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MANDIBULAR MOVEMENT IN 4D: ACCURACY OF A DIGITAL MANDIBULAR MOVEMENT RECORDING DEVICE

ACCURACY OF A DIGITAL MANDIBULAR MOVEMENT RECORDING DEVICE

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ABSTRACT

Purpose: The objective of this study is to assess the accuracy and repeatability of a new digital mandibular recording device called the MODJAW.

Materials & Methods: The Denar Mark II articulator was mounted in a custom-made apparatus and used to simulate the mandibular motion of a patient. The MODJAW trackers were placed on the articulator and the articulator was guided into protrusion, left laterotrusion, and right laterotrusion movements. The readings from the MODJAW for left protrusive condylar path angle, right protrusive condylar path angle, left progressive mandibular lateral translation, and right progressive mandibular lateral translation were reported for each recording. Equivalence tests using paired t-tests were performed to determine if the predetermined articulator settings for protrusive condylar path angle and progressive mandibular lateral translation were equivalent to those reported by the MODJAW.

Results: The 90% confidence interval of the mean difference for the left protrusive condylar path angle was (3.34, 3.98) and for the right protrusive condylar path angle was (2.59, 3,53). Both the left and right protrusive condylar path angles were within the equivalence limits (-5, +5) and the results were considered equivalent. The 90% confidence interval of the mean difference for the left progressive mandibular lateral translation angle was (-2.00, -1.18) and for the right progressive mandibular lateral translation angle was (-3.17, -2.20). Both the left and the right progressive mandibular lateral translation angles were within the equivalence limits (-5, +5) and the results were considered equivalent.

Conclusion: The digital jaw motion recording software, MODJAW, can provide clinically accurate readings for protrusive condylar path angle and progressive mandibular lateral translation angle to within ±5 degrees.

Keywords: Mandibular movement; pantograph; progressive mandibular lateral translation angle; protrusive condylar path angle

INTRODUCTION

Gnathology, a term coined by Stallard in 1924, is the science that relates to the anatomy, histology, physiology, and pathology of the stomatognathic system with treatment based on examination, diagnosis, and treatment planning. This system includes the teeth, supporting tissues, temporomandibular joints, and the associated hard and soft tissues of the head and neck.[1] Gnathology advocates for the concepts of organic occlusion. Organic occlusion is the organization of the occlusal scheme to include disocclusion, cusp-fossa relationships, centric relation occlusion, uniform centric contacts, forces directed along the long axis of the teeth, tripodized cusps, cross tooth stability, narrow occlusal table, maximum cusp height and fossa depth with supplemental anatomy.[1] The occlusal harmony created using the concepts of organic occlusion aids in minimizing excessive stress to the teeth, the periodontium, the muscles, the ligaments and the temporomandibular joints.[2]

In order to properly understand and treat the stomatognathic system, an appreciation for the component parts and their relationships must be considered.[3, 4] The concepts of centric relation, anterior guidance, occlusal vertical dimension, the intercuspal design, and the relationship of the determinants of mandibular movements that are recorded with complex instrumentation are central to the fundamentals of gnathology. The goal is to make maxillomandibular records that accurately reproduce the border jaw movements, to aid in prescribing the best occlusal interface for the individual patient. The use of accurate protrusive and lateral records allows for more accurate programming of the articulator and closer approximating the instrument to the patient's actual jaw movements. This has an effect on the cusp height, fossa depth, and proper positioning of occlusal ridges and grooves.[1] Maximizing the cusp height allows for increased masticatory efficiency, while enhancing esthetics and stability within the arch. The disadvantage of increasing cusp height is an increased risk of incorporating interferences during mandibular movements. Interferences are occlusal contacts that may result in undesirable deviation of the mandible during closure to maximum intercuspation and hinder the smooth transition to and from the intercuspal position. This occlusal disharmony can lead to pathologic occlusion, resulting in heavy wear facets, fractured cusps, and tooth mobility.[2]

