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The virtual articulator in aligner orthodontics

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The assignment of the mandible to the maxilla and thus the occlusal relationship in the virtual treatment simulation was previously performed exclusively in centric occlusion by means of a buccal scan. When the tooth position is changed in the virtual treatment simulation, the assignment of the mandible to the new occlusion is made by means of "best fit", a pure vertical elevation of the mandible that differs from the closing and opening movement of the mandible in real motion according to the global centre of rotation, formerly known as the hinge axis. Thus, the occlusal relationship set at the end of the virtual treatment simulation always differs from the patient's occlusion at the end of treatment. Recording the real motion and subsequent matching in the virtual treatment simulation, on the other hand, makes it possible to correct virtual tooth positions under the patient's individual opening and closing movement using their real motion within the global centre of rotation. In addition, the assignment of the mandible to the maxilla in the virtual treatment simulation can take place in a corrected, physiological condylar position. Arch motion analysis, followed by use of the virtual articulator in the virtual treatment simulation, represents the missing link in a fully digital orthodontic workflow.

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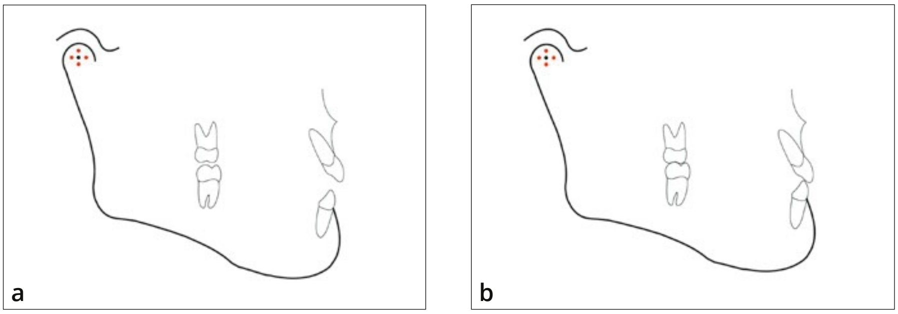
Introduction

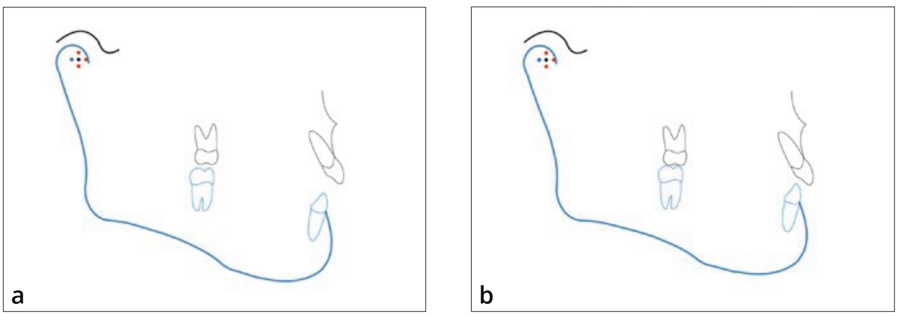
Every functional diagnosis starts with a clinical examination[1]. Functional diagnosis and therapy are simplified, improved and objectively visualised by digital movement acquisition systems[2], which can be applied for functional treatment and documentation[3]. The condyle position is dominated by the occlusion in the final maximum bite position. Any change in the occlusion consequently also alters the condylar position. In a healthy joint, the joint space should not be changed by correcting a malpositioned tooth. If the joint space is altered pathologically, this means a temporomandibular dysfunction is present or will be in the future. Orthodontic treatment should adjust the joint space to a new, physiological positional relationship. Matching the real movement pattern in virtual treatment simulation (VTS) software makes this possible.

Occlusal change due to different centres of rotation

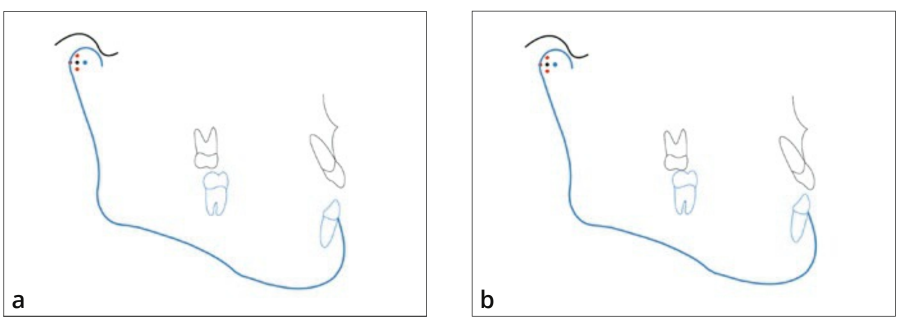
Figures 1 to 5 demonstrate the different occlusal relationships that appear when the virtual axis is moved from the



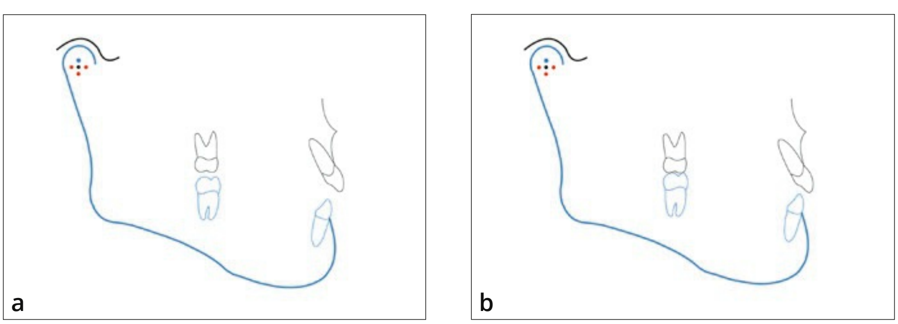
Figs 1a-b **(a)** Arch closure is achieved by rotation in the global centre of rotation (GCR). **(b)** The occlusal contacts occur in the GCR posteriorly (molars) and anteriorly (incisors) in a physiological contact point pattern.



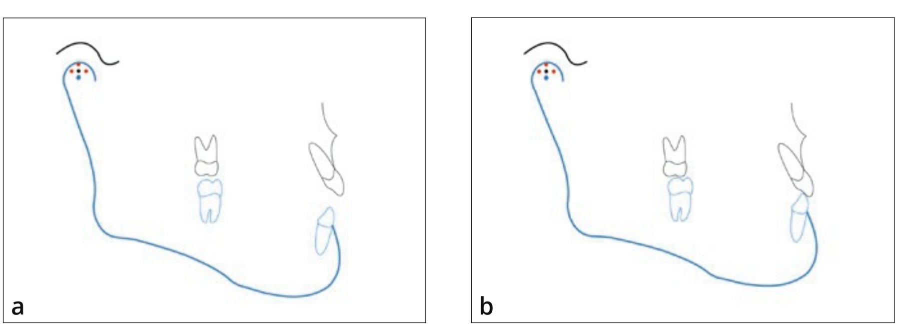
Figs 2a-b **(a)** Arch closure takes place through the retrally displaced axis. **(b)** The occlusal contacts result in arch closure only posteriorly (molars).



