

IN VITRO TESTING OF THE ACCURACY
OF A COMPUTERIZED PANTOGRAPH

A MASTER'S THESIS
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Richard R. Dryer, D.D.S.

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE (DENTISTRY)

Faculty Adviser
Heather J. Conrad, D.M.D., M.S.

June 2014

© Richard R. Dryer, June 2014

ACKNOWLEDGEMENTS

I would like to thank Dr. Heather Conrad and Dr. James Holtan for their dedication to my education in prosthodontics.

DEDICATION

I dedicate this master's thesis to Rekha, Kiran, and Sonia for their love and support.

ABSTRACT

Statement of the problem. The accuracy of a computerized pantograph has not been confirmed in laboratory or clinical studies.

Specific aims. The purpose of this in vitro study is to test the accuracy of a computerized pantograph to record predetermined condylar settings on a fully adjustable articulator for condylar inclination with flat versus 3/8" inserts, top wall, rear wall, progressive side shift, and immediate side shift.

Materials and methods. Computerized pantographic sensors were mounted on a fully adjustable articulator with an arbitrary determination of the hinge axis. Tracings were made on the articulator with known condylar settings for condylar inclination with flat and 3/8" curved inserts, immediate side shift, progressive side shift, top wall and rear wall. Means, standard deviations, *P*-values, equivalence testing and Bonferonni adjustments were determined for each condylar setting.

Results. The computerized pantograph accurately recorded the immediate side shift at 0, 1.2 mm and 2.0 mm ($P < .0001$). Condylar inclination with the 3/8" curved insert at 10 and 25 degrees was accurately determined at the 10 mm condylotrack distance ($P < .0001$). Condylar inclination with the flat insert, progressive side shift, top wall and rear wall were non-significant.

Conclusion. The computerized pantograph is a valid instrument for recording immediate side shift and condylar inclination with a curved 3/8" fossa at the 10 mm condylotrack distance.

TABLE OF CONTENTS

Acknowledgements	pg. i
Dedication	pg. ii
Abstract	pg. iii
Table of Contents	pg. iv
List of Tables	pg. v
List of Figures	pg. vi
Introduction	pg. 1
Specific Aims	pg. 14
Hypotheses	pg. 15
Materials and Methods	pg. 16
Statistical Analysis	pg. 24
Results	pg. 25
Discussion	pg. 39
Conclusion	pg. 45
References	pg. 46

LIST OF TABLES

Table	Title	Page
I.	Dataset	pg. 25
II.	Means and Standard Deviations	pg. 32
III.	<i>P</i> -value, Equivalence, and Bonferroni Adjustment	pg. 34
IV.	10 mm Condylotrack Means, STD, <i>P</i> -value, Equivalence and Bonferroni Adjustment	pg. 37

LIST OF FIGURES

Figure	Title	Page
Figure I.	Fully Adjustable Articulator (Denar D5A, <u>Whip Mix Corporation</u>).	pg. 17
Figure II.	Rear Wall, Progressive Side Shift, and Immediate Side Shift (Left) and Top Wall (Right) Settings on D5A.	pg. 18
Figure III.	3/8" Insert (Left) & Flat Insert (Right).	pg. 18
Figure IV.	Condylar Element of Denar D5A.	pg. 19
Figure V.	Cadiax Compact 2 (Clinical View).	pg. 20
Figure VI.	Computerized Pantograph Mounted on Fully Adjustable Articulator.	pg. 21
Figure VII.	Lateral View of Computerized Pantograph.	pg. 21
Figure VIII.	Cadiax Compact 2 Computerized Pantographic Tracing.	pg. 23
Figure IX.	D5A Condylar Settings from the Gamma Dental Software.	pg. 23
Figure X.	Immediate Side Shift Means and Standard Deviations.	pg. 31
Figure XI.	3/8" Insert Means and Standard Deviations at 10 mm Condylotrack Distance.	pg. 38

INTRODUCTION

The goal of dental prosthetic reconstruction is to create a prosthesis that is in functional harmony within the boundaries of a patient's mandibular movements and mimics the patient's dentition in form and function. Prosthetic reconstruction is dependent on several important factors: accurate duplication of the patient's dentition, orientation of the maxilla to the cranial base, orientation of the maxilla to the mandible, and recording of the mandibular border movements. This information is assembled on a dental articulator prior to the fabrication of the dental prosthesis. These procedures can be completed in the digital or analog world or a combination of the two. In the near future, the majority of prosthetic reconstructions will likely be completed digitally.

Conventional & Digital Impressions

Early attempts at recording the dentition of a patient for prosthetic reconstruction date to the mid-18th century. In 1756, Phillip Pfaff, dentist to Frederick the Great, described a wax impression technique of the dentition and pouring them in plaster.¹ Currently, the American Dental Association (ADA) specification 19 states that an elastomeric impression should be able to continuously replicate 1 of the 0.02 mm width horizontal lines in 2 of 3 specimens and should not display more than 0.5% dimensional change after 24 hours of polymerization of the material.² Commercially available impression materials that conform to ADA specification 19 include: polysulfides, condensation silicones, polyethers and addition silicones. Williams evaluated time dependent dimensional stability of elastomeric impression materials and found that polysulfides, condensation silicones, and polyether demonstrated the greatest accuracy and

dimensional stability only when immediately poured.³ The addition silicones demonstrated excellent dimensional stability after 1, 4 and 24 hours of storage.³

Digital intraoral impressions and the creation of a 3-dimensional virtual model for the fabrication of dental restorations are increasing in popularity. Lee⁴ evaluated dental students and experienced dental professional's perception of digital and conventional implant impressions and determined that digital impressions were preferred by dental students as the most efficient impression technique with the least difficulty. Cardelli⁵ evaluated single unit computer aided design/computer aided manufacturing (CAD/CAM) zirconia crowns generated from a digital intraoral impression (Lava COS) and determined a mean marginal gap of 48.65 μm (SD 29.45 μm). Andreas⁶ analyzed the precision of conventional full arch impressions completed with an elastomeric impression material and poured in gypsum compared to digital impressions and concluded that digital impressions were significantly less accurate in precision and trueness compared to conventional full arch impressions.

Transverse Horizontal Axis (Facebow)

The next phase of prosthetic reconstruction determines the location of the transverse horizontal axis. The transverse horizontal axis is defined by the Glossary of Prosthodontic as an imaginary line around which the mandible rotates in the sagittal plane.⁷ Facebows are used to identify the transverse horizontal axis and relate the occlusal surfaces of the maxillary teeth to this axis. The facebow recording orientates the digital or analog reproduction of the maxilla to the dental articulator for prosthetic reconstruction. Inaccuracies in determining the transverse horizontal axis can lead to errors in recording mandibular condyle movement and errors in prosthetic reconstruction.

Location of the transverse horizontal axis can be determined by either a kinematic or arbitrary facebow. Kinematic facebows determine the exact location of the axis of rotation of the mandible; whereas, arbitrary facebows utilize anatomic averages to locate the transverse horizontal axis. The arbitrary facebow typically utilizes the right and left external auditory meatus to relate the maxillary teeth to the transverse horizontal axis and an estimated value of 13 mm anterior to the tragus of the ear on a line from the tragus to the outer canthus of the ear. In a study by Schallhorn⁸, 95% of subjects had a kinematic center within a radius of 5 mm from the arbitrary center. Kois⁹ evaluated the relationship of the maxillary incisor to the arbitrary transverse horizontal axis on 73 patients and noted that 89.04% were located within 5 mm of a mean distance of 100 mm (arbitrary hinge axis to incisal edge).

Arstad¹⁰ noted that a 5 mm error in the location of the true hinge axis will result in an error of 0.2 mm with the molar antagonist after a 2 mm hinge movement. Weinberg¹¹ came to a similar conclusion when he evaluated the use of an arbitrary hinge axis location that is within ± 5 mm of the true hinge axis and stated that a negligible anteroposterior error in the magnitude of 0.2 mm is introduced at the second molar.

Several researchers have concluded that the arbitrary hinge axis does not coincide with the true hinge axis. Lauritzen¹² studied variations in the location of arbitrary and true hinge axis points and noted that only 33% of participants were within 5 mm of the true hinge axis. These discrepancies between the arbitrary and true hinges axes were noted by Walker¹³ where only 22% of participants had a true hinge axis within 5 mm of the 13 mm arbitrary location.

The computerized pantograph (Cadiax Compact 2; Whip Mix Corporation, Louisville, KY) utilizes an arbitrary facebow (Denar Slidematic Facebow; Whip Mix Corporation) to determine the transverse horizontal axis, as well as, an arbitrary hinge location for the pantographic tracings. Berhardt¹⁴ compared arbitrary and kinematic location of the transverse horizontal axis in mandibular movements with the Cadiax Compact system. The author enrolled 30 students and recorded two recordings with the Cadiax Compact pantograph. The first recording utilized an arbitrary transverse horizontal axis determination and the second utilized a kinematic transverse horizontal axis. Berhardt¹⁴ determined that the kinematic determination of the transverse horizontal axis was the most precise method; however, the arbitrary determination demonstrated acceptable reproducibility. This study compared recordings for the horizontal condylar inclination with the kinematic versus arbitrary facebow for the Cadiax Compact system and did not report values for immediate side shift, progressive side shift, top wall or rear wall.