Ideally during restorative treatment, occlusal restoration should be in harmony with centric relation. Centric relation is defined as the maxillomandibular relationship in which the condyles articulate in the

anterior-superior position against the posterior slopes of the articular eminences.[5] This position is an unstrained, physiologic position that is independent of tooth contact. In this position, the mandible is restricted to a purely rotary movement in which the patient can make vertical, lateral or protrusive movements.[5] It is considered the most orthopedically and musculoskeletally stable position of the mandible. This is a repeatable reference position and clinically useful when mounting casts on an articulator.[2] The most ideal situation for prosthetic rehabilitations occurs when centric relation coincides, or is made to coincide, with maximal intercuspation.

The determinants of mandibular movement include the right and left temporomandibular joints (TMJs), the teeth, and the neuromuscular system. The TMJs are the posterior determinants and influence the mandibular movements based on the paths that the condyles must follow as the mandible moves. The use of many programmable articulators is based on the measurement and reproduction of these condylar movements. The anterior determinants are the teeth, which provide additional guidance to the mandible during movement. The posterior teeth are the vertical stops for the mandible and guide the mandible into maximal intercuspation. The anterior teeth aid the mandible in excursive and protrusive movements. The farther a tooth is located from a determinant, the less it is influenced by that determinant. The neuromuscular system monitors the mandibular position and movement via proprioception.

Mandibular movement consists of a series of motions that occurs around three axes: a horizontal axis, vertical axis, and sagittal axis. The movements of the mandible involve motions that travel concurrently around one or more of these axes of rotation. As the mandible opens and closes, thus moving up and down, a combination of both a hinge and translation movement occurs. First, the condyles begin to rotate within the lower compartments of the TMJs resulting in a purely hinge movement that creates 20 to 25 mm of separation of the anterior teeth. McCollum described this phenomenon in the 1920s as the basis of the terminal hinge axis theory.[4] Today, this is known as the transverse horizontal axis, which consists of an imaginary line around which the mandible may rotate within the sagittal plane.[5] Weinberg advocated for the importance of locating the terminal hinge axis, as it is the starting point for all mandibular movements.[6] Similarly, Stuart and Stallard stated that without a correct location of the terminal hinge axis, all adjustments in the articulator would be incorrect.[7] Although locating the terminal hinge axis gives the greatest accuracy, approximating the hinge axis can be fairly accurate and produce only slight errors when used. Teteruck and

Lundeen found that 75.5% of true hinge axes are within a 6mm circle of the arbitrary articulator hinge axis.[8] Weinberg found that removal of a 3mm centric relation record will produce an anterioposterior mandibular displacement of 0.2mm if the hinge axis is 5mm off of the true hinge axis.[9]

Mandibular movements also include protrusion, laterotrusion, and mediotrusion. In the protrusive movement, the mandible slides anterior to the centric relation position without lateral deviation.[5] Ideally, the mandible will be guided by the maxillary and mandibular anterior teeth until they meet in an edge-to-edge relationship, resulting in complete disocclusion of the posterior teeth, as described by Christenson. As the mandible moves in lateral excursion, the side toward which the mandible moves is termed the working-side, or laterotrusive side. The side of the mandible that moves toward the medial line is termed the nonworking-side, or balancing side. During the excursive movements, the working condyle moves laterally and rotates, while the nonworking condyle will move forward and medially.[2]

Bennett was the first to describe the bodily shift of the mandible in the working movement.[10] The Bennett angle is a term used to describe the angle in the horizontal plane that forms between the pathway of the nonworking condyle, the mandibular lateral translation, and the sagittal plane. An immediate mandibular lateral translation (IMLT) has been reported to occur in 86% of condyles, but may be clinically insignificant.[3, 11] The IMLT is the translatory portion of the lateral movement in which the nonworking condyle appears to essentially move in a straight, medial line as it leaves centric relation. Following the IMLT, the progressive mandibular lateral translation (PMLT) describes a further gradual shifting of the mandible at a rate proportional to the forward movement of the nonworking condyle.[5]

