	**Time**	
	0.2	0.3	514	1.2	1.2	220	
	0.3	0.3	440	2.2	1.7	254	**Articulator**
	0.2	0.2	509	0.4	0.2	220	**1**
Mean	0.23	0.27	487.7	1.27	1.03	231	
Std Dev	0.06	0.06	41.4	0.90	0.76	19.6	
Var	0.003	0.003	1710	0.81	0.58	385	
	0.2	0	326	1.7	1.2	204	
	0.1	0.3	498	0.9	1.3	165	**Articulator**
	0.3	0.4	380	0.6	0.6	202	**2**
Mean	0.2	0.23	401.3	1.07	1.03	190.3	
Std Dev	0.1	0.04	88.0	0.57	0.43	22.0	
Var	0.01	0.04	7737	0.32	0.18	482	
	0.2	0.2	424	1.6	1.4	203	
	0.3	0	382	0.7	0.7	189	**Articulator**
	0	0.3	459	0.7	0.9	179	**3**
Mean	0.17	0.17	421.7	1	1	190.3	
Std Dev	0.15	0.15	38.6	0.52	0.36	12.06	
Var	0.02	0.02	1486	0.27	0.13	145	
Mean	0.20	0.22	436.9	1.11	1.02	204	
Std Dev	0.11	0.14	65.3	0.61	0.46	26.0	**Combined**
Var	0.01	0.02	4261	0.37	0.21	673	

Figure 45: Specific Aim Two Combined Mean Error Bar Graph.



Aim Two Combined Error
1.2
1
0.8
0.6
0.4
0.2
0
Mean Error (mm)
K
O
Instrument

Figure 46: Specific Aim Two Combined Procedure Time Bar Graph.



Aim Two Combined Time
Time (sec)
500
450
400
350
300
250
200
150
100
50
0
K
O
Instrument

Table 3: Specific Aim Three Mechanical Pantograph Data: progressive mandibular lateral translation angle error (degrees), protrusive condylar path angle error (degrees) and time (seconds). Means, standard deviations and variances.

Specific Aim 3

Set PMLT - 10
Set PrCp - 50

Mechanical

	PMLT Right	PMLT Left	PrCp Right	PrCp Left	Time	
	2.5	5	0	4	725	**Articulator 1**
	0	2	5	1	803	
	1	1	1	2	745	
Mean	1.17	2.67	2.00	2.33	758.0	
Std Dev	1.26	2.08	2.65	1.53	40.5	
Var	1.58	4.33	7.00	2.33	1641	
	5	1	4	2	733	**Articulator 2**
	2	2.5	1	8	840	
	2	2.5	3	2	705	
Mean	3	1.83	2.33	4.00	759.0	
Std Dev	1.73	0.76	1.97	3.46	71.2	
Var	3	0.58	3.87	12.00	5076	
	5	2	5	5	764	
	2	4	4	10	699	**Articulator 3**
	2	0	0	0	751	
Mean	3	2.00	3.67	5.00	738.0	
Std Dev	1.73	2.00	1.53	5.00	34.4	
Var	3	4.00	2.33	25.00	1183	
Mean	2.39	2.22	2.56	3.78	752.0	**Combined**
Std Dev	1.65	1.54	2.07	3.35	45.6	
Var	2.74	2.38	4.28	11.19	2081	

Table 4: Specific Aim Three Optoelectronic Pantograph Data: progressive mandibular lateral translation angle error (degrees), protrusive condylar path angle error (degrees) and time (seconds). Means, standard deviations and variances.

Specific Aim 3

Optoelectronic

Set PMLT - 10
SetPrCp - 50

	PMLT		PrCp			
	Right	Left	Right	Left	Time	
	2.7	2.1	11	9	132	**Articulator 1**
	2.5	1.9	14	9	141	
	2.4	2.1	10	8	138	
Mean	2.53	2.03	11.70	8.67	137.0	
Std Dev	0.15	0.12	2.08	0.58	4.6	
Var	0.02	0.01	4.30	0.33	21	
	1.8	2.1	10	10	144	**Articulator 2**
	2.4	1.7	7	4	127	
	2.2	2.1	12	7	130	
Mean	2.13	1.97	9.67	7.00	133.7	
Std Dev	0.31	0.23	2.52	3.00	9.1	
Var	0.09	0.05	6.30	9.00	82	
	2.2	2.3	11	11	150	**Articulator 3**
	2.4	1.5	7	10	128	
	1.6	2.1	10	9	136	
Mean	2.07	1.97	9.33	10.00	138.0	
Std Dev	0.42	0.42	2.08	1.00	11.1	
Var	0.17	0.17	4.30	1.00	124	
Mean	2.24	1.99	10.20	8.56	136.0	**Combined**
Std Dev	0.35	0.25	2.22	2.07	7.8	
Var	0.12	0.06	4.94	4.28	61	

Table 5: Specific Aim Three Electronic-Stylus Pantograph Data: progressive mandibular lateral translation angle error (degrees), protrusive condylar path angle error (degrees) and time (seconds). Means, standard deviations and variances.