Centric Relation

The next phase in prosthetic reconstruction involves the orientation of the maxilla to the mandible through a centric relation record and transferring this relationship to the dental articulator. Initial attempts at orientating the maxilla to the mandible date to the early 19th century. In 1805, Jean Baptiste Gariot¹⁵ described the first use of a simple plaster articulator to preserve the relationship of the maxilla to the mandible. Current prosthodontic techniques employ centric relation records to establish the orientation of the maxilla to the mandible. According to The Glossary of Prosthodontic Terms, centric relation is defined as the maxillomandibular relationship in which the condyles articulate

with the thinnest avascular portion of their respective disks with the complex in the anterior-superior position against the shapes of the articular eminencies.¹⁶ Multiple techniques are utilized to record centric relation including: bimanual manipulation, chin point guidance, Gothic arch tracing and may employ the use of Lucia jig or leaf gauge. Keshvad¹⁷ and colleagues compared the reproducibility of chin point guidance with a jig, bimanual manipulation with a jig, and Gothic arch tracing for fourteen patients at four time intervals and demonstrated that bimanual mandibular manipulation with a jig had the highest repeatability. McKee¹⁸ demonstrated the repeatability of recording centric relation with bimanual manipulation to within a tolerance level of 0.11 mm.

Mandibular Movement

The final phase of prosthetic reconstruction involves recording mandibular movement. Mandibular movement is a complex action involving neural stimulus, muscle contraction, ligament support, bilateral temporomandibular joint discs, and anterior and posterior hard tissue determinants. The anterior determinants involved in mandibular movement are the anterior teeth. Bilaterally, the mandibular condyles represent the posterior determinants of occlusion. The combined effects of anterior guidance and posterior condylar anatomy affect the shape of the posterior dentition and disclusion of the posterior teeth.

The complexity of mandibular movement or condylar movement in the mandibular fossa was best described by Ramfjord and Ash¹⁹ in their textbook on occlusion in 1973. They described the complexity of condylar movement as follows: the working condyle in the frontal plane may move straight laterally, laterally and superiorly, or laterally and inferiorly; whereas, the movement in the horizontal plane may

be straight laterally, laterally and posteriorly, or laterally and anteriorly. In addition, they stated that the greater the Bennett angle of the non-working condyle then the greater the amount of lateral shift of the working condyle.

Historically, scientific interest in recording the movement of the mandible dates back to the mid to late 19th century. In 1866, Balkwill²⁰ introduced a device that would record the angle formed from a line drawn from the condyles to the incisors and occlusal plane. This angle was named the “Balkwill’s Angle” and was estimated to be 26 degrees. Luce²¹ was the first scientist to develop a device that reproduced and traced condylar movement and reported these results in 1889. In 1894, Bonwill²² described the forward movement of the condyles. Bonwill’s Triangle is introduced in 1899 based on his observations of 10,000 specimens where the average jaw measures four inches from the center of each condylar process to the mandibular central incisors forming an equilateral triangle.²³

Scientific interest in describing mandibular movement continued into the early 20th century with Norman Bennett describing the lateral movement of the condyle, now referred to as ‘Bennett Movement’ in 1908.²⁴ Gysi²⁵ refined the measurement of condylar paths, measuring the “Balkwill-Bennett” movements, and incorporating condylar paths into an articulator in 1910.

The next major milestone in defining mandibular movement came in 1955 when McCollum²⁶ defined the transverse horizontal axis of the mandibular condyles. The transverse horizontal axis is defined by the Glossary of Prosthodontic as an imaginary line around which the mandible rotates in the sagittal plane.²⁷ Posselt²⁸ refined the 3-dimensional movement of the mandible incorporating centric relation, maximum

intercuspatation, and the mandibular border movements into our current understanding of mandibular movement in 1957. Clayton²⁹ demonstrated that patients will function to the mandibular border movements recorded by a pantograph during the course of a chewing cycle, as long as, deflective occlusal contacts are not present.

The downward and forward movement of the mandibular condyle as it travels down the slope of the mandibular eminence is defined as the horizontal condylar inclination. Horizontal condylar inclination can be determined from protrusive interocclusal recordings, mechanical or computerized pantographic tracings, and radiographically. Horizontal condylar inclination influences cusp height and can result in either occlusal interferences or inadequate occlusal morphology if it is not determined accurately. Santos³⁰ compared condylar inclination settings obtained by wax records versus pantographic tracings on 10 subjects and determined a mean of 38.30° and standard deviation of 6.98 for the pantograph and a mean of 29.80° and standard deviation of 9.25 with the protrusive wax record. The investigators determined that condylar inclination determined by the pantographic method resulted in statistically significant higher angles than condylar inclination determined by the protrusive wax method. Curtis³¹ demonstrated similar results with an average condylar inclination determined by the pantograph of 29.5° and an average condylar inclination of 25.8° with a protrusive wax record.

The dynamic movement of the mandibular condyles can be recorded by interocclusal records, simplified motion analyzers, or pantographic tracings. Curtis³² compared immediate side shift recorded by pantographic tracing to interocclusal records obtained in polyvinylsiloxane and wax with chin point guidance from 20 participants.

The average immediate side shift was recorded by a pantograph as 0.54 mm, polyvinylsiloxane ($0.63 \text{ mm} \pm 0.59 \text{ mm}$) and wax ($0.81 \pm 0.72 \text{ mm}$). Pantographic tracing and lateral interocclusal polyvinylsiloxane records were determined to not be statistically significant. Ecker and Goodacre³³ evaluated compared condylar settings for 16 patients obtained by wax records and two simplified mandibular motion analyzers and concluded condylar inclination values obtained by a protrusive wax record were 31.41° and standard deviation of 7.87; one simplified motion analyzer (Whip Mix Corporation) resulted in condylar inclination values of 48.37° and standard deviation of 7.16; while another mandibular motion recorder (Panadent Corporation) resulted in 37.38° and standard deviation of 6.59. In addition, immediate side shift values were reported as 0.73 mm with a standard deviation of 0.42 for lateral occlusal wax records; 0.98 mm and 0.35 mm standard deviation with the Whip-Mix motion analyzer; and 0.86 mm with a 0.38 mm standard deviation for the Panadent motion analyzer. An in vitro study by Pelletier and Cambell³⁴ compared settings for horizontal condylar inclination and immediate side shift obtained by interocclusal records, electronic pantograph, or simplified mandibular motion analyzers and determined that the most accurate and reliable method was the electronic pantograph for both horizontal condylar inclination and immediate side shift.

Payne³⁵ evaluated the condylar determinants of fifty five patients with an electronic pantograph and determined the following: immediate side shift average was 0.44 mm (range 0 to 1.85 mm) and eighty percent of patients recorded an ISS less than 0.75 mm, progressive side shift average of 6.22° (range 0.3° to 11.57°), and average condylar inclination of 42.71° (range 16.5° to 62.37°). The author concluded that the use of arbitrary condylar values is inappropriate. The condylar values for the top and rear

condylar walls were not reported in this study. Lundeen³⁶ evaluated 163 subjects and noted an average immediate side shift of 0.75 mm with 80% of subjects with 1.5 mm or less. In addition, the author noted that patients with 0.75 mm of Bennett movement or less would have a minimal possibility of eccentric occlusal interferences. The higher range of lateral working condylar movement has been reported to be 3 mm by Guichet.³⁷

In addition to horizontal condylar inclination, immediate side shift and progressive side shift, the fully adjustable articulator enables the clinician to establish the top wall and rear wall of the condylar elements. The top wall determines groove height and the rear wall determines groove direction of the dental restoration. Winstanley³⁸ studied the Denar fully adjustable articulator and a mechanical pantograph and noted that the sagittal condylar inclination, immediate side shift and progressive side shift can be set with a reasonable degree of accuracy; however, the value of the top and rear wall settings in recording mandibular movement were determined to be questionable. Coye³⁹ confirmed these results in an in vitro study with the Denar fully adjustable articulator and demonstrated that the largest magnitude of error occurred with the top and rear wall.

Anderson and Schulte⁴⁰ investigated the effects of immediate side shift on top and rear wall condylar elements in an in vitro study with an electronic pantograph. They demonstrated that the electronic pantograph (Pantronic; Whip Mix Corporation) accurately recorded horizontal condylar inclination, immediate side shift and progressive side shift. In addition, they noted that rear and top wall angulations were not recorded with an immediate side shift of zero and as the immediate side shift increased, the

reliability and validity of recording rear and top wall measurements increased. This study only reported means and standard deviations with no further statistical analysis.

The influence of horizontal condylar inclination on tooth morphology is well understood. Increased horizontal condylar inclination allows for increased cusp height; whereas, decreased horizontal condylar inclination requires decreased cusp height. The effects of top wall, rear wall, immediate side shift and progressive side shift on cusp molar occlusal anatomy are unclear. Schulte⁴¹ elucidated the effect of the top and rear condylar wall and the immediate and progressive side shift on occlusal morphology. Schulte evaluated the movement of the mesiolingual cusp of the maxillary first molar during working mandibular movement while varying top and rear wall settings and found that a top wall change from +25 degrees to -25 degrees at 2 mm of cusp travel increased the angle of cusp movement to 38 degrees and would produce a 0.2 mm occlusal interference and rear wall adjustments from +25 degrees to -25 degrees would produce a difference of 8 degrees in cusp trajectory and was determined to be insignificant. Schulte⁴² evaluated the effect of progressive side shift and immediate side shift on the mesial lingual cusp of a maxillary first molar during a nonworking movement and determined that total changes in progressive side shift are relatively insignificant at the occlusal surface, while changes in immediate side shift do effect the width of the central groove and origin of the distal buccal groove.

