CLINICAL TESTING OF THE PRECISION OF A DIGITAL CONDYLOGRAM

A THESIS SUBMITTED TO THE FACULTY OF THE
UNIVERSITY OF MINNESOTA BY

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IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

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March 2015

ACKNOWLEDGEMENTS

I would like thank Dr. Heather Conrad for her significant contribution to my education and to Dr. Richard Dryer for contributing his expertise to this thesis.

DEDICATION

To my wife Tamsen and four children: Aiden, Abby, Benjamin and Charlie. Thank you for being with me every step of the way.

ABSTRACT

Purpose: This study was designed to determine the repeatability of a digital condylogram to generate condylar recordings on patients at two separate time periods.

Materials and Methods: A digital condylogram was used on 16 patients to record condylar movements at two separate time periods approximately 1 month apart. Data manager software was used to calculate recommended settings of a Denar D5A fully adjustable articulator for each trial. The differences between the calculated angles of trials 1 and 2 for each patient were determined and analyzed.

Results: Immediate side shift (ISS) and progressive side shift (PSS) demonstrated significant differences on average between trial 1 and 2. Variation between the trials was large, particularly for rear wall and top wall angles. The average amount of time that elapsed between trials 1 and 2 did not have a significant effect on the results.

Conclusion: The digital condylogram records sagittal condylar inclination, rear wall and top wall angles predictably over time; however, ISS and PSS were not recorded predictably. Results demonstrated significant variation that may be due to the patients' abilities to reproduce jaw movements precisely or that may be due to the operator's ability to connect the condylogram predictably.

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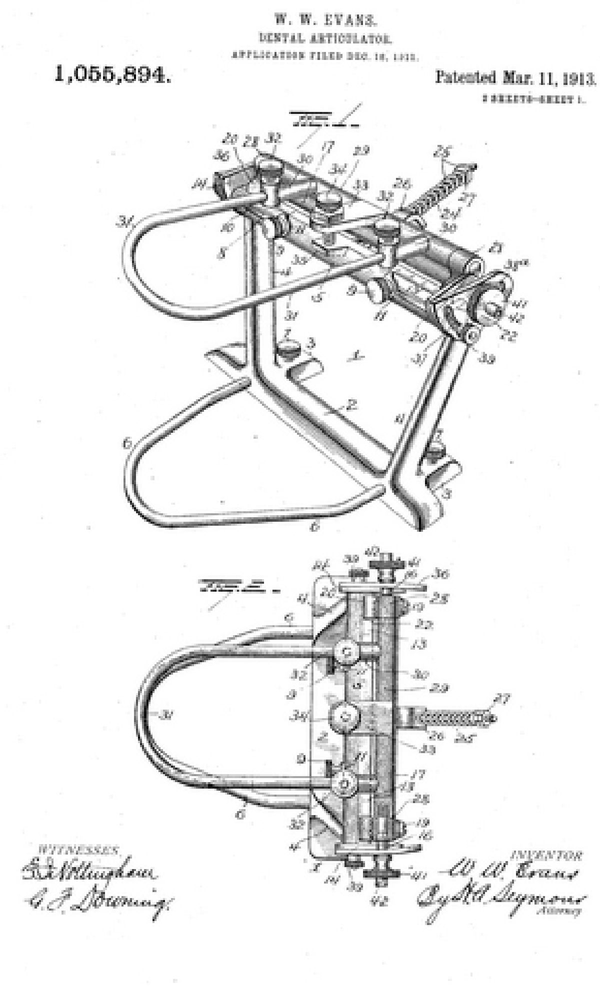
INTRODUCTION

When a dental restoration is fabricated, the anatomy of the restoration is influenced by mandibular movement. Cusps, fossae, grooves and marginal ridges need to be positioned correctly to harmonize one with another dynamically. If the movement of the mandible is not replicated and casts are articulated statically, some anatomical detail in restorations is left to the imagination of the technician, which can lead to significant adjustments chair-side or even costly re-makes. Prior to the 19th century, consideration was not given to the complex movements of the mandible. Plaster casts were created and articulated by hand, or articulated in maximum intercuspation with indexed plaster bases.[1] Door hinges were also used to create a more dynamic axis and curvature was introduced to the mandibular movement. Then in 1805, the first mechanical articulator was introduced to the dental market by Gariot.[2] Known as the "plane-line" articulator, it was a simple hinge articulator that mimicked opening and closing only. By 1840, the concept of the articulator began expanding to include mandibular excursive movements and numerous investigators like Evans (Figure 1), Bonwill[3], Hayes and Walker developed their own versions of articulators with various degrees of condylar and protrusive adjustability. The next 6 decades saw many variations of articulators come and go with minor modifications until Gysi and Snow almost simultaneously developed and introduced facebows to be used with their articulators.[4] The facebow allowed casts to be mounted in a more precise relationship with the condyles of an articulator than it had before. Their inventions were based on earlier work from Luce, Walker and Ulrich who were experimenting a decade earlier with tracing mandibular movement.[5] Their methods involved cumbersome facebow-like devices (Figure 2) and complex photographic records that were impractical for clinical use. Snow's and Gysi's facebows were simple enough to be used clinically and many subsequent investigators were able to examine more accurately the way the condyles and mandibular motion affect occlusion.

Figure 1. Patent from 1913 for Evan's articulator.



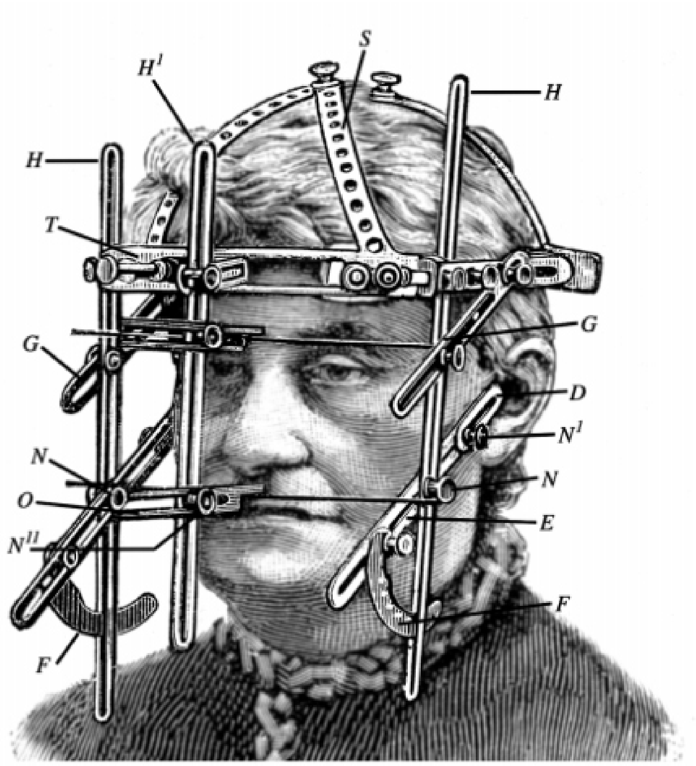


Figure 2. Facial clinometer used by Walker.

With the introduction of new articulators in the early 20th century came the development of new theories about jaw movement and the axis about which it moves. McCollum and Harlan, building on Bennett and Gysi's earlier work, are given credit for being first to locate a hinge axis around which the mandible rotates.[6] Using a modified Snow facebow, they mechanically located the hinge axis in 1924. Two years later, Phillips developed a device that was used intraorally to trace a "gothic arch" on a horizontal plane. The tracing could be transferred to his articulator and the articulator was programmed to reproduce the hinge and excursive condylar movements.[1]

Many other inventors and manufacturers developed their own method of transferring the hinge axis to articulators By the mid-20th century there were 4 main competing theories that attempted to define the mandibular axis of rotation.[7] Championed by researchers like McCollum, Stewart, and Stallard, the first group taught that the mandible has 1 unique axis of rotation that can be located and with some work, it can be transferred to the articulator accurately.[8]

The second group believed that the hinge axis could be reproduced using anatomical average measurements. This was the concept behind Gysi's, Snow's and later Hanau's facebow systems. Using average measurements they would locate a point along the ala-tragus line measured from the tragus of the ear and label it the hinge axis.[4] Weinburg[9] also supported the arbitrary hinge axis theory, as long it was located within 5 mm of the true axis, and the interocclusal records used to articulate casts were no thicker than 3 mm in the posterior and 6 mm in the anterior. His mathematical thesis on the subject showed that when these parameters are respected the errors, though cumulative, are negligible. Others like Winstanley[10] and Simpson[11] would also support this theory.