In restorative dentistry, the goal is to create harmony between the teeth and the TMJs, thus minimizing stress to the determinants of mandibular motion.[2] When harmony between the teeth and the TMJs does not exist, an undesirable occlusal contact may occur, thus producing an interference. During closure to maximal intercuspation, interferences may cause the mandible to deviate and or obstruct the smooth motion to and from the intercuspal position.[2] These occlusal interferences include centric, working, nonworking, and protrusive interferences. The nonworking interferences are said to be particularly destructive due to the potential damage caused by changes in the mandibular leverage, placement of the forces outside the long axes of the teeth, and disruption of normal muscle function.[2] Further, interferences caused by contacts between the posterior teeth during protrusion may interfere with the patient's ability to

incise. These interferences are potentially destructive due to the proximity of the teeth to the muscles and the oblique vector of forces placed on the teeth.[2]

Complete evaluation of the stomatognathic system is currently not feasible to do intraorally. Anatomic structures and their function must be replicated extraorally to allow comprehensive diagnosis and treatment.[4] The need for instrumentation and techniques to accurately simulate function and jaw position has led to the development of articulators and mandibular movement recording devices. By accurately recording and transferring patient information to a properly selected articulator, more in-depth evaluation and customized restoration designs may be made for the patient. McCullum states that an articulator must replicate the hinge axis of the mandible in order to reproduce the other mandibular movements.[12] Various methods and devices have been developed throughout history to record mandibular movement. Currently, the pantograph is the most accepted instrument for accurately producing a complete recording of jaw movement and border positions.[13]

A pantograph produces a graphic recording of the paths of mandibular movement in one or more planes. The information gathered allows the detailed programming of an articulator, permitting the movements of the articulator to be in harmony with the mandibular movements of the patient.[4, 14] Historically, pantograph instruments have been able to be roughly grouped into categories which include mechanical, electronic, and optoelectronic recording devices.[13, 15] Each of these function slightly differently with certain advantages and disadvantages.

Mechanical pantographs are composed of styli that physically contact recording plates to record mandibular movement.[15] This apparatus is considered accurate and reliable, with a relatively low cost compared to other recording devices. However, mechanical pantographs are considered time consuming due to the high degree of complexity required to manually record movements and program the articulator.[13]

Electronic pantographs, such as the Pantronic and Cadiax Compact II, were developed to improve the precision and efficiency of recording mandibular movement.[15] These devices contain styli that contact digital recording plates. The information recorded by the digital plates is transferred to a computer and processed by the computer software.[13] The articulator is programed using values that are generated by the computer. Electronic pantographs are lighter and generally require less time to complete recordings when compared with the mechanical pantographs. The increased efficiency and precision of the electronic

pantograph comes with an increased cost.[13] Studies have shown the electronic pantograph is a clinically acceptable alternative to the mechanical pantograph.[16]

Optoelectronic pantographs, including the Freecorder Bluefox, were developed to further improve the tracking of mandibular movement.[13] The maxillary and mandibular facebows each contain coded sensors which are optically tracked by cameras to record mandibular movement. The sensors are wireless, and information is processed by a computer, which then generates values for programming the articulator.[13] Optoelectronic pantographs are even more lightweight than the mechano-electronic devices and require less time to record movements. The price of optoelectronic pantographs is much higher compared to mechanical and mechano-electronic pantographs.[13]

Previous investigations have demonstrated inaccuracies in pantograph recording of condylar guide assembly values, including PrCp, PMLT, and IMLT.[13, 15] Various investigators have determined a clinically acceptable range for lateral condylar inclination and progressive mandibular lateral translation to be ±5°, while the tolerance level for immediate mandibular lateral translation is ± 0.2mm.[3, 17, 18] Therefore, although reports demonstrate inaccuracies with pantograph usage, the discrepancies reported fall within the clinically acceptable range. Although pantograph devices are considered clinically acceptable, practitioners desire a more accurate and easier instrument for recording mandibular movement. Additionally, the analog pantograph does not translate to the digital environment.