The current computerized pantograph that is commercially available to analyze mandibular movement and set a dental articulator for prosthetic reconstruction is the Cadiax Compact and Cadiax Compact 2. Chang⁴³ demonstrated in an in vitro study that the Cadiax Compact electronic pantograph was both reliable and valid in calculating

condylar settings for 5 different articulators, including a fully adjustable articulator (Denar D5A; Whip Mix Corporation). They determined that the 10 mm condylotrack distance provided the most reliable and accurate readings and this value should be used to program the horizontal condylar setting of the articulator. In addition, they determined that the smallest deviations for the preset values were found for the Denar Mark II for horizontal condylar inclination and progressive lateral side shift and the Panadent PCH for immediate lateral side shift. The Denar Mark II and Panadent PCH are semi-adjustable articulators with average condylar fossa inserts that incorporate mandibular fossa curvature, progressive side shift and immediate side shift. Limitations of this study included the utilization of a kinematic facebow and no measurements of top wall or rear wall condylar determinants. In addition, the study reported non-significant *P*-values for horizontal condylar inclination, immediate side shift and progressive side shift for the fully adjustable articulator.

Additional methods of recording mandibular movement include the use of ultrasonic or optoelectronic tracking devices. Wagner⁴⁴ compared pantographs from conventional computerized axiographs (Cadiax Compact) and optical axiography for horizontal condylar inclination, Bennett angle and mandibular pathway on ten healthy patients. They determined that the values obtained from optical and conventional axiography for the mandibular pathway and horizontal condylar inclination were significant, while the Bennett angle was non-significant.

The Dental Articulator

Ultimately, the information obtained from the recording the patient's dentition, transverse horizontal axis, centric relation, and mandibular movement are used to program a dental articulator. There are essentially three types of dental articulators used

for prosthetic reconstruction: 1) simple hinge articulators, 2) semi-adjustable articulators and 3) fully adjustable articulators. Simple hinge articulators orientate the maxilla to the mandible and typically do not incorporate a facebow and do not allow for any condylar adjustments. Semi-adjustable articulators allow for adjustment to some aspects of condylar movement, such as horizontal condylar inclination, and rely on the use of pre-determined condylar fossa elements that were determined from published research on average condylar values for progressive side shift and immediate side shift. The fully adjustable articulator allows for the adjustment of six condylar elements: 1) intercondylar distance, 2) progressive side shift, 3) immediate side shift, 4) top condylar wall, 5) rear condylar wall, and 6) horizontal condylar inclination. Currently, the only fully adjustable articulator in production is the Denar D5A (Whip Mix Corporation).

Intercondylar condylar distance determines the angle between laterotrusive and mediotrusive movement. The horizontal condylar inclination is the posterior determinant of cusp height. The top wall setting on the fully adjustable articulator determines groove height, while the rear wall setting determines groove direction. The immediate side shift determinant would influence the cusp to fossa relationship in condylar movement and is an important determinant to eliminate posterior occlusal interferences. The progressive side shift represents the lateral movement of the condylar and its influence on molar anatomy.

A pantographic tracing, either mechanical or computerized, records the movement of the mandible and enables the dentist to reproduce that movement on a dental articulator. The fully adjustable articulator provides the clinician with the most precise method of duplicating the patient's mandibular movements for complex prosthetic

reconstructions. Ultimately, the accuracy of a dental prosthetic reconstruction is dependent on an accurate impression of the dentition, recording of centric relation, location of the transverse horizontal axis, recording of mandibular movement, and the appropriate selection and programming of a dental articulator. Currently, there are a limited number of published articles in the peer reviewed literature regarding the accuracy of commercially available computerized pantographs to track mandibular condylar movement and program a fully adjustable dental articulator.

SPECIFIC AIMS

The purpose of this in vitro study is to test the accuracy of a computerized pantograph (Cadiax Compact 2; Whip Mix Corporation) to record pre-determined condylar settings on a fully adjustable articulator (Denar D5A; Whip Mix Corporation) for condylar inclination with flat versus 3/8' inserts, top wall, rear wall, progressive side shift, and immediate side shift.

HYPOTHESES

Null Hypothesis (H_0): The recommended settings obtained from the computerized pantograph (Cadiax Compact 2; Whip Mix Corporation) for horizontal condylar inclination, top wall, rear wall, progressive side shift, and immediate side shift for a fully adjustable articulator (Denar D5A; Whip Mix Corporation) equal the pre-determined condylar settings of the fully adjustable articulator.

Alternative Hypothesis (H_1): The recommended settings obtained from the computerized pantograph (Cadiax Compact 2; Whip Mix Corporation) for horizontal condylar inclination, top wall, rear wall, progressive side shift, and immediate side shift for a fully adjustable articulator (Denar D5A; Whip Mix Corporation) do not equal the pre-determined condylar settings of the fully adjustable articulator.

MATERIALS AND METHODS

A fully adjustable articulator (Denar D5A; Whip Mix Corporation) was purchased new and did not require calibration prior to testing (Figure I). Final impressions of a completed full mouth rehabilitation completed in graduate prosthodontics at the University of Minnesota were completed with the elastomeric impression material polyvinylsiloxane. The final impressions were boxed and poured in ADA Type V die stone (Fuji Rock; GC Dental Products, Kasugai, Japan). The maxillary cast was mounted with an arbitrary facebow (Denar Slidematic Facebow; Whip Mix Corporation), as recommended by the manufacturer in Type II fast set mounting plaster (Fuji; Whip Mix Corporation). The anterior reference point for the Denar Slidematic Facebow is 43 mm superior to the maxillary central incisors. The mandibular cast was mounted with a centric relation record utilizing bimanual manipulation with an anterior Lucia jig fabricated from Duralay resin (Reliance Dental Mfg., Worth, IL) and placement of bite registration material (Exabite, GC Dental Product) bilaterally in the posterior.

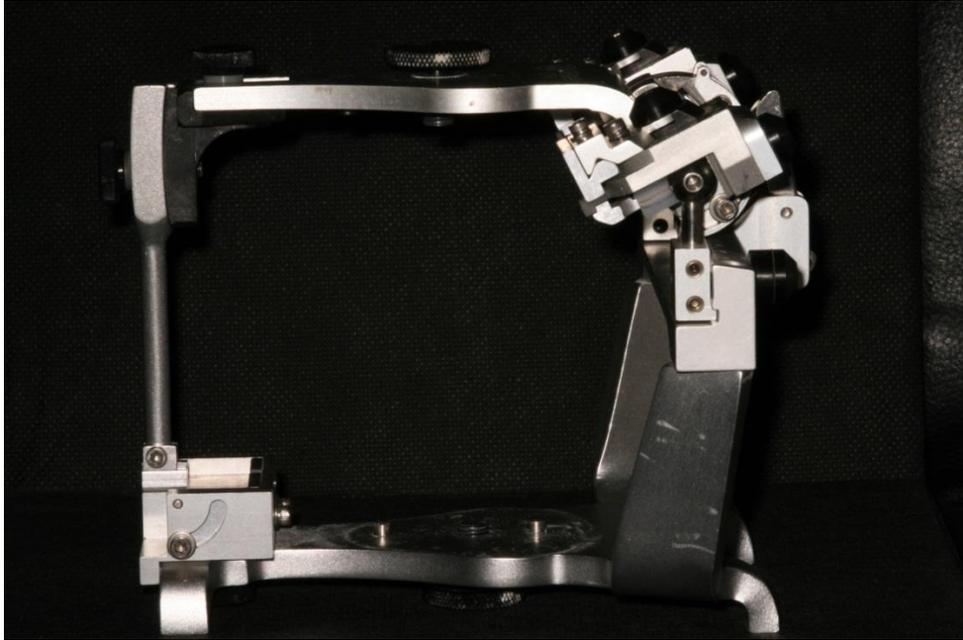


Figure I. Fully Adjustable Articulator (Denar D5A; Whip Mix Corporation).

Superior wall inserts were placed in the condylar housings and condylar settings were adjusted prior to assembly of the Gamma Dental Facebow (Whip Mix Corporation) onto the Denar D5A (Figure II-IV). The superior condylar inserts evaluated in this study were either the flat or 3/8" insert. The 3/4" condylar insert is no longer manufactured by Whip Mix Corporation. The condylar settings that were manipulated in this in vitro study included: horizontal condylar inclination with the flat insert (0°, 15°, and 25°); horizontal condylar inclination with the 3/8" insert (0°, 10°, and 25°); top wall (-25, -15, 0, 15, 25); rear wall (-25, -15, 0, 15, 25); progressive side shift (0°, 15°, 25°); and immediate side shift (0 mm, 1.2 mm, 2.0 mm).

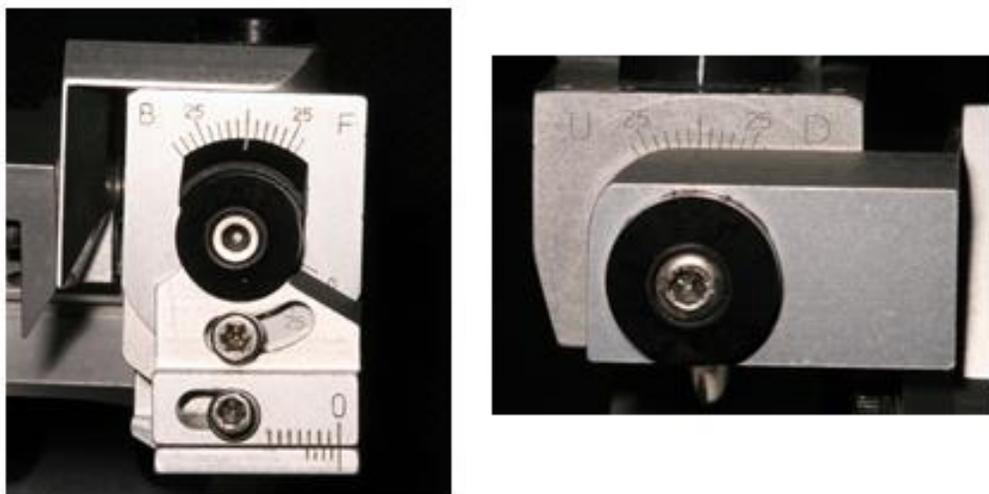


Figure II. Rear Wall, Progressive Side Shift, and Immediate Side Shift (Left) and Top Wall (Right) Settings on D5A.