Specific Aim 3

Electronic

Set PMLT - 10
Set PrCp - 50

	PMLT Right	PMLT Left	PrCp Right	PrCp Left	Time	
	1	0	2	1	30	**Articulator 1**
	4	3	4	1	28	
	0	2	4	2	35	
Mean	1.67	1.67	3.33	1.33	31.0	
Std Dev	2.08	1.53	1.15	0.57	3.6	
Var	4.33	2.33	1.33	0.33	13	
	2	1	4	1	32	**Articulator 2**
	4	2	2	1	27	
	0	2	1	0	30	
Mean	2	1.67	2.33	0.67	29.7	
Std Dev	2	0.58	1.53	0.58	2.5	
Var	4	0.33	2.33	0.33	6	
	0	0	3	0	27	**Articulator 3**
	0	1	4	1	34	
	2	0	3	1	30	
Mean	0.67	0.33	3.33	0.67	30.3	
Std Dev	1.15	0.58	0.58	0.58	3.5	
Var	1.33	0.33	0.33	0.33	12	
Mean	1.44	1.22	3.00	0.89	30.3	**Combined**
Std Dev	1.67	1.09	1.12	0.60	2.9	
Var	2.78	1.19	1.25	0.36	8	

Table 6: Specific Aim Three Combined Mean Pantograph Data: progressive mandibular lateral translation angle error (degrees), protrusive condylar path angle error (degrees) and time (seconds). Means, standard deviations and variances.

Specific Aim 3

Set PMLT - 10
Set PrCp - 50

	Mechanical PMLT Right	Left	PrCp Right	Left	Time	
Mean	2.39	2.22	2.56	3.78	752.0	**Combined**
Std Dev	1.65	1.54	2.07	3.35	45.6	
Var	2.74	2.38	4.28	11.19	2081	

	Optoelectronic PMLT Right	Left	PrCp Right	Left	Time	
Mean	2.24	1.99	10.20	8.56	136.0	**Combined**
Std Dev	0.35	0.25	2.22	2.07	7.8	
Var	0.12	0.06	4.94	4.28	61	

	Electronic PMLT Right	Left	PrCp Right	Left	Time	
Mean	1.44	1.22	3.00	0.89	30.3	**Combined**
Std Dev	1.67	1.09	1.12	0.60	2.9	
Var	2.78	1.19	1.25	0.36	8	

Figure 47: Specific Aim Three Combined Error Bar Graph. Mean error: progressive mandibular lateral translation (degrees), protrusive condylar path (degrees). M - mechanical pantograph, O - optoelectronic pantograph and E - electronic stylus pantograph.