A new digital mandibular recording device called MODJAW was developed to combat these shortcomings, utilizing 3D technologies and motion capture. A set of tracking devices are placed on the patient's head and mandibular arch. These trackers are correlated to pre-recorded 3D models by registering fiducial markers on a handheld stylus.[19] An optical camera uses infrared to track mandibular motion and transfers data to the MODJAW software. When the patient is directed into jaw motion, the camera records the point animations from fiducial markers on the "tiara" and "butterfly" attached to the patient. The software uses this information to reproduce the mandibular movements of the 3D models on the screen.[19] Computational geometry allows the 3D software to show contact points and dynamic occlusion using the 3D models. The jaw movements are recorded in real time, allowing the fourth dimension of time to be included in the jaw motion capture. This 4D technology is a new feature that for mandibular tracking devices and allows the clinician to analyze and replay mandibular movements as they are occurring. [19]

MATERIALS AND METHODS

The Denar Mark II articulator was used as the test patient within this study. It features a centric holding latch, adjustable protrusive condylar path (PrCp) angles, adjustable progressive mandibular lateral translation (PMLT) angles, adjustable immediate mandibular lateral translation (IMLT) and straight-line PrCp, PMLT, and IMLT movement.

The MODJAW jaw motion tracking device features two sensors placed on the patient, allowing the camera to track the patient. One sensor (the "tiara") is placed around the crown of the patient's head and another sensor (the "butterfly") is affixed to the patient's mandible via chemical cure bis-acryl interim restorative material. A third sensor positioned on a stylus is used to locate specific points on the patient. These points act as fiducial markers to pair with digital models imported in the MODJAW software. The system also includes a camera, which tracks the patient's movement, and a computer that configures the information in the MODJAW software. The system analyzes the mandibular movements to determine PrCp and PMLT.

The investigation was modeled after previous in vitro pantograph studies.[13, 15] It was designed to determine the ability of the digital jaw motion recording software, MODJAW, to accurately analyze preset values for PrCp and the PMLT angles.

Trial 1:

Null hypothesis: There is a statistical difference between predetermined articulator settings for PrCp and the reported PrCp from MODJAW.

Trial 2:

Null hypothesis: There is a statistical difference between predetermined articulator settings for PMLT angles and the reported PMLT angles from MODJAW.

An apparatus (Figure 1) was fabricated to suspend the test articulator securely. The holder permitted only the movement of the mandibular element of the articulator. Thus, the articulator functioned in a similar manner to the mandibular motion of the patient. The tiara, which would be positioned on the patient's head, was positioned 25mm above the horizontal plane of the articulator. This allowed correct registration of the third point of reference (nasion minus 25.4 mm) to be registered similar to patient treatment. The mandibular recording butterfly device was secured to the mandibular arch via Triad gel

(Dentsply Sirona, Charlotte, NC). This allowed tracking of the mandibular arch similar to patient treatment. The test computerized tracings recorded mock patient movement, allowing the in vitro PrCp and PMLT determinations to be performed in a clinically relevant manner.

Maxillary and mandibular occlusal rims with a central bearing device were scanned via the CEREC Primescan (Dentsply Sirona, Charlotte, NC). The scans were used to fabricate printed models via the Form3B (Formlabs, Somerville, MA) for the maxillary and mandibular elements of the mock patient. Reference marks were drilled into the maxillary and mandibular casts and used as reference points to align the digital models in the MODJAW software. A digital scan of the models was accomplished using the CEREC Primescan (Dentsply Sirona, Charlotte, NC). The casts were mounted in the articulator with Blue Mounting Stone (Whip-Mix Corp. Louisville, KY) in accordance with the manufacturer's instructions.

