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Digital motion analysis of temporomandibular joint functions

Doctoral thesis

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List of abbreviations

CBCT - Cone Beam Computed Tomography

CO - centric occlusion

CR - Centric relation

DC-TMD - Diagnostic Criteria for Temporomandibular Disorders

EPA - Electronic Position Analysing

GPT - Glossary of Prosthodontic Terms

ICC - instantaneous centre of curvature

ICR - instantaneous centre of rotation

MIP - maximum intercuspal position

mm - millimetres

MRI - magnetic resonance imaging

OVD - occlusal vertical dimension

RCP - retral contact position

THA - terminal hinge axis

thpb - tongue at the hard-soft palate border

TMJ - temporomandibular joint

tpr - tongue at the palatal rugae

1. Introduction

The temporomandibular joint (TMJ) is a paired, limited free joint located at the base of the skull. It can be argued that in many ways it is one of, if not the, most distinctive joint in the human body.(1) The articular surfaces of the joint are the mandibular processus condylaris and the os temporale fossa articularis. The articular surfaces are covered by fibrous cartilage, a distinguishing characteristic that differentiates this joint from other joints in the body covered by hyaline cartilage. The histology of the articular disc present within the joint is also unique. It is composed of compact fibrous connective tissue, thus not meeting the criteria for being considered a true disc from a histological perspective.(2, 3) The bilaminar zone is another anatomical structure of the TMJ that is worth highlighting. This is a complex of fibres, blood vessels and nerves located in the dorsal part of the joint. It extends between the posterior (dorsal) part of the discus and the fossa articularis, also posterior (dorsal). It is worth noting, that the cranial part of the tissue is mainly composed of elastic fibers, while the caudal part is mainly composed of collagen fibers.(3, 4) This complex plays an essential role in opening and closing the mouth.(5) The last anatomical formula worth mentioning is the musculus pterygoideus lateralis, which has a key role in the functioning of the joint. The latter is a smaller muscle and is further divided into two distinct parts: the venter inferior and the venter superior. The venter superior originates from the os sphenoidale ala major crista infratemporalis and inserts at the articular capsule of the TMJ and the anterior (ventral) surface of the discus. The venter inferior originates from the outer half of the processus pterygoideus and inserts in a notch of the processus condylarais mandibulae.(3) It is also involved in the anterior movement of the mandible when the mouth is opened and in the anterior movement of the discus. It is also active when the mouth is closed and is involved in counteracting the discus, so it is a muscle that is active both agonistically and antagonistically.(3, 5)

According to the anatomical features under consideration, the TMJ can thus be divided into two joints. The disco-mandibular joint, situated between the mandible and the discus, and the disco-temporal joint, located between the disc and the os temporale.(2, 3, 5) This has anatomical as well as functional significance. Two distinct movements can occur in the two joints. The disco-mandibular joint is capable of producing rotational movement, while the disco-temporal joint is capable of producing translational movement.(3) During mouth opening and various jaw movements, these movements occur mostly simultaneously, but – rarely – they can occur separately.(6)

From a clinical perspective, specific static mandibular positions have significant importance. In each case, the position of the condyle in the fossa, the activity of the masticatory muscles and the tooth contact together determine the actual position. The **centric relation (CR)** is a term used to describe a specific, important position. In this position, the condyles assume an anterior superior position in the fossa articularis, in close proximity to the posterior half of the eminentia articularis. This position is the result of the base functioning of the masticatory muscles.(7, 8) The tooth contacts formed in this condylar position are designated **centric occlusion (CO)**. The significance of this position is that it is well reproducible in both dentate and edentulous patients.(7) The maximum interocclusal position (MIP) is defined as the maximal intercuspation of the teeth, also referred to as the maximum tooth contact. In this case, the position of the condyles in the fossa is not clearly defined and is associated with minimal muscular activity.(7, 9) Significantly, in dentate patients, it is the easiest and most clearly reproducible position. The third dominant position of the joint is the **retral contact position (RCP)**, where the condyle reaches the posterior half of the articular fossa. This position is notable for its high reproducibility, and the condyle is located in the most dorsal position in this case.(7)

Gnatology is a discipline dealing with the jaw joint, its function and diseases. The name originates from the Greek words of gnathos and logos. Gnathos means jaw, while logos translates as research. The history of this subject is almost contemporaneous with the development of modern dentistry. As early as in the 17th century, evidence gathered by Philip Pfaff indicates that dentists of that era were interested in the position of the jaw and the methodology for determining it.(10) During the nineteenth- and twentieth-century, several prominent researchers – among others: Christensen, Bonvill, Evans, Gysi, and Földvári - dedicated their work to studying this field.(10, 11) This field is characterised by its multidisciplinary character. In the course of their daily work, orthodontists, oral surgeons and prosthodontists are all involved in the field. Consequently, the existing research on this subject shows great variety and diversity. Different researchers use different approaches in line with their specific areas of expertise.(12-14)

For over a century, a constant in TMJ research has been the study of the positions and movements of the joint with axiography being one of the most suitable methods to examine these.(15-18) Initially, the technique was analogue, but with the development of modern technology, they are now digital. Axiography is a diagnostic method with a history of more than a century.

The seminal study of mandibular movements was pioneered by the English dentists George G. Campion and Norman G. Bennett.(15) These instruments were regarded as the forerunners of the axiograph and were rather rudimentary devices with limited utility. In essence, they were similar to modern facebows.

The next major leap was Alfred Gysi's devices, but even these were not real axiographs in the strict sense. The first true axiograph capable of registering mandibular movements in three dimensions of space was created by Beverly B. McCollum. These instruments used a graphite tip to draw each movement on paper. This was sufficient to determine the basic shapes of the movements, but it could only be described as accurate to the nearest millimetre (mm).(11)

The next major advancement was the advent of the digital age. This allowed for increased accuracy and better analysis with various softwares.(19) In many cases, these devices are no longer true axiographs but digital motion analysers. They are not necessarily registered at the axis of rotation of the condyle and the first Bonwill point. After a few more rudimentary attempts and the use of different technologies, ultrasonic devices appeared at the end of the 1990s.(20) This novel technology has enabled the acquisition of measurements with an accuracy that can be expressed in tenths of a millimeter. These devices have become relatively widespread in different areas of dentistry with different indications. Their improved versions are now helping to overcome the digital challenges of the present day. Such devices are now optically based with infrared emitters and sensors, possibly video-recorded, thus, their use has been further simplified.(21)

The complex joint structure described above, the resulting complex movements, and the daily challenges of defining CR raise a number of questions that digital motion analysis can help to answer in a novel way. I have chosen to address these questions, most of which have been recurring for decades, using this new testing tool as the topic of my doctoral dissertation.

2. Objectives

In the field of gnatology, there are still many divisive topics and concepts where there is no general, international consensus. Two of these areas surfaced during the research of our working group. One is the potential differences between the various CR determination methods that have been presented in the literature. The second question concerns the phenomenon of pure rotational movement during the initial stage of mouth opening.

Two studies were carried out to address the above issues. The objective of the first study was to compare the different methods for determining CR in dentate patients. The purpose of this study was to compare the maxillo-mandibular relationship determined by different methods described in the literature. Clinical practice showed that these methods do not necessarily define the same position in all cases. The situation is further complicated by the publication of a new definition of CR in the Glossary of Prosthodontic Terms (GPT) in 1987. As a result, the methods described before and after this new definition define a different preferred position, defined as CR.(7, 22, 23)

The objective of the second study was to determine if pure rotation occurs during mouth opening or if translational movement was present in addition to rotation. The study also examined if translation was present and whether it occurred immediately from the first moment or only at a slightly later stage of mouth opening. There are few studies in the existing literature on this topic using digital motion analysis devices. The use of ultrasound technology makes it possible to achieve a remarkably high degree of accuracy. This decision was made in light of the necessity to employ a specialized instrument to address these specific challenges.

The two null hypotheses we have tested are therefore as follows:

1. *The methods used to determine the different maxillo-mandibular relationship do **not** determine the same maxillo-mandibular relationship.*
2. *In the initial stage of mouth opening, **there is no** pure rotational motion without translation.*

3. Methods

3.1. Participation in an investigation

The study was conducted at the Department of Prosthodontics of Semmelweis University between 2013 and 2020. The research was approved and registered by the Ethics Committee of Semmelweis University under number 92/2013. A total of 34 volunteers participated in the study comparing CR determination methods, while 46 participated in the other study. The first one included 24 female and 10 male participants, with an average age of 29.1 (± 7.3) years. In the second study, the higher number of participants was due to the fact that no extra device (gothic arch tracer) was needed, so more patients agreed to participate in the study. The data collection period was also longer in the second study. In that case, 31 female and 15 male volunteers participated, with an average age of 28.6 (± 7.1) years. All patients participating in the study were informed about the research and completed a consent form. Subjects were selected based on recommendations from previous publications in the field.(20, 24-26) This was done to ensure the inclusion of individuals with intact, healthy stomatognath systems in the study and to provide data relevant to a healthy population. The conditions for participation in the study were:

1. Good general health and an absence of dental and jaw developmental disorders.
2. Preserved or restored dentition. Excluding the missing of wisdom teeth.
3. If the patient had a restored dentition, the occluding surfaces of the restoration are not guiding in the articulatory movements.
4. The patient has had no previous orthodontic treatment.
5. There was no history of craniomandibular dysfunction (CMD) (neither myogenic nor intracapsular) and no complaints at the time of examination.
6. Based on the patient's history and dental examination, the participant had no occurrence of bruxism or other parafunction and no abnormal tooth guidance (e.g. hyperbalance guidance).