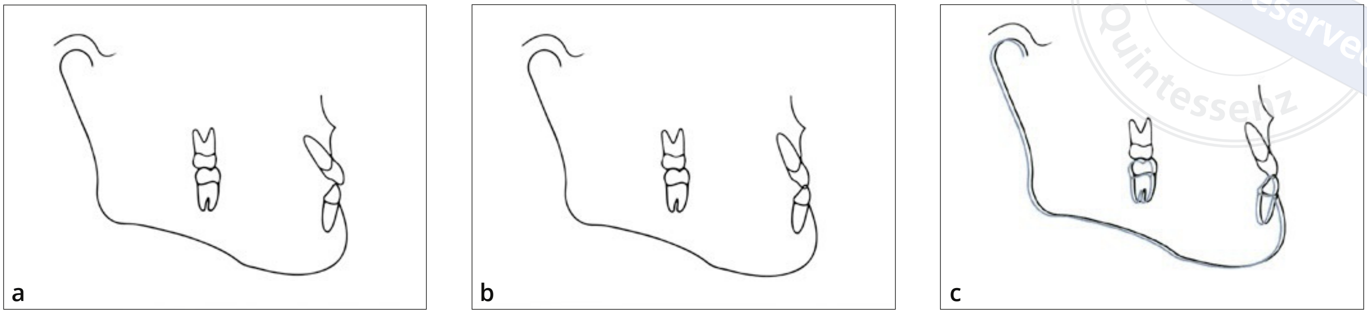
Figs 3a-b **(a)** Arch closure takes place through the anteriorly displaced axis. **(b)** The occlusal contacts result in arch closure only posteriorly (molars).



Figs 4a-b **(a)** Arch closure takes place through the cranially displaced axis. **(b)** The occlusal contacts result in arch closure only posteriorly (molars).



Figs 5a-b **(a)** Arch closure takes place through the caudally displaced axis. **(b)** The occlusal contacts occur only anteriorly with arch closure and an anterior contact occurs with a posterior open bite, i.e., a lack of posterior support. This represents a fatal situation for the temporomandibular joint (TMJ) at the end of treatment.



Figs 6a-c **(a)** In the physiological TMJ position, there is physiological occlusion. **(b)** When the maxillary incisors are reclined in the VTS, an edge-to-edge position occurs. **(c)** The mandible was placed in an ideal occlusion using the best fit or jump procedure. The condyle shifts to a retral position.

Figs 7a-d **(a and b)** Intraoral situation with sensors bonded on the maxillary right canine and first premolar and mandibular left canine and first premolar. **(c and d)** Scan of the maxillary and mandibular teeth after cleaning and drying for optimal representation of the dental anatomy.

global centre of rotation (GCR) (formerly hinge axis) to a posterior, anterior, cranial or caudal position.

Changing the position of the condyles using the best fit or jump procedure

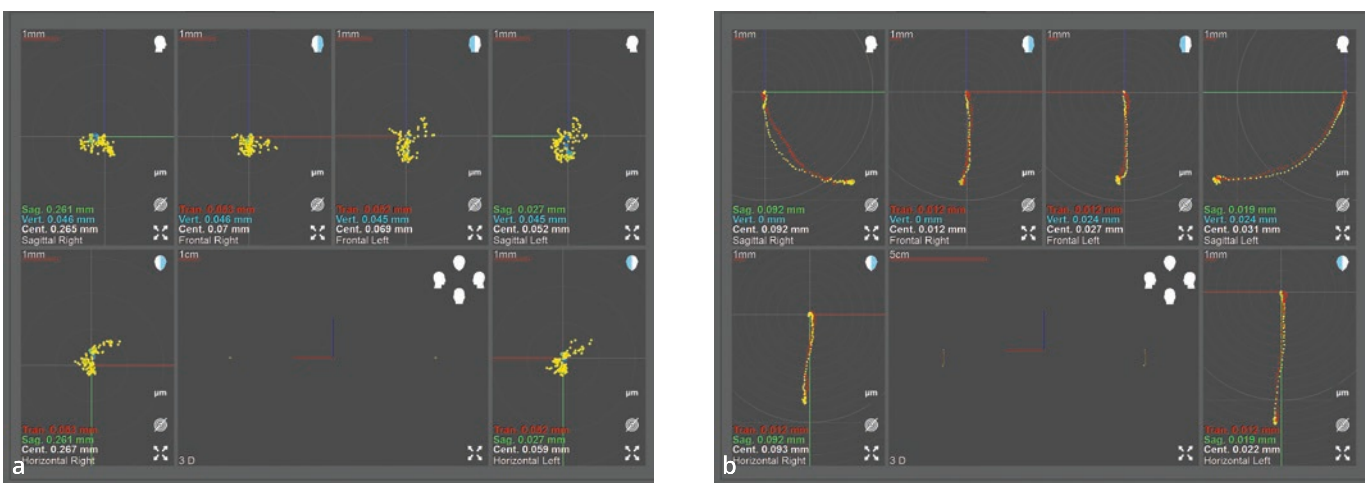
Figures 6a to c show the displacement of the condyles by reclination of the maxillary incisors and a subsequent best fit or jump procedure. Here, the condyles move into a posterior position and thus into the bilaminar zone.

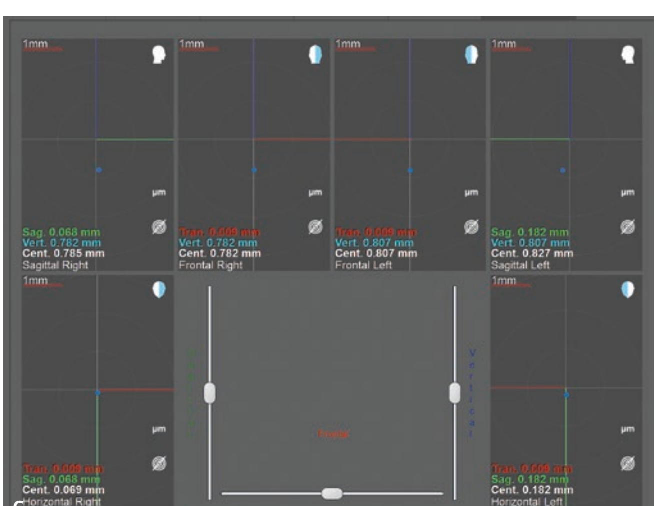
Overview of the technical procedure from scans to aligners

The technical procedure is composed of the following steps:

- scanning of the maxillary and mandibular teeth (Fig 7);
- digital joint recording using Digital Motion Decoder (DMD; Ignident, Ludwigshafen, Germany) (Figs 8a and b);
- evaluation of the DMD digital joint recording (Figs 9a to c);
- determination of the first contact with the closing movement of the mandible within the axis in physiological condyle position (Fig 10);

Fig 8 DMD digital recording of joint space and movement of the condyles.





Figs 9a-c Evaluation of the DMD digital joint recording. **(a)** The joint space measurement is 3D in the recording. As described in Fig 14 (joint space), the TMJ requires a free joint space dorsocranially. This joint space is not present in the right TMJ. **(b)** The left TMJ shows a physiological track in the opening (yellow) and closing (red) movements, but the opening and closing tracks diverge in the right TMJ. At the end of the opening movement, there is a jump, which cannot be shown completely in an image. **(c)** A condylar position is determined on the track and a 3D check is performed. This point is defined as an axis and is transferred to the VTS software (OnyxCeph V.T.O.3D, Image Instruments, Chemnitz, Germany). Here, vertical displacement of the condyles can be seen. This is necessary because the joint space measurement **(a)** showed that the joint has no vertical capacity. The CBCT image of this patient shows that the condyle is affected by grade 3 osteoarthritis (Fig 15).

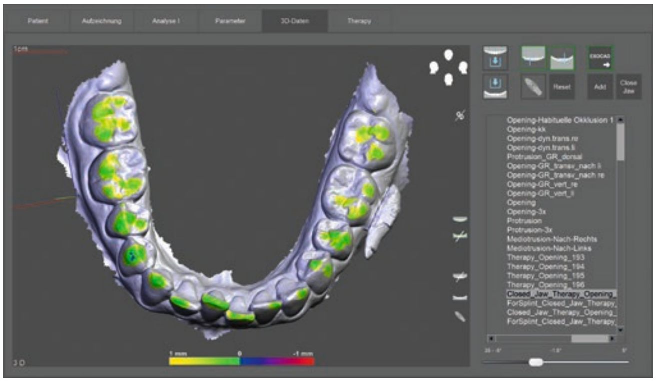


Fig 10 Determination of the first contact with the closing movement of the mandible within the axis in physiological condyle position, the so-called "Closed_Jaw" position.