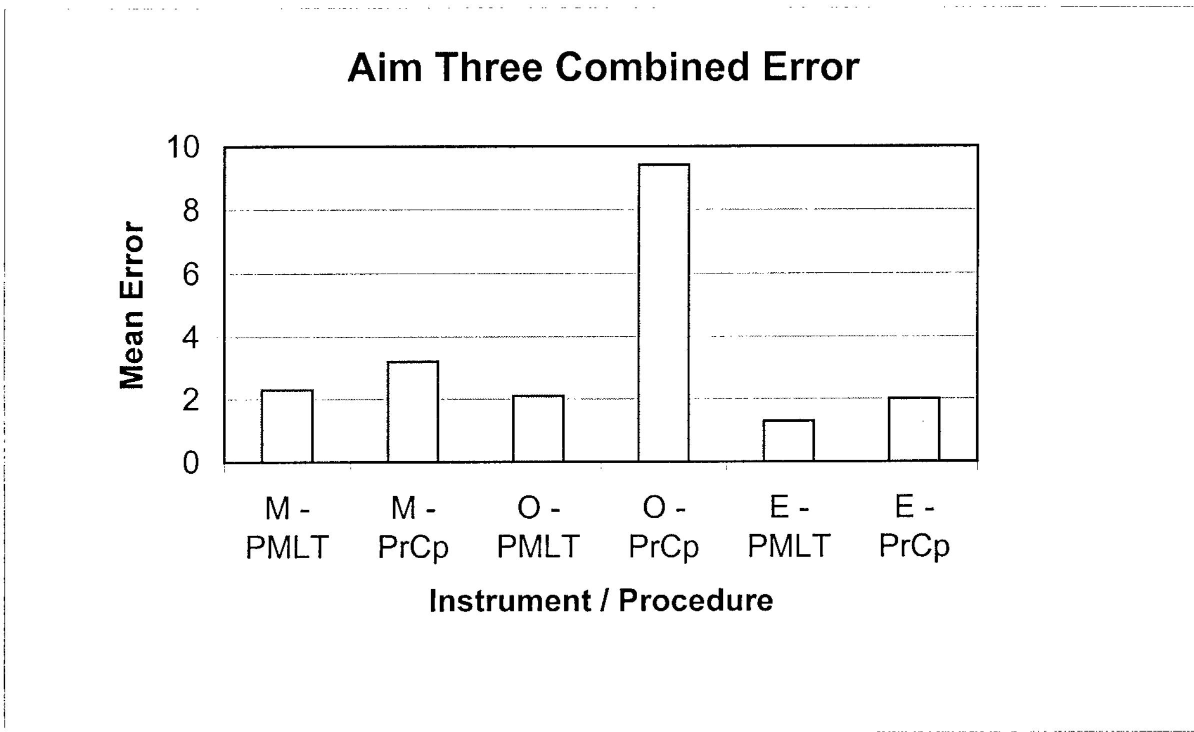
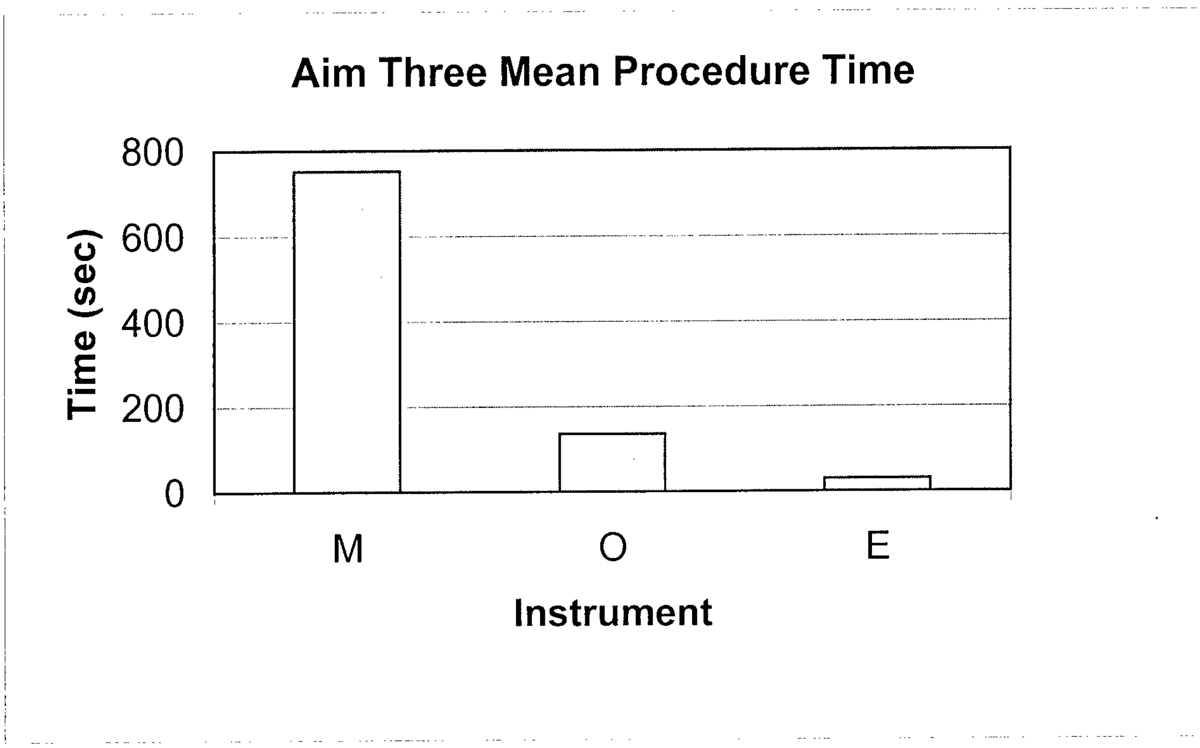

Aim Three Combined Error
Mean Error
10
8
6
4
2
0
M - PMLT
M - PrCp
O - PMLT
O - PrCp
E - PMLT
E - PrCp
Instrument / Procedure

Figure 48: Specific Aim Three Combined Procedure Time Bar Graph.


Aim Three Mean Procedure Time
800
600
400
200
0
Time (sec)
M
O
E
Instrument

The data was entered on a spreadsheet. Means, standard deviations, and variances were calculated (Tables 7-10). A three-way ANOVA was performed. The three-way ANOVA showed: no significant difference existed between the determinations performed on the right and left sides of the articulators and no significant difference existed between determinations performed on the three individual articulators. The results of the three-way ANOVA ($p=0.0019$) followed by the Bonferroni post hoc analysis indicated the electronic-stylus pantograph was superior when determining preset values for PMLT angles. The results of the three-way ANOVA ($p=0.0001$) followed by the Bonferroni post hoc analysis indicated the electronic-stylus pantograph performed significantly better when determining the PrCp angles. The results of the three-way ANOVA ($p=0.0891$) followed by the Bonferroni post hoc analysis suggested the mechanical pantograph was superior when determining preset values for the amount of IMLT. The electronic-stylus determinations were significantly (two-way ANOVA, $p=0.0001$, followed by the Bonferroni post hoc analysis) faster than the other instruments.

The results revealed the electronic-stylus pantograph demonstrated the best statistical ability to determine preset values for PMLT angles. The mean error for PMLT was 2.0° (MP), 1.85° (OP) and 1.35° (EP). The kinematic face-bow was better when determining IMLT values. The mean error for IMLT was 0.2 mm (MP), 0.4 mm (OP) and 0.4 mm (EP). The electronic-stylus pantograph determined the PrCp angles statistically better than the optoelectronic and mechanical pantographs. The mean error was 2.8° (MP), 8.5° (OP) and 0.8° (EP). As in Aim 3, the electronic-stylus computerized pantograph performed determinations significantly faster than the other pantographs.