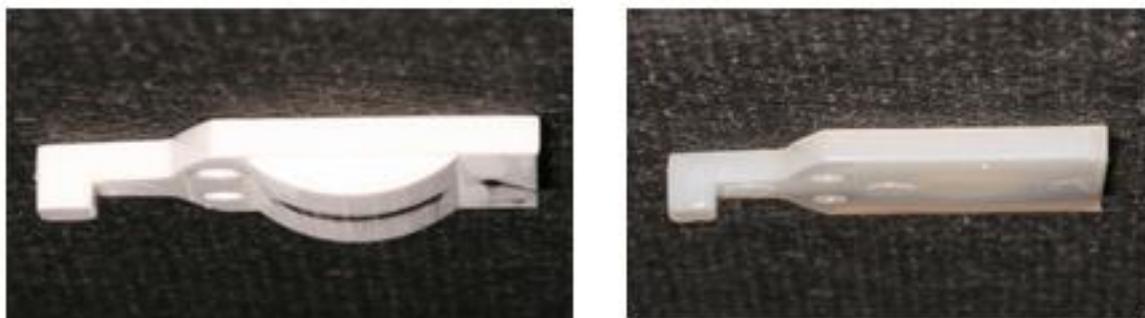


Figure III. 3/8" Insert (Left) & Flat Insert (Right).

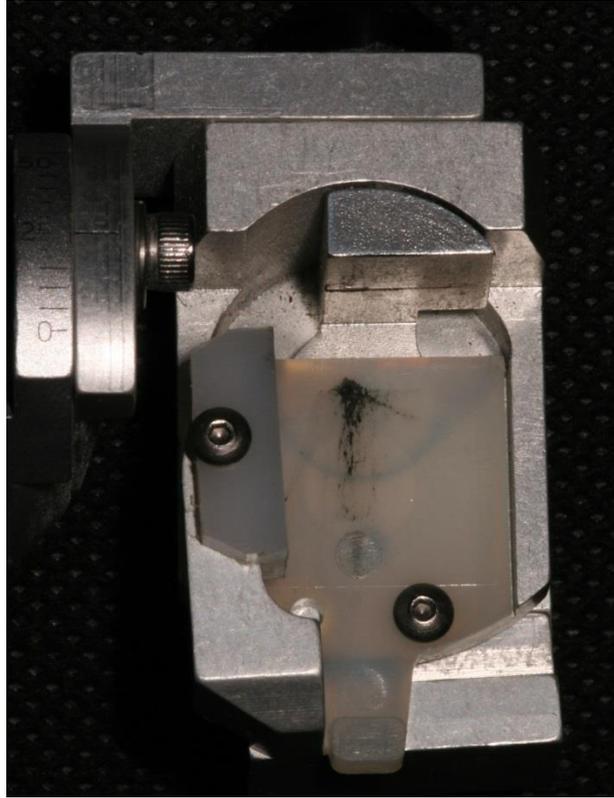


Figure IV. Condylar Element of Denar D5A.

The computerized pantograph was assembled onto the fully adjustable to simulate the recommended clinical protocol (Figure V-VI). An anterior jig was fabricated in Triad (Dentsply Prosthetics, York, PA) to stabilize the anterior component of the Gamma Dental Facebow (Whip Mix Corporation) at a location approximating the clinical location of the facebow in relation to nasion. Nasion is the third point of reference used with the Gamma Dental Facebow (Whip Mix Corporation) and is demonstrated in Figure V.

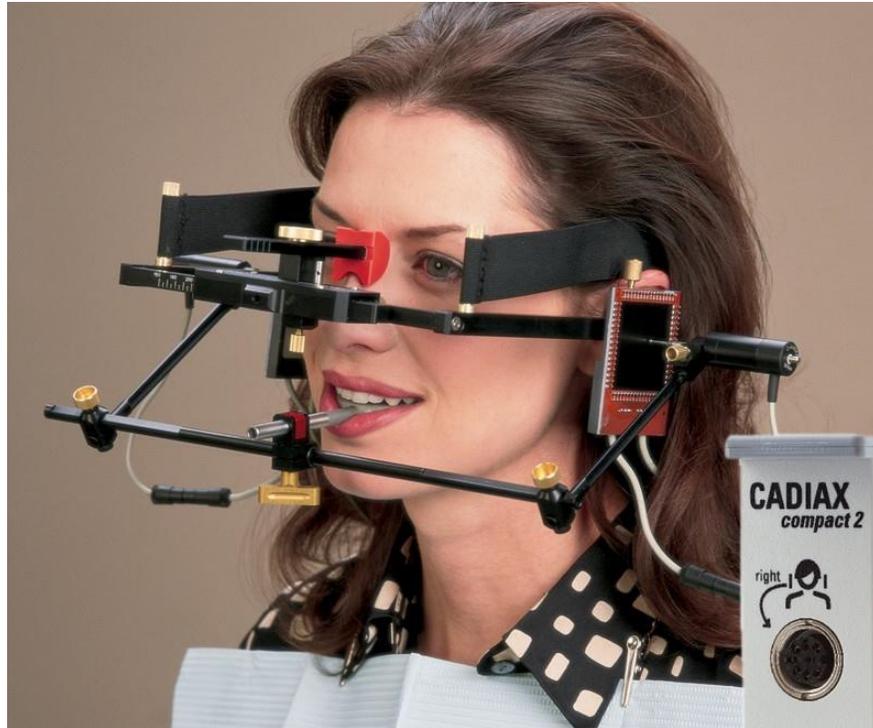


Figure V. Cadiax Compact 2 (Clinical View).

The Triad (Dentsply Prosthetics) jig was luted to the Gamma Dental Facebow (Whip Mix Corporation) with Duralay resin (Reliance Dental Mfg). The posterior elements of the facebow which are placed in the auditory canal were assembled onto the fully adjustable condylar housings approximating the arbitrary facebow location to within 5 mm of the kinematic center of rotation.

The mandibular clutch was luted to the mandibular cast with a rigid polyvinylsiloxane bite registration material (Exabite; GC Dental Product) and the lower member of the facebow was related to the upper facebow member with the styli engaging the upper member. The styli were removed and right and left computerized sensor flags were attached to the upper member. Recording styli were attached to the lower facebow member and engaged the sensors (Figure VII).

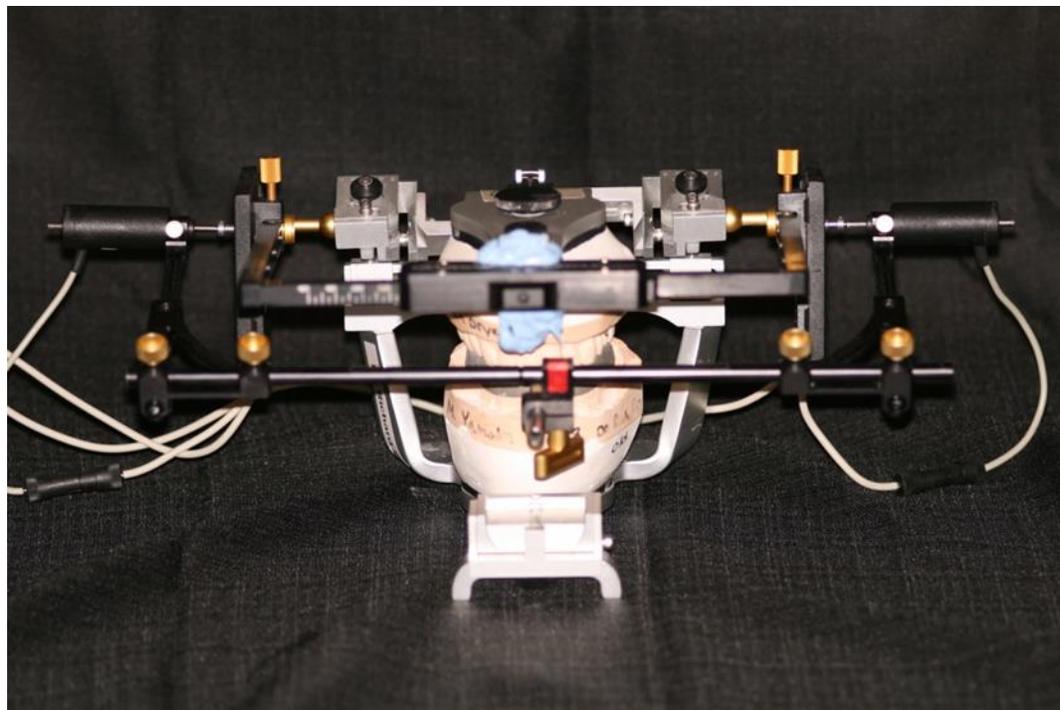


Figure VI. Computerized Pantograph Mounted on Fully Adjustable Articulator.



Figure VII. Lateral View of Computerized Pantograph.

The intercondylar distance was recorded from the facebow and entered into the Cadiax Compact 2 Software (Whip Mix Corporation) at 230 mm. Centric relation was confirmed visually on the articulator and recorded as the reference point in the software prior to each run. Three runs were completed for each of the following mandibular movements: protrusion, left mediotrusion and right mediotrusion with the computerized pantograph. Accurate condylar tracings were confirmed for each trial and repeated as necessary prior to exportation for software analysis (Figure VIII.). Ten trials were completed for each condylar setting. Pantographic tracings were completed by one calibrated investigator. The maxillary teeth were separated from the mandibular clutch during mandibular movements to prevent occlusal contacts from interfering with the computerized pantographic tracings.