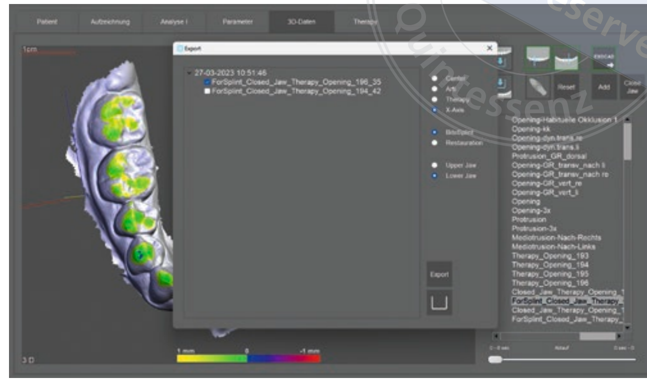


Fig 11 Matching of the scan and DMD data for transfer into OnyxCeph V.T.O.3D.

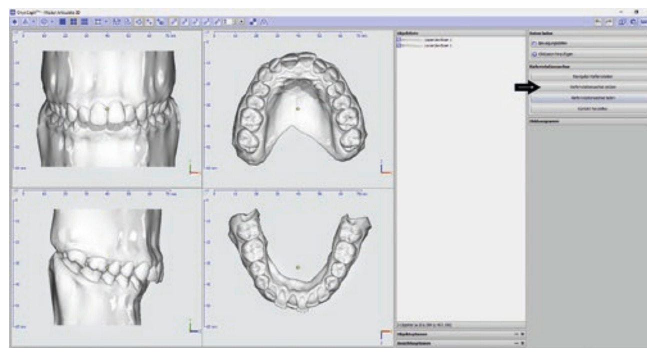


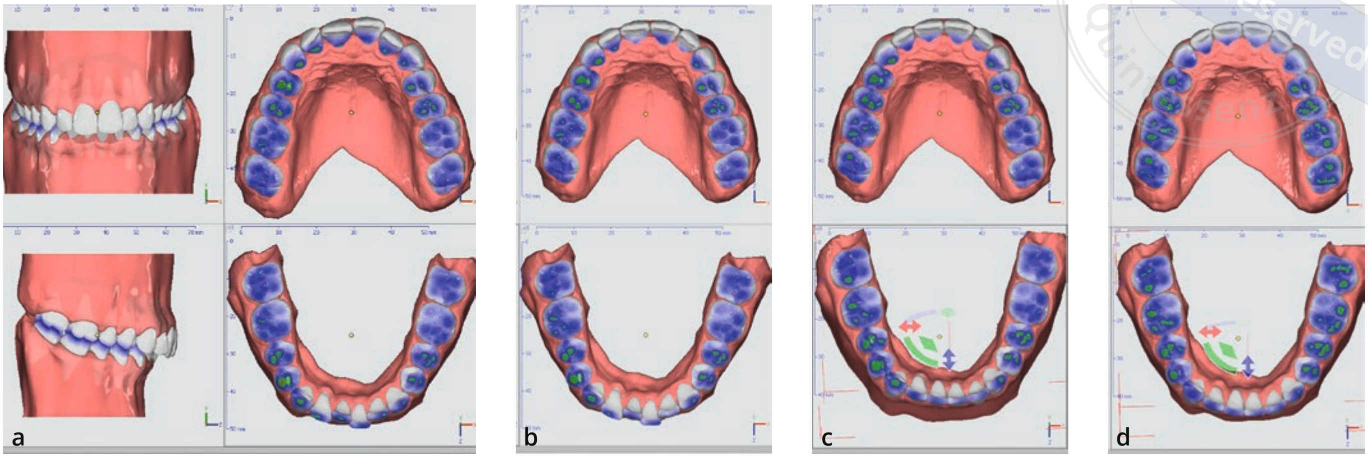
Fig 12 Matching of the scan and DMD data (mounting of the mandible to the maxilla in centric relation [CR] and the correct individual axis) in OnyxCeph V.T.O.3D.

- matching of the scan and DMD data for transfer into OnyxCeph V.T.O.3D software (Image Instruments, Chemnitz, Germany) (Fig 11);
- matching of scan and DMD data in OnyxCeph V.T.O.3D (Fig 12);
- VTS: simulation of virtual tooth movement in OnyxCeph V.T.O.3D with a virtual articulator (Fig 13);
- transfer of the VTS data to the printer and manufacturing of aligners.

Figure 13 demonstrates the virtual tooth movement in OnyxCeph V.T.O.3D with the virtual articulator. Figure 13a shows the malocclusion in the maxilla and mandible with occlusal contacts: the mandible was matched to the maxilla by matching the DMD data in OnyxCeph V.T.O.3D. The comparison with Fig 10, the first contact in the closed arch position, shows the same occlusal contacts, with the first contact being on the mandibular right first premolar. The maxillary incisors are levelled in three dimensions and the mandible is rotated in the individual axis. This results in the next occlusal contacts (Fig 13b). In Fig 13c, the maxillary and mandibular incisors are undergoing 3D movement. Rotation of the mandible in the patient's individual axis results in the next occlusal contacts. The final outcome shows an exact occlusion in the patient's individual condylar position, as seen in Fig 13d. The virtual tooth movement was performed using an individual virtual articulator.

Technical procedure for digital joint recording

The goal of digital joint motion analysis in orthodontics is to allow diagnosis of the joint space and movement and program a virtual articulator to create and optimise a functional occlusion. The DMD system records mandibular movements using magnetic field technology with a recording frequency of 100 Hz via two sensors, so-called marker tools that weigh 3 g each (Fig 7) and are bonded to the teeth in the opposing arch quadrant (i.e., the first and third quadrants) close to the occlusion, the movements of the mandible in all



Figs 13a-d **(a)** Initial situation with contact on the mandibular right first premolar. **(b)** Levelling of the maxillary incisors with the next occlusal contacts. **(c)** Alignment of the maxillary and mandibular anterior teeth with the next occlusal contacts. **(d)** Final planned situation in the VTS with exact occlusion in the patient's individual condylar position.

three translational and rotational movement directions with reference to the velocity of the movement, without affecting the static and dynamic occlusion. The movements are recorded close to the occlusal plane, which means that very precise patterns of functional movements can be recorded and transferred directly into exocad (exocad, Darmstadt, Germany)[4] or OnyxCeph software. The data can be used to perform temporomandibular joint (TMJ) diagnostics and program an articulator, or integrated directly into the computer-aided design (CAD) software. Since the TMJ has a very complex spectrum of movement, no static physical articulator is able to reproduce all of these functions[5]. According to Goob et al[4], the system-related variance in vitro, which represents the reproducibility of the DMD system, is smaller than the biological variance observed in vivo. The reproducibility of the DMD system seems to be higher than the range of biological variances. Thus, it can be assumed that measurements taken under clinical conditions are reliable. DMD recording involves scanning of the maxilla and mandible, bonding of the sensors (Fig 7) and digital recording of the joint space and joint movement (Fig 8).

Evaluation of the recording

Analysing TMJ function using condylar path tracings is a challenge in functionally orientated dentistry[6]. Most of the TMJ problems are joint space problems. As Christiansen[7] concludes, "The pathology of a movement track is always coupled with a restricted joint space. TMD patients also displayed a non-physiological movement track in at least one joint. The joint space was restricted in at least one direction, whether cranial, dorsal or medial. This so-called malposition was again determined by occluding in static occlusion". Kubein-Meesenburg[8] surmises that "condylar malpositions can only be corrected by changing the occlusion".

Evaluation of the joint space and track

Within the DMD recording, the condyles are manipulated dorsally and the dorsocranial joint space is recorded. Every healthy joint shows joint play in the form of rolling and sliding and thus a space that allows the joint to move in all dimensions[9]. In Fig 14, the joint spaces are marked in colour. There is a free space in the dorsocranial direction in a physiological TMJ. If this joint space cannot be depicted in the digital recording, it can be assumed that the joint is displaced dorsocranially. The condylar position is then in the zones marked in the red area shown in Fig 14, and a joint pathology is very likely[10].