The mean procedure time was 824 seconds (MP), 137 seconds (OP), and 31 seconds (EP). See Specific Aim Four Bar Graphs, Figures 49 and 500.

Table 7: Specific Aim Four Mechanical Pantograph Data: progressive mandibular lateral translation angle error (degrees), protrusive condylar path angle error (degrees), immediate mandibular lateral translation (mm) and time (seconds). Means, standard deviations and variances.

Specific Aim 4

Set PMLT - 10
Set PrCp - 50
Set IMLT -1

Mechanical

	PMLT Right	Left	PrCp Right	Left	IMLT Right	Left	Time	
	2	3	5	1	0.3	0.1	800	Articulator
	3	3	1	2	0.3	0.3	795	1
	2	2	4	5	0.2	0.2	880	
Mean	2.33	2.67	3.33	2.67	0.26	0.20	825.0	
Std Dev	0.57	0.58	2.08	2.08	0.06	0.10	47.7	
Var	0.33	0.34	4.33	4.33	0.004	0.01	2275	
	2	3	4	4	0.5	0	835	Articulator
	3	0	3	2	0.2	0.2	840	2
	1	1	2	2	0.2	0.2	799	
Mean	2	1.33	3.00	2.67	0.30	0.13	824.7	
Std Dev	1	1.53	1.00	1.15	0.17	0.12	22.4	
Var	1	2.33	1.00	1.33	0.030	0.010	500	
	1	2	1	4	0.3	0.3	805	Articulator
	2	1	4	3	0.2	0.3	855	3
	3	2	2	1	0.3	0.2	807	
Mean	2.00	1.67	2.33	2.67	0.27	0.27	822.3	
Std Dev	1.00	0.58	1.53	1.53	0.06	0.06	28.3	
Var	1	0.33	2.33	2.33	0.003	0.003	801	
Mean	2.11	1.89	2.89	2.67	0.28	0.20	824.0	Combined
Std Dev	0.78	1.05	1.45	1.41	0.10	0.10	29.9	
Var	0.61	1.11	2.11	2.00	0.009	0.01	896	

Table 8: Specific Aim Four Optoelectronic Pantograph Data: progressive mandibular lateral translation angle error (degrees), protrusive condylar path angle error (degrees), immediate mandibular lateral translation (mm) and time (seconds). Means, standard deviations and variances.

Specific Aim 4

Set PMLT - 10
Set PrCp - 50
Set IMLT -1

Optoelectronic

	PMLT Right	PMLT Left	PrCp Right	PrCp Left	IMLT Right	IMLT Left	Time	
	2.1	2.2	9	12	0.5	0.5	135	**Articulator**
	2.4	2.4	7	10	0	0.5	136	**1**
	1.5	1.7	4	4	0.3	0.2	144	
Mean	2.00	2.10	6.67	8.67	0.27	0.40	138.3	
Std Dev	0.46	0.36	2.52	4.16	0.25	0.17	4.9	
Var	0.21	0.13	6.30	17.30	0.06	0.03	24	
	2.3	1	13	10	0	0.6	132	**Articulator**
	2.1	2.3	10	2	0.7	0.6	129	**2**
	1.7	1.8	11	5	0.2	0.3	144	
Mean	2.03	1.70	11.30	5.67	0.30	0.50	135.0	
Std Dev	0.31	0.66	1.53	4.04	0.36	0.17	7.9	
Var	0.09	0.43	2.33	16.30	0.13	0.03	63	
	1	1.8	10	10	0.5	0.6	145	**Articulator**
	1.5	2	6	9	0.1	0.2	137	**3**
	1.8	1.9	2	1	0.7	0	133	
Mean	1.43	1.90	6.00	6.67	0.43	0.27	138.3	
Std Dev	0.40	0.10	4.00	4.93	0.31	0.31	6.1	
Var	0.16	0.01	16.00	24.30	0.09	0.09	37	
Mean	1.82	1.90	8.00	7.00	0.33	0.39	137.2	**Combined**
Std Dev	0.45	0.42	3.54	4.03	0.28	0.22	5.8	
Var	0.2	0.17	12.50	16.25	0.08	0.05	34	

Table 9: Specific Aim Four Electronic-Stylus Pantograph Data: progressive mandibular lateral translation angle error (degrees), protrusive condylar path angle error (degrees), immediate mandibular lateral translation (mm) and time (seconds). Means, standard deviations and variances.