The dataset for the condylar curves recorded by the computerized pantograph (Cadiax Compact 2; Whip Mix Corporation) was exported to the Gamma Dental Software program (Whip Mix Corporation) for analysis. Condylar settings were determined for the fully adjustable articular (Denar D5A; Whip Mix Corporation) by the software and a hard copy was produced for statistical analysis. The software recommended settings at condylotrack points of 3 mm, 5 mm and 10 mm for horizontal condylar inclinations (flat or 3/8" insert), progressive side shift and immediate side shift and a single recommended setting for the top wall and rear wall (Figure IX.).

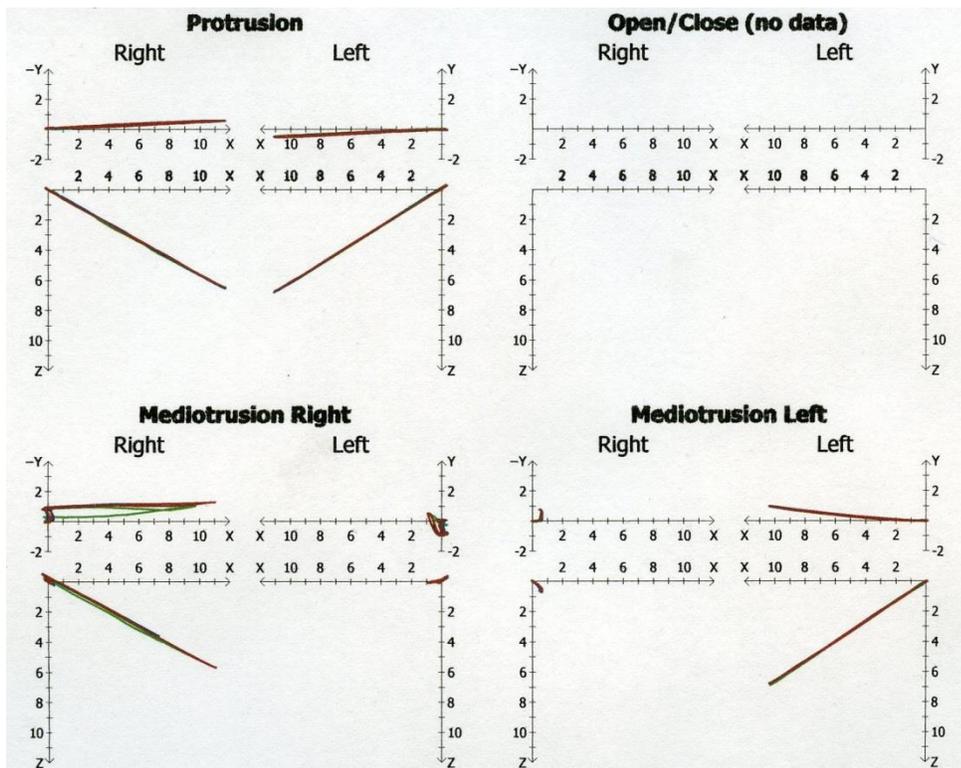


Figure VIII. Cadiax Compact 2 Computerized Pantographic Tracing.

Sagittal Condylar Guidance Denar® D5A R

	Right			Left		
	3rd mm	5th mm	10th mm	3rd mm	5th mm	10th mm
Flat	●31°	●30°	●30°	●31°	●31°	●32°
3/4"	15°	16°	20°	15°	17°	23°
3/8"	4°	6°	14°	5°	8°	16°

Transversal Condylar Guidance Denar® D5A R

	Right			Left		
	3rd mm	5th mm	10th mm	3rd mm	5th mm	10th mm
Angle	5°	5°		5°	5°	5°
ISS	0.9	0.9		0.0	0.0	0.0
	Rear Wall 0			Rear Wall 0		
	Top Wall 0			Top Wall 0		

ISS Threshold: 2.0

Figure IX. D5A Condylar Settings from the Gamma Dental Software.

STATISTICAL ANALYSIS

Equivalence testing was performed for each group with an allowable error of +/-5 for condylar inclination, top wall, rear wall, and progressive side shift. Allowable error for the immediate side shift group was +/- 0.5 mm. Condylar inclination was recorded at 0°, 15° and 25° with the flat condylar insert and 0°, 10°, and 25° for the 3/8" condylar insert. Right, left, 3 mm, 5 mm and 10 mm condylar inclination settings were combined for statistical analysis to eliminate error for a total of n=60. Top wall (U/D) and rear wall (F/B) settings were converted to a positive/negative scale. Positive settings for the top wall were U and F for the rear wall. Negative settings were D for the top wall and B for the rear wall. Top wall settings were recorded at -25, -15, 0, 15, 25 for a total of n=20. Rear wall settings were recorded at -25, -15, 0, 15, 25 for a total of n=20. Right and left sides were combined in the statistical analysis. The immediate side shift was measured in millimeters. Three settings were analyzed for the immediate side shift at 0, 1.2 mm and 2.0 mm for a total of n=30. The progressive side shift was recorded at 0, 15° and 25° for a total of n=30. The mean, standard deviation, *P*-value, unadjusted equivalence testing (0.05) or significance level and adjusted equivalence (0.0023) or Bonferroni adjustment (significance level of 0.05/N) were calculated. The Bonferroni correction is an adjustment to *P*-values when several dependent or independent statistical tests are being performed to reduce the number of false-positive results (Type I errors).

RESULTS

In vitro testing of a computerized pantograph mounted on a fully adjustable articulator was completed. Five variables were addressed: horizontal condylar inclination with a flat insert or a 3/8" curved insert, top wall, rear wall, immediate side shift, and progressive side shift. Horizontal condylar inclination values for the flat insert were set at 0°, 15°, and 25°. In the 3/8" curved insert, the horizontal condylar inclination values that were evaluated were 0°, 10°, and 25°. Rear wall condylar settings range from B to zero to F and were analyzed with low and high values ranging from 25 B, 15 B, 0, 15 F and 25 F. These were converted to negative to zero to positive values for statistical evaluation. Top wall condylar settings ranged from D to zero to U and were analyzed with low and high values ranging from 25 D, 15 D, 0, 15 U, and 25 U. Progressive side shift angles ranged from 0° to 15° to 25°. The immediate condylar side shift values analyzed in this study ranged from 0 mm to 1.2 mm to 2 mm. The dataset is presented in Table I.

Table I. Dataset

I. Condylar Inclination

(A) Flat Insert

Right Side Sagittal Condylar Inclination

Value	Trial	2	3	4	5	6	7	8	9	10
	#1									
0(3mm)	28	28	0	0	0	11	2	0	5	1
0(5mm)	18	26	5	2	0	12	4	3	7	4

0(10mm)	11	18	8	5	5	13	8	6	8	7
15(3mm)	13	11	21	16	10	16	16	14	18	13
15(5mm)	17	15	21	18	15	18	19	17	19	16
15(10mm)	20	19	22	20	19	20	20	20	21	20
25(3mm)	29	33	30	30	30	28	33	31	29	30
25(5mm)	29	31	30	30	30	30	32	31	30	31
25(10mm)	30	30	30	30	30	31	32	31	31	31

Left Side Sagittal Condylar Inclination

Value	Trial #1	2	3	4	5	6	7	8	9	10
0(3mm)	0	10	7	8	6	10	8	9	9	8
0(5mm)	3	9	7	8	6	9	8	8	9	8
0(10mm)	5	9	8	8	7	10	8	8	9	8
15(3mm)	21	19	23	23	19	20	21	21	23	22
15(5mm)	22	20	23	23	20	21	21	21	23	22
15(10mm)	22	21	24	23	21	22	22	22	23	23
25(3mm)	33	41	43	31	33	12	31	33	31	31
25(5mm)	32	35	37	31	33	19	32	33	31	31
25(10mm)	32	32	33	32	32	25	32	33	32	32

(B) 3/8" Insert

Right Side Sagittal Condylar Inclination

Value	Trial#1	2	3	4	5	6	7	8	9	10
0(3mm)	1	0	0	0	0	0	7	0	0	0
0(5mm)	0	0	0	0	0	2	7	1	1	0
0(10mm)	0	1	2	3	3	5	8	4	3	5
10(3mm)	0	8	3	5	0	8	3	5	5	8
10(5mm)	0	10	8	8	3	11	7	9	8	10
10(10mm)	7	12	12	11	9	13	11	11	11	13
25(3mm)	8	6	6	5	11	12	12	14	11	20
25(5mm)	17	15	13	18	17	19	17	19	18	24
25(10mm)	23	22	21	24	23	24	23	24	23	26

Left Side Sagittal Condylar Inclination

Value	Trial#1	2	3	4	5	6	7	8	9	10
0(3mm)	1	0	0	0	0	0	6	0	7	0
0(5mm)	5	3	2	3	0	3	8	2	8	1
0(10mm)	7	6	5	5	3	6	8	5	8	5
10(3mm)	7	7	8	7	7	10	7	9	8	9
10(5mm)	8	9	10	9	8	11	10	11	10	10
10(10mm)	12	11	12	11	11	12	12	12	12	12
25(3mm)	20	16	17	18	18	20	18	21	20	6
25(5mm)	24	20	20	24	21	23	22	24	22	4
25(10mm)	26	25	24	27	25	26	26	26	26	23