Figure 15 shows the CBCT and digital TMJ recording for a 52-year-old woman. Direct comparison of a CBCT scan with the DMD digital joint recording reveals a displacement and pathology of the TMJ.

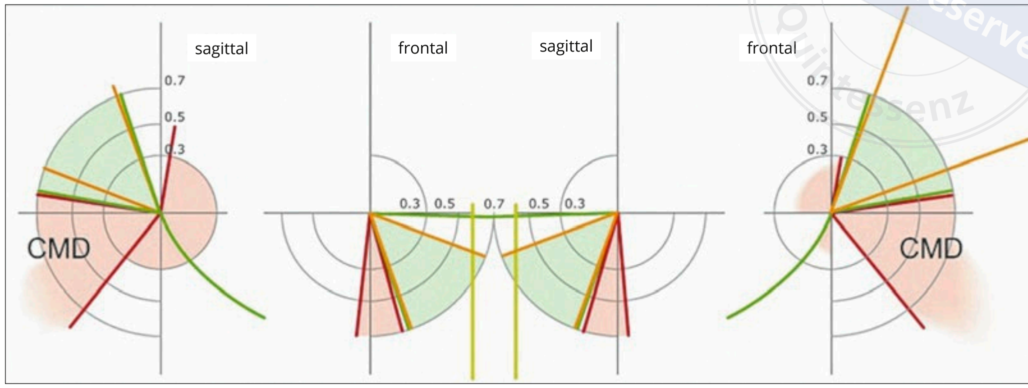
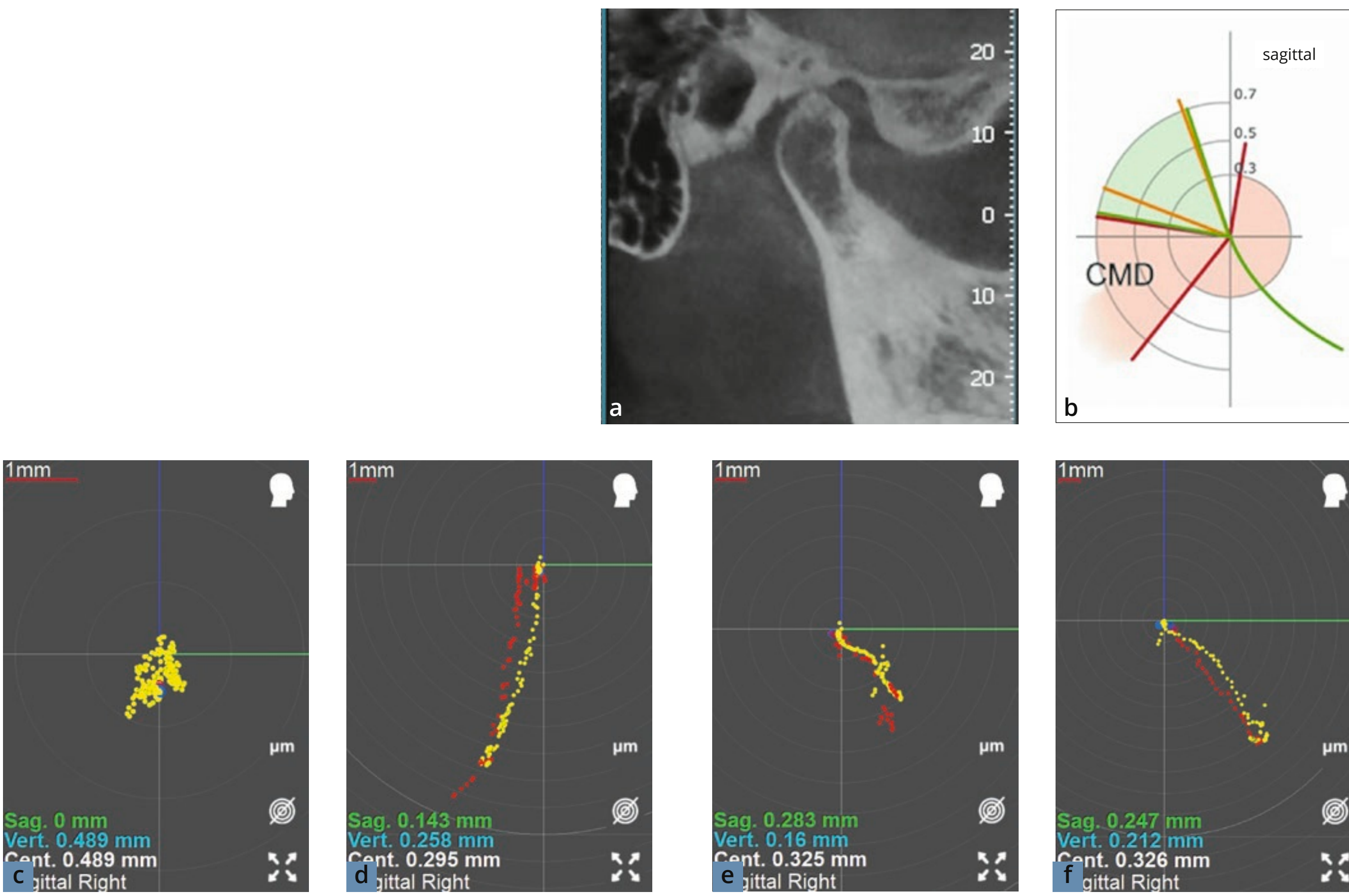
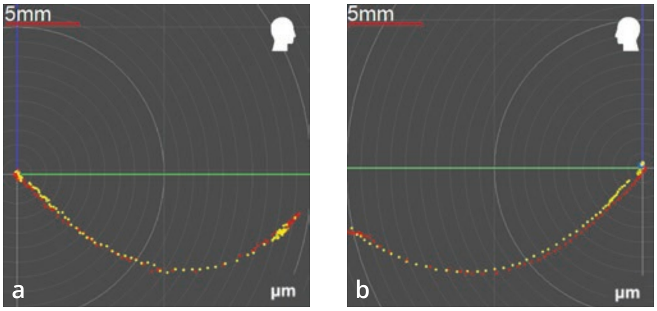


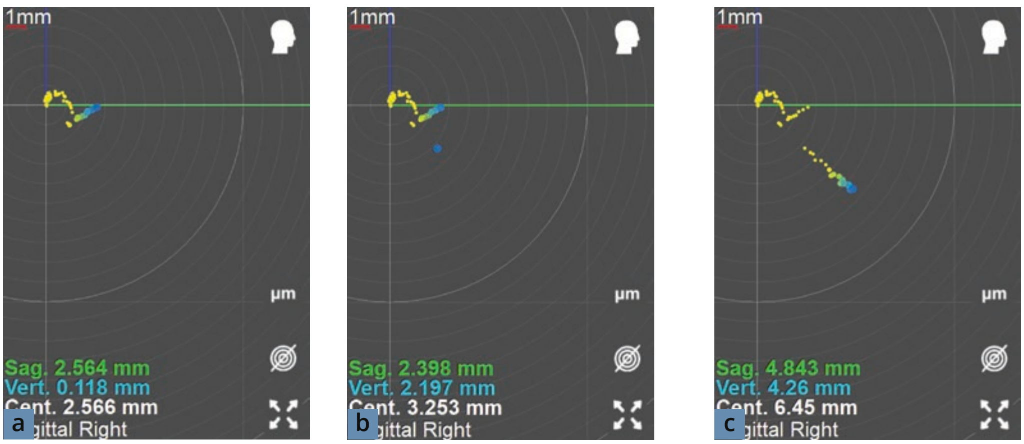
Fig 14 Joint space: condyles showing a capacity for physiological trajectory movement in the green area. The movement capacity of dysfunctional condyles stretches to at least one of the red areas. (Reprinted from Christiansen[10] with permission.)