Specific Aim 4

Set PMLT - 10
Set PrCp - 50
Set IMLT -1

Electronic

	PMLT Right	Left	PrCp Right	Left	IMLT Right	Left	Time	
	1	1	0	0	0.4	0.2	28	Articulator
	1	1	3	0	0.4	0.5	32	1
	0	1	1	0	0.3	0.60	27	
Mean	0.67	1.00	1.33	0.00	0.37	0.43	29.0	
Std Dev	0.56	0.00	1.53	0.00	0.61	0.21	2.6	
Var	0.33	0.00	2.33	0.00	0.37	0.04	7	
	0	0	1	1	0.2	0.5	34	Articulator
	0	2	1	1	0.5	0.5	32	2
	1	2	1	0	0.3	0.40	33	
Mean	0.33	1.33	1.00	0.67	0.33	0.47	33.0	
Std Dev	0.58	1.15	0.00	0.56	0.15	0.06	1.0	
Var	0.32	1.33	0.00	0.33	0.02	0.004	1	
	0	2	0	0	0.3	0.4	29	Articulator
	1	4	4	0	0.3	0.3	35	3
	1	0	1	1	0.4	0.00	32	
Mean	0.67	2.00	1.67	0.33	0.33	0.23	32.0	
Std Dev	0.56	2.00	2.08	0.58	0.06	0.21	3.0	
Var	0.33	4.00	4.33	0.32	0.003	0.04	9	
Mean	0.56	1.44	1.33	0.33	0.34	0.38	31.3	Combined
Std Dev	0.53	1.24	1.32	0.50	0.09	0.19	2.7	
Var	0.28	1.53	1.75	0.25	0.01	0.03	8	

Table 10: Specific Aim Four Combined Mean Pantograph Data: progressive mandibular lateral translation angle error (degrees), protrusive condylar path angle error (degrees), immediate mandibular lateral translation (mm) and time (seconds).Means, standard deviations and variances.

Specific Aim 4

Set PMLT - 10
Set PrCp - 50
Set IMLT - 1

Mechanical	**PMLT Right**	**PMLT Left**	**PrCp Right**	**PrCp Left**	**IMLT Right**	**IMLT Left**	**Time**	
Mean	2.11	1.89	2.89	2.67	0.28	0.20	824	**Combined**
Std Dev	0.78	1.05	1.45	1.41	0.10	0.10	29.9	
Var	0.61	1.11	2.11	2.00	0.009	0.01	896	

Optoelectronic	**PMLT Right**	**PMLT Left**	**PrCp Right**	**PrCp Left**	**IMLT Right**	**IMLT Left**	**Time**	
Mean	1.82	1.90	8.00	7.00	0.33	0.39	137.2	**Combined**
Std Dev	0.45	0.42	3.54	4.03	0.28	0.22	5.8	
Var	0.2	0.17	12.50	16.25	0.08	0.05	34	

Electronic	**PMLT Right**	**PMLT Left**	**PrCp Right**	**PrCp Left**	**IMLT Right**	**IMLT Left**	**Time**	
Mean	0.56	1.44	1.33	0.33	0.34	0.38	31.3	**Combined**
Std Dev	0.53	1.24	1.32	0.50	0.09	0.19	2.7	
Var	0.28	1.53	1.75	0.25	0.01	0.03	8	

Figure 49: Specific Aim Four Combined Error Bar Graph. Mean error: progressive mandibular lateral translation (degrees), protrusive condylar path (degrees) and immediate mandibular lateral translation (mm). M - mechanical pantograph, O - optoelectronic pantograph and E - electronic stylus pantograph.