3.2. The procedure of the examination

To ensure that the inclusion criteria were met, detailed medical history was obtained at the first visit, and a thorough stomato-oncologic and TMJ screening was performed. In

all cases, TMJ screening was performed according to the RDC-TMD or later DC-TMD protocol.(27) In all cases, this was performed by the same colleague with decades of work experience in the relevant field. This was followed by a lower and upper putty-wash situational impression. The impressions were made with C-silicone (ZetaPlus, Oranwash, Catalisator, Zhermack, Badia Polesine, Italy), perforated, metal, stock tray (Medesy, Maniago, Italy) and if a visible impression failure was detected after removal, a new impression was made. In every case, the impressions were poured after waiting for the elastic recoil time, but before any significant shrinkage, at a time interval of 2-6 hours. The impressions were cast from Class IV gypsum in the dental laboratory (Fuji Rock, GC International AG, Lucerne, Switzerland). The resulting casts were then utilised in the fabrication of the gothic arch tracers.
During the second and third visits, measurements were obtained using a digital motion analyser. It is important to note that the two measurements were taken at different times for each participant. First, a comparison of CR determination methods was performed, and during the next appointment followed by an examination of mouth opening. As a result, the process of blood filling the retrodiscal area was circumvented, which, otherwise, could have led to false results due to the (slightly) altered relative position of the mandible in the fossa articularis.(3) The CR positions were tested first by trying the intraoral tracer. This was followed by the determination of the maxillimandibular relationship using different CR determination methods and the digital recording of these positions. During the mouth opening test, the patient performed three consecutive maximum mouth openings from the closed position (from MIP). The Arcus Digma II (KaVo, Biberach, Germany) digital motion analyser was used.(28)

3.3. **Instruments used for the study**

3.3.1. Intraoral tracing device

In order to perform the measurements, it was necessary to prepare an intraoral tracing device for each patient. In clinical practice, due to its relative convenience and better adjustability, the placement of the tracing tip on the maxilla is more common, and this was the design of the device used in the study. In addition, it is important that the plate holding the drawing pin is parallel to the occlusal plane, so that the drawing pin makes a

90-degree angle with it. The pin should be positioned on the centre line between the first and second premolars. The tracing table is placed on the lower jaw in this case.(29) The material of the devices was light-curing acrylate (Elite LC Tray, Zhermack, Badia Polesine, Italy). The tracing table surface was coloured using blue and red articulating paper. One of the main challenges when using a gothic arch tracer is to fix the jaws in the determined position. A highly cooperative patient is required to find and hold the jaw in the correct position (at the apex of the arrow), until this position is fixed. In order to assist this, a small device was designed and printed using 3D design software. This could be attached with wax to the tracing table of the intraoral tracing device so that the hole in the centre pointed to the apex of the gothic arch. Then, by placing the tracer in the mouth, the design of the device guided the pin to the correct position, making it easier to fix the jaw position. (Figure 1., Figure 2.)

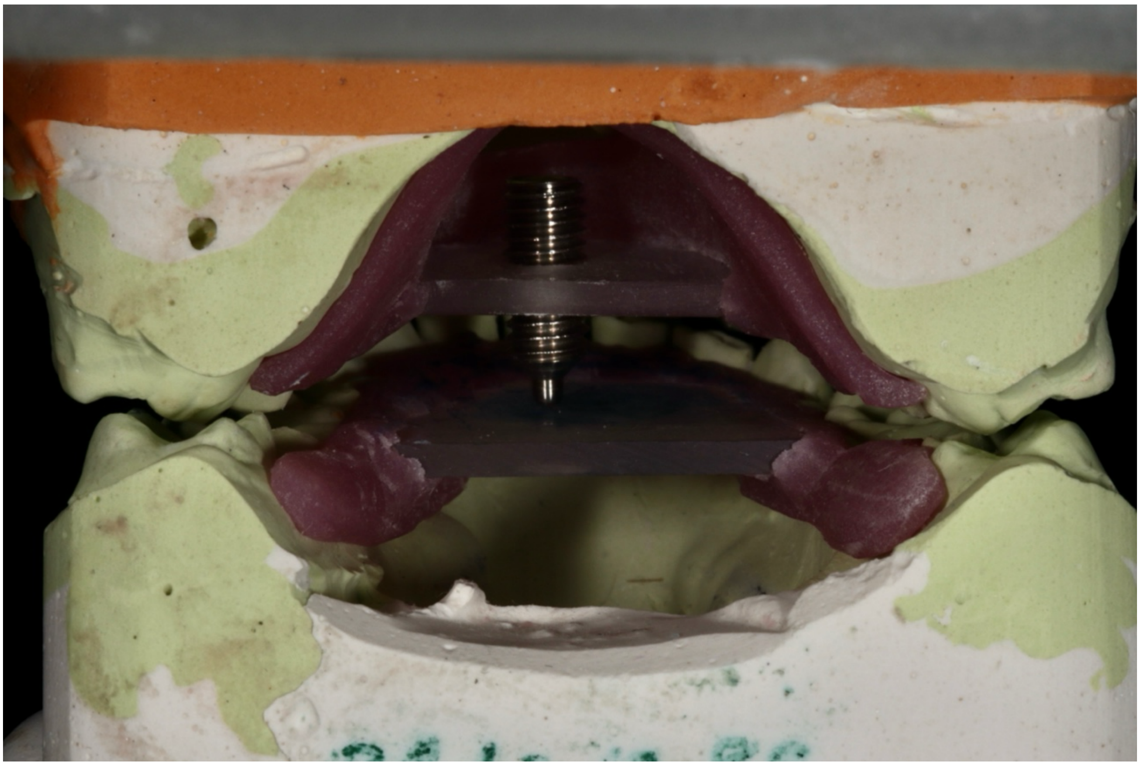

Figure 1. Gothic arch tracer (own photo)

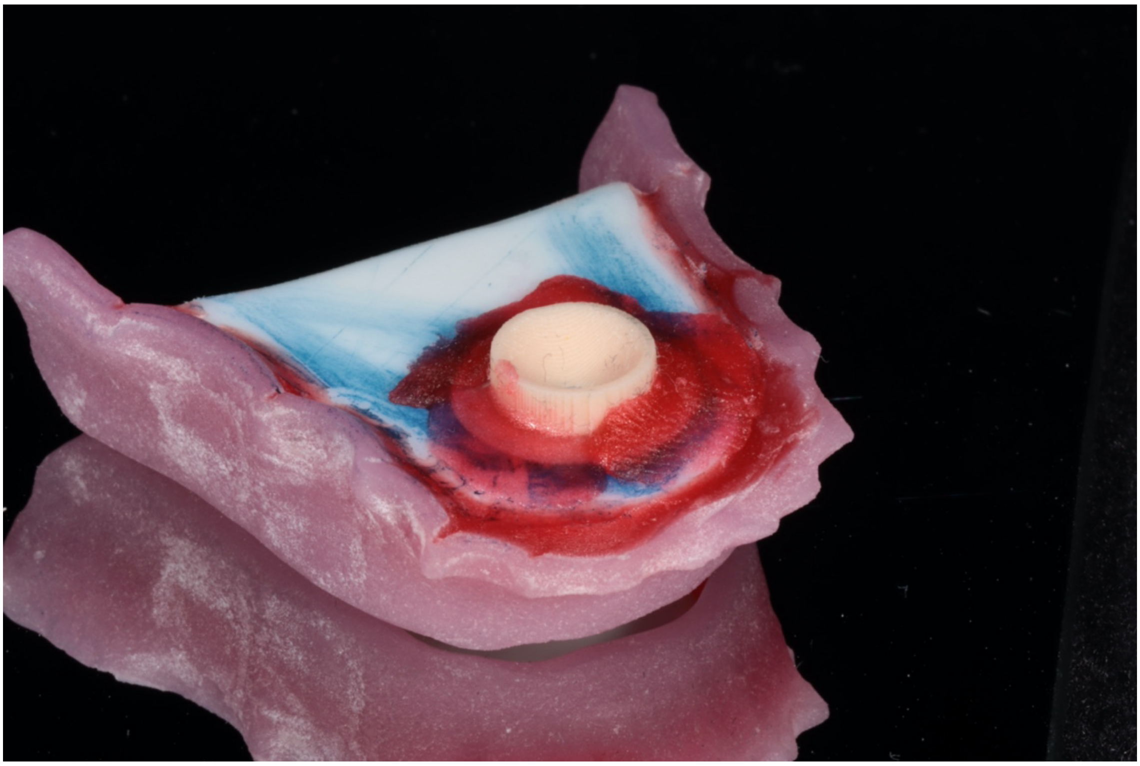

Figure 2. The device to assist in the fixation of the determined position on the drawing table of the gothic arch tracer. (own photo)

3.3.2. Arcus Digma II digital motion analyser

The Arcus Digma II – as mentioned in the Introduction section - is an ultrasonic digital motion analysis device.(28, 30-32) It has 4 transducers connected to the lower jaw and 8 sensors connected to the upper jaw. (Figure 3.) The ultrasonic method is advantageous because it can achieve a high sampling rate of 50 frames per second. The result of these static positions every 0.02 seconds is a dynamic path.(33) In its application, a so-called paraocclusal clutch is first attached to the buccal surface of the teeth of the lower jaw. This is a metal appliance in the shape of a dental arch, with a part extending from the mouth to allow the lower unit of the device (with the transducers) to be fixed with a magnet. It is important that the fixation is firm and stable, as even the slightest movement of the transducer during the test is unacceptable. Should that occur, a noticeable inaccuracy would inevitably manifest in the results obtained, requiring the test to be repeated. To place the paraocclusal clutch, the surface must first be dried and then fixed to the buccal surface of the tooth with self-curing acrylic. In the majority of cases, the minimal amount of acrylic applied on the interdental area is sufficient to provide adequate retention to hold the lower part of the device.(30) There are, however, cases (e.g. severe deep bite or overbite) where the surface area available in MIP is not sufficient for adequate retention. In such cases, it is possible for the dental technician to fabricate a "base" for the paraocclusal clutch to fit the tooth's equator, using a light-curing acrylic material, based on a situational cast. The upper (receiver) units - which are the ultrasonic sensors - are fixed using a facebow. A special feature of the facebow is that the glabella support can be moved in two directions on it. This configuration enables the facebow to be precisely positioned and securely fixed in a position calibrated to the Frankfort horizontal plane. After adjustment, rubber straps ensure stability.

Calibration of the device is necessary before measurements are started. The manufacturer provides several options for this. The "arbitrary axis" calibration was used throughout the study. Although the name may be misleading, it allows calibration to an arbitrary plane.(30) In the investigations, the plane in question was always identified as the Frankfort horizontal plane.