The selected test settings remained the same for all determinations. The tiara and butterfly were attached to the mock patient. Using the handheld stylus, the reference points were selected on the mock patient and matched with the pre-scanned digital models. The terminal hinge axis was located using the MODJAW software hinge axis calculation. The mock patient was guided into protrusive, left lateral, and right lateral movement for each recording session. The data was stored in the MODJAW software and displayed graphically and numerically. 30 recordings for each movement were made per trial. There were two trials attempted as follows:

Trial 1:

Operator adjusted the mock patient's right and left PrCp angles to 30 degrees under 5.0X magnification. The selected test settings remained the same for all determinations. The operator performed protrusive guided movements of the mock patient. Data was recorded and transferred to spreadsheet.

Trial 2:

Operator adjusted the mock patient's right and left PMLT angles to 15 degrees under 5.0X magnification. The selected test settings remained the same for all determinations. Operator performed right and left laterotrusive guided movements of mock patient. Data was recorded and transferred to spreadsheet.

The condylar assembly values were transferred to a spreadsheet for statistical analysis. Two one-sided tests (TOST) level 0.05 equivalence analyses were performed to determine whether the predetermined PrCp angle and PMLT angle articulator settings were equivalent to the values determined by the MODJAW recording software. The equivalence limits (clinically meaningful limits) were set at ±5 degrees for PrCp angle and ±5 degrees for PMLT angle, based on values previously described in the literature. [3, 17, 18] The mean errors, standard deviations, and confidence intervals for differences were determined. Analyses were performed with SAS 9.4 Analytics Software (Cary, NC).

RESULTS

An equivalence test was used to estimate the sample size for this study. A total of 30 recordings achieved 80% power showing that the PrCp and PMLT angles reported by the MODJAW software were equivalent to the predetermined PrCp and PMLT angles for a two one-sided test with a significance level α of 0.05 assuming the mean ratio of 1.08, a correlation of 0.35 between the paired PrCp and PMLT angles, and equal coefficient of variation (CV) of 0.2.

The mean value for left PrCp angle was 33.66 degrees, with a range of 32 to 36 degrees. The standard deviation for left PrCP angle was 1.07 degrees. The mean value for right PrCp angle was 33.06 degrees, with a mean value of 30 to 36 degrees. The standard deviation for right PrCp angle was 1.56 degrees (Table 1). The mean value for left PMLT angle was 13.41 degrees, with a range of 12 to 20 degrees. The standard deviation for left PMLT angle was 1.36 degrees. The mean value for right PMLT angle was 12.31 degrees with a range of 10 to 15 degrees. The standard deviation of right PMLT angle was 1.62 degrees (Table 1).

The reference value for the PrCp angle was set at 30 degrees. There was a mean difference from the reference for the left PrCp angle of 3.66 degrees and a mean difference from the reference for the right PrCp angle of 3.06 degrees. The 90% confidence intervals of the mean difference of left PrCp angle were 3.34 and 3.98 degrees, while that of the right PrCp angle were 2.59 and 3.53 degrees (Table 2). Both the left and right PrCp angles 90% confidence intervals of the mean difference were within the equivalence limits (-5, 5). Thus, the null hypothesis for trial 1 was rejected and the PrCp angles reported by MODJAW was considered equivalent to the predetermined articulator values.

The reference value for the PMLT angle was set at 15 degrees. There was a mean difference from the reference for the left PMLT angle of -1.59 degrees and a mean difference from the reference for the right PMLT angle of -2.69 degrees. The 90% confidence levels of the mean difference of left PMLT angle were -2.00 and -1.18 degrees, while that of the right PMLT angle were -3.17 and -2.20 degrees (Table 2). Both the left and right PMLT angles 90% confidence intervals of the mean difference were within the equivalence limits (-5, 5). Thus, the null hypothesis for trial 2 was rejected and the PMLT angles reported by MODJAW were considered equivalent to the predetermined articulator values.