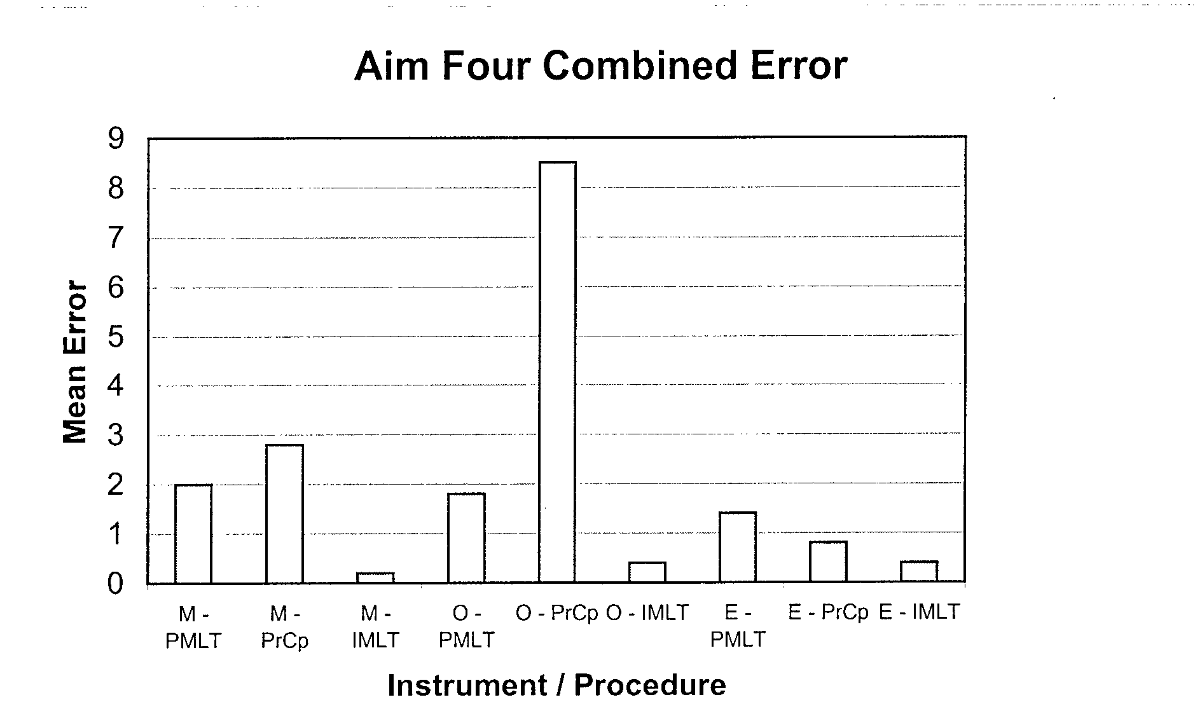
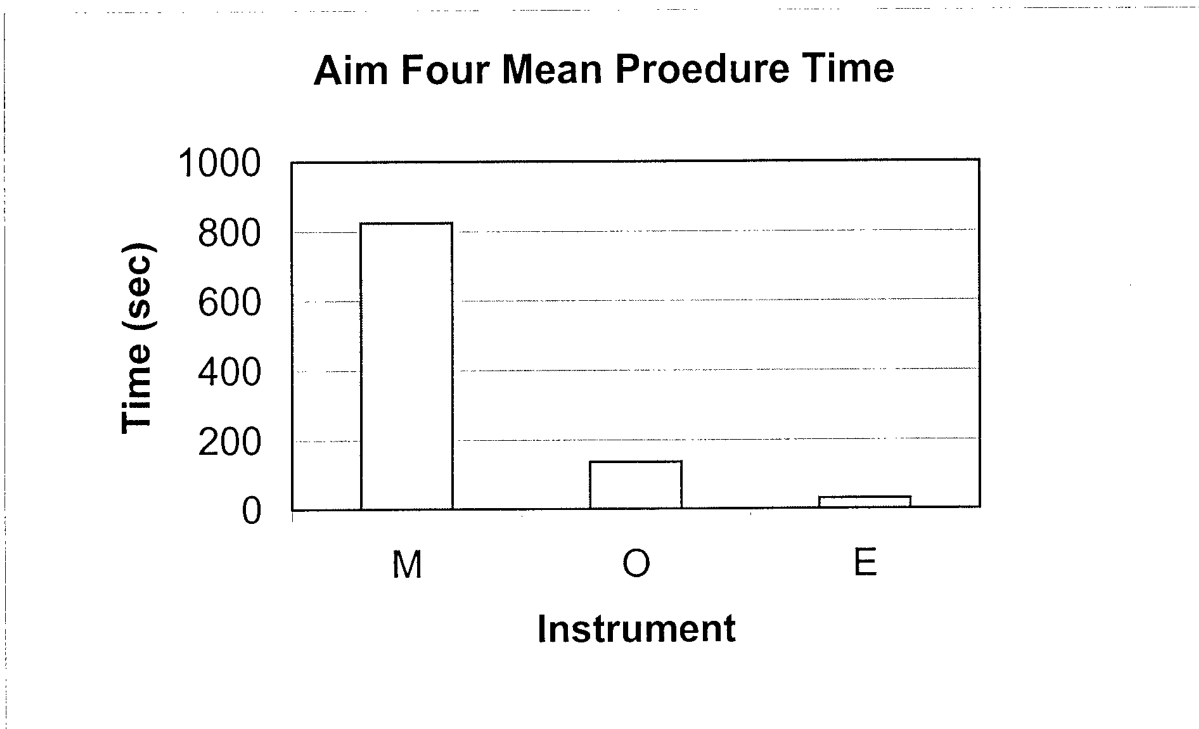

Aim Four Combined Error
Mean Error
0
1
2
3
4
5
6
7
8
9
M - PMLT
M - PrCp
M - IMLT
O - PMLT
O - PrCp
O - IMLT
E - PMLT
E - PrCp
E - IMLT
Instrument / Procedure

Figure 50: Specific Aim Four Combined Procedure Time Bar Graph.


Aim Four Mean Proedure Time
1000
800
600
400
200
0
Time (sec)
M
O
E
Instrument

V. DISCUSSION

In 1926, McCollum and 15 others formed the Gnathologic Society of California, Inc. (McCollum 1955). McCollum and Stallard coined the term "gnathology" to describe the science that encompasses the study and treatment of the stomatognathic system based on examination, diagnosis, and treatment planning. The teeth, supporting tissues, temporomandibular joints, and associated hard and soft tissues can collectively be described as the stomatognathic system (Bauer 1976, Solnit 1988, GPT-7 1999). The gnathologic treatment concept is based on the treatment of the oral cavity and related structures as an integrated organ instead of a collection of unrelated parts (Guichet 1969).

Complete understanding of the stomatognathic system requires in-depth study of its component parts and their function (Solnit 1988). However, patient-induced variability and error can limit in vivo investigations (Beard 1988). To this end dental professionals have long recognized the need for in vitro simulation of the function and component parts of the stomatognathic system (Beard 1986, Donaldson 1986, Pelletier 1991). Advances in the study of the stomatognathic system have closely paralleled improved instrumentation and techniques designed to accurately duplicate form and function. Development of articulators and mandibular movement recording devices, including the pantograph, are notable advances (Bauer 1976, Solnit 1988).