The calibration process is performed with the help of the lower unit. Initially, an MIP registration is established, followed by the use of a known-length stick to indicate the skin projection points of the right and left condylus articulare and the left infraorbital points. These points are then recorded. Consequently, the device's software generates a three-dimensional coordinate system. The origin of the coordinate system is the MIP, as determined by the initial MIP calibration, and all subsequent condyle position is placed within this virtual coordinate system. For each measurement point, the three-dimensional coordinate values are paired. Following the initial phases, a number of test modules are available. The motion analysis and EPA (Electronic Position Analysing) modules were selected for the evaluation.

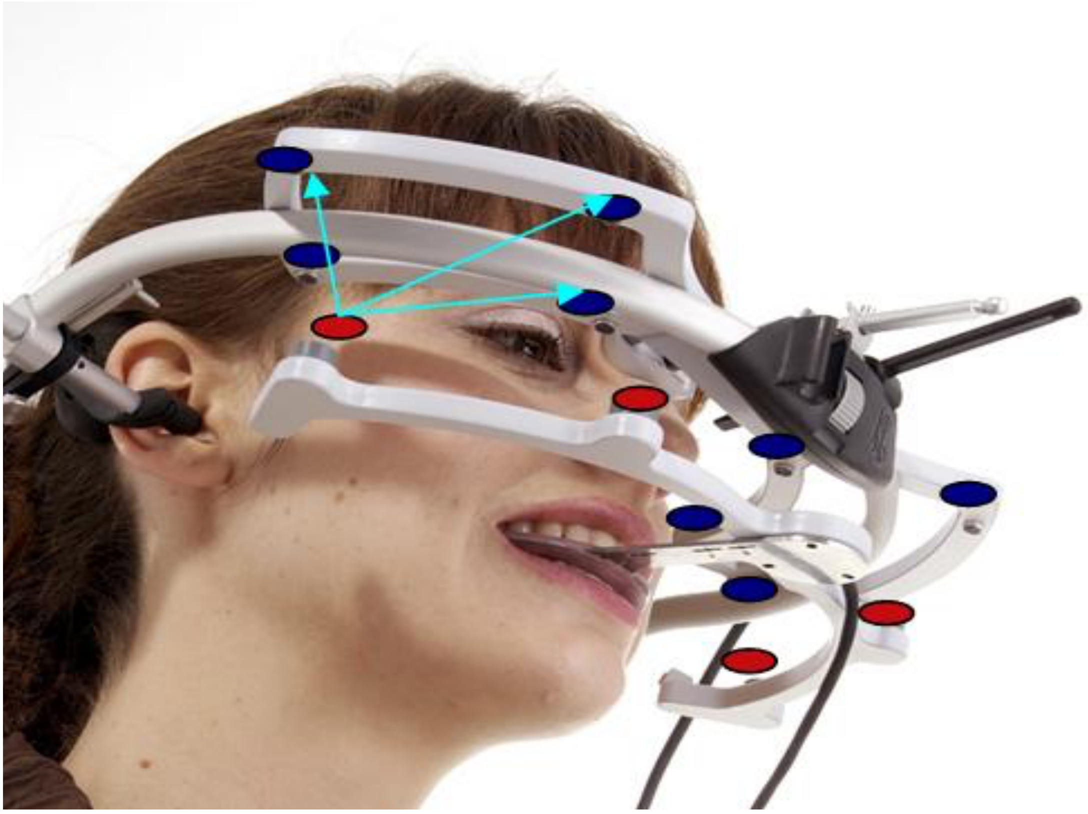

Figure 3. The Arcus Digma in its installed state. Also visible are the bite fork attached to the lower teeth and the associated transducer. The arrows show the possible path of the ultrasound signals from the transducer to the sensors.(30)

3.4. **Comparison of CR determination methods - first test session**

The EPA module makes it easy to compare different static jaw positions. This allowed comparisons of condyle positions in CR positions determined with different methods. The MIP was used as the starting and reference point in all cases due to the reproducibility, comparability and calibration capabilities of the device.(34) This outcome was attributed to the inclusion criteria of the study, which required a stable MIP. The positions of the different CR determination methods were then recorded as follows (Table 1.):

(1) The apex of the gothic arch defined by the gothic arch tracer. In this case, it was necessary to establish a minimum vertical opening, i.e., to increase the occlusal vertical dimension (OVD), to ensure technical applicability.(29)

(2) The adduction field is defined by the gothic arch tracer. It is also important to note that the measurements for this method were performed with a minimally increased OVD.(29)

(3) Position defined by Dawson's bimanual manipulation.(35)

(4) By placing the tip of the tongue in the area of the palatum rugae (tpr). The description of this method is attributed to the Swiss dentist Walter Wild. He named the phenomenon linguomandibular homotropy, which involves moving the mandible into the CR position by moving the tongue.(36)

(5) Position defined by pulling the tip of the tongue back to the border of the hard and soft palate (thpb). Also related to the principle of linguomandibular homotropy described above.(36)

(6) Position of the mandible retruded by the patient. Also known as active retrusion.

(7) Lastly, the position of the jaw retruded by the operator. In this case, the subject pushed the mandible backwards from a resting position with 20 N force. This two methods were used to check whether the previous methods did not cause an overly retruded jaw position.(25)

During the examination, all measurements were taken by the same operator. Two randomly selected patients were measured twice. The second measurement was not included in the study data. The Cohen's kappa coefficient was between 0.88 and 0.93.

Table 1. Description of different CR determination methods from various points of view.

	Apex of gothic arch	Adduction field	Dawson's manipulation	Linguomandibular homotropy	Chin back
Time investment	5-10 min.	5-10 min.	5 min.	2-5 min.	2-5 min.
Technology sensitivity	high (due to drawing device)	high (due to drawing device)	high (due to practice the manoeuvre)	low	low
Expense (y/n)	yes	yes	no	no	no

3.5. **Mouth opening test - second test session**

The second instance of the mouth opening study was conducted using the Arcus Digma motion analysis module. During this module, the patient performs horizontal, sagittal border movements of the mandible and three maximum mouth openings. The average of these three mouth openings was used. Also, during this study all measurements were performed by one operator. Furthermore, in the case of two randomly selected patients, measurements were performed twice. In this case the Cohen's kappa coefficient was between 0.87 and 0.92.

3.6. **Processing the data**

Data from the two studies were processed at the same time. The data were organised, processed and extracted using the manufacturer's own software (KaVo KiD, Kavo, Biberach, Germany). The software provides a graphical interface that shows the results of each measurement. However, it is also possible to export completely raw data. As described above, the system consists of coordinate points in a three-dimensional coordinate system, with a time stamp associated to each point. In this coordinate system, the origin was in all cases the MIP.

The axes were the following. In all cases, the x-axis was shown as a sagittal displacement. A positive displacement indicates an anterior position, while a negative sign indicates a posterior position. The y-axis is defined as the vertical direction of the displacement. In this case, positive values indicate a more cranial position and negative values a more caudal position. The z-axis indicates horizontal displacement. Here, a positive value indicates a more left lateral position for the patient, while a negative value indicates a more right lateral position for the patient. (Figure 4.)

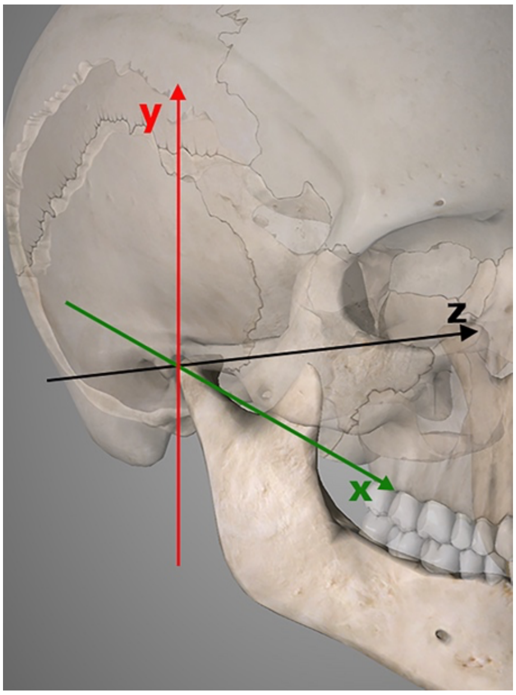

Figure 4. Individual axes of the three-dimensional coordinate system. (37)

The large raw data set obtained after export was first processed in Microsoft Excel (Microsoft, Redmond, USA). Following the structuring of the data for each CR position, the deviations from the origin for each method were first averaged along each axis. Next, the values per side were examined, as well as the values resulting from the two sides together as a sum. The 95% confidence interval (95CI) was then calculated. The use of the confidence interval shows that if the same test is repeated with a similar number of items, the resulting data will fall within the specified range with a 95% chance. This 95% chance corresponds to a significance level of 0.05%. The statistical calculations were carried out using GraphPad Prism software (GraphPad Software, Boston, USA).

Raw data for the mouth opening investigation study were also processed in Microsoft Excel (Microsoft, Redmond, USA). To aid in further data analysis, cubic spline interpolation was used because sampling was done at a specific time interval and not at specific mouth opening positions. This approach ensured that the data were resampled, thereby, providing data for each value from each measurement, which enabled averaging of the data and then statistical evaluation of the measurements. The cubic spline interpolation was calculated using the MATLAB spline() function without any further smoothing, and statistical analysis was performed using GraphPad Prism statistical software.