Figs 15a-f **(a)** The patient's CBCT scan reveals osteoarthritis in the left TMJ. The joint space is greatly reduced and shows a bony contact in the cranial region. **(b)** Manual dorsal mobilisation of the mandible should allow for dorso-caudal displacement of the joint. This space is shown here in green. Mobilisation into the red area shows a pathology. (Reprinted from Christiansen[10] with permission.) **(c)** The digital joint recording of the joint space indicates that manual mobilisation of the condyle in a dorso-cranial direction is not possible. Mobilisation is performed in a dorso-caudal direction, the red area shown in **(b)**. **(d)** The opening and closing track of the right TMJ shows a dorsally directed movement. The track should be anterior, sufficiently long and concave (according to Fig 16). **(e)** The patient's protrusion trajectory is severely shortened, not concave and shows jumps, and the back-and-forth curves display a different course. **(f)** After 17 weeks of treatment with an occlusal splint, planned in the DMD system and 3D printed with TC-85DAC material (Graphy, Seoul, Korea), the patient is pain-free. The digital joint recording after the occlusal splint therapy did not show physiological tracks in the opening (yellow) and closing (red) movements. The initial opening track **(d)** was reversed and in a backwards direction. After occlusal splint therapy, the track is now slightly shortened, straight and in the correct direction. The new DMD measurement is used for the following calculation of the virtual articulator for matching in OnyxCeph V.T.O.3D to design the in-office aligner treatment.



Figs 16a-b **(a)** Right track and **(b)** left track. The tracks of this physiological TMJ show sufficient length and concavity, the excursive and incursive path are nearly congruent, and there is no jump or deviation (yellow, opening; red, closing).



Figs 17a-c The track shows a jump, the condyle is seated under the disc in the opening movement. **(a)** The opening begins with an upward movement of the track. **(b)** This is followed by a jump; the condyle shifts caudally and jumps onto the disc. **(c)** After this, the disc-condyle complex moves further anteriorly.

Every physiological opening and all protrusion tracks are characterised by:

- sufficient length;
- concavity;
- almost congruent excursive and incursive paths (Figs 16a and b);
- no stop-and-go phenomena;
- no rebound;
- no jumps (Figs 17a to c);
- no deviation.

Transversal and cranial manipulation should not change the track.

Finding the physiological condyle position

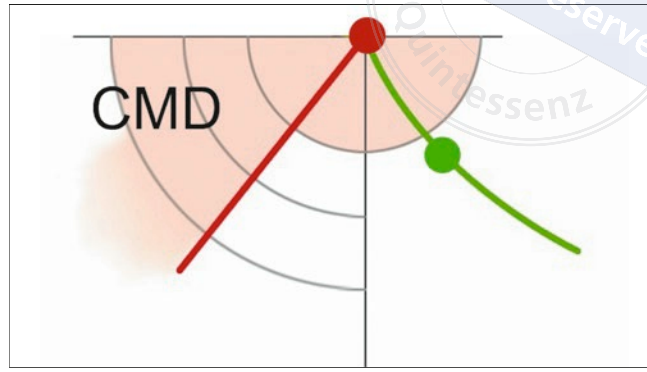
The digital joint recording (performed with DMD) shows three coordinates for the condylar position: horizontal, vertical and sagittal. In the absence of joint space, it is necessary to find a condyle position on the track that provides physiological joint space for both condyles. The beginning of all the tracks represents a condyle position in habitual intercuspation. From habitual intercuspation (the red dot in Fig 18), the condyles are relocated into the determined position (the green dot in Fig 18). This position is defined by three coordinates for each condyle. For the symmetrical 3D physiological joint space, these are vertical (0.6 to 0.8 mm), sagittal (0.6 to 0.8 mm) and horizontal (0.6 mm).

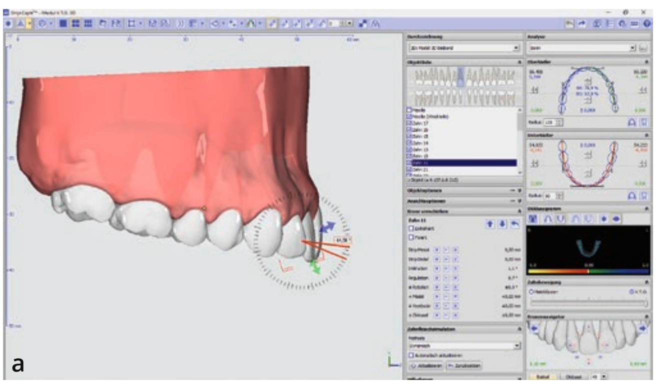
From the DMD recording, the joint position thus determined is matched in the VTS along with the scan data. The mandibular position at the first occlusal contact and the axis found are transferred to the VTS (OnyxCeph Aligner 3D). The same approach is taken in patients with a healthy joint, but without displacement of the condyles.

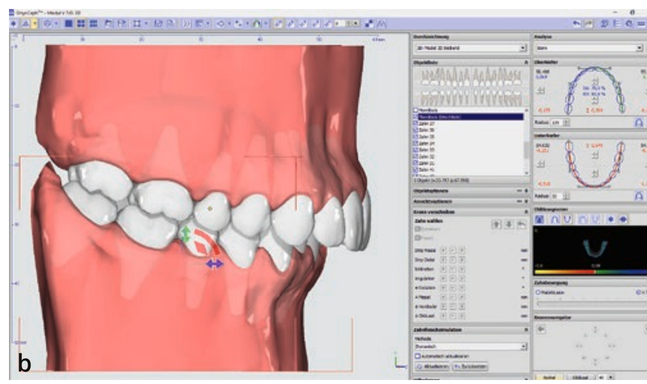
Transfer of the new physiological occlusion and the real motion into the VTS

Earlier theories assumed that during the first phase of mouth opening or the last phase of mouth closing, the TMJ performs a pure rotational movement. Under clinical conditions, it is generally not possible to find the true terminal hinge axis when small translational movements occur dur-

Fig 18 The newly determined condylar position (centric relation [CR]), represented by the green dot, always lies on the condylar path (green curve). This means that the engram of the condylar movement is inevitably preserved. The starting point is centric occlusion (CO), represented by the red dot in the centre of the coordinate system. If a pathology is present and a new CR is set, this is usually 0.6 to 0.8 mm ventrocaudal to the CO. The CR must not be set in the area shown in orange; this represents the non-functional joint space. (Reprinted from Christiansen[10] with permission.)







Figs 19a-b Virtual treatment in OnyxCeph V.T.O3D. **(a)** In the VTS software, a virtual treatment target can be defined based on a segmented digital model discretised with reference points. **(b)** The mandible is rotated into the new occlusion according to the movement of the tooth or teeth.

ing the first phase of mouth opening. Instead, a GCR is measured[11]. The patient's individual axis and the exact 3D assignment of the mandible to the maxilla from the DMD analysis in the "Closed_Jaw" position are integrated into OnyxCeph V.T.O.3D. This makes it possible to correct misaligned teeth in the VTS with continuous arch movement. Transferring the DMD data into the VTS software allows the practitioner to plan an occlusion in the virtual articulator and thus with an individual movement pattern (open/close).

VTS with real motion parameters

The V.T.O.3D ("Virtual Setup") module in the OnyxCeph software provides tools to simulate realistic treatment targets in a time-effective manner and use them for subsequent planning of aligner treatment. It does not serve to generate treatment proposals automatically.

In the module, a virtual treatment target can be defined based on a segmented digital model discretised with reference points. For this purpose, the module provides options and control elements to, on the one hand, adjust the spatial shape of the maxilla and mandible to each other and to the individual patient's skeletal conditions and, on the other hand, control the relative position and alignment of the individual teeth in the associated dental arch. The tooth movement resulting from both movement options (control of the tooth position by means of the dental arch and through offsets relative to it) is described accordingly as the sum of two separate 3D transformations.