The transverse horizontal axis (THA) has been the classic posterior pantographic reference (Donaldson 1986, McCollum 1955). The THA is a unique and reproducible landmark (McCollum 1955, Aull 1963, Lucia 1983, Solnit 1988). Stuart (1979) stated "if the posterior reference were not on the THA, it would be impossible to have the correct interaction of the vertical axes around which lateral movements are made." In two separate Aims, this investigation demonstrated a significant difference (three-way ANOVA, p=0.0001) in the test instruments ability to verify and locate the THA. The combined mean error for Aim One was 0.2 mm (kinematic) versus 0.6 mm (optoelectronic), with standard deviations of 0.2 mm (kinematic) versus 0.3 mm (optoelectronic). The combined mean error for Aim Two was 0.2 mm (kinematic) versus 1.0 mm (optoelectronic), with standard deviations of 0.2 mm (kinematic) versus 0.5 mm (optoelectronic). In both Aims the kinematic THA location was statistically more accurate and reliable.

Accurate and reliable kinematic THA location is dependent on many factors. The most important factors are patient conditioning, operator training, lighting, contrasting backgrounds, magnification, and procedure time. A stable, rigid, and smoothly functional apparatus is also critical. Each of these factors must be well understood, appropriately applied, and manipulated to produce accurate THA location (Kurth 1951, Borgh 1958, Lauritzen 1961, Aull 1963, Winstanley 1979, Walker 1980, Razek 1981, Winstanley 1985, Bowley 1990, Bowley 1992).

Optoelectronic THA location removes the lighting, contrasting backgrounds, magnification, and procedure time factors. However, the optoelectronic method adds computer programs, data cables, computer ability (processor speed and power) and infrared light sending, reflecting, and sensor apparatus. The optoelectronic THA procedures were significantly (two-way ANOVA, p=0.0001) faster than the kinematic THA locations. The mean procedure time was 437 seconds (kinematic) versus 204 seconds (optoelectronic), with a standard deviation of 65 seconds (kinematic) versus 26 seconds (optoelectronic). Unfortunately, many of the advanced optoelectronic hardware and software applications can be more difficult to understand, difficult to isolate potential problems, and virtually impossible to manipulate when the THA location is inaccurate.

McCollum (1955), Cohen (1956), Posselt (1960), Kotowicz (1970) and Shields (1978) have determined that pantographs with properly oriented styli can accurately and reproducibly record mandibular movements. McCollum (1955), Clayton (1971) and Lucia (1983) have stated that pantography is the most accurate, comprehensive, and clinically practical means of recording jaw movement and providing information about the temporomandibular joints, surrounding tissues, and the mandible's border movements. The primary clinical application of pantography is to program an articulator (Curtis 1986, Donaldson 1986).

Articulator advances have led to the development of instruments that have potentially the same three-dimensional movement as the jaw joints (Stuart 1979, Celenza 1979). However, even the best instrument can yield poor results if improperly programmed (Stuart 1979). Proper recording of mandibular movement and programming and storage of individualized patient information in the articulator will permit articulator movements to be in harmony with the patient's mandibular movements (Stuart 1979, Curtis 1986). Restorations fabricated on properly programmed articulators with the ability to accurately duplicate mandibular movement should function in the patient's mouth without potentially damaging occlusal interferences (Clayton 1971, Lundeen 1984, Anderson 1987, Curtis 1987, Watchel 1987, Pelletier 91).

Progressive mandibular lateral translation (PMLT) movement of the mandible affects the cusp location, cusp height, and ridge and groove direction of the teeth

(Huffman 1969, Clayton 1971, Jaarda 1979). Therefore, proper patient articulator programming data improves articulator simulation. Statistical analysis of the Aim Three data suggest the electronic stylus pantograph was superior (three-way ANOVA p=0.069 and the Bonferroni post hoc analysis) in determining PMLT angles. The Aim Three mean error was 2.3° mechanical pantograph (MP), 2.1° optoelectronic computerized pantograph (OP) and 1.3° electronic stylus computerized pantograph (EP), with a standard deviation of 1.6° MP, 0.3° OP, 1.3° EP. Statistical analysis of the Aim Four data revealed the EP was superior (three-way ANOVA p=0.001 and the Bonferroni post hoc analysis) in determining PMLT angles. Aim Four mean error results for PMLT was 2.0° MP, 1.85° OP and 1.35° EP, with a standard deviation of 0.9° MP, 0.4° OP, 0.9° EP. The mean errors in this investigation are in agreement with mean error values noted in previous movement studies (Coye 1977, Clayton 1983, Beard 1986, Price 1988 and Pelletier 1991).

Protrusive condylar path (PrCp) movement of the mandible affects cusp location, cusp height, and ridge and groove direction (Huffman 1969, Clayton 1971 and Jaarda 1979). Thus a properly programmed articulator is essential to simulate patient function. Aim Three and Four revealed the EP performed significantly better (three-way ANOVA, p=0.0001 and Bonferroni post hoc analysis) than the OP and MP in PrCp determinations. The Aim Three mean error was 3.2° MP, 9.4° OP, and 2.0° EP, with a standard deviation of 1.4° MP, 2.2° OP and 1.1° EP. The Aim Four mean error was 2.8° MP, 8.5° OP and 0.8° EP, with a standard deviation 1.4° MP, 3.8° OP and 0.9° EP. The PrCp mean errors for the MP and EP in this investigation are in agreement with mean error values noted in previous movement studies. However, the mean errors obtained from the optoelectronic are greater than the previously reported protrusive condylar path values from electronic stylus and mechanical pantographs (Clayton 1983, Beard 1986, Price 1988 and Pelletier 1991).