4. Results

4.1. Results of the study comparing CR determination methods

The deviation of the coordinates from the origin for each method is shown on the x, y and z axes with 95% confidence intervals. The deviation between each position along the horizontal z axis was 0 mm, 95% CI [-0.03, 0.03]. Therefore, these values were set to zero for both sides in the study and were not considered for the remainder of the study.
The following positions were plotted along the x and y axes. The position marked with A indicates the point at the apex of the gothic arch tracing. The point of the adduction field (B) was located very close to it. The result closest to the origin was shown for the CR position determined with the Dawson's bimanual manipulations (C). The position of the tongue at the palatal rugae (tpr) (D) showed a larger deviation. The deviation from the origin was also minimal for the tongue at the hard-soft palate border technique (thpb) (E). In the case where the patient pulled the chin backwards under his own power, i.e. performed an active retrusion (F), a more posterior position was indeed readable. The last data was read off the operator's mandibular retracted position (passive retrusion) (G) deviation.
On the x-axis, the condyle position did not significantly differ from the condyle position associated with MIP (x=0) on either side for the CR position determined by Dawson's manipulation (C) and tongue hard-soft palate border (thpb) (E). Similarly, the position determined with the adduction field (B) on the left side showed no significant difference from MIP. The position defined by the apex of the gothic arch (A) and the position of the tongue to the rugae (tpr) (D) showed a significant difference, in anterior direction compared to the condyle position associated with the MIP. There was also a dorsal shift in active (F) and passive retrusion (G). Also, anterior (ventral) was the condyle position defined by the adduction field (B) on the right side. (Figure 5., Figure 6., Table 2., Table 3.)
On the y-axis, as on the x-axis, the condyle position for the Dawson method (C) and for the tongue at the hard-soft palate border was not significantly different (y=0) from the condyle position in MIP. Interestingly, the condyle position for passive retrusion (G) neither did not differ significantly from MIP on either side. In addition, the position obtained by placing the tongue on the area of the rugea (tpr) (D) on the right side and the position obtained by defining the adduction field (B) on the left side did not differ

significantly from MIP. However, there was also a significant difference in this case, with a more caudal condyle position on both sides, as determined by the gothic arch tracer (A) and the active retrusion (F), compared to the MIP condyle position. By placing the tongue to the rugae (tpr) (D) on the left side, in cases defined by the adduction field (B) on the right side was significantly difference to the origin (MIP) in a more caudal direction. (Figure 5., Figure 6., Table 2., Table 3.)

Table 2. The magnitude of deviations (means and 95% confidence intervals) from the MIP on the x (sagittal) and y (vertical) axes for the different CR determination techniques on the right. Significant differences from MIP (i.e. sagittal: x≠0, verticalis: y≠0) are marked by italics and asterisks.

	Sagittal	Vertical
Apex of gothic arch (A)	*0.28 mm, 95% CI [0.06, 0.51]**	*-0.5 mm, 95% CI [-0.87, -0.12]**
Adduction field (B)	*0.37 mm, 95% CI [0.02, 0.72]**	*-0.47 mm, 95% CI [-0.88, -0.06]**
Dawson manipulation (C)	0 mm, 95% CI [-0.23, 0.23]	0.17 mm, 95% CI [-0.11, 0.45]
Tongue at the palatal rugae (D)	*0.78 mm, 95% CI [0.35, 1.22]**	-0.24 mm, 95% CI [-0.54, 0.05]
Tongue at the hard-soft palate border (E)	0.1 mm, 95% CI [-0.15, 0.36]	0.23 mm, 95% CI [-0.02, 0.48]
Active retrusion (F)	*-0.24 mm, 95% CI [-0.37, -0.11]**	*0.34 mm, 95% CI [0.11, 0.58]**
Passive retrusion (G)	*-0.35 mm, 95% CI [-0.56, 0.14]**	-0.05 mm, 95% CI [-0.43, 0.33]

Table 3. The magnitude of deviations (means and 95% confidence intervals) from the MIP on the x (sagittal) and y (vertical) axes for the different CR determination techniques on the left. Significant differences from MIP (i.e. sagittal: x≠0, verticalis: y≠0) are marked by italics and asterisks.

	Sagittal	Vertical
Apex of gothic arch (A)	*0.3 mm, 95% CI [0.02, 0.58]**	*-0.47 mm, 95% CI [-0.89, -0.05]**
Adduction field (B)	0.29 mm, 95% CI [-0.01, 0.6]	-0.38 mm, 95% CI [-0.81, 0.05]
Dawson manipulation (C)	0.01 mm, 95% CI [-0.21, 0.22]	0.18 mm, 95% CI [-0.06, 0.42]
Tongue at the palatal rugae (D)	*0.79 mm, 95% CI [0.4, 1.19]**	*-0.29 mm, 95% CI [-0.57, -0.01] **
Tongue at the hard-soft palate border (E)	0.13 mm, 95% CI [-0.15, 0.4]	0.18 mm, 95% CI [-0.05, 0.41]
Active retrusion (F)	*-0.28 mm, 95% CI [-0.43, -0.14]**	*0.34 mm, 95% CI [0.14, 0.55]**
Passive retrusion (G)	*-0.46 mm, 95% CI [-0.7, -0.23]**	-0.06 mm, 95% CI [-0.39, 0.27]

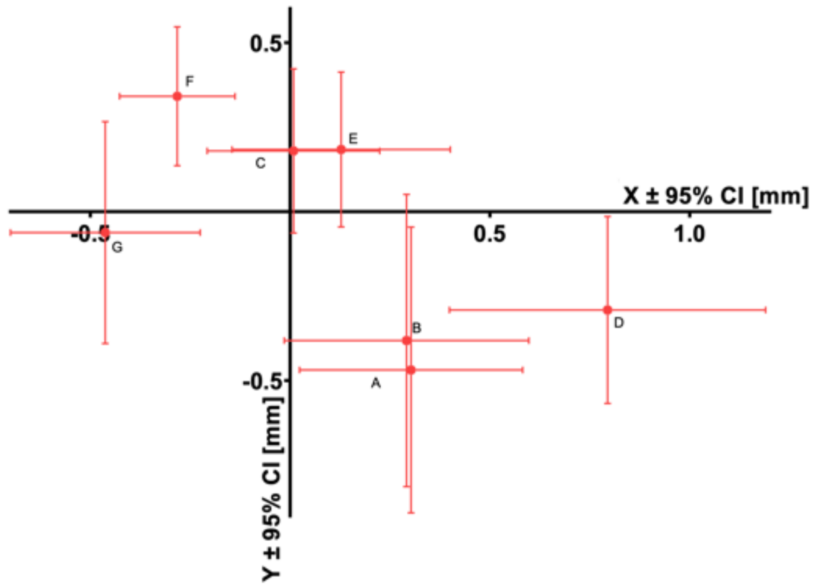

Figure 5. Deviations of the condyle from MIP (origin) after different CR determination techniques on the left: apex of gothic arch (A), adduction field (B), Dawson manipulation (C), tongue at the palatal rugae (D), tongue at the hard-soft palate border (E), active retrusion (F) and passive retrusion (G).(37)

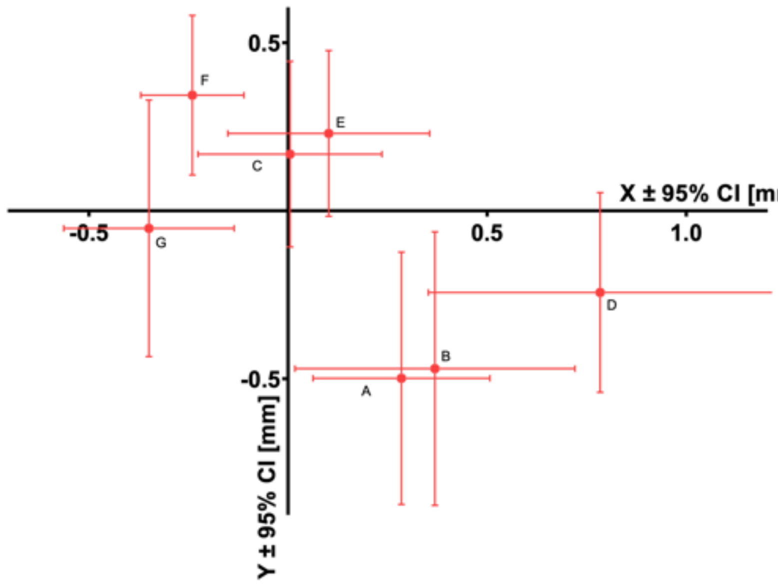

Figure 6. Deviations of the condyle from MIP (origin) after different CR determination techniques on the right: apex of gothic arch (A), adduction field (B), Dawson manipulation (C), tongue at the palatal rugae (D), tongue at the hard-soft palate border (E), active retrusion (F) and passive retrusion (G).(37)

The results obtained were calculated not only per side but also by averaging the two sides. Although, the two side joints can move separately, these movements are still influenced and limited by the opposite joint. In this case, there was no significant change in the results either, in fact, only a clarified result.

For the x-axis, there was no significant difference from MIP for condyle positions as determined by Dawson's manoeuvre (C) and thpb (E). For all other methods, a significant difference was found. (Figure 7.)

Similarly, on the y-axis, there was no significant deviation from the origin (MIP) for the the Dawson (C) and thpb (E) CR determination methods. However, for this axis, the condyle position determined by the tpr (D) position and active retrusion (F), did not differ significantly from the MIP. Also along this axis, all other methods (A, B, G) showed significantly different results from MIP. (Figure 7. and Table 4.)

Table 4. The magnitude of deviations (means and 95% confidence intervals) from the MIP on the x (sagittal) and y (vertical) axes for the different CR determination techniques as the average of two sides. Significant differences from MIP (i.e. sagittal: x≠0, verticalis: y≠0) are marked by italics and asterisks.