Rather than having clarity on the matter of the hinge axis, there was a lot of confusion and many researchers tried to prove or disprove the 2 theories above. Some showed that the arbitrary hinge axis could not locate the true hinge axis[12-14] and others believed that a hinge axis did not even exist.[15] Those that believed the hinge axis was a myth formed the third group.

The fourth group formed the theory of transographics[16]: that the condyle did not rotate around 1 axis, but 2 independent axes. Page[17] published work to support this theory and later work by Trapozzano and Lazzari[18] also indicated that there may be more than 1 axis of rotation. A "transograph" articulator was even developed that had a flexible joint to allow for the rotation of 2 different axes at the same time.[9] Ultimately, the theory of transographics was not widely supported, and researchers like Beard and Weinburg soundly rejected their claims.[19]

As theories about mandibular movement became more complex, so did theories on articulator design. Up until the mid-20th century, articulators were able to accommodate adjustment for sagittal condylar inclination, Bennett angle, and immediate side shift. Most could accept a facebow record, centric record and a protrusive record. Some also had adjustable intercondylar distances. In 1958, Weinburg[20] classified these articulators as arbitrary, positional, semi-adjustable and fully adjustable. Arbitrary articulators simulated jaw movements using anatomical average measurements. Positional articulators reproduced static jaw positions and jaw movement on these devices could only be reproduced rectilinearly. The semi-adjustable articulators incorporated customizable settings that simulated curvelinear motions. The fully adjustable articulators are the most complicated and replicate all the movements of the condyle including retrusion and surtrusion.

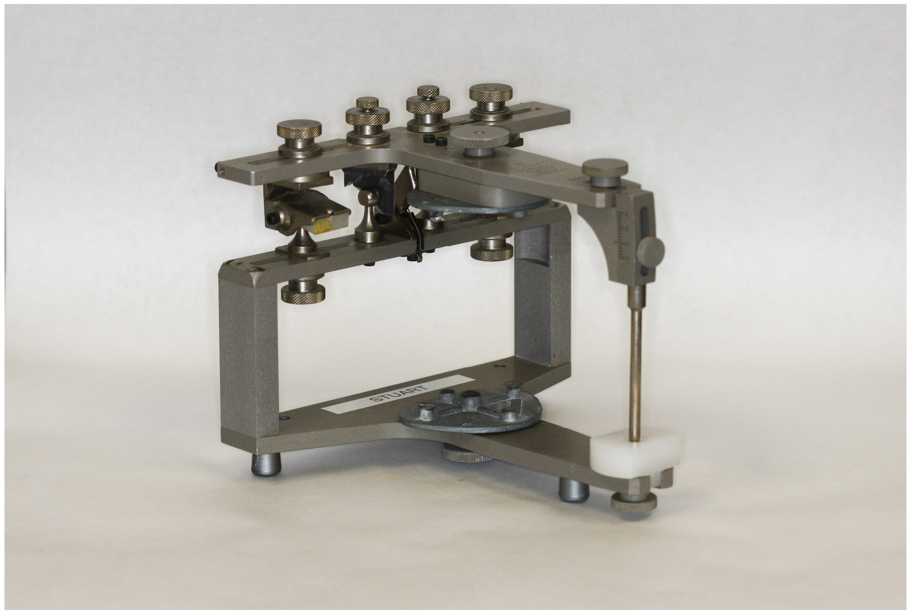


Figure 3. Stewart fully adjustable articulator.

In 1956, Stewart introduced one of the first fully adjustable articulators.[21] (Figure 3). It had settings for sagittal angle, transverse angle, immediate side shift, intercondylar distance, surtrusion, retrusion and custom incisal guidance. By definition, according to Rihani[22], a fully adjustable articulator must be able to accept 5 records: facebow, centric jaw record, protrusive jaw record, lateral jaw records and intercondylar distance. Stewart's articulator was designed to accept all 5 records. Some other fully adjustable articulators that followed Stewart were the TMJ articulator from Swanson in 1965, the D4A by Guichet in 1968 and Granger's Dental Simulator in 1971. The TMJ articulator was unique as it was a "scribing" articulator. The joint space of the articulator was customized with moldable resin and customized using pantographic tracings to represent the exact anatomy of the glenoid fossa (Figure 4).

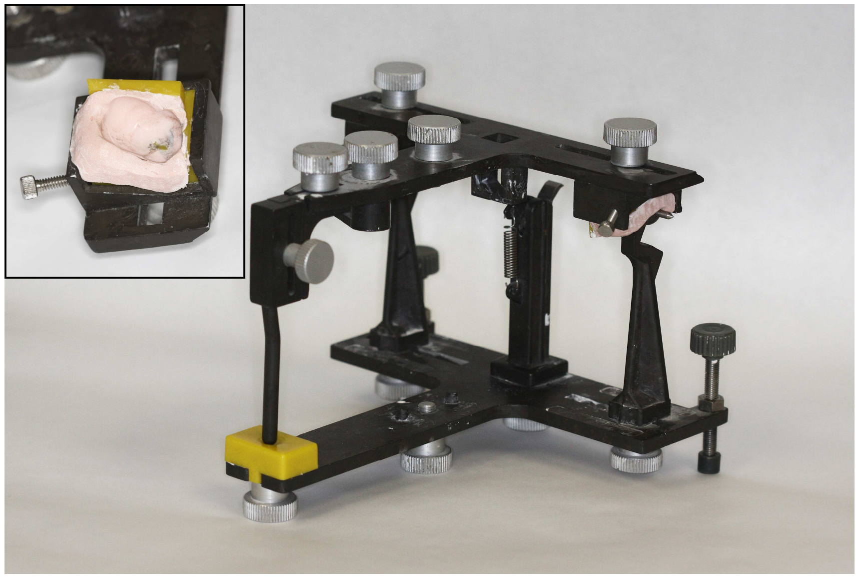


Figure 4. Swanson's TMJ articulator. Inset shows custom molded acrylic fossa.

In order to program a fully adjustable articulator, the hinge axis must be located and the pathways of the condyles during excursive movements should be replicated as accurately as possible. The simplest method to set the condyles is to use anatomical average measurements and excursive check bites. Weinburg[20] showed that when arbitrary settings are used for hinge axis location, anterior reference point, Bennett movement and a straight condylar path is used, the cumulative error in cusp height would be 0.7 mm at the balancing second molar and 1.2 mm at the working second molar. He concludes that this error is clinically acceptable for denture construction, but not for extensive fixed prosthetic work. Javid[23] showed that wax records determine the Bennett movement more accurately than by calculating it using Hanau's formula: H/8 + 12. Watchtel[24] supports the use of flat condylar paths, showing that there was minimal difference between protrusive movements when straight condyles are used versus curved condylar inserts.

Granger[25] stated, “a correct protrusive registration can record only the slant and anteroposterior curve of the condyle path”. He advocates for lateral bite records to fully register the working and non-working movements of each condyle. Nagy[26] wrote that a distance of 10 mm anterior to the tragus along Camper’s plane was adequate for locating the hinge axis accurately.

Some have attempted to measure the condyle radiographically and translate measurements from images to the articulator. Tannamala[27] devised a method of measuring the protrusive angle from a panoramic radiograph that agrees with the protrusive records. On the other hand, Shreshta[28] and Christensen[29] found measurements from computed tomography scans and cephalometric images to be unreliable when used to determine sagittal condylar inclination.

Pantography is another method that is used to translate condylar movements to an articulator. Advocates of the pantographic transfer method state that arbitrary condylar settings and wax records are not accurate enough to replicate mandibular motion on an articulator. Dos Santos[30] found that there is more variation in condylar settings when wax bite records are used to set an articulator than extraoral tracings. He attributes the increased variation to the wax records being unable to replicate the true curvilinear motion of the condyles. Ecker[31] found that wax records recorded less immediate side shift than did pantographic tracings.