The basic prerequisite for the virtual setting of a physiological occlusion is the correct 3D assignment of the mandible to the maxilla in habitual intercuspation (centric occlusion [CO]) or centric relation (CR), which should be the starting point for all virtual treatments. As Meyer[12] states, "Any dental treatment, including orthodontic treatment, is based upon the CR, not upon the habitual intercuspation". This assignment in CR as well as the patient's individual rotation axis are transferred from the DMD software to OnyxCeph V.T.O3D and the teeth are moved in a fully adjustable virtual articulator (Fig 19).

Figs 20a-g Extra- and intraoral situation at the beginning of treatment. The extraoral situation shows harmonic and competent lip closure **(a and b)**. The intraoral situation reveals asymmetrical narrow arches with crowding and rotations, a reclined maxillary right central incisor and a protruded mandibular left central incisor. Both sides show a Class I relationship with missing posterior support **(c to g)**.

A standard axis is integrated in OnyxCeph V.T.O.3D. This axis is arbitrary and is adapted to an arbitrary articulator axis. This enables mandibular rotation and is therefore more accurate than a best fit; however, it is not possible to make a condylar adjustment on the track with this.

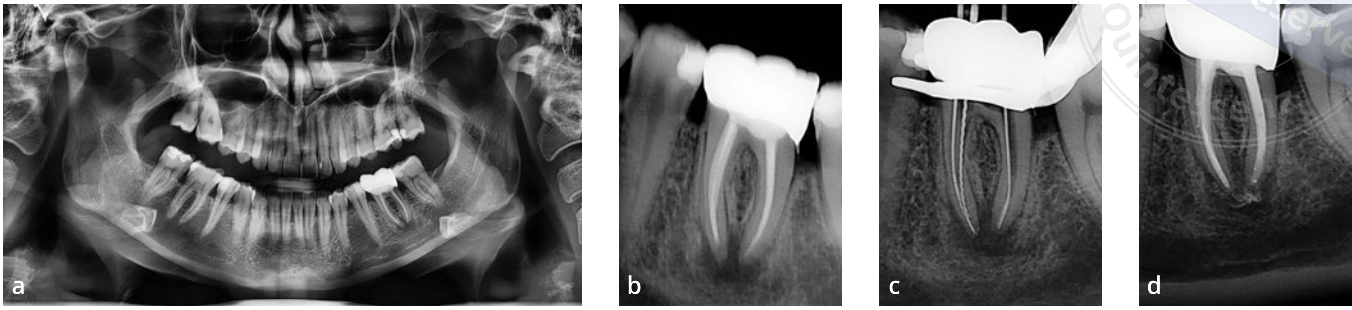
Treatment example

A 39-year-old woman with temporomandibular disorder (TMD) and abrasion of the incisors underwent treatment performed using the in-office aligner procedure, which lasted 16 weeks and was composed of eight steps. Subjectively, the patient reported that she no longer experienced any pain, and objectively, the tracks in the DMD analysis displayed a physiological movement pattern after treatment.

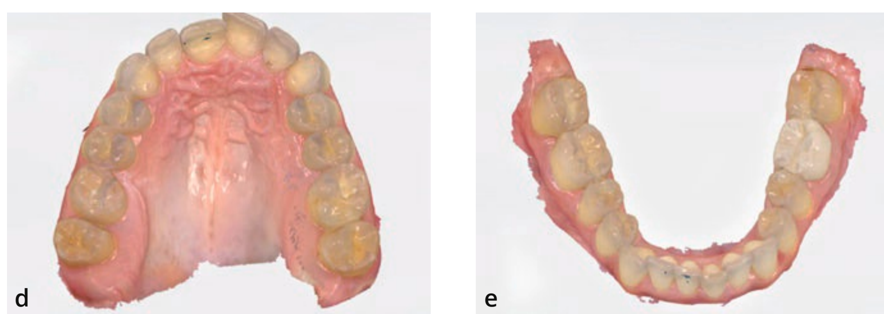
Each treatment step included two aligners made from CA Pro material (Scheu Dental, Iserlohn, Germany), the first with a thickness of 0.500 mm and the second with a thickness of 0.625 mm. This is a multilayer aligner material made of copolyester and thermoplastic elastomer with an elastic modulus of 1600 MPa.

Course of treatment

The patient attended the present authors' office with severe TMD symptoms. The extraoral situation showed harmonic, competent lip closure (Figs 20a and b) and the intraoral situation revealed asymmetrical narrow arches with a reclined maxillary right central incisor, proclined mandibular left central incisor and a Class I molar relationship with missing posterior vertical support (Figs 20c to g). The panoramic radiograph showed a stable periodontal situation with restorations, but the mandibular left first molar

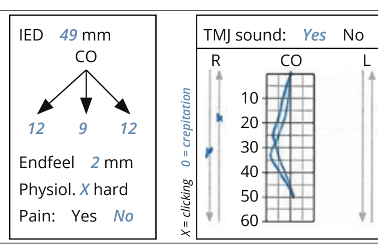


Figs 21a-d Panoramic radiograph taken at the start of treatment showing a stable periodontal situation with restorations **(a)**. The root filling for the mandibular left first molar was insufficient and revision was recommended **(b to d)** (Dr David Appel, Bonn, Germany).



Figs 22a-e Intraoral scan taken at the start of treatment with the first occlusal contacts in habitual intercuspation on the right central incisors.

Short screening test		
1) Asymmetrical mouth opening	*Yes*	No
2) Limited mouth opening	Yes	*No*
3) Traumatic eccentric occlusion	Yes	*No*
4) Joint sounds/joint pain	*Yes*	No
5) Pain on muscle palpation	Yes	*No*
6) CR ≠ CO cotton roll test	*Yes*	No
≥ 2	*Yes*	No



a

TMJ pain	R	L
TMJ lateral	–	–
TMJ posterior	+	–

b

Figs 23a-b The clinical functional findings show deviation on arch opening and closing, crepitation in the right TMJ and palpation pain in the right TMJ posteriorly. The movement capacity was not restricted. IED, incisal edge distance.

displayed insufficient root filling and revision was recommended, and performed by Dr David Appel, Bonn, Germany (Figs 21a to d). The intraoral scan showed a first contact in habitual intercuspation on the right central incisors (Figs 22a to e). The clinical functional findings show deviation on arch opening and closing, crepitation in the right TMJ and palpation pain in the right TMJ posteriorly (Fig 23).

The movement capacity is not restricted. In the right TMJ, there is no dorsocranial space for the condyle; in the left TMJ, this space is highly reduced as shown in Fig 24. In a physiological joint, joint play should be possible in the area marked in green (also demonstrated in Fig 14). Figure 25 demonstrates the procedure in OnyxCeph software. The initial therapeutic condyle position is corrected to approxi-