	Sagittal	Vertical
Apex of gothic arch (A)	*0.29 mm, 95% CI [0.06, 0.53]**	*-0.48 mm, 95% CI [-0.86, -0.11]**
Adduction field (B)	*0.33 mm, 95% CI [0.01, 0.65]**	*-0.43 mm, 95% CI [-0.82, -0.03]**
Dawson manipulation (C)	0.07 mm, 95% CI [-0.21, 0.22]	0.17 mm, 95% CI [-0.08, 0.42]
Tongue at the palatal rugae (D)	*0.79 mm, 95% CI [0.38, 1.19]**	-0.27 mm, 95% CI [-0.55, 0.01]
Tongue at the hard-soft palate border (E)	0.11 mm, 95% CI [-0.14, 0.37]	0.21 mm, 95% CI [-0.02, 0.44]
Active retrusion (F)	*-0.26 mm, 95% CI [-0.39, -0.14]**	*0.34 mm, 95% CI [0.13, 0.55]**
Passive retrusion (G)	*-0.41 mm, 95% CI [-0.62, -0.19]**	-0.06 mm, 95% CI [-0.4, 0.29]

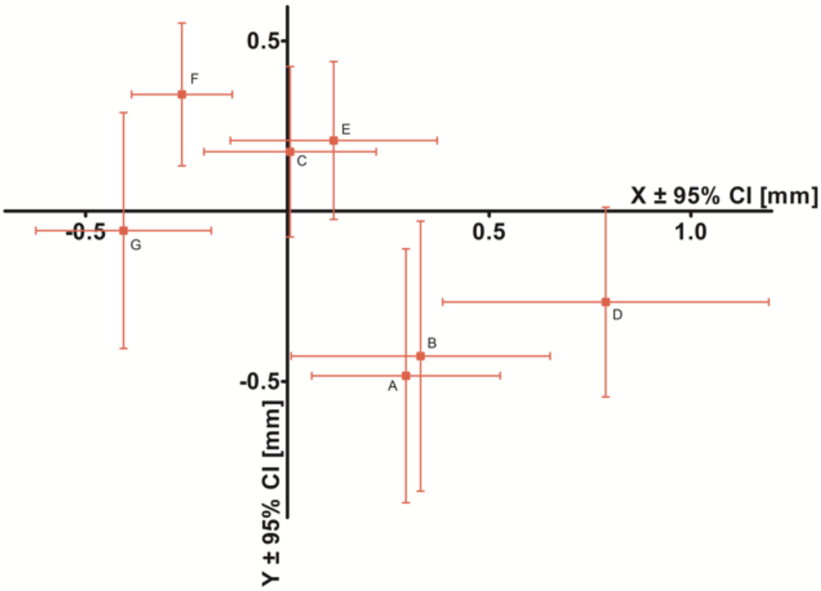

Figure 7. Deviations of the condyle from MIP (origin) after different CR determination techniques with the means of both sides: apex of gothic arch (A), adduction field (B), Dawson manipulation (C), tongue at the palatal rugae (D), tongue at the hard-soft palate border (E), active retrusion (F) and passive retrusion (G). (own figure)

4.2. **Results of the investigations of mouth opening**

As described above, the device records a three-dimensional coordinate every two hundredths of a second for the right and left condyle and incisivus points. Thus, information is obtained simultaneously on the amount of mouth opening at the incisors (incisivus point) and the amount of translation of the condyles. From the coordinates that can be exported from the software interface of the measuring instrument, the length of the paths followed can be mathematically determined with an accuracy of hundredths of a millimetre. Thus, the extent of translation as a function of mouth opening for each patient could be visualised. In the evaluation of the results, the data obtained at the initial 0.2 mm of opening were not taken into account. This is the initial, steeper slope of Figure 8. In these sections, the presence of varying slope steepness is evident, indicating the presence of an artifact.

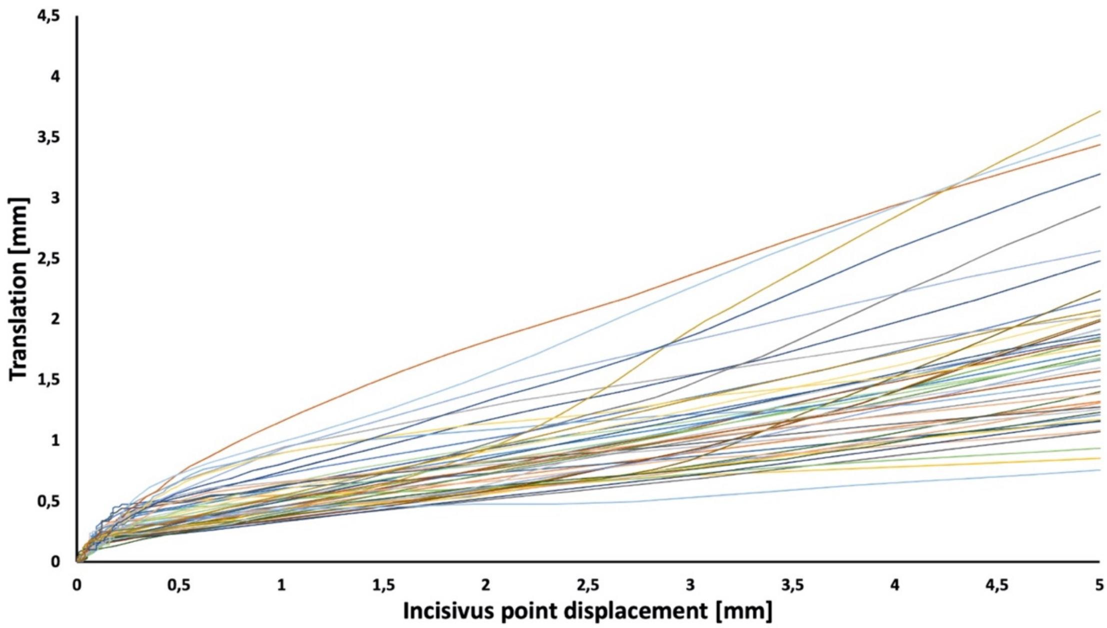

Figure 8. Translational movement of condyles as a function of the displacement of the incisivus point.(38)

After the statistical analysis, the measured data were transformed to a continuous variable and, after repeated sampling, the relationship between translation and opening (displacement of incisivus point) was quantified by linear regression. The best-fitting regression line yielded an impressive coefficient of determination (R^2) of 0.9981. It had a slope of 0.3044 (with a 95% confidence interval of 0.3023 to 0.3065) and an intercept of 0.2382 (with a 95% confidence interval of 0.2318 to 0.2445). This slope was significantly different ($p<0.0001$) from the slope of 0, which is the horizontal line, that representing only rotational movement. (Figure 9.)

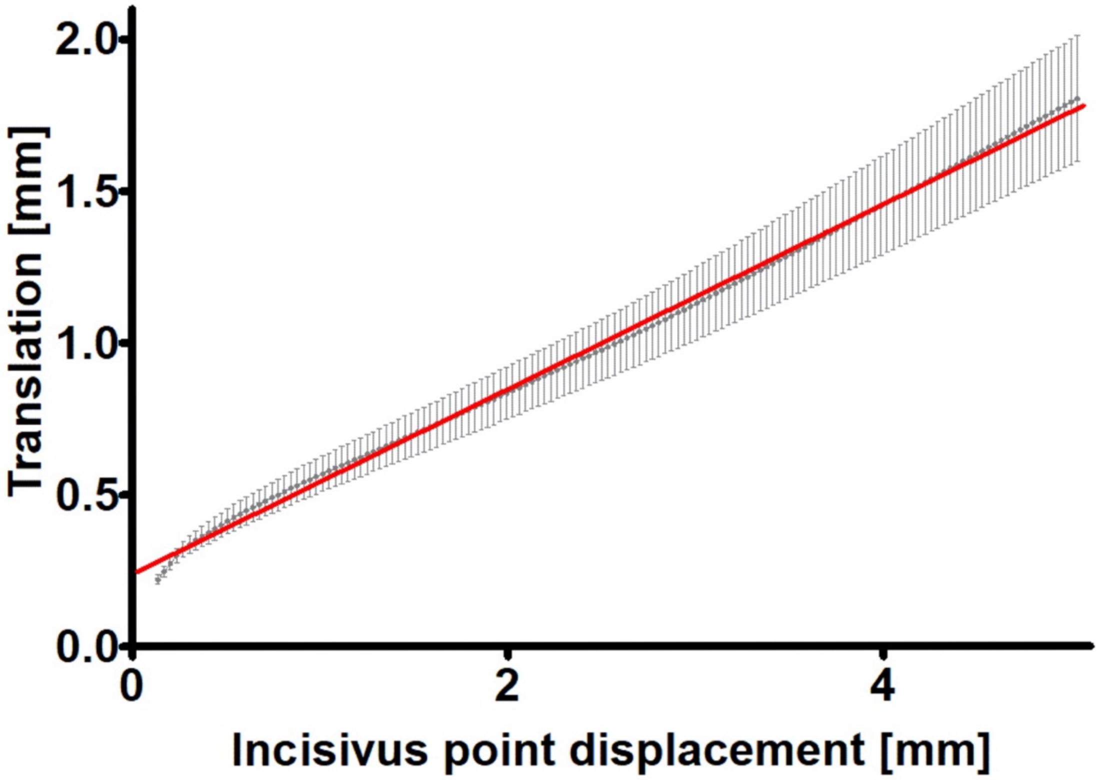

Figure 9. Displacement of the incisivus point (mm) as a function of the translational movement of the condyle (mm) and the best-fitting regression line. The data are shown as the average ± 95% CI; n=46.(38)

5. Discussion

The two topics discussed are not entirely novel, as the previously mentioned in the introduction, both topics have long been of interest to researchers in the field. As a result, over 50 years' worth of data is available to compare and serve as a point of reference.

5.1. Comparison of CR determination methods

Studies comparing the different CR determination methods were presented in early, as well as recent literature.(39-41) This shows the importance of CR determination methods in the daily work of dentists. The accuracy of these methods is difficult to determine, nonetheless, it is absolutely vital. Most authors only provide a description, theoretical and practical demonstration of their methods, but are not accompanied by in vivo studies where their methods are compared vis-a-vis a standard position.(42, 43) Notwithstanding the importance of previous results, no method can truly be called an accurate method without a standardised point of reference. Due to the nature of the topic, perhaps unsurprisingly, *in vitro* research does not exist. However, the *in vivo* researches that does exist can be divided into two major categories. Some of the studies have investigated methods of CR determination in edentulous patients.(40, 44) The other group included volunteers with no tooth loss or with small restorations that did not affect articulation movements.(17, 25, 39, 45) This is important because in both cases a different reference position can and should be chosen. In the second group, which includes the present study, the CR position determined by different methods is compared with MIP.(34, 46) The advantage of this position (MIP) is that it is clinically extremely easy and accurate to reproduce.