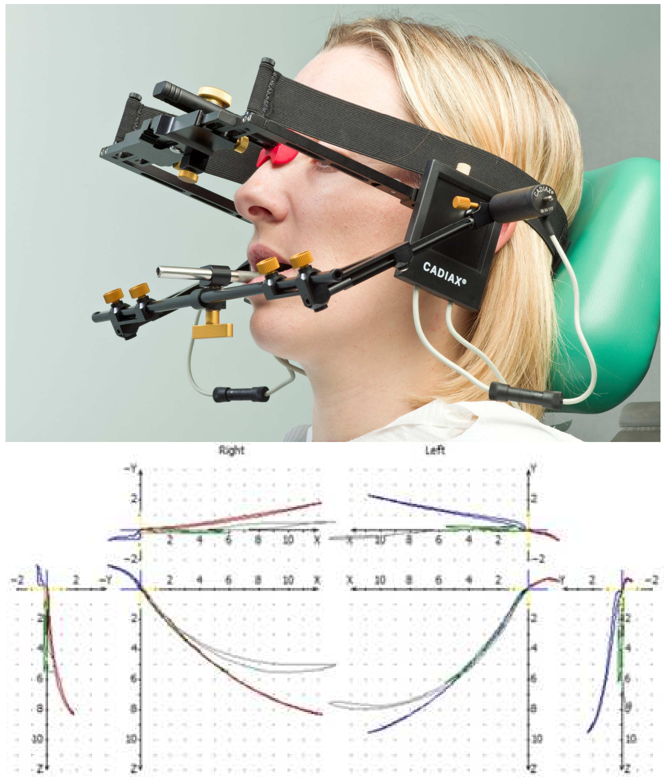


Figure 5. Digital condylogram connected to a patient and a patient tracing. (Top image taken from Gamma Dental software instruction manual).

With the advent of 3-dimentional digital technology, the mechanical pantogram has evolved into a digital version (Cadiax Compact 2; Whip Mix Corporation, Louisville, KY). The Cadiax Compact 2 (Figure 5) is a digital condylographic tracer that uses magnetic styli that trace condylar movement on digital sensors in the sagittal plane. The tracing is generated immediately on a computer monitor and calculations are made to determine condylar settings for 26 different types of articulators. As an example, if a fully adjustable articulator (Denar D5A; Whip Mix) is used, the computer will generate the sagittal condylar angle, transverse condylar angle (progressive side shift), immediate side shift, rear wall angle and top wall angle. Numerous studies have been performed on digital condylograms to test their accuracy and validity. Mantoux[32] discovered that when the Cadiax Compact 2 is connected to an articulator, it can detect the sagittal condylar angle and the Bennett angle with a high degree of accuracy. Kucukkeles[33] studied the SAM digital system and found that the mechanical and digital pantograms performed equally accurate in vivo. The only source of potential error he found was from the hand measurement of the mechanical tracing angles. This potential confounding factor was addressed by Coye[34] in 1977 when he also found that errors arose when condylar angles had to be interpreted and measured by hand. He determined however that the errors were minor and would not have any clinical relevance. Beard[35] also found the mechanical and digital condylograms comparable. Pelletier[36] compared the Denar Pantogram (a mechanical pantogram), Denar Pantronic (an electronic pantogram), and wax records on articulators. His findings suggest that the Pantronic is most accurate, followed by the mechanical pantogram which was more accurate than the wax records. Dryer[37] studied the Cadiax Compact 2 on an articulator and found that it was not able to measure rear wall angle, top wall angle or progressive side shift accurately. It also inaccurately measured sagittal condylar guidance when a flat condylar insert was used. Dryer's results partially corroborate the findings of Andersen [38] where he showed in a similar bench-top study that a condylogram was unable to accurately record rear wall angle and top wall angle settings.

Most of the literature that examines the electronic pantographic tracing devices on the market today are in vitro studies. There are very few studies that observe an electronic pantogram in a clinical setting. Payne measured 55 patients with the Cadiax Compact 2 to obtain average values for condylar angles. He determined that the patient population is highly variable and it is important to obtain customized measurements for each patient. Bernhardt[39] found a high degree of correlation between a digital condylogram that was oriented to the patient using an arbitrary hinge axis locator, and a condylogram that was positioned kinematically. Tuppy[40] studied the mandibular movement of patients symptomatic for temporomandibular joint disorders and found that the movement from centric relation (CR) to maximum intercuspation was repeatable and does not depend on the operator guiding the patient. Petrie[41] used the Pantographic Reproducibility Index (PRI) to examine the consistency of a mechanical and a digital condylographic tracing device on patients at 2 time intervals. The PRI scale was created by Clayton[42] in 1985 as a way to quantify temporomandibular joint disorder in patients using a pantographic tracing device. Petrie found that the mechanical pantogram was able to consistently measure the same condylar angles on patients at 2 different time intervals, but the digital pantogram was not. She also found that the digital pantogram had problems consistently recording CR.

In response to the dearth of clinical studies aimed at testing the consistency, or precision of a digital pantographic tracing device, this study is designed to shed more light on the subject. The purpose of this paper is to determine the precision of the Cadiax Compact 2, a digital condylogram, by using it to measure condylar movements on patients at two time intervals approximately one month apart. The null hypothesis is that there will be no difference between the two measurements for each participant.

SPECIFIC AIM

The purpose of this study is to determine if a digital condylogram is capable of measuring human condylar movements precisely under the assumption that asymptomatic patients have stable, unchanging joints. We will compare the condylar recordings taken at 2 separate times and determine if they differ significantly from each other.

STATEMENT OF THE PROBLEM

Minimal research exists on the ability of digital condylograms to record condylar movements clinically. Historically, most studies have been performed in vitro using articulators to simulate patient movement. There is a need to determine if a digital condylogram is able to reproduce a patient's condylar movements accurately and precisely.

NULL HYPOTHESIS (H_0)

There is no significant difference between condylar recordings (including sagittal condylar guidance, progressive side shift, immediate side shift, rear wall angle and top wall angle) of a patient measured at 2 time periods.

ALTERNATIVE HYPOTHESIS (H_1)

There is a significant difference between condylar recordings (i.e. sagittal condylar guidance, progressive side shift, immediate side shift, rear wall angle and top wall angle) of a patient measured at two time periods.

MATERIALS AND METHODS

In order to test the precision of the digital pantogram, Cadiax Compact 2, 16 participants were recruited to participate in this study ranging in age from 25 to 63. Eight subjects were female and 8 were male. Subjects were screened based on the condition of their temporomandibular joints bilaterally, and the soundness of their dentition. If anyone reported a history of temporomandibular joint disorder, or if fremitus, clicking or popping of the joints was detected upon digital palpation of the joints, the subjects were excluded from the study. Furthermore, if any patient was undergoing dental treatment of any kind they were also excluded. Each patient consented to have their jaw movements recorded with the Cadiax Compact 2 twice. Each recording was separated by 3 to 6 weeks. For each trial, a clutch was attached to the mandibular dentition using a quick-set polyvinyl siloxane (PVS) bite registration material. The clutch was filled with PVS and positioned with the shaft of the clutch aligned as close as possible to the mid-sagittal plane of the patient's face and held in place until polymerized (Figure 6). The maxillary component of the Cadiax Compact 2 was then connected, positioning the ear pieces in the external auditory meati bilaterally and fastening a stabilizing strap around the patient's head. Set screws fastened the lateral arms of the maxillary component to ensure stability of the intercondylar distance. A rest was then placed at the glabella and tightened (Figure 7). Care was taken to ensure there was no tension in the system between the head strap and glabellar rest.

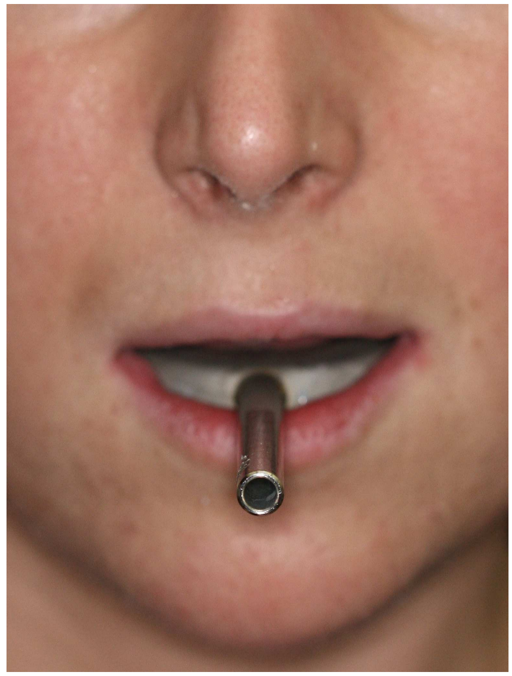


Figure 6. Mandibular clutch. Care was taken to ensure proper alignment of the clutch with the midline of the face.