0(10mm)	0	0	0	0	0	0	0	0	0	0
---------	---	---	---	---	---	---	---	---	---	---

V. Progressive Side Shift

Progressive Side Shift

Actual Value	Trial #1	2	3	4	5	6	7	8	9	10
25(3mm)	5	5	5	29	5	5	5	5	25	5
25(5mm)	30	30	30	28	30	30	30	30	26	30
25(10mm)	30	30	30	24	30	29	30	30	28	30
15(3mm)	5	5	5	5	5	5	5	5	5	5
15(5mm)	21	24	24	20	22	25	5	7	5	5
15(10mm)	21	21	21	20	17	21	5	7	6	7
0(3mm)	5	5	5	5	5	5	5	5	5	5
0(5mm)	5	5	5	5	5	5	5	5	5	5
0(10mm)	5	5	5	5	5	5	5	5	5	5

The mean and standard deviations for the horizontal condylar inclinations with the flat condylar insert and set condylar inclination were recorded as follows: 0° (mean = 7.92°, std = 5.90°); 15° (mean = 19.58, std = 3.17); 25° (mean = 31.02, std = 3.95). The mean and standard deviations with the 3/8" condylar insert and set condylar inclinations were recorded as follows: 0° (mean = 2.67, std = 2.83); 10° (mean = 8.68, std = 3.16); 25° (mean = 19.12, std = 6.04). The mean and standard deviations for the top wall demonstrate the inability of the computerized pantograph to record this element of

condylar movement as demonstrated by the following results: -25° (mean = 0.90, std = 7.35); -15° (mean = 0, std = 0); 0° (mean = 0, std = 0); 15° (mean = 0, std = 0); 25° (mean = 0, std = 0). This inability of the computerized pantograph to record certain aspects of condylar movement on the dental articulator is further demonstrated by the following means and standard deviations recorded for the rear wall: -25° (mean = -4.0, std = 12.31); -15° (mean = 0, std = 0); 0° (mean = 0, std = 0); 15° (mean = 0, std = 0); 25° (mean = 0, std = 0). The computerized pantograph demonstrated a higher level of accuracy in recording the immediate side shift. The means and standard deviations for the immediate side shift with the appropriate condylar settings are presented as follows: 0 mm (mean = 0 mm, std = 0 mm); 1.2 mm (mean = 1.30 mm, std = 0.42 mm); and 2.0 mm (mean = 1.74 mm, std = 0.26 mm) and demonstrated in Figure X.



Figure X. Immediate Side Shift Means and Standard Deviations

In terms of the progressive side shift, the recorded means were within an acceptable degree of error; however, there were large fluctuations in the recordings that resulted in large standard deviations for the higher values. The means and standard deviations for the progressive side shift are as follows: 0° (mean = 5.0°, std = 0°); 15° (mean = 11.80°, std = 8.12°); 25° (mean = 22.63°, std = 10.92°). The means and standard deviations recorded from the computerized pantograph for each condylar determinant are presented in Table II.

Table II. Means and Standard Deviations

	Setting	n	Mean	St. Dev.
Flat Insert	0	60	7.92	5.90
	15	60	19.58	3.17
	25	60	31.02	3.95
3/8" Insert	0	60	2.67	2.83
	10	60	8.68	3.16
	25	60	19.12	6.04
Top Wall	-25	20	0.90	7.35
	-15	20	0.00	0.00
	0	20	0.00	0.00
	15	20	0.00	0.00
	25	20	0.00	0.00
Rear Wall	-25	20	-4.00	12.31
	-15	20	0.00	0.00
	0	20	0.00	0.00
	15	20	0.00	0.00

	25	20	0.00	0.00
Immediate Side Shift	0	30	0.00	0.00
	1.2	30	1.30	0.42
	2	30	1.74	0.26
Progressive Side Shift	0	30	5.00	0.00
	15	30	11.80	8.12
	25	30	22.63	10.92

The *P*-value obtained with the flat condylar insert at 0°, 15° and 25° were 0.9998, 0.1567 and 0.9747. These values were non-significant and were not acceptable with the Bonferroni adjustment. The *P*-value with the 3/8" insert at 0° and 10° was determined to be significant ($P < .0001$). Adjusted equivalence or Bonferroni adjustment for these two data points were determined to be significant ($P < .0001$). The *P*-value at 25° with the 3/8" insert was 0.8691 and was non-significant. *P*-values for the top wall and rear wall at -25°, -15°, 15° and 25° were determined to be non-significant. *P*-values at 0° and were determined to be significant ($P < .0001$) for the top and rear wall.

The *P*-values for the immediate side shift at 0 mm, 1.2 mm and 2 mm were significant ($P < .0001$) and remained significant with equivalence testing and Bonferroni adjustment.

Table III. *P*-value, Equivalence, and Bonferroni Adjustment

Condylar Setting	Setting	Allowable Error	n	<i>P</i>-value	Equivalent (0.05)	Adjusted Equivalent (Bonferroni) (0.0023)
Condylar Inclination	0	+/- 5	60	0.9998	No	No
(Flat Insert)	15	+/- 5	60	0.1567	No	No
	25	+/- 5	60	0.9747	No	No
Condylar Inclination	0	+/- 5	60	< .0001	Yes	Yes
(3/8" Insert)	10	+/- 5	60	< .0001	Yes	Yes
	25	+/- 5	60	0.8691	No	No
Top Wall	-25	+/- 5	20	1.000	No	No
	-15	+/- 5	20	1.000	No	No
	0	+/- 5	20	< .0001	Yes	Yes
	15	+/- 5	20	1.000	No	No
	25	+/- 5	20	1.000	No	No
Rear Wall	-25	+/- 5	20	1.000	No	No
	-15	+/- 5	20	1.000	No	No
	0	+/- 5	20	< .0001	Yes	Yes

	15	+/- 5	20	1.000	No	No
	25	+/- 5	20	1.000	No	No
Immediate Side Shift	0	+/- 0.5	30	< .0001	Yes	Yes
	1.2	+/- 0.5	30	< .0001	Yes	Yes
	2	+/- 0.5	30	< .0001	Yes	Yes
Progressive Side Shift	0	+/- 5	30	< .0001	Yes	Yes
	15	+/- 5	30	0.1172	No	No
	25	+/- 5	30	0.0985	No	No

The computerized pantograph (Cadiax Compact 2; Whip Mix Corporation) records condylar settings and three condylotrack distances: 3 mm, 5 mm and 10 mm. Chang⁴³ reported that the recommended condylar settings obtained at the 10 mm condylotrack distance were the most accurate. Our study addressed the accuracy of the computerized pantograph at the 10 mm condylotrack distance for the condylar settings with the flat insert, 3/8" condylar insert and the progressive side shift. *P*-values and Bonferroni adjustments with the flat insert at the 10 mm condylotrack distance were as follows: 0° (*P*-value = 1.0, Bonferroni = no); 15° (*P*-value = 0.9993, Bonferroni = no); 25° (*P*-value = 0.9931, Bonferroni = no). The 3/8" condylar insert had the following *P*-values and Bonferroni adjustments: 0° (*P*-value = 0.2189, Bonferroni = no); 10° (*P*-value <0.0001, Bonferroni = yes); 25° (*P*-value <0.0001, Bonferroni = yes). Progressive side

shift *P*-value and Bonferroni adjustments were as follows: 0° (*P*-value <0.0001, Bonferroni = yes); 15° (*P*-value = 0.0388, Bonferroni = no); 25° (*P*-value = 0.0854, Bonferroni = no). The obtained data for the progressive side shift at the 10 mm condylotrack distance did demonstrate equivalency testing at the 0° and the 15° condylar setting, but the 15° condylar setting was not significant with the Bonferroni adjustment. Means, standard deviations, *P*-values, equivalency testing and Bonferroni adjustments at the 10 mm condylotrack distance for the horizontal condylar inclinations with the flat insert and 3/8" insert and the progressive side shift are presented in Table IV.

Table IV. 10 mm Condylotrack Means, STD, *P*-value, Equivalence

And Bonferroni Adjustment

						0.05	0.0056
Condylar Insert	Setting	Allowable Error	Mean	St. Dev.	<i>P</i>-value	Equivalent?	Adjusted Eq?
Flat Insert	0	+/- 5	8.45	2.98	1.0000	No	No
	15	+/- 5	21.20	1.44	0.9993	No	No
	25	+/- 5	31.05	1.73	0.9931	No	No
3/8" Insert	0	+/- 5	4.60	2.26	0.2189	No	No
	10	+/- 5	11.35	1.35	<.0001	Yes	Yes
	25	+/- 5	24.35	1.63	<.0001	Yes	Yes
Progressive Side Shift	0	+/- 5	5.00	0.00	<.0001	Yes	Yes
	15	+/- 5	14.60	7.31	0.0388	Yes	No
	25	+/- 5	29.10	1.91	0.0854	No	No