5.1.1. The history of the CR definition

One of the oldest such comparative studies in the field dates back to 1972 by Kantor and colleagues.(47) In this study, 4 methods for determining CR status were examined in participants without tooth loss:

- Swallowing and free closure (Shanahan) - in which the patient maintains a comfortable position while swallowing. This technique is described as positioning the mandible not only vertically, but also horizontally, thus defining the central relation condyle position. It is important that the dentist does not touch the jaw in any way during this procedure.(48)

- Position defined by pressure on the chin (McCollum) - corresponding to an active retrusion. The basic principle of the method is that CR is the position from which the mandible is capable of pure rotation.(16) This is only possible from the RCP.
- Anterior jig (Lucia) - an oblique plane placed on the maxillary front teeth to eliminate tooth contact and thus eliminate proprioceptive sensation with the teeth. In that way the muscles move the jaw to the CR position.(41)
- Bilateral manipulation based technique (Long) - Long's observation was that active retraction of the mandible often results in inferior (caudal) displacement and to avoid this he suggested a more superior (cranial) positioning with slight retrusion. (49)

The study included 15 participants and CR was determined six times using all four methods. In the investigation phase registration was performed using wax sheets coated with metal oxide and the conventional gypsum casts were fixed in articulators. Measurement was possible along two axes on millimetre paper. The 6 points determined by each method at different times were plotted separately. In this way, in addition to the relative position of each method in relation to the other, the reproducibility of each method (each point as close as possible to the other) could be concluded. In this study, bilateral manipulation was found to be the most reproducible. The results demonstrated that the CR position determined by swallowing was most ventrally located.(47)

In order to better understand this result, it is necessary to briefly discuss the history of the definition of CR. This definition has significantly changed over the years, perhaps one of the most in dentistry. The first definition of CR was described by Hanau in 1929: "I have defined centric relation as that position of the mandible in which the condyle heads are resting upon the menisci in the sockets of the glenoid fossae, regardless of the opening of the jaws, and have stated that the relation is either strained or unstrained."(50) Later, with the introduction of the GPT, there was a change in the definition of CR. In the first editions of the GPT, the definition of CR was the rearmost available position of condyles in the fossa articularis. "The most retruded relation of the mandible to the maxillae when the condyles are in the most posteriorly unstrained position in the glenoid fossae from which lateral movements can be made, at any given degree of jaw separation."(51)

Finally, the term was changed again in the fifth edition of the GPT and is still in use today: "A 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 slopes of the articular eminences. This position is independent of tooth contact. This position is clinically discernible when the mandible is directed superiorly and anteriorly and restricted to a purely rotary movement about a transverse horizontal axis. This term is in transition to obsolescence."(23) A simplified, shortened version of this phrase has been added. However, this no longer represents a change in content.(7, 52)

Due to the frequent changes in the definition of CR, the results published by Kantor and his colleagues in 1972 can be evaluated quite differently today than when they were published. Techniques which were considered to be accurate at the time (jig, bilateral manipulation, passive retrusion) resulted in a too retruded positioned condyle position according to today's concepts. On the other hand, the position defined by swallowing, then described as too ventral, may be the closest to the anterior superior CR position preferred today.

An interesting and controversial aspect is that the CR determination techniques that were included in the present study - with the exception of the Dawson method - all existed at the time of the publication of Kantor et al. cited above.(29, 36, 41) However, in this publication, most of these methods were not even examined: of all the techniques examined, passive retrieval was found to be one of the most accurate (closest to CR in the terms used at the time) of all the techniques. The explanation for this is twofold. On the one hand, it may be related to the changing definition of CR in GPT, and on the other hand, it may be due to the evolution of medical devices and, with them, of diagnostic tools.

In the 1970s, methods that existed at that time but are now accepted (such as intraoral drawing or linguomandibular homotropy) became widespread after the change of definition of CR in GPT in 1987. As noted above, this was when the definition of CR changed to the anterior superior position still used today.(53) This could be a possible explanation for the wider use of these methods. The condyle is then positioned in the desired anterior superior position, as determined by the current state of knowledge in the field. And it is quite understandable that no methods were investigated that almost

certainly defined anterior (ventral) CR position too much according to the desires of the time.
The development and evolution of diagnostic tools allows for significantly more accurate and, thus, less subjective measurements. This progress started already in the mid-1980s with Hobo et al. who developed a self-designed mandibular motion analyser, which not only measured movements but also different static CR positions.(19) During the second half of the 1990s, the first generations of digital motion analysers - still in use today - appeared.(54)

5.1.2. CR determination nowadays

According to the relevant literature since the turn of the millennium, there have been fewer studies than before that have examined the accuracy of some methods. During this period, more and more studies focused on the reproducibility of the methods.(46, 55, 56) Accuracy was examined in a publication by McKee et al. where the authors analysed the accuracy of bimanual manipulation (Dawson) and CR positions defined by the anterior jig.(57) A limitation of the study was that they compared the positions by mounting the casts an articulator, as previously used in other studies. This allowed a thin (0.11 mm) graphite tip to mark each position. Therefore, smaller differences reamined hidden. Nevertheless, no significant difference in accuracy was found between anterior deprogramming and bimanual manipulation. However, it is mentioned that both methods require an increase in the OVD, which may affect the accuracy of the methods.(57)
A number of studies on the reproducibility of each method can be found. A study published in 2003 examined deprogramation with an anterior jig, gothic arch tracing and bilateral manipulation.(46) Each of these methods was used to determine CR on four different occasions. Again, the limitation of the study was that the positions determined by each method were compared in an articulator after an facebow transfer using a specially developed tool (mandibular position indicator). This solution was able to visualise differences of 0.1 mm. The study included 14 patients with natural dentition. The origin and reference point was the MIP. Their results showed CR positions that both bimanual manipulation and with an anterior jig determined were well reproducible. However, for the position determined with the gothic arch tracer, a discrepancy was found between the positions recorded at different points of time. The reason, in their opinion, is that gothic arch tracer is an active method. It is the movement and contraction of the

patient's muscles that gives the result (the gothic arch shape). For all these reasons, current emotional state can also influence the examination. The authors mentioned as an observation that, for some methods, it was not even possible to know exactly whether the condyle was actually in the desired anterior superior position after each method. Several answers to this question have since been proposed. In a number of studies, each CR determination method has been performed while monitoring the position of the condyles in the fossa articularis by some imaging techniques. These imaging techniques could be cone-beam computed tomography (CBCT) or magnetic resonance imaging (MRI).(25, 58)

Kandasamy et al. compared three condyle positions using MRI.(25) These were MIP, active retrusion and CR position determined by the Roth power centric technique. Of the 38 joints of 19 participants, 33 showed no difference in anteroposterior direction between the positions. In the transverse plane, there was also no significant difference between condyle positions. The results show that there was only a few mm difference between the condyle positions.(25) The position of the condyles can also be determined using CBCT. However, a limitation is that the position of the discus articularis can only be inferred in this case. Ferreira et al. investigated the difference between MIP and CR position determined by anterior jig using CBCT.(58) The study group consisted of TMD asymptomatic adults (n=10). After the recordings were made, the distances between condyle and fossa/eminentia articularis were measured along each axis in this case as well. The results showed no significant difference between the head positioning MIP and CR.(58)

In recent years, the number of in vivo studies on this topic has decreased and review publications have been the most common. These have investigated the relationship between CR and MIP and its significance.(34) A comparison was made between the various CR determination methods that can be used.(59) The most important result of these is that if a patient has a stable MIP, but this does not coincide with the CR, then it is not necessary to change the MIP.

5.1.3. Present study

In comparison with the relevant literature, the use of a digital motion analyser represents a novel methodological advantage. In our research, we conducted the most extensive comparison with the literature listed above. The accuracy of seven different techniques used to determine CR, previously and currently commonly used in day-to-day clinical practice, was investigated. Similarly to previous studies, the reference point was the MIP for simplicity and reproducibility.(46) Five out of the seven techniques showed significant deviations along at least one axis on at least one side of the reference point (MIP). The Dawson technique and the tongue at the hard-soft palate border (thpb) technique showed no significant deviation from the reference point on either side of either the x or y axis. The tongue at the palatal rugae position, although showing no significant deviation in the y-axis on the right side, showed the largest deviation in the x-axis, so using this method may result in a more protruded position of the lower jaw than desired. Regarding linguomandibular homotropy, it is important to note that Walter Wild did not provide a precise description of the method. He merely stated that the mandible could be moved to a different position by moving the tongue.(36) Thus, over the decades, different methods have been developed by placing the tongue in the area of the rugae palatinae or the border between the hard and soft palate.(60)

The active and passive retrusion of the mandible has clearly resulted in a more retruded position than desired. This corresponds exactly to the position previously accepted as CR, which was then common because of its ease of reproduction.(49) The use of these methods, however, clearly carries the risk of locking the condyles in RCP, which is posterior to the CR position. The results obtained with intraoral tracing are controversial. The position defined by the apex of the gothic arch shows a significant difference on both sides and along both axes. However, for the position defined by the adduction field, there is no significant difference on the left side along either axis. On the right, there is a significant difference along both axes.

To resolve this, it may be useful to examine the average of the two sides. In this case, however, this method also shows a difference along both axes. The reason for the discrepancy in the positions determined with the intraoral tracing device can be found in the compromised use of the technique. The reason for the discrepancy may be that the minimum opening may also be associated with a translational movement of the condyle (see mouth opening datas) and, as a consequence, significantly anterior and inferior condyle positions were detected. Thus, it can be stated that in cases where the examination cannot be performed at the OVD (e.g. fully dentate patients), the dentist can and should expect some inaccuracy in this method.

The coordinate system showing each method provides important guidance on the issue. Next to each method, by adding the condyle position it defines, each point can be seen to accurately represent the shape of the fossa and eminentia articularis. (Figure 10.)