The mandibular component was then placed on the shaft of the clutch and 2 metal pins were guided through holes at the distal end of the mandibular component bilaterally. The pins were aligned with dimples on the maxillary component and when they were fully and passively seated the rods were fixed in place with set screws. The mandibular component was then tightened with screws to lock the horizontal plane of the cross bar, and the pins could be removed. The observer confirmed the location of the hinge axis by positioning himself at eye level with the distal portion of the mandibular lateral bar, and directing the patient to open and close so that only rotation was occurring. If the lateral bar deviated from pure rotation, the mandibular component was removed and the procedure was repeated until pure rotation was achieved. Electronic flags were attached to the facebow and magnetic tracing pins were fastened to the mandibular bar (Figure 7).

The patient rehearsed border movements to ensure that the tracing rod was operating smoothly and did not extend beyond the border of the flag on each side.

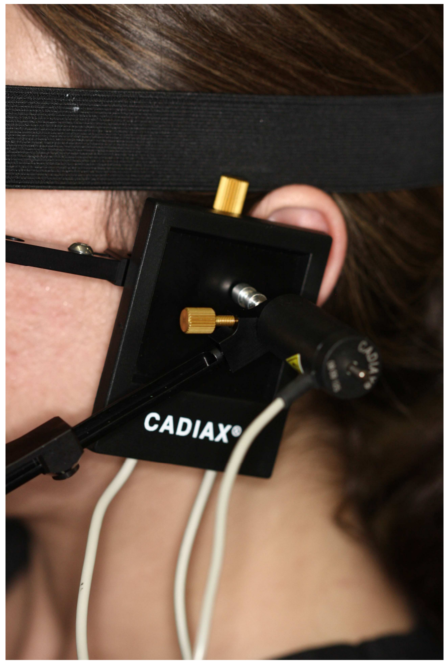


Figure 7. Recording plate and stylus positioned to record left condylar movements.

Once the patient was connected to the digital pantographic device, the operator guided the patient into CR using chin-point guidance. The recording software was activated and CR was registered as the starting position. Patients were then asked to perform protrusion, right laterotrusion, left laterotrusion and full opening while the software recorded the movement. The patient was returned to CR after every recording. Each jaw movement was performed 3 times. After all recordings were complete, the device was disassembled and the patient was dismissed until the follow up recording approximately 4 weeks subsequent to the first session where the same protocol was repeated. All experimental trials were performed by the same operator, calibrated to the use of the Cadiax Compact 2 device.

Table 1. Example of the calculated condylar settings recommended by Gamma Dental software for the Denar D5A articulator.

CADIAX® Curves

	Protrusion		Mediotrusion right		Mediotrusion left	
	SCI right	SCI left	S C I	T C I	S C I	T C I
1st	12.9°	33.7°	28.3°	10.0°		
2nd	16.8°	38.3°	28.0°	5.8°	27.6°	−4.8°
3rd	18.0°	40.6°	28.9°	4.2°	31.2°	−2.4°
4th	18.8°	40.0°	29.8°	3.3°	32.8°	−0.7°
5th	19.6°	37.3°	30.5°	2.7°	33.6°	0.4°
6th	21.4°		31.0°	2.4°	33.9°	1.6°
8th			30.8°	1.7°	32.9°	2.8°
10th					31.5°	3.8°
14th						
	Retrusion					
-1.	29.6°r	47.7°r				
-2.	32.9°r	37.9°r				

Sagittal Condylar Guidance Denar® D5A R

	Right			Left		
	3rd mm	5th mm	10th mm	3rd mm	5th mm	10th mm
Flat	**•16°**	**•19°**		**•37°**	**•38°**	
3/4"	0°	5°		21°	25°	
3/8"	0°	0°		10°	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°	5°
ISS	0.1	0.1	0.1	0.0	0.0	0.0
	Rear Wall 30 F			Rear Wall 30 F		
	Top Wall 30 D			Top Wall 30 U		

ISS Threshold: 0.5

After all data was collected, each trial was imported into data manager software (Gamma Dental Software; Gamma, Austria) for analysis. The articulator condylar guidance settings were generated for each trial and the Denar D5A was used as the reference articulator. A summary of the recommended articulator settings for the D5A was generated for each trial (Table 1). For statistical analysis, the results at the 3 mm track distance with flat condylar inserts were used. Settings for the sagittal condylar guidance, progressive side shift, immediate side shift, surtrusion (top wall) and retrusion (rear wall) were compiled for each patient at both trials. For each patient, the difference between the first set of articulator settings and the second set of articulator settings was calculated. Wilcoxian signed rank test was used to analyze the left and right condyles separately. A linear mixed model was used to analyze both condyles together.

RESULTS

Each participant was subjected to 2 sessions of digital condylographic tracing. The sessions were separated by an average of 32.56 days (minimum = 16 days, maximum = 42 days). Age of subjects ranged from 24 to 63 years, with an average of 34.4 years of age. Gamma Dental software calculated the recommended settings for a Denar D5A fully adjustable articulator from each recording (Table 2).

Table 2. Dataset. SCG = Sagittal condylar guidance, PSS = progressive side shift, ISS = immediate side shift, RW = rear wall angle, TW = top wall angle.

Patient 1 **Female**
Age 25

	Trial 1	Trial 2	Difference
Date	12-Jun	21-Jul	39
SCG Right	52	57	5
SCG Left	42	53	11
PSS Right	5	16	11
PSS Left	23	7	-16
ISS Right	0	0	0
ISS Left	0.2	0.1	-0.1
RW Right	30	0	-30
RW Left	30	-40	-70
TW Right	-30	0	30
TW Left	-30	-30	0

Patient 2 **Male**
Age 29

	Trial 1	Trial 2	Difference
Date	12-Jun	21-Jul	39
SCG Right	42	38	-4

SCG Left	36	43	7
PSS Right	13	5	-8
PSS Left	5	10	5
ISS Right	0	0	0
ISS Left	0	0	0
RW Right	30	30	0
RW Left	30	0	-30
TW Right	-30	30	60
TW Left	-30	0	30

Patient 3 **Male**
Age 28

	Trial 1	Trial 2	Difference
Date	27-Jun	29-Jul	32
SCG Right	55	42	-13
SCG Left	56	60	4
PSS Right	12	7	-5
PSS Left	5	5	0
ISS Right	0	0.1	0.1
ISS Left	0	0	0
RW Right	30	30	0
RW Left	0	0	0
TW Right	-8	30	38
TW Left	0	0	0

Patient 4 **Female**
Age 41

	Trial 1	Trial 2	Difference
Date	23-Jun	21-Jul	28
SCG Right	26	16	-10
SCG Left	43	37	-6
PSS Right	5	5	0
PSS Left	5	5	0
ISS Right	0	0.1	0.1
ISS Left	0	0	0
RW Right	0	30	30
RW Left	0	30	30

TW Right	0	-30	-30
TW Left	0	30	30

Patient 5 **Female**
Age 63

	Trial 1	Trial 2	Difference
Date	24-Jun	29-Jul	35
SCG Right	45	49	4
SCG Left	53	58	5
PSS Right	5	5	0
PSS Left	5	5	0
ISS Right	0	0	0
ISS Left	0	0.3	0.3
RW Right	23	0	-23
RW Left	0	0	0
TW Right	19	0	-19
TW Left	0	0	0

Patient 6 **Male**
Age 24

	Trial 1	Trial 2	Difference
Date	24-Jun	29-Jul	35
SCG Right	53	54	1
SCG Left	53	46	-7
PSS Right	5	5	0
PSS Left	13	5	-8
ISS Right	0	0	0
ISS Left	0	0.1	0.1
RW Right	0	-40	-40
RW Left	0	0	0
TW Right	0	-30	-30
TW Left	0	0	0

Patient 7 **Female**
Age 29

	Trial 1	Trial 2	Difference

Date	12-Jun	24-Jul	42
SCG Right	56	60	4
SCG Left	40	39	-1
PSS Right	16	8	-8
PSS Left	8	10	2
ISS Right	0	0.3	0.3
ISS Left	0	0.3	0.3
RW Right	-40	0	40
RW Left	-40	-40	0
TW Right	-26	0	26
TW Left	30	30	0