DISCUSSION

The mock patient within this study was designated as the articulator with the maxillary and mandibular arches represented by occlusal rims with a central bearing device. This setup allowed for smooth protrusive and laterotrusive movements but lacked the ability to represent the influence of anterior guidance. In a dentate patient, the anterior teeth may provide anterior guidance, thus influencing the separation of the maxillary and mandibular arches. Although anterior guidance may influence the occlusal morphology of teeth, it should have no influence on the condylar assembly. Additional studies are needed to demonstrate MODJAW's ability to report the PrCp angle and PMLT angle independent of the influence of anterior guidance.

Within this study, the MODJAW demonstrated the ability to report values of the PMLT angle and the PrCp angle that were statistically equivalent to the predetermined values of the articulator. These values may be used to program the digital articulator within digital design software. The tiara that is mounted on the patient's head, is used to record a third point of reference within the software and the accuracy of the third reference point is dependent on the location of the tiara. During the pilot study, the location of the tiara was moved within the apparatus built to hold the articulator. Upon recording, the angles reported by MODJAW for PMLT and PrCp changed based on the location of the tiara, indicating the tiara functioned as a facebow apparatus that aided in the determination of the horizontal reference plane. It was found that when the nasion portion of the tiara was placed approximately 25.4 mm above the horizontal plane of the articulator, PMLT and PrCp angles were reported correctly. This indicates the MODJAW uses the nasion minus 25.4 mm as the third point reference and approximating the location of the orbitale.[20] Thus, the horizontal reference plane used for the MODJAW is the axis-orbitale. When using the values reported by

MODJAW to program a digital articulator, it may be important to use an articulator that uses the nasion as the third point of reference and the axis-orbitale as the horizontal reference plane.

A second key component to determining the PMLT and PrCp angles is the location of the terminal hinge axis. When setting up a case within the MODJAW system, the user is prompted to locate the left and right condyle on their patient. Unless the terminal hinge axis has been previously located on the patient and marked with a tattoo, this selection creates an arbitrary hinge axis. Within the software, MODJAW can locate the terminal hinge axis and the user can decide to use either the arbitrary or true hinge axis. Within this study, the terminal hinge axis was calculated by the software and used as the posterior determinants for the horizontal plan, thus allowing more accurate measures of the PMLT and PrCp angles. Additional studies will need to be performed to determine the accuracy of the MODJAW's terminal hinge axis calculation.

The MODJAW currently does not have the ability to calculate values for IMLT. Although IMLT can influence the cusp height and fossa width, a recent review of IMLT determined there is no evidence demonstrating adverse clinical events when IMLT is not included in the restorative occlusal scheme. Further, the recordings of IMLT appear to be dependent on the reference point and recording instrument.[11] Thus, it may not be necessary for MODJAW to record IMLT and reproduce this movement on the digital articulator.

This study provides promising results demonstrating MODJAW's ability to recreate the movements of the mandible in real time and report accurate values for PMLT and PrCp. Additional studies are required to determine MODJAW's ability to locate the terminal hinge axis and act as a facebow to accurately mount casts within the digital articulator, so that the PMLT and PrCp values can be used within digital design software.

CONCLUSION

The digital jaw motion recording software, MODJAW, can provide clinically accurate readings for the PMLT angle and the PrCp angle within ± 5 degrees.

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TABLE 1

Variable	Mean	Std Dev	Lower 95% CL for Mean	Upper 95% CL for Mean	Minimum	Maximum
PrCpLeft	33.66	1.07	33.27	34.04	32.00	36.00
PrCpRight	33.06	1.56	32.50	33.63	30.00	36.00
PMLTLeft	13.41	1.36	12.91	13.90	12.00	20.00
PMLTRight	12.31	1.62	11.73	12.89	10.00	15.00

TABLE 2

TOST Level 0.05 Equivalence Analysis	Mean Difference from Reference	90% CL Mean		Assessment
PrCpLeft	3.66	3.34	3.98	Equivalent
PrCpRight	3.06	2.59	3.53	Equivalent
PMLTLeft	-1.59	-2.00	-1.18	Equivalent
PMLTRight	-2.69	-3.17	-2.20	Equivalent

FIGURE 1