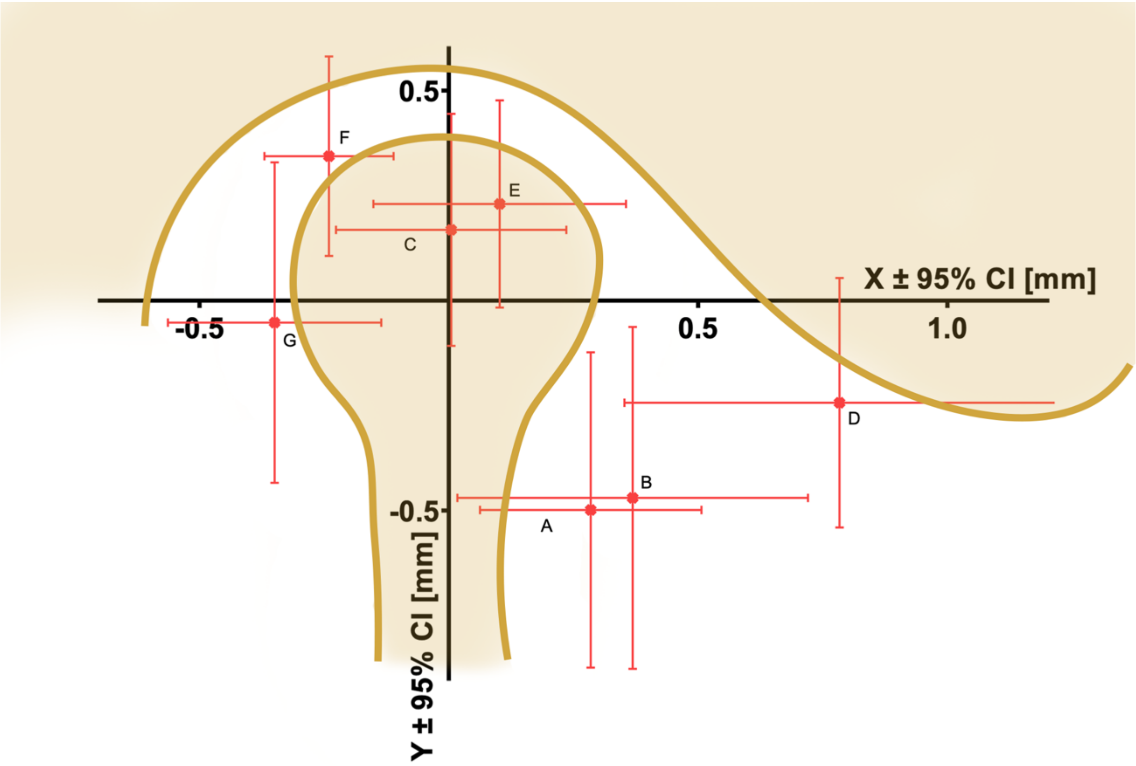

Figure 10. Relationship between condyle positions determined by each CR definition method and MIP projected onto the TMJ schematic image. Apex of gothic arch (A), adduction field (B), Dawson manipulation (C), tongue at the palatal rugae (D), tongue at the hard-soft palate border (E), active retrusion (F) and passive retrusion (G). (own figure)

In 2021, Ramaswamy et al. published a systematic review. The authors conducted a comprehensive search of major bibliographic databases, including MEDLINE, PubMed, Cochrane, and Google Scholar between 1998 and 2019 for the terms Centric relation techniques AND/OR Retruded mandibular position. Out of 958 publications, 9 met the criteria. Of these, 4 involved dentate and 5 examined edentulous participants. Based on these data for dentate patients, the review concluded that Dawson's bimanual manipulation was the most accurate overall.(61) This finding is consistent with the results of our study.

5.2. **Movement of the mandible during initial phase of mouth opening**

5.2.1. The history of theory pure rotation

Research on mouth opening dates back to the 18th century. It was first described by Ferrain in 1744 that the TMJ can be divided into two joints and that different movements occur in each joint during mouth opening and closing. This was first visualised by Ulrich and Walker, who recorded the movements of the mandible with a drawing instrument fixed to the mandible and a plate fixed to the skull.(62)

The next major step was taken by George E. Campion, who attached a device similar to a facebow to the maxilla, which recorded the displacements of the condyle on a plate placed on the skin projection point of the condyle. On the basis of his measurements, he already suggested that during opening, the mandible does not rotate around an intercondylar axis, but that this axis changes in a continuous translation.(15)

In the early 20th century, Eitner described the concept of hinge movement theory. Andersen furthered this concept to create a facebow to define this axis.

Nevertheless, the most significant step was taken by McCollum in 1934, when he created a device to record the rotation of the mandible, that was the kinematic pantograph, and its associated articulator.(15) He had already tried to determine rotation using a facebow, but it was this device that provided a major breakthrough. The part of the pantograph attached to the mandible drew concentric circules on the upper part of the skull during mouth opening. If the circles disappeared and only one point was visible, then only rotation was present during opening. At this point, the pantograph made it possible to determine the true individual axis of rotation (terminal hinge axis-THA).(42, 63) The instrument was also the first to allow the study of mandibular movements in three dimensions of space. This method was eventually further developed by Lucia in the 1960s. Digital versions of these are our most important functional measuring devices as of today.(62)

5.2.2. Examination of the instantaneous centre of rotation

Since the 1970s, research on the instantaneous centre of rotation (ICR) has come to the fore.(64) These have been more cautious about the presence of pure rotation. Nevertheless, there is still universal consensus on the topic of pure rotational motion during mouth opening.(20, 24, 26, 65) This can be followed in the publications that appear and in GPT, where it is not clear exactly which movements are exactly present during various stage of mouth opening and with what magnitude.

The method described in the 1970s attempted to determine the ICR. This method, which is adapted from anatomy, shows that the bones that make up a joint rarely move along a single axis when they are displaced.

This experience was put into practice by Grant in 1973.(64) He mathematically calculated the ICR for different degrees of opening from the direction of pull of the muscles and the extent/strength of this pull. The results show that rotation occurs around a continuously variable axis during opening and closing. Based on these data, he rejected the possibility of pure rotational motion.

Around the turn of the millennium, Chen et al. performed an in vivo study using the basis of Grant's research.(66) In this case, the ICR was calculated mathematically, but the data required were not calculated, rather, it was real data collected from photographs of seven volunteers. On these participants marker points were assigned and tracked by photos as they changed. Based on the results, the authors concluded that the ICR changes continuously during opening and closing. Thus, pure rotational motion certainly cannot happen in the TMJ. However, they do note that ICRs are closer to the centre of the condyles during the initial phase of opening (up to 10° mouth opening), indicating the dominance of rotational movement over translational movement.(66)

A limitation of the above study is that the method only examined displacements in two dimensions. Ferrario et al. investigated the position of the ICR and the resulting instantaneous centre of curvature (ICC) during opening and closing using a Sirognathograph.(65) Their results showed that only rotation was not present during either opening or closing at any stage of the movement. Thus, the ICR theory proved to be true in this case as well. Furthermore, they found that the speed of movement affected the position of the ICR.

Ahn et al. investigated the change in ICR position during mouth opening and mouth closing in a virtual space using a digital pantograph model. The study was highly accurate with a resolution of one thousandth of a second (0.001 s). The design of this study was rather similar to ours, but it was an in vitro study. Even here, the ICR was not held constant during the simulations. The points registered during opening and closing did not coincide, which is consistent with what we found in our study.(67) This is due to the contraction of the suprahyoid muscles and, to a lesser extent, infrahyoid muscles towards to caudal directiom during mouth opening.

During mouth closure, on the other hand, the mandible elevate muscles (m. masseter, m. pterygoideus medialis, m. temporalis) pull the lower jaw in a cranial direction, which presses the condyles into the fossa articularis. This is the reason why the displacement of the condyles does not follow the same path during the opening and closing.(3) A distance of less than 1 mm was detected between the instantaneous centres of rotation measured at the initial and 10 mm mouth opening.(67) This is important because it may explain previous data in which pure rotational movement was demonstrated with mechanical pantographs.

Taking into account the inaccuracies of this mechanical measuring instruments (e.g. thickness of the tip of a drawing pencil) and the perceptual limitations of the human eye, which, taken together, can hide such a small difference. This result (a measured translation of 1 mm) is below the translation recorded in our study, which was close to 2 mm for the first 5 mm of mouth opening. The reason for the difference between the results of the two studies is not entirely clear, but may be related to the fact that some researchers have questioned the relevance of ICR, as its measurement accuracy raises several problems, and it has been found to be insufficiently accurate and reproducible.(68)

5.2.3. Pure rotation in the context of the latest research

In an in vivo study, Mapelli et al. examined the relative contribution of rotation and translation to mandible displacement during mouth opening and closing using an optoelectronic device that provides 3D images.

The displacement of the incisivus point and lateral point of condyles and the distance between these points in the sagittal plane (as the rotation about the vertical and sagittal axes was negligible) was recorded for each of the 26 participants. In addition, the degree of rotation of the mandible about the intercondylar axis was measured. For comparability of the results, the path of the incisivus point sagittal projection to maximum mouth opening was divided into ten equal parts in percentage. For each section, the percentage of the symphysis point displacement contributed by rotation was examined. The displacement due to rotation was always greater than the displacement due to translation, but never approached 100%, so no pure rotation was ever found. The extent of translation was similar between sexes, but the condyles of males, regardless of mandibular size, had taken a longer path than those of females. A linear correlation between the maximum mouth opening and the distance the condyles translate was also investigated, but no significant correlation was found between the two.(26)

In a study conducted in 2018, Mehl et al. tried to determine whether the pantograph is at all capable of distinguishing between pure rotation and combined movement (rotation and translation).(69) In addition, the researchers examined the extent of inaccuracy in THA determination due to the presence of translation in combination with rotation. The analysis was mathematically derived and the results were verified by computer simulation. The results showed that these instruments are not capable for the detection of pure rotation. A translation of 1.1 mm can result in a displacement of the THA of 6.7 mm, and a translation of 2.2 mm can result in a displacement of the THA of up to 13.5 mm.(69) All these results indicate that the results reported in the literature for mechanical pantograph tests used to determine THA should be treated with caution.