Immediate mandibular lateral translation (IMLT) can effect fossa width, cusp height, and ridge and groove direction. An articulator individualized for each patient through proper programming will yield better results (Huffman 1969, Clayton 1971, and Jaarda 1979).. The Aim Four results suggested the mechanical pantograph demonstrated the best statistical (three-way ANOVA, p=0.0891 and Bonferroni post hoc analysis) ability to determine preset values for IMLT values. The mean error for IMLT was 0.2 mm MP, 0.4 mm OP and 0.4 mm EP, with a standard deviation of 0.1 mm MP, 0.3 mm OP and 0.1 mm EP. These values are in agreement with previous study values (Clayton 1983, Coye 1977, Price 1988, Pelletier 1991)

Mechanical pantography has been found to be accurate and reliable (McCollum 1955, Beard 1986, Donaldson 1986, Pelletier 1991), but the time and complexity involved in recording movements and programming articulators are major shortcomings (Coye 1977, Price 1989). An electronic-stylus computerized pantograph was developed to quickly analyze patient movements and minimize articulator-programming errors by generating numerical condylar values. The electronic pantograph has been shown to be an acceptable alternative to mechanical pantography (Clayton 1983, Beard 1986, Anderson 1987, Price 1989, Pelletier 1991). In this investigation, the electronic stylus pantograph determined the test values significantly (two-way ANOVA, p=0.0001) faster than the other pantographs in Aims Three and Four. This validates the results of the previously cited investigations. The Aim Three mean procedure time was 752 seconds

MP, 136 seconds OP, and 30 seconds EP, with a standard deviation of 46 seconds MP, 8 seconds OP and 3 seconds EP. The Aim Four procedure time was 824 seconds MP, 137 seconds OP, and 31 seconds EP, with a standard deviation of 30 seconds MP, 6 seconds OP and 3 seconds EP.

The results of this investigation support previous findings of researchers using the mechanical and electronic stylus pantograph. Both are accurate and reliable techniques (Clayton 1983, Beard 1986, Anderson 1987, Price 1988 and Pelletier 1991). Additionally, the electronic pantograph is a time saving and accurate alternative to mechanical pantography (Clayton 1983, Beard 1986, Anderson 1987, Price 1988 and Pelletier 1991). The optoelectronic pantograph research is new; however, the results statistically show it's function is not equal to the electronic stylus and mechanical pantographs. In THA location the optoelectronic instrument is neither as accurate nor as reliable, however it shortens procedure time. The results of this investigation indicate that the optoelectronic pantograph is not an acceptable alternative to mechanical and electronic pantography.

VI. CONCLUSIONS

This investigation compared the accuracy, repeatability, and procedure time of three pantographic and two THA location systems. The results of this investigation indicate that statistically significant differences exist among the instruments' capabilities.

1. The kinematic face-bow was better at verifying the THA.
2. The kinematic face-bow was better at locating the THA, and correcting to the THA.
3. The kinematic face-bow was slower than the optoelectronic pantograph at locating and correcting to the THA.
4. The electronic-stylus pantograph was superior when determining PMLT and PrCp values.
5. The mechanical pantograph was better when determining IMLT values.
6. The electronic-stylus computerized pantograph was the fastest instrument when determining PMLT, IMLT and PrCp values.
7. The optoelectronic method is not be a practical alternative for quick, accurate, and reliable transverse horizontal axis location and posterior condylar setting determination.

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Vita

Jay Douglas Graver was born on October 2, 1960 to Heber T. and Lois E. Graver in Allentown, Pennsylvania. He graduated from Norristown Area High School, Norristown, Pennsylvania in 1978. He then attended The University of Pennsylvania where he majored in Molecular Biology. He earned a Bachelor of Arts degree in 1982.

In September 1982, he entered The University of Pennsylvania School of Dental Medicine. He married Susan M. Kienlen on June 29, 1985. He graduated and received a Doctor of Medical Dentistry degree in May 1986. Upon graduation he accepted a teaching position at the University of Pennsylvania School of Dental Medicine and a practice position in Worcester, Pennsylvania.

In August 1992, he was commissioned in the United States Air Force. His initial assignment was Randolph Air Force Base, Texas. In August 1996 he was assigned to Lajes Air Base, Azores, Portugal.

In June 1998, he entered the Post-Doctoral Prosthodontic Residency at Wilford Hall United States Air Force Medical Center and the University of Texas Health Science Center at San Antonio, Texas.

He and Susan have four children: Hunter (Bub) Ryan (10 years), Elizabeth (Bethie) Kathryn (9 years), Tyler (Bud) Thomas (8 years) and Ethan (Effers) Michael (1.5 years).

Upon graduation, he will be assigned as a staff prosthodontist at Bolling Air Force Base, Washington DC.