Patient 8 **Female**

Age 32

	Trial 1	Trial 2	Difference
Date	23-Jun	9-Jul	16
SCG Right	43	49	6
SCG Left	49	38	-11
PSS Right	6	5	-1
PSS Left	10	8	-2
ISS Right	0	0.2	0.2
ISS Left	0.1	0	-0.1
RW Right	30	0	-30
RW Left	0	30	30
TW Right	-30	0	30
TW Left	0	4	4

Patient 9 **Male**

Age 27

	Trial 1	Trial 2	Difference
Date	23-Jun	24-Jul	31
SCG Right	48	47	-1
SCG Left	42	60	18
PSS Right	5	5	0
PSS Left	6	5	-1
ISS Right	0	0	0
ISS Left	0.1	0	-0.1

RW Right	30	0	-30
RW Left	30	0	-30
TW Right	-30	0	30
TW Left	-30	0	30

Patient 10 **Female**
Age 48

	Trial 1	Trial 2	Difference
Date	27-Jun	24-Jul	27
SCG Right	49	52	3
SCG Left	39	51	12
PSS Right	5	5	0
PSS Left	5	5	0
ISS Right	0	0.1	0.1
ISS Left	0.2	0	-0.2
RW Right	30	0	-30
RW Left	0	0	0
TW Right	30	0	-30
TW Left	0	0	0

Patient 11 **Female**
Age 55

	Trial 1	Trial 2	Difference
Date	23-Jun	21-Jul	28
SCG Right	47	54	7
SCG Left	42	51	9
PSS Right	19	9	-10
PSS Left	17	7	-10
ISS Right	0	0	0
ISS Left	0	0	0
RW Right	0	0	0
RW Left	0	30	30
TW Right	0	0	0
TW Left	0	30	30

Patient 12 **Male**
Age 32

	Trial 1	Trial 2	Difference
Date	26-Jun	24-Jul	28
SCG Right	36	52	16
SCG Left	46	54	8
PSS Right	5	5	0
PSS Left	5	5	0
ISS Right	0	0.1	0.1
ISS Left	0.3	0	-0.3
RW Right	0	30	30
RW Left	0	30	30
TW Right	0	-30	-30
TW Left	0	30	30

Patient 13 **Female**
Age 26

	Trial 1	Trial 2	Difference
Date	27-Jun	5-Aug	39
SCG Right	43	44	1
SCG Left	44	43	-1
PSS Right	7	5	-2
PSS Left	9	5	-4
ISS Right	0	0	0
ISS Left	0	0	0
RW Right	0	0	0
RW Left	-40	30	70
TW Right	0	0	0
TW Left	30	-30	-60

Patient 14 **Male**
Age 25

	Trial 1	Trial 2	Difference
Date	24-Jun	21-Jul	27
SCG Right	40	41	1
SCG Left	60	43	-17
PSS Right	5	5	0
PSS Left	5	5	0

ISS Right	0	0	0
ISS Left	0	0.1	0.1
RW Right	-40	-40	0
RW Left	0	-40	-40
TW Right	30	30	0
TW Left	0	-30	-30

Patient 15 **Male**
Age 38

	Trial 1	Trial 2	Difference
Date	27-Jun	5-Aug	39
SCG Right	56	47	-9
SCG Left	56	51	-5
PSS Right	13	21	8
PSS Left	5	5	0
ISS Right	0	0	0
ISS Left	0	0	0
RW Right	-40	-40	0
RW Left	0	0	0
TW Right	30	7	-23
TW Left	0	0	0

Patient 16 **Male**
Age 29

	Trial 1	Trial 2	Difference
Date	23-Jun	29-Jul	36
SCG Right	49	41	-8
SCG Left	50	54	4
PSS Right	5	22	17
PSS Left	15	5	-10
ISS Right	0	0	0
ISS Left	0	0	0
RW Right	-40	0	40
RW Left	0	0	0
TW Right	0	0	0
TW Left	0	0	0

Data were summarized to examine average values for sagittal condylar guidance, progressive side shift, immediate side shift, rear wall angle and top wall angle. Results are summarized by gender as well as combined (Table 3). Average sagittal condylar guidance (SCG) for females and males were 45.75 degrees, and 48.47 degrees, respectively. Progressive side shift (PSS) was measured at 8.13 degrees for females and 7.56 degrees for males. Immediate side shift (ISS) for females was 0.06 mm and for males 0.03 mm. Rear wall angle (RW) and top wall angle (TW) for females was 2.91 degrees and -0.09 degrees and for males it was -0.31 degrees and -0.97 degrees. When the sample was combined the average values were: SCG = 47.11 degrees, PSS = 7.84 degrees, ISS = 0.04 mm, RW = 1.3 degrees and TW = -0.53 degrees.

Table 3. Average D5A condylar settings calculated by the digital condylogram.

	Female	Male	Combined
SCG	45.75	48.47	47.11
PSS	8.13	7.56	7.84
ISS	0.06	0.03	0.04
RW	2.91	-0.31	1.30
TW	-0.09	-0.97	-0.53

Condylar measurements of each patient for trial 2 were subtracted from trial 1 and summarized in Table 4. Minimum, maximum and quartiles for each variable were also calculated and are illustrated in Figures 8 to 13.

Table 4. Summary statistics of the calculated differences between trial 1 and trial 2.

SIDE	N	Variable	N	Mean	Std Dev	Median	Minimum	Maximum
Left	16	SCG_DIFF	16	1.8750000	9.3300589	4.0000000	-17.0000000	18.0000000
		PSS_DIFF	16	-2.7500000	5.4711364	0	-16.0000000	5.0000000
		ISS_DIFF	16	1.734723E-18	0.1549193	0	-0.3000000	0.3000000
		RW_DIFF	16	1.2500000	33.4414912	0	-70.0000000	70.0000000
		TW_DIFF	16	4.0000000	24.1660919	0	-60.0000000	30.0000000
Right	16	SCG_DIFF	16	0.1875000	7.4852633	1.0000000	-13.0000000	16.0000000
		PSS_DIFF	16	0.1250000	6.9845067	0	-10.0000000	17.0000000
		ISS_DIFF	16	0.0562500	0.0892095	0	0	0.3000000
		RW_DIFF	16	-2.6875000	26.6000470	0	-40.0000000	40.0000000
		TW_DIFF	16	3.2500000	29.1444677	0	-30.0000000	60.0000000

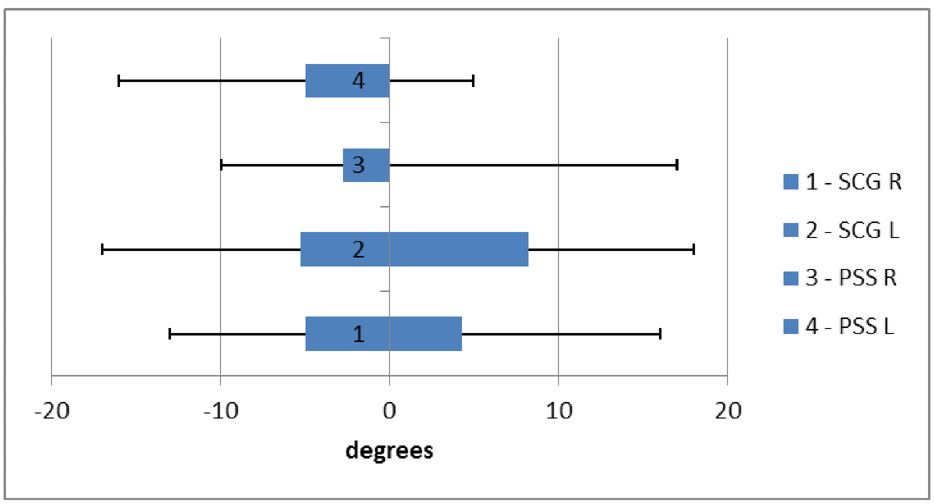


Figure 8. Difference between trials 1 and 2 for sagittal condylar guidance and progressive side shift. Left and right sides are separate.