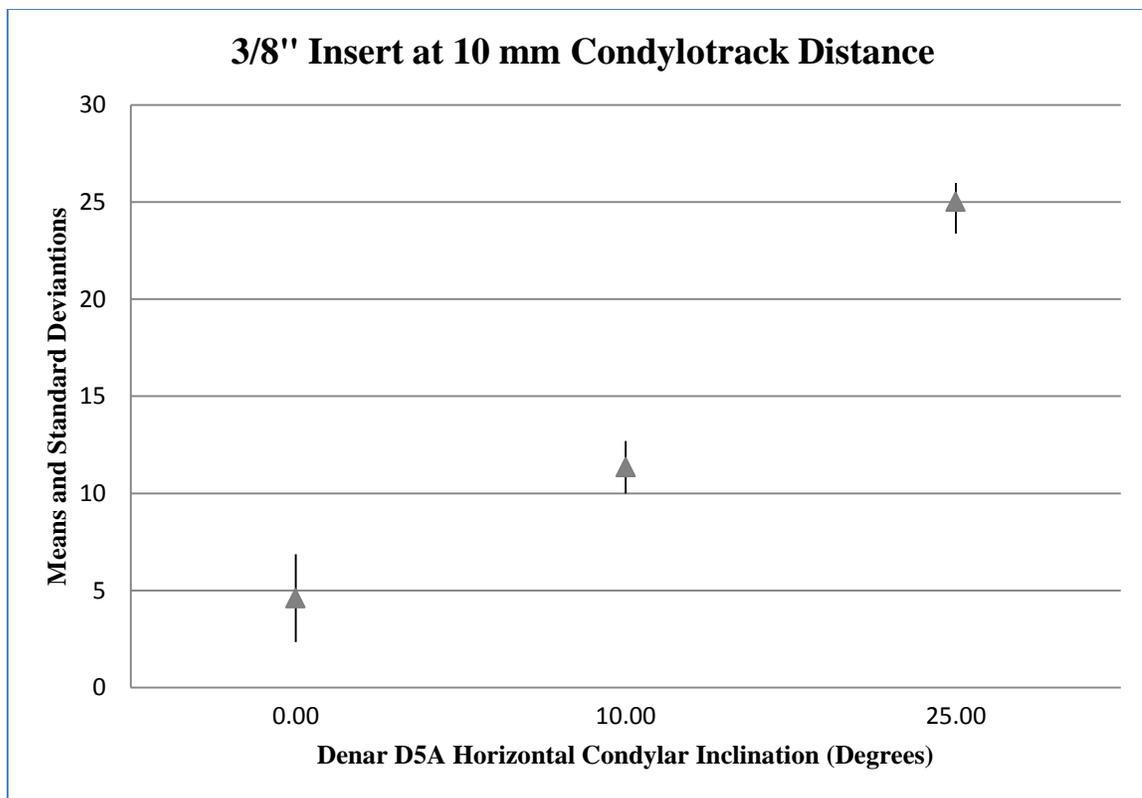


Figure XII. 3/8" Insert Means and Standard Deviations at 10 mm Condylotrack Distance

DISCUSSION

The results of our in vitro study lead to the rejection of the null hypothesis that the computerized pantograph (Cadiax Compact 2; Whip Mix Corporation) accurately recorded the pre-determined condylar settings for horizontal condylar inclination, top wall, rear wall, progressive side shift and immediate side shift. The alternative hypothesis that the computerized pantograph (Cadiax Compact 2; Whip Mix Corporation) does not accurately record pre-determined condylar settings for condylar inclination, top wall, rear wall, progressive side shift and immediate side shift is accepted. The statistical analysis of individual condylar settings leads to a partial rejection of the null hypothesis. The computerized pantograph accurately determined the immediate side shift at three settings and the horizontal condylar inclination of the 3/8" insert at two of three settings at the 10 mm condylotrack distance.

This is the first study to compare the accuracy of a computerized pantograph to determine horizontal condylar inclination for flat versus 3/8" condylar inserts. *P*-values, equivalence testing and Bonferroni adjustments demonstrated that the values for horizontal condylar inclination obtained by the computerized pantograph with the flat insert utilizing condylotrack points of 0, 5 and 10 mm combined and 10 mm condylotrack distance in isolation were non-significant. In contrast, horizontal condylar inclination at the 10 mm condylotrack distance with the 3/8" insert was determined to be statistically significant ($P < .0001$) at horizontal condylar inclination values of 10 and 25 degrees. These results confirm the results presented by Chang⁴³ who demonstrated that the 10 mm condylotrack distance was accurate and reliable in recording horizontal condylar inclination.

In contrast to previous studies, this study attempted to isolate the accuracy of top and rear wall settings independent of the immediate side shift setting. The measurements recorded for the top wall and rear wall were non-significant. Equivalence testing and Bonferroni adjustments were accurate only when the condylar elements were set to 0 for the top and rear walls. Regardless of the set condylar values for the top and rear wall, the computerized pantograph recommended a setting of 0 for these condylar elements. Infrequent, random outliers were recorded by the computerized pantograph and recommended as condylar settings when the top and rear walls were set at values other than 0. Our results confirm the results of Anderson and Schulte⁴⁰ who demonstrated that top and rear wall settings were not recorded with an immediate side shift setting of zero. Top and rear wall settings in their study were only reliable with an immediate side shift of 1 mm. Coye³⁹ demonstrated similar results where top and rear wall measurements were only recorded when there was a significant immediate side shift. Furthermore, the results of our in vitro study confirm the work by Winstanley³⁸ who demonstrated unpredictable results in setting and recording top and rear wall condylar elements. Chang⁴³ did not evaluate top and rear wall settings for the fully adjustable articulator with the computerized pantograph.

Recording of the progressive side shift by the computerized pantograph demonstrated significant error in our study. Progressive side shift settings ranged from a low value of zero, to fifteen in the middle, and twenty five on the high range. The standard deviation recorded increased with increasing progressive side shift. *P*-values, equivalence testing and Bonferroni adjustment demonstrated accuracy only at a progressive side shift setting of 0 ($P < .0001$). In contrast to Chang⁴³, determination of the

progressive side shift at the 10 mm condylotrack distance was non-significant in our study.

The results of our in vitro study indicate that the computerized pantograph (Cadiax Compact 2, Whip Mix Corporation) can accurately record an immediate side shift ($P < .0001$). Accurately recording the presence or absence of an immediate mandibular side shift and the degree of that side shift may be the most critical mandibular movement to record. These results substantiate the conclusion from other researchers^{34, 40, 43} that the computerized pantograph is a valid instrument to record the immediate side shift of the mandible.

The accuracy of computerized pantographs to record mandibular movement in a clinical environment is limited. The pantographic reproducibility index (PRI) was established to determine the accuracy of recording mandibular movements at separate time intervals in a clinical environment.⁴⁵ Mechanical pantographic tracings have demonstrated excellent pantographic reproducibility indices in patients with no temporomandibular joint dysfunction.^{45, 46, 47} The limitations of the computerized pantograph in a clinical setting were presented by Petrie.⁴⁶ This study evaluated 10 patients at two different time intervals separated by two to four weeks with a mechanical pantograph and a computerized pantograph. The mandibular tracings from the computerized pantograph were inconsistent across time compared to the mechanical pantograph. In addition, pantographic reproducibility index scores for the computerized pantograph rated as very poor and the initial reference point or centric relation was not consistently reproduced in 30% of cases.

One major limitation of this in vitro study is the assumption that a fully adjustable dental articulator accurately simulates the mandibular movement of a patient. In addition, this study employed the use of an arbitrary facebow mounting on the dental articulator, as compared to the kinematic facebow orientation utilized by Chang.⁴³ Future in vitro studies may set top and rear wall settings in addition to progressive and immediate side shift settings to determine the influence these settings have on accurate top and rear wall measurements. Determination of the accuracy of the computerized pantograph to record increased horizontal condylar inclination values greater than 25 degrees with the 3/8" condylar insert were not attempted due to limitations and stability of the testing apparatus mounted on the articulator. Clinical studies are required to confirm or reject the results of this in vitro study and determine the accuracy of computerized pantographs to record mandibular movement.

The future of prosthetic reconstruction is rapidly moving to a digital medium. Increasingly, prosthetic reconstruction is utilizing digital technologies including: cone beam computed tomography, digital impressions, virtual articulators and CAD-CAM fabrication of dental restorations. One major limitation with current CAD-CAM restorations created from virtual articulators is the inability to relate the maxilla to the cranial base via the mandibular condyles. Virtual articulators employ average calculations in mounting virtual casts to the articulator. Solaberrieta⁴⁸ developed a digital coordinate system to orientate digitized casts to a virtual articulator. Initially, digital casts were created with an intraoral digital scanner (Lava COS; 3M ESPE, St. Paul, MN). The optical scanner utilized six points of reference. The three cranial base points were right and left temporomandibular joints and the left infraorbital notch. Intraorally, three

prominent maxillary cusps were identified on the occlusal surface to identify the maxillary cast. This six point coordinate systems enabled the orientation of the maxillary cast to the virtual articulator. Unfortunately, this device was experimental and is not manufactured for clinical use, thus virtual dental reconstructions must rely on anatomic averages previously determined from the literature.

The utilization of cone beam computed tomography in dentistry is increasing. Cone beam computed tomography (CBCT) is a routine diagnostic tool used in treatment planning the surgical placement of dental implants. The American Academy of Oral and Maxillofacial Radiology recommends that cross-sectional imaging be used for the assessment of all dental implant sites and that CBCT is the imaging method of choice for gaining this information.⁴⁹ In addition, CBCT may be utilized to determine stable radiographic condylar landmarks that influence condylar movement. Shreshta⁵⁰ compared condylar guidance by radiographic and clinical methods, specifically interocclusal wax records, Lucia jig, and Gothic arch tracings. The results indicated very little or no association between the values obtained from radiographic, computed tomography, and clinical methods. The computed tomography scans gave higher mean condylar inclination values than the clinical methods. Tannamala⁵¹ compared horizontal condylar inclination obtained from panoramic x-rays to values obtained from 6 mm protrusive check bite records and determined that radiographic values were 4° greater when determined from the panoramic x-ray. This study did not compare mechanical or computerized pantographic tracings to stable radiographic landmarks determined from the computed tomography.