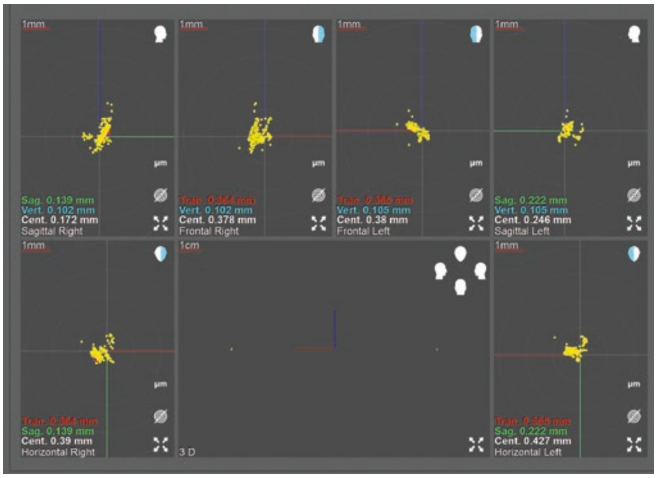
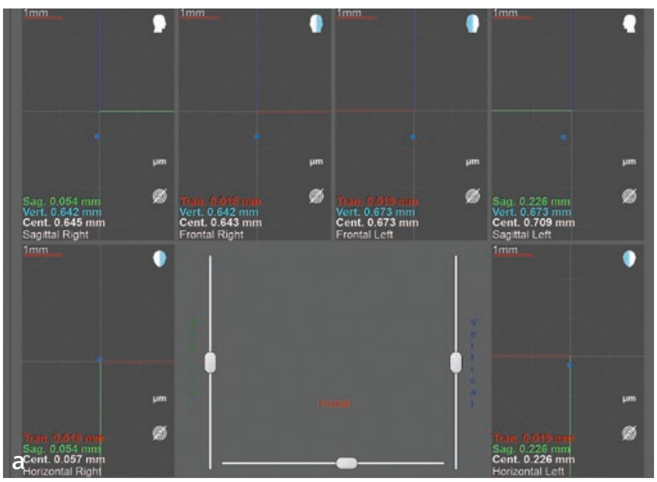
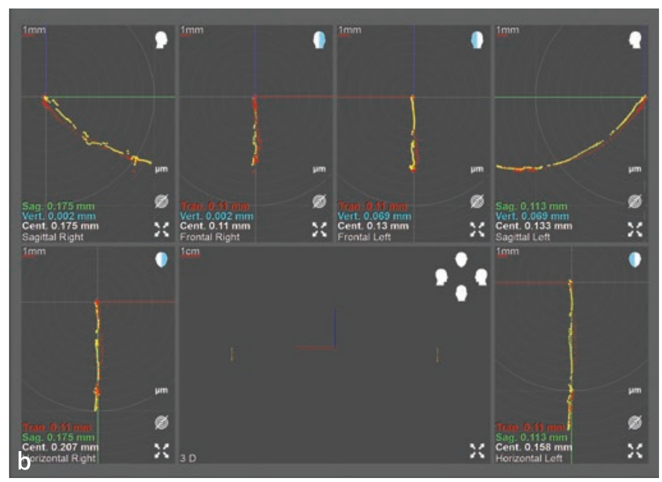
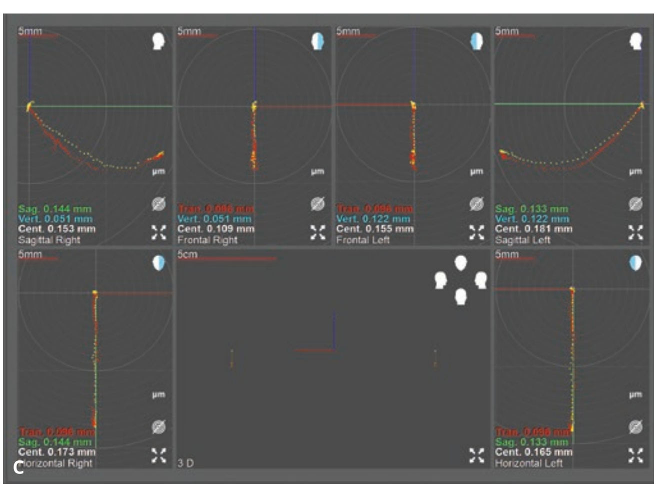


Fig 24 In the right TMJ, there was no dorsocranial space for the condyle; in the left TMJ, this space was highly reduced. In a physiological joint, joint play should be possible in the area marked in green as shown in Fig 15b.







Figs 25a-c **(a)** The initial therapeutical condyle position is corrected to approximately 0.65 mm caudal. **(b)** The initial protrusion track is physiological on the left. In the right TMJ, the track is shorter, straight and not concave, and shows jumps. This pathology also shows up in the right TMJ in the joint space measurement (Fig 24). **(c)** The closing movement (red track) shows a jump on the right side.

mately 0.65 mm caudal (Fig 25a). The initial protrusion track is physiological on the left. In the right TMJ, the track is shorter, straight and not concave, and shows jumps (Fig 25b). This pathology also shows up in the right TMJ in the joint space measurement (Fig 24). The closing movement (red track) shows a jump on the right side (Fig 25c).

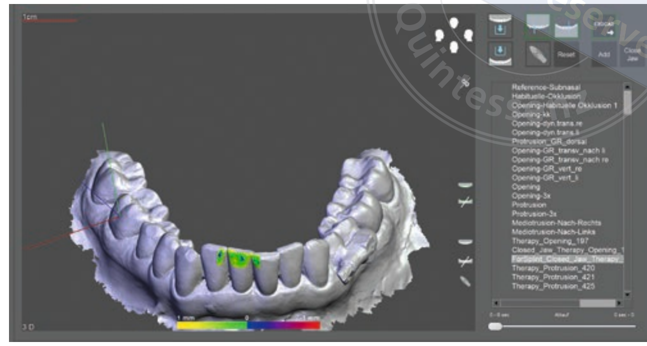


Fig 26 In the corrected condylar position, the "Closed_Jaw" function was used to determine the first contact in CO, in this case on the mandibular central incisors and right lateral incisor.

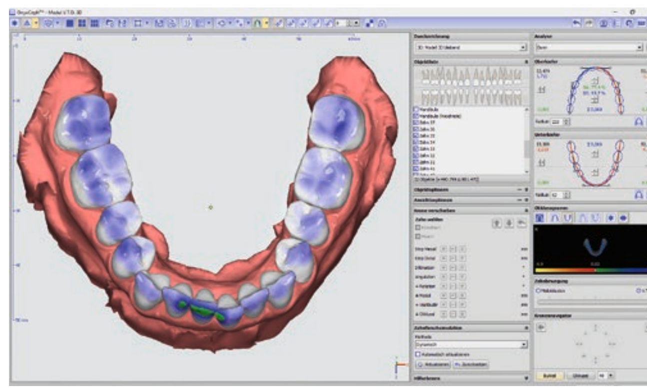
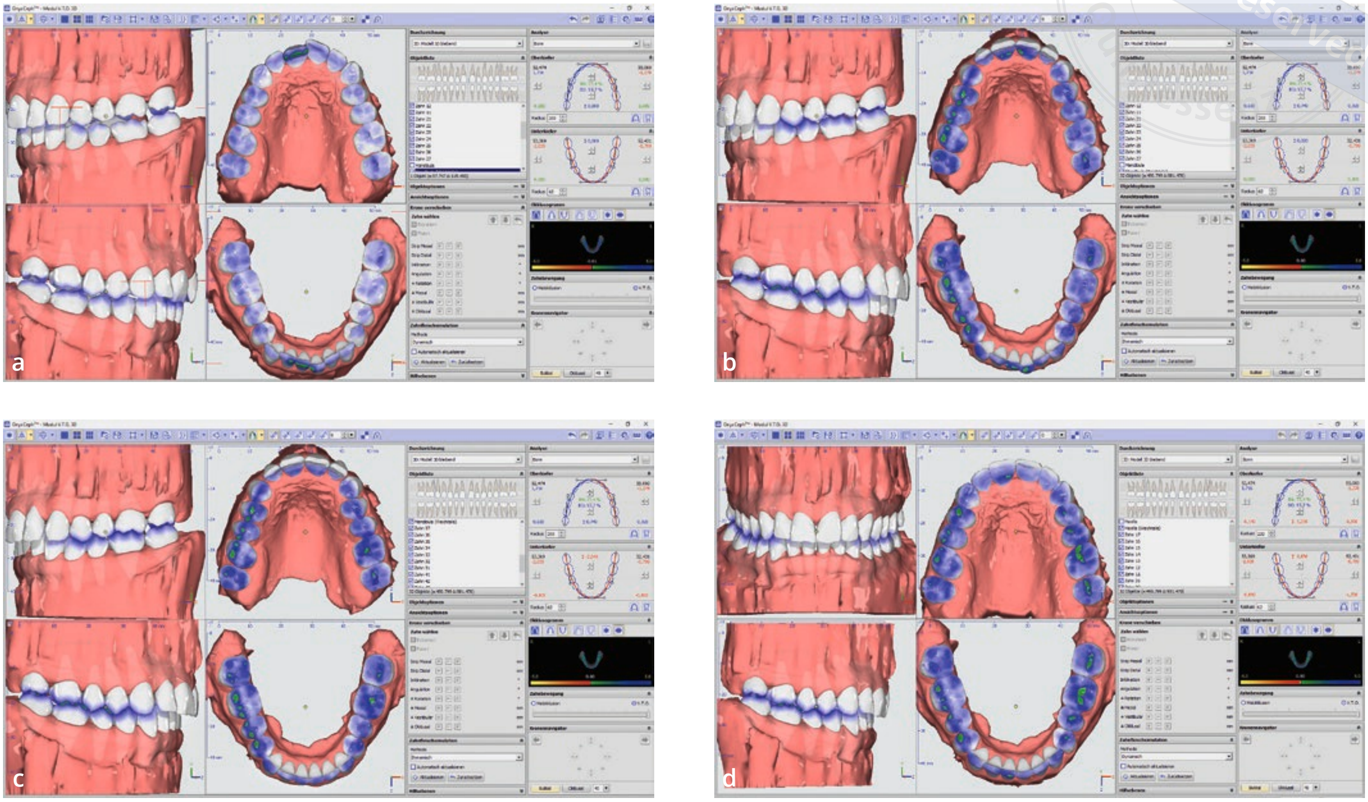