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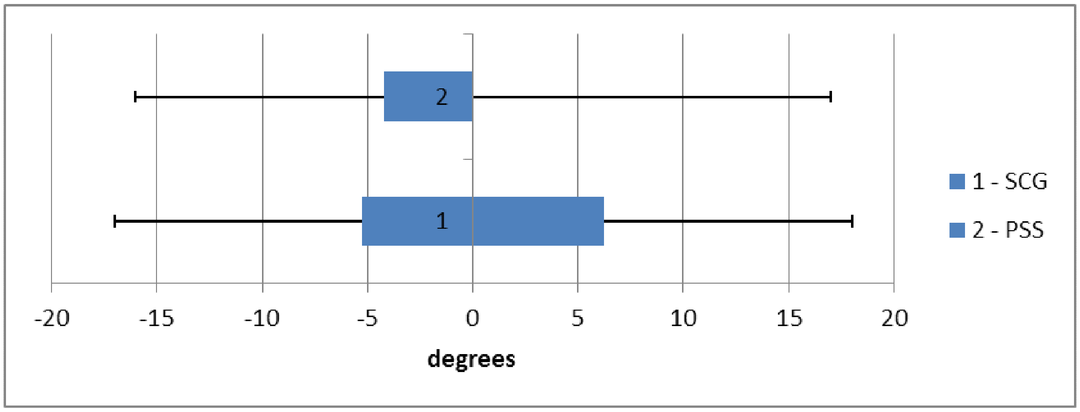

Figure 9. Difference between trial 1 and 2 for sagittal condylar guidance and progressive side shift. Left and right sides are combined.

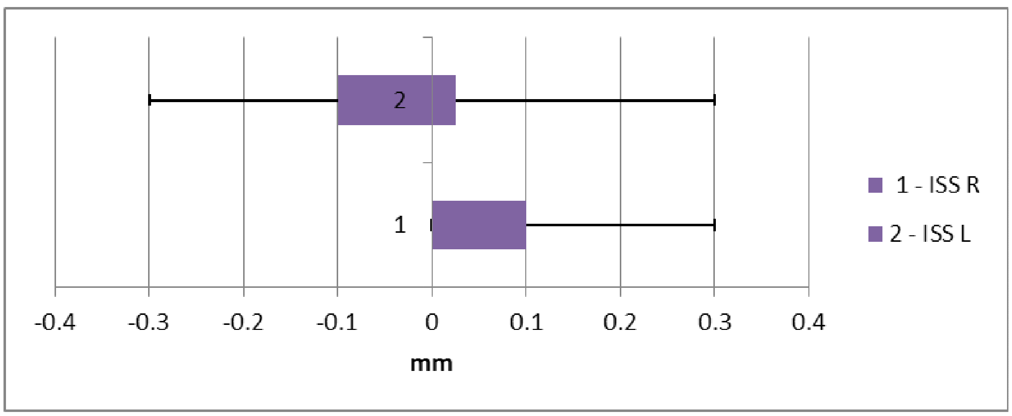

Figure 10. Difference between trial 1 and 2 for immediate side shift. Left and right sides are separate.

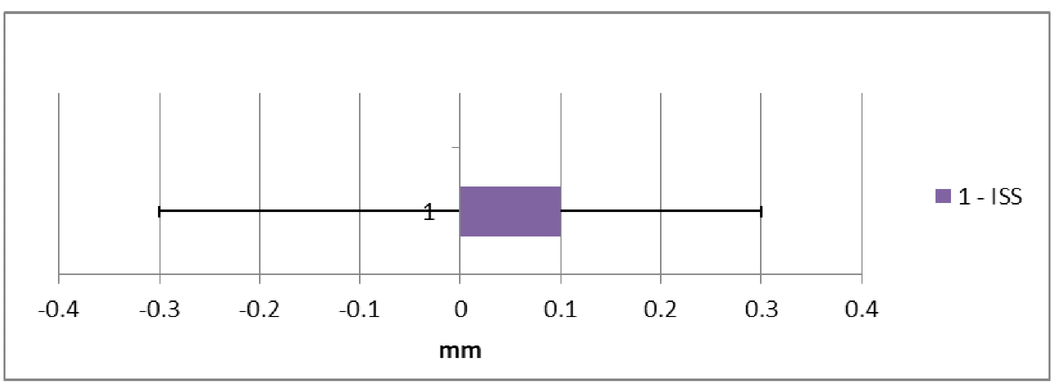

Figure 11. Difference between trial 1 and 2 for immediate side shift. Left and right sides are combined.

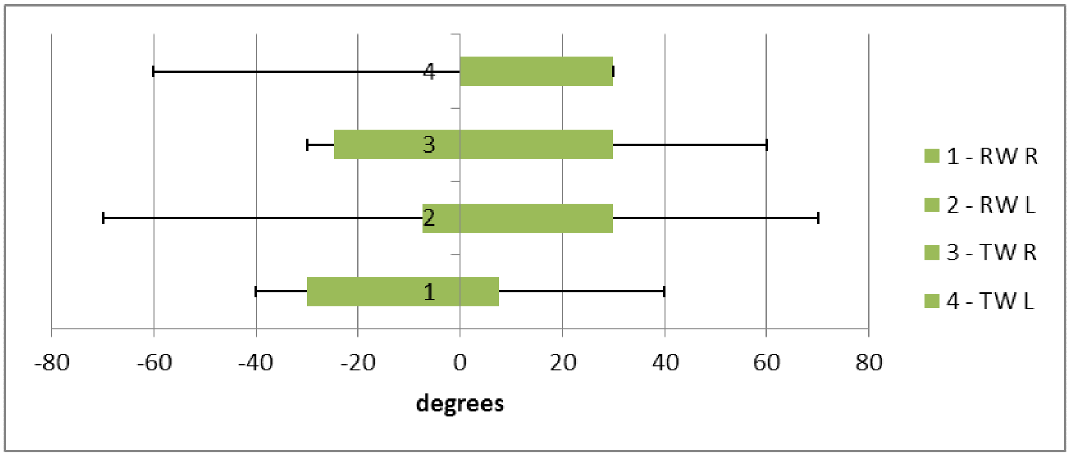

Figure 12. Difference between trial 1 and 2 for rear wall angle and top wall angle. Left and right sides are separate.

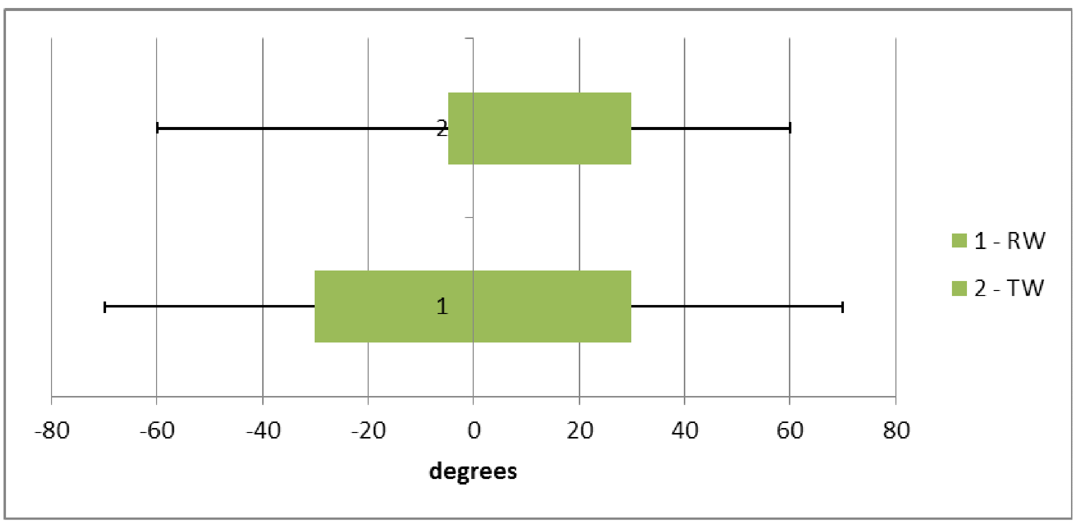

Figure 13. Difference between trial 1 and 2 for rear wall angle and top wall angle. Left and right sides combined.

In order to assess the precision of the Cadiax Compact 2, the differences between trial 1 and trial 2 for each patient were calculated. The differences between the 2 trials for sagittal condylar guidance, progressive side shift, immediate side shift, rear wall and top wall of the sample were compared using a Wilcoxian signed-rank test. Analysis was performed according to gender, without gender differentiation, and comparison of males to females was also done. Left and right side condyles were analyzed separately (Table 5). The only variable that was significantly different between trial 1 and trial 2 was immediate side shift on the right side when males and females were combined (P = 0.0313).