Developments in digital dentistry may lead to the development of a virtual articulator that incorporates a three dimensional reconstruction of the condylar determinants from the CBCT with virtual scanning of the dentition for the occlusal determinants. The virtual articulator may orientate the maxilla to the cranial base from the CBCT or digital facebow and utilize computerized occlusal analysis to relate the maxilla to the mandible. Computerized pantographs may be used by the virtual articulator to determine important mandibular movements, such as the immediate side shift, and eliminate potential occlusal interferences. Prosthetic reconstruction in the digital world will require hardware and software integration from multiple mediums, effective laboratory communication, increased capital investment and advanced clinical training to ensure patient outcomes are achieved.

CONCLUSIONS

The computerized pantograph (Cadiax Compact 2, Whip Mix Corporation) is a valid instrument for recording an immediate side shift at 0 mm, 1.2 mm and 2.0 mm and horizontal condylar inclination at 10° and 25° at the 10 mm condylotrack distance with the 3/8" condylar insert. The computerized pantograph did not accurately determine horizontal condylar inclination with the flat insert, top wall, rear wall or progressive side shift condylar settings. Additional in vitro testing should be conducted to confirm or reject the results of this study. Clinical testing should be completed to determine the validity of the computerized pantograph to record mandibular movement in a patient population.

REFERENCES

- 1) Pfaff, P. Abhandlung von der zahnen des menschlichen korpers und deren krankheiten. Berlin, Haude und Spener 1756; 148-153.
- 2) American National Standard/American Dental Association. Specification no. 19 for non-aqueous, elastomeric dental impressions. J Am Dent Assoc 1977; 94:733-41; addendum 1982; 105:686.
- 3) An evaluation of the time-dependent dimensional stability of eleven elastomeric impression materials. J Prosthet Dent 1984; 52:120-125.
- 4) Lee, S., MacArthur, R., Gallucci, G. An evaluation of student and clinician perception of digital and conventional implant impressions. J Prosthet Dent 2013; 110:420-423.
- 5) Cardelli, P., Scotti, R., Monaco, C. Clinical fitting of CAD/CAM zirconia single crowns generated from digital intraoral impression based on active wavefront sampling. J of Dentistry 2011; 1783:1-8.
- 6) Andreas, E., Mehl, A. Accuracy of complete arch dental impressions: A new method of measuring trueness and precision. J Prosthet Dent 2013; 109:121-128.
- 7) The Glossary of Prosthodontic Terms. J Prosthet Dent 2005; 94:10-81.
- 8) Schallhorn, R. A study of the arbitrary center and the kinematic center of rotation for face-bow mountings. J Prosthet Dent 1957; 7:162-169.
- 9) Kois, J., Kois, D., Chaiyabutr, Y. Occlusal errors generated at the maxillary incisal edge position related to discrepancies in the arbitrary horizontal axis location and to the thickness of the interocclusal record. J Prosthet Dent 2013; 110:414-419.

- 10) Arstad, T. The capsular ligaments of temporomandibular joint and retrusion facets of the dentition in relationship to mandibular movements. Oslo. 1954.
- 11) Weinberg, L. An evaluation of the face-bow mounting. J Prosthet Dent 1961; 11:32-42.
- 12) Lauritzen, A., Bodner, G. Variations in location of arbitrary and true hinge axis points. J Prosthet Dent 1961; 11:224-229.
- 13) Walker, P. Discrepancies between arbitrary and true hinge axes. J Prosthet Dent 1980; 43:279-285.
- 14) Bernhardt, O., Kuppers, N., Rosin, M., Meyer, G. Comparative tests of arbitrary and kinematic transverse horizontal axis recordings of mandibular movements. J Prosthet Dent 2003; 89:175-179.
- 15) Gariot, J. Traite des maladies de la bouche. Paris, De L' Imprimerie De Baudouin 1805; 305-313.
- 16) The Glossary of Prosthodontic Terms. J Prosthet Dent 2005; 94:10-81.
- 17) Keshvad, A., Winstanley, R. Comparison of the replicability of routinely used centric relation registration techniques. J of Prosthodontics 2003; 12:90-101.
- 18) McKee, J. Comparing condylar position repeatability for standardized versus nonstandardized methods of achieving centric relation. J Prosthet Dent 1997; 77:280-284.
- 19) Ramfjord, S., Ash, M. Occlusion. W.B. Saunders Co. 1973.
- 20) Balkwill F. The best form and arrangement of artificial teeth for mastication. Trans Odontol Soc Great Britain 1866; 5:133-158.
- 21) Luce, C. The movements of the lower jaw. Boston Med Surg J 1889; 121:8-11.

- 22) Bonwill, W. Articulation and articulators. *Trans Am Dent Assoc* 1864; 4:76-79.
- 23) Bonwill, W. The scientific articulation of the human teeth as founded on geometrical, mathematical, and mechanical laws. *Dent. Items of Interest* 1899:617-643.
- 24) Bennett, N. A contribution to the study of movements of the mandible. *J Prosthet Dent* 1958; 8:41-54.
- 25) Gysi, A. The problem of articulation (Part I-IV). *Dent Cosmos* 1910; 3: 1,19, 148-169, 268-283, 403-418.
- 26) McCollum, B., and Stuart C. A Research Report. Scientific Press 1955.
- 27) The Glossary of Prosthodontic Terms. *J Prosthet Dent* 2005; 94:10-81.
- 28) Posselt, U. Movement areas of the mandible. *J Prosthet Dent* 1957; 7:375.
- 29) Clayton, J., Kotowicz, W., Zahler, J. Pantographic tracings of mandibular movements and occlusion. *J Prosthet Dent* 1971; 25:389-396.
- 30) Santos, J.D., Nelson, S., Nowlin, T. Comparison of condylar guidance setting obtained from a wax record versus an extraoral tracing: A pilot study. *J Prosthet Dent* 2003; 89:54-59.
- 31) Curtis, D. A comparison of protrusive interocclusal records to pantographic tracings. *J Prosthet Dent* 1989; 62:154-156.
- 32) Curtis, D. A comparison of lateral interocclusal records to pantographic tracings. *J Prosthet Dent* 1989; 62:23-27.
- 33) Ecker, G., Goodacre, C., Dykema, R. A comparison of condylar control settings obtained from wax interocclusal records and simplified mandibular motion analyzers. *J Prosthet Dent* 1984; 51:404-406.

- 34) Pelletier, L., Campbell, S. Comparison of condylar control settings using three methods: A bench study. *J Prosthet Dent* 1991; 66:193-200.
- 35) Payne, J. Condylar determinants in a patient population: electronic pantograph assessment. *J of Oral Rehabil* 1997; 24:157-163.
- 36) Lundeen, H., Shryock, E., Gibbs, C. An evaluation of mandibular border movements: Their character and significance. *J Prosthet Dent* 1978; 40:442-452.
- 37) Guichet, N. Applied gnathology: Why and how. *Dent Clin North Am* 1969; 13:687.
- 38) Winstanley, R. Observations on the use of the Denar pantograph and articulator. *J Prosthet Dent* 1977; 38:660-672.
- 39) Coye, R. A study of the variability of setting a fully adjustable gnathologic articulator to a pantographic tracing. *J Prosthet Dent* 1977, 37:460-465.
- 40) Anderson, G., Schulte, J., Arnold, T. An in vitro study of an electronic pantograph. *J Prosthet Dent* 1987; 57:577-580.
- 41) Schulte, J., Wang, S., Erdman, A., Anderson, G. Working condylar movement and its effects on posterior occlusal morphology. *J Prosthet Dent* 1985; 54:118-121.
- 42) Schulte, J., Wang, S., Erdman, A., Anderson, G. Three-dimensional analysis of cusp travel during a nonworking mandibular movement. *J Prosthet Dent* 1985; 53:839-843.
- 43) Chang, W., Romberg, E., Driscoll, C., Tabacco, W. An in vitro evaluation of the reliability and validity of an electronic pantograph by testing with five different articulators. *J Prosthet Dent* 2004; 92:83-89.

- 44) Wagner, A., Seemann, R., Schicho, K., Ewers, R., Piehslinger, E. A comparative analysis of optical and conventional axiography for the analysis of temporomandibular joint movements. *J Prosthet Dent* 2003; 90:503-509.
- 45) Clayton, J. A pantographic reproducibility index for use in diagnosing temporomandibular joint dysfunction: A report on research. *J Prosthet Dent* 1985; 54:827-831.
- 46) Petrie, C., Woolsey, G., Williams, K. Comparison of recording obtained with computerized axiography and mechanical pantography at 2 time intervals. *J Prosthodont* 2003; 12:102-110.
- 47) Crispin, B., Myers, G., Clayton, J. Effects of occlusal therapy on pantographic reproducibility of mandibular border movements. *J Prosthet Dent* 1978; 40:29-34.
- 48) Solaberrieta, E., Minguez, R., Barrenetxea, L., Etxaniz, O. Direct transfer of the position of digitized casts to a virtual articulator. *J Prosthet Dent* 2013; 109:411-414.
- 49) Tyndall, D., Price, J., Tetradis, S., Ganz, S., Hildebolt, C., Scarfe, W. Position statement of the American Academy of Oral and Maxillofacial Radiology on selection criteria for the use of radiology in dental implantology with emphasis on cone beam computed tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol* 2012; 113:817-826.
- 50) Shreshta, P., Jain, V., Bhalla, A., Pruthi, G. A comparative study to measure the condylar guidance by the radiographic and clinical methods. *J Adv Prosthodont* 2012; 4:153-157.
- 51) Tannamala, P., Pulagam, M., Pottem, S., Swapna, B. Condylar guidance: correlation between protrusive interocclusal record and panoramic radiograph image. A pilot study. *J Prosthodont* 2012; 21:181-184.