5.2.4. Clinical investigation into the presence of pure rotational movement in TMJ

In the present study, the previously presented ultrasonic motion analysis device (Arcus Digma II) has a much higher accuracy (50μm) than its mechanical predecessor.(28, 30, 70) As described above, most of the studies published on this topic are in vitro studies using casts. The significance and novelty of our study is that it is an in vivo study with a relatively large number of patients.

The measurements were performed by examining the full mouth opening. From these data, the first 5 mm were taken and analysed. The initial steeper section - about the first 0.2 mm of opening - looks anomalous in the data. As can be read in the results, this section was identified as an artifact and was not considered in the statistical analysis. This may be due to the physical size of the transducers on the paraocclusal clutch and its inertia at the beginning of the movement. The results showed that no pure rotation movement was found in any of the cases. During the first 5 mm of opening, rotation had occurred by a translation that varied between individuals, ranging from 0.5 to 3.5 mm. It is also important to note that this translation movement is continuous and progressive, rather than occurring instantaneously at the first stage. A limitation of this study is that instead of defining an exact kinematic axis, only the arbitrary axis was defined.

This difference is also reflected in the use of arbitrary facebows in everyday practice. Furthermore, these devices do not show significant inaccuracy compared to kinematic facebows.(71) Thus, the minimal difference between the two axes, however, did not affect the obtained results in any significant way. Based on these results, a new test method was used to confirm that no pure rotation happens in the temporomandibular joint during the initial stage of mouth opening. Translation is also present from the beginning of the movement. This statement is in agreement with the most recent research results in the literature.(6, 32, 72-74)

5.3. Relationship between the two studies

5.3.1. The historical relationship between mandibular movements and the position of CO

At first glance, it may be difficult to find a correlation and a link between the two studies described. However, I will attempt to show that there is indeed a connection and correlation between the two.

First of all, it is important to examine the saggital border movement of the mandible. This can be done with the saggital Posselt's diagram showing the displacement of the incisivus point.(3, 5) The upper part of the diagram shows the RCP-MIP transition, sliding. From there the further protrusion through the incisive bite to the maximal protrusion. From this point follows the characteristic curve of the mouth opening up to the maximum mouth opening. Then the posterior part of the curve, during which the patient close the mandible with active retrusion throughout. The deflection point is formed in the middle of the movement and finally returns to the initial RCP.

During the movement between the deflection point and the RCP, a mouth opening of 20-35 mm is/can be possible, depending on the individual.(5) Examining the same 20-35 mm in the saggital plane of the condyles, it can be seen that the condyles remain in it position, i.e. they do not show any translational movement.

It follows, that only pure rotational movement occurs in the TMJ in the direction cranial from the deflection point.(3) This fact should be compared with the fact that until 1987 the CR position was the same as the RCP (when the term CR was changed to the upper first position, which is still used today).(53)

This, in fact, confirms the statement that from the CR position an opening of 20-35 mm is possible with pure rotation.(75) Naturally, it should be added that during this type of opening the patient must be actively retruded. Therefore, the previous definitions, which were in line with the knowledge at the given time, are acceptable.

Finally, it is worth comparing the saggital Posselt's diagram and the normal mouth opening. Here again, it can be established beyond doubt that there is no pure rotational movement during mouth opening. In most cases, the back border of the Posselt's diagram and the path of the mouth opening do not coincide. (Figure 11.)

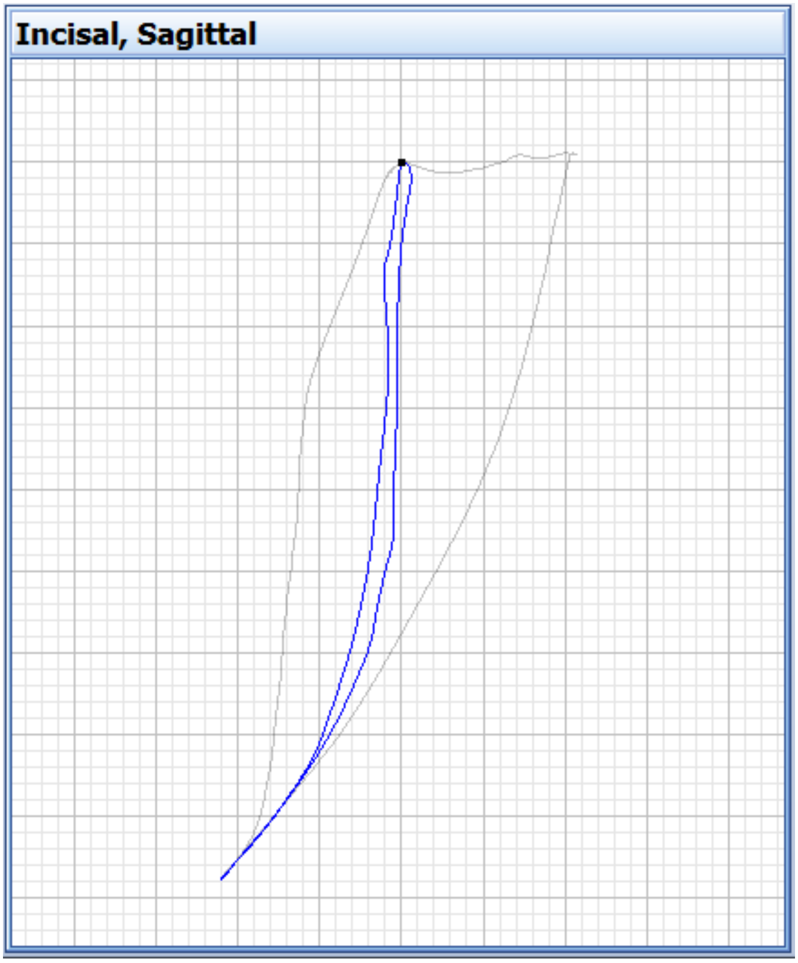

Figure 11. Displacements of the incisivus point during saggital border movements of the mandible (saggital Posselt's diagram) (grey) and mouth opening (blue). (own figure)

5.3.2. The relationship between CR positions determined by intraoral tracing and mouth opening

As shown above, the CR positions (gothic arch and adduction field) determined with the intraoral tracer were approximately 0.4 mm ventral and caudal to the origin (MIP) (Figure 7.) To perform the determination method, the OVD usually must be raised by approximately 1 mm, so a 1 mm opening can be used. Considering the figure obtained from the mouth opening study, it can be seen that an average of 0.5 mm of translation is associated with a mouth opening of 1 mm. (Figure 9.) This finding lends further support to the assumptions of our study on CR positions, as corroborated by the results of the mouth opening study.

5.3.3. The relevance of the test for today's dental practice

The impact of our studies in day-to-day dental practice is diverse. During prosthetic rehabilitation, orthodontic planning or even splinting, a common stage of work is the step of determining the maxillo-mandibular relation. In these cases, it is of paramount importance which CR determination method is used, in order to achieve correct positioning of the condyles in the anterior superior position within the fossa articularis.

The importance of the translation during the mouth opening is also twofold and can be approached from both prosthetic and orthodontic perspectives. Among the prosthetic treatments, bite elevation is where the presence of translation from the very beginning of the opening should be expected in all cases. This means that it is certainly not possible to make a sufficiently accurate prosthetic rehabilitation in any case where bite elevation occurs only along a hinge movement, e.g. in the articulator. In orthodontic planning, it is also important to consider that the smallest change in OVD should already count for the presence of translation.

Overall, it can be said that several areas of dentistry are worth considering the results of these studies.

6. Conclusions

6.1. CR determinations comparing research

A comparative analysis of the most commonly used CR determination methods in clinical practice reveals several key conclusions.

- The present study indicates that, in patients with natural or restored dentition and intact TMJ, the CR determination method with no significant deviation from the MIP is Dawson's bimanual manipulation and lingumandibular homotropy with the tongue placed at the border of the hard and soft palate.
- The results of the present study indicate that if the CR position is determined with linguomandibular homotropy (the patient places the tongue in the area of the rugae) or with a gothic arch tracer (apex of the gothic arch or adduction field), an anterior deviation is to be expected. The amount of this deviation in this area is a few tenths which is not significant compared to the dimensions of the joint. Thus, it cannot be clearly stated that the use of these techniques is contraindicated.
- The present study's findings indicate that a retruded condylar position is achieved through active and passive retrusive movement of the mandible. Therefore, the use of these methods should be avoided in all cases.

The null hypothesis is thus confirmed.

6.2. Research on translation during mouth opening

Based on the results of the ultrasonic motion analysis of the mouth opening, it can be stated that from the very first phase of the opening (after the initial 0.2 mm), translational motion is present along with pure rotational motion.
The null hypothesis is thus confirmed.

7. Summary

The TMJ is in many ways the most unique joint in our body. Examination methods that have become available in the 21st century have allowed much more accurate and much more complex analysis of these joint than ever before. These methods include digital motion analysis. In the present studies, a KaVo Arcus Digma II ultrasonic digital motion analyser was used. This device has a resolution of 50 μm, so that both static positions and dynamic movements can be investigated with high accuracy. The first study compared the various CR determination methods commonly used in clinical practice.

As the study group consisted of individuals with natural or restored dentition (with minimal restorations), the MIP was used as the reference point. The CR positions determined by different methods were, thus, compared to this reference. The results showed that the CR positions determined by Dawson's manipulation and by raising the tongue to the border of the hard and soft palate (linguomandibular homotropy) did not differ significantly from the MIP.

These methods can, therefore, be safely used to determine CR position. Positions determined by gothic arch tracer (adduction field, apex of gothic arch) and positions recorded by placing the tongue to the palatal rugae are significantly different from MIP along at least one axis in the caudal or ventral direction.

However, this deviation is so small and, given the limitations, these methods are probably safe to use in everyday practice. However, methods involving passive and active retrusion of the jaw always result in a posterior deviation from MIP and are not recommended.

In the second study, joint movements occurring in the first 5 mm of mouth opening were investigated. The average of three consecutive mouth openings of the patients was analysed. The data obtained clearly show that from the first millimetre of mouth opening onwards, in addition to rotation, there is a continuous translational movement of the condyle. These data should be taken into account in any dental treatment involving a change of vertical or horizontal maxillo-mandibular position.

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