Table 5. Comparison of D5A condylar settings calculated by a digital condylogram between males and females.

Variable	**Side**	**P-value Male (N = 8)**	**P-value Female (N = 8)**	**P-value combined (N = 16)**	**P-value comparison of male to female**
SCG	Left	0.6641	0.5859	0.4103	0.7962
	Right	0.4351	0.1875	0.8302	0.1025
PSS	Left	0.3750	0.1875	0.0859	0.5914
	Right	0.7500	0.6250	>0.9999	0.3939
ISS	Left	>0.9999	0.8750	>0.9999	>0.9999
	Right	0.5000	0.1250	0.0313	0.2651
RW	Left	0.5000	0.5625	>0.9999	0.1710
	Right	>0.9999	0.8750	>0.9999	0.7485
TW	Left	0.6250	0.8750	0.4063	0.8664
	Right	0.5625	>0.9999	0.5625	0.7929

To examine the data with left and right sides combined, a linear mixed-model analysis was used. Again, the results are summarized according to gender and without gender as a variable, as well as comparison of males to females (Table 6). Data was assumed to be normally distributed. When the subjects were not grouped by gender, immediate side shift was significantly different between trials ($P = 0.0468$). When the results are separated by gender, only immediate side shift ($P = 0.0167$) and progressive side shift ($P = 0.0206$) in females are significantly different between trial 1 and 2.

Table 6. Comparison of D5A condylar settings between men and women with left and right condyles combined.

Variable	P-value Male (N = 8)	P-value Female (N = 8)	P-value combined (N = 16)	P-value comparison of male to female
SCG	0.6959	0.2953	0.6133	0.3111
PSS	0.7222	0.0206	0.0618	0.1343
ISS	0.6135	0.0167	0.0468	0.1421
RW	0.7184	0.942	0.823	0.7592
TW	0.3485	0.9271	0.4548	0.5452

To see if there is a correlation between the time that elapsed between the two trials, the differences between trials for each condylar determinant for each patient was plotted. Linear regression analysis was performed and R^2 values calculated (Figures 14-18). None of the variables showed a dependence on the amount of time that elapsed between the two trials.

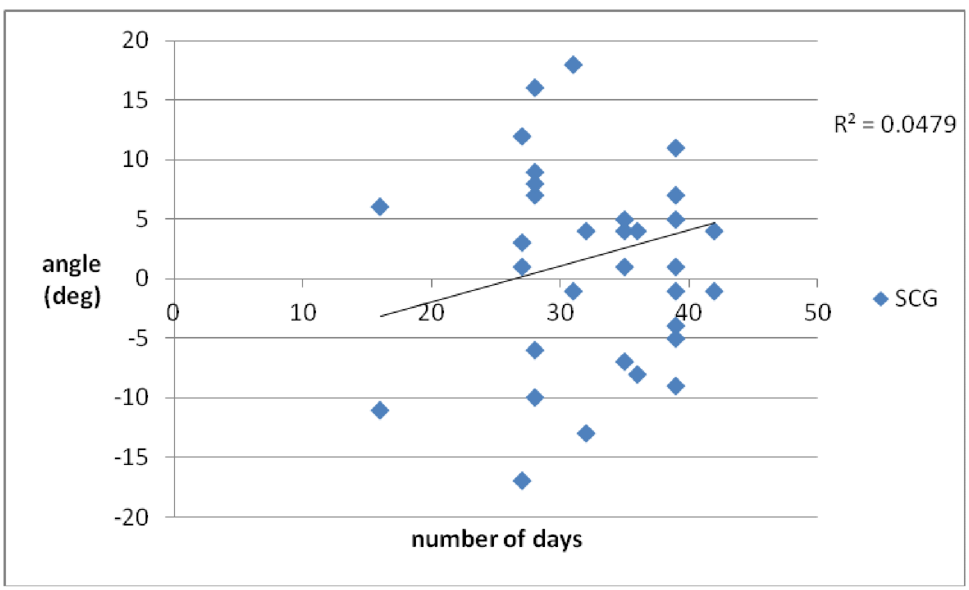

Figure 14. Number of days between trial 1 and trial 2 for each subject; left and right condyles plotted separately. Sagittal condylar guidance.

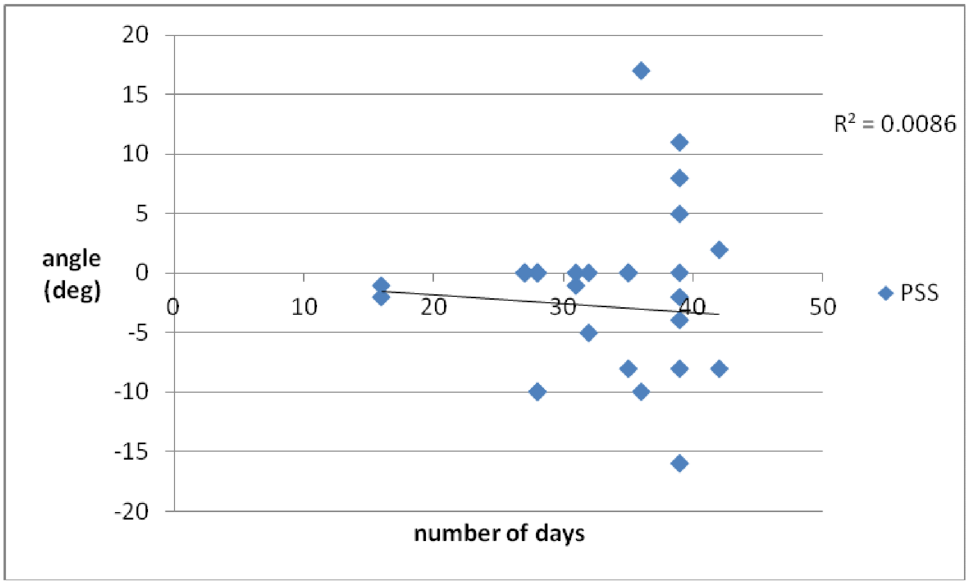

Figure 15. Number of days between trial 1 and trial 2 for each subject; left and right condyles are plotted separately. Progressive side shift.

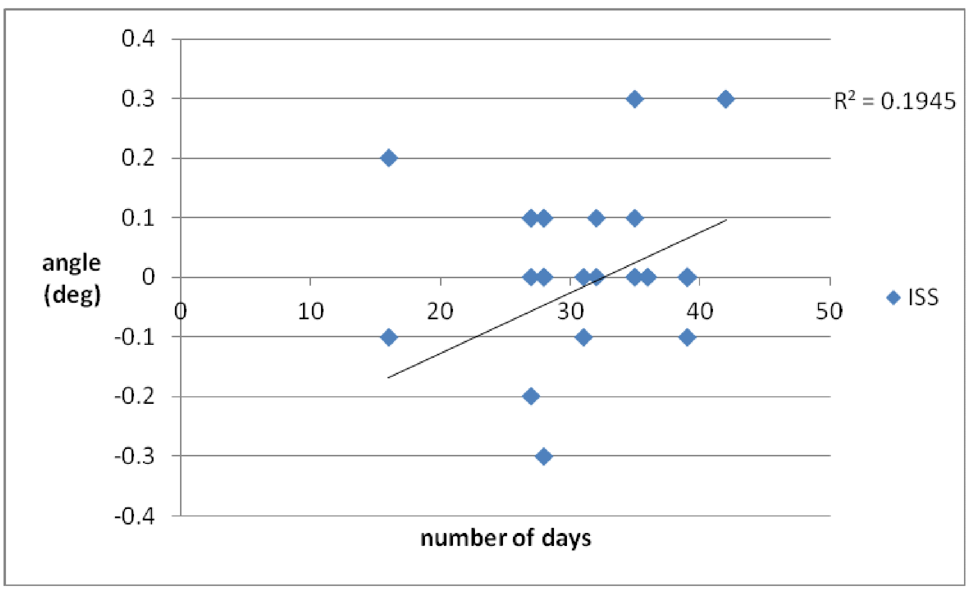

Figure 16. Number of days between trial 1 and trial 2 for each subject; left and right condyles are plotted separately. Immediate side shift.

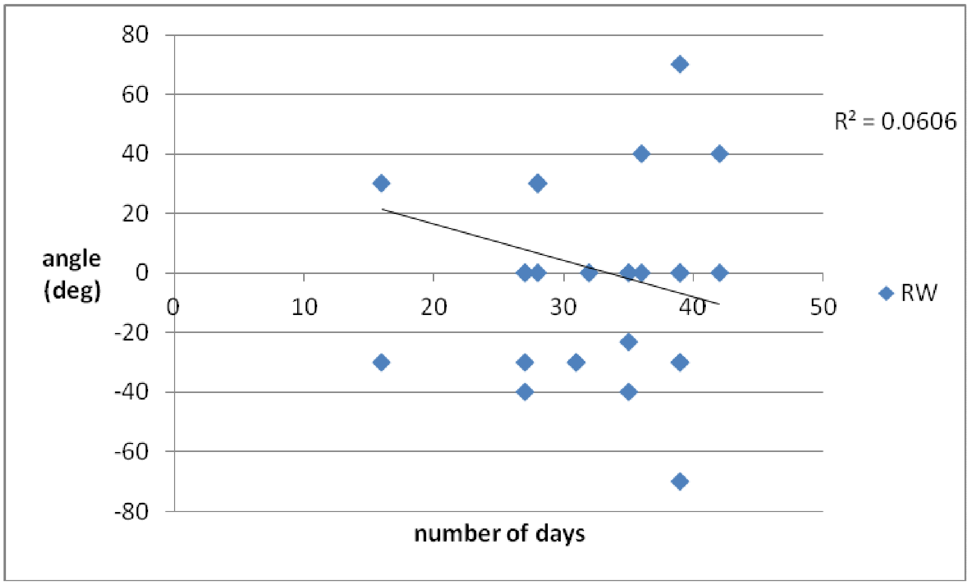

Figure 17. Number of days between trial 1 and trial 2 for each subject; left and right condyles are plotted separately. Rear wall angle.

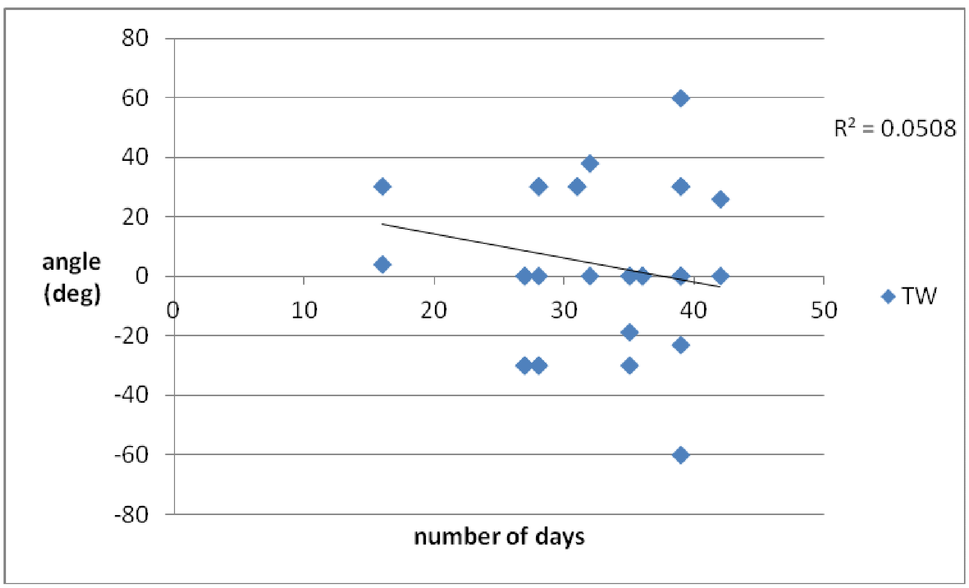

Figure 18. Number of days between trial 1 and trial 2 for each subject; left and right condyles are plotted separately. Top wall angle.

DISCUSSION

The data from this study partially support the acceptance of the null hypothesis; that there is no difference between recordings of a digital pantogram at two separate time periods. As the results show, the differences between 2 trials repeated on the same patient are on average, not significantly different from each other except for immediate side shift on one side, and progressive side shift in females.

These results should be interpreted with caution due to the large amount of variation in the data. The standard deviations for differences in measured angles for sagittal condylar guidance and progressive side shift ranged from 5.47 to 9.33 degrees on the left and right sides. For immediate side shift, the standard deviation is less than 1 mm. For rear wall angle and top wall angle the standard deviations ranged from -26.60 to 33.44 degrees. The variation present between the two trials may or may not be relevant clinically. Schulte[43] discovered that if the progressive side shift angle on an articulator is changed from 0 to 25 degrees, the path of the mesiobuccal cusp of the maxillary first molar in the horizontal plane decreases from 50 to 36 degrees. He also found that as immediate side shift increases, it causes a direct lateral movement of the mesiobuccal cusp of the maxillary first molar in the horizontal plane, equal in magnitude to the increase that affects the progressive side shift angle. The sagittal condylar guidance angle is dependent on the amount of incisal guidance present in the system. A second study by Schulte[44] found that when the top wall angle is changed from -25 to +25 degrees, the mesiobuccal cusp of the maxillary first molar moves vertically by 0.1 mm and the cusp path in the horizontal plane can be altered by up to 44 degrees. When RW is altered from

-25 to +25 degrees the cusp trajectory only changes by 8 degrees. He concluded that immediate side shift and top wall angle may have the most significant effect on cusp movement and in turn, the anatomy of restorations. More research is needed to determine how much of an effect these angles would have on clinical crowns and if the relationship between condylar angles and cusp trajectories is the same in vivo.

Winstanley[45], Coye[34], Anderson[38] and Dryer[37] all found that the rear wall angle and top wall angle were the least reliable recordings in vitro. Coye hypothesizes that the reason for the inconsistency in these angles is due to the very small amount of condylar movement that occurs during working movements along the top and rear aspects of the fossa. These movements require magnification to be detected properly. Our findings support Winstanley, Coye, Anderson and Dryer. The results with the most variation in our study were the rear wall angle and top wall angle measurements. It is possible that the Cadiax Compact 2 is not sensitive enough to detect the slight movements that might be occurring along the top and rear aspects of the fossae.

One of the limitations of this study is sample size. We included 8 males and 8 females for a total of 32 condyles studied. Increasing the sample size from 16 to 50 would likely reduce the variation noted in this study.

There may have also been variation and/or bias introduced by the examiner, the patient or the equipment. Despite the fact that only one calibrated examiner was connecting and operating the device, there may have been errors introduced in the location of the hinge axis, clutch position, third point of reference, or the directions given to the patient. Sheppard[46] found that the presence of the clutch on the mandibular teeth can inadvertently induce condylar translation, or limit movement of the mandible. Petrie[41] noted that tooth contact against the clutch can alter mandibular movement. She also postulated that the PVS material in the clutch was soft enough to allow the clutch to move during jaw excursions. Whether or not there is significant error introduced by the clutch requires further study.

There may have also been variability due to patient behavior, muscle tone, amount of fluid in the tissue or the time of day, none of which were controlled for in this study. Variation caused by the ligaments of the temporomandibular joint seems unlikely based on the literature. Grasso[47] found significant variability between gothic arch tracings when repeated on patients 29 days apart but he concluded that it was due to the musculature of the jaw and not the ligaments. In a cadaver study, Boucher[48] found that the temporomandibular and capsular ligaments did not guide mandibular movement or lend themselves to full seating of the condyles in the glenoid fossae. Shafagh[49] discovered circadian rhythm in jaw movements when locating and recording centric relation. He attributed it to diurnal fluctuations in the fluid levels around the joints and changes in muscle tone. He cites Devan's[50] and Boos'[51] studies that showed measurable differences in mucosal tissue fluid levels over time.

Future studies are needed to determine the causes of the variation noted in this study. A larger study with more participants may reduce variation. It would also be useful to determine how much variation in the recording of jaw movements is clinically acceptable.

CONCLUSION

The Cadiax Compact 2, a digital condylogram, records sagittal condylar guidance, rear wall angle and top wall angle predictably in patients over time on average; however, the ability of the digital condylogram to record immediate side shift and progressive side shift repeatably is not predictable. Individual variation of the recordings for some subjects was large, especially for the rear wall and top wall angles. The results of this study may be confounded by inconsistency of patient jaw movements, or operator error in connecting and operating the device. Further research is needed to determine the sources of the variation in this study.

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