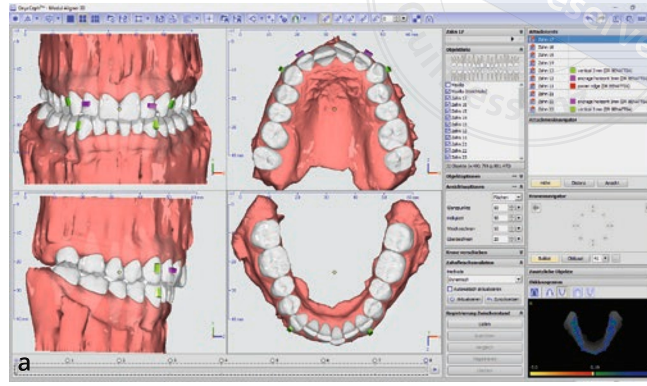
Fig 27 The transfer (match) of the mandibular position from DMD (Fig 26) into OnyxCeph is completely accurate. The CO contacts are identical in both programs.

In the corrected condylar position, the "Closed_Jaw" function is used to determine the first contact in CO (Fig 26), in this case on the mandibular central insicors and right lateral incisor. Figure 27 shows the exact transfer (match) of the mandibular position from DMD into OnyxCeph. The CO contacts are identical in both programs. Figure 28a shows the initial situation with occlusal contacts in CR on the maxillary right central incisor/mandibular left central incisor, and the mandibular right central and lateral incisors. Figure 28b shows the first correction step in the VTS. The maxillary right central incisor was proclined and then the mandible was rotated in the patient's individual axis until the next first contact points were reached. These appear on the maxillary right first and second molars, first and second premolars and central incisor, the maxillary left central incisor/mandibular left central incisor, and the mandibular right first and second molars and first and second premolars. Figure 28c shows the second correction step in the VTS with reclination of the mandibular left central incisor and alignment of the maxillary and mandibular incisors. After mandibular rotation in the individual axis, the occlusal contacts appear on the maxillary right first and second molars, first and second premolars, maxillary left first molar, maxillary left first molar/mandibular left second molar, mandibular left first molar, and the mandibular right first and second molar and first and second premolars. Figure 28d shows the final VTS. The occlusal contacts were set with mandibular rotation in the patient's individual axis and the spaces between the maxillary canines and lateral incisors could be closed. A contact remained on the maxillary right central incisor. As a result of the abrasion palatal to this tooth caused by the malocclusion, its anatomy was changed. Thus, a plan was made in the VTS for the tooth to be reshaped at the end of the orthodontic treatment. The abnormal shape of the tooth was planned to be corrected, but not by changing its position. In Fig 29, the planning of the attachments, torque element (integrated on the maxillary right central incisor) and staging in the V.T.O.3D ("Aligner") module in OnyxCeph is shown. The horizontal, rectangular attachments on the maxillary lateral incisors



Figs 28a-d **(a)** Initial situation: the occlusal contacts in CR are on the maxillary right central incisor/mandibular left central incisor, and the mandibular right central and lateral incisors. **(b)** The first correction step in the VTS: the maxillary right central incisor was proclined and then the mandible was rotated in the patient's individual axis until the next first contact points were reached. These appear on the maxillary right first and second molars, first and second premolars and central incisor, the maxillary left central incisor/mandibular left central incisor, and the mandibular right first and second molars and first and second premolars. **(c)** The second correction step in the VTS: the mandibular left central incisor was reclined and the maxillary and mandibular incisors were aligned. After mandibular rotation in the individual axis, the occlusal contacts appear on the maxillary right first and second molars, first and second premolars, maxillary left first molar, maxillary left first molar/mandibular left second molar, mandibular left first molar, and the mandibular right first and second molar and first and second premolars. **(d)** Final VTS: the occlusal contacts were set with mandibular rotation in the patient's individual axis and the spaces between the maxillary canines and lateral incisors could be closed. A contact remained on the maxillary right central incisor. As a result of the abrasion palatal to this tooth caused by the malocclusion, its anatomy was changed. Thus, a plan was made in the VTS for the tooth to be reshaped at the end of the orthodontic treatment. The abnormal shape of the tooth was planned to be corrected, but not by changing its position.

are inclined towards the incisal edge and the attachments on the canines are turned in the direction of derotation. Eight steps were planned for the treatment and two aligners were fabricated for each step (0.500- and 0.625-mm CA Pro). The protocol of total tooth movement and interproximal reduction (IPR) required is demonstrated in Fig 29b. Figure 30 shows the final intraoral situation with aligned anterior arches and Fig 31 demonstrates the occlusal contact in the final intraoral situation and in the VTS. The planned contact palatal of the maxillary right central incisor was present exactly as shown in the VTS. After 16 weeks of treatment, contacts on all molars and premolars were visible (Fig 32). In the mandible, a lingual retainer was bonded from the mandibular left first premolar to the right first premolar. In the maxilla, the patient inserted the last aligner for retention at night. Figure 33 shows the final opening and final protrusion curve. At the end of treatment, the tracks of opening and protrusion were both of sufficient length, with a concave shape and without jumps or rebounds during opening and closing movements. The tracks were on top of each other. In contrast to the tracks at the beginning of treatment, no pathology was visible.



Figs 29a-b (a) Planning of the attachments, the torque element (on the maxillary right central incisor) and staging in the V.T.O.3D ("Aligner") module in the OnyxCeph software. The horizontal, rectangular attachments on the maxillary lateral incisors are inclined towards the incisal edge and the attachments on the canines are turned in the direction of derotation. Eight steps were planned for the treatment and two aligners were fabricated for each step (0.500- and 0.625-mm CA Pro). **(b)** Protocol for total tooth movement and interproximal reduction (IPR) required. *According to FDI notation.

Maxilla																
Tooth*	18	17	16	15	14	13	12	11	21	22	23	24	25	26	27	28
Mesial IPR (mm)																
Distal IPR (mm)																
Inclination (degrees)		16.90	−16.40	−14.70	−15.30	−3.50	−1.10	1.60	−6.40	−2.50	−4.50	−20.30	−15.80	−12.50	1.90	
Inclination +/− (degrees)								12.30	0.80	−0.30	1.50					
Angulation (degrees)		−2.00	2.00	−3.60	3.00	8.90	4.20	−2.90	2.90	5.10	20.30	0.20	3.40	−5.20	−1.50	
Angulation +/− (degrees)								−1.00	−3.50	0.60	−1.50					
Rotation +/− (degrees)								−4.30	−13.30	2.50	−5.20	−0.10	0.10			
Mesial +/− (mm)								−0.33	−0.10	−0.03	−0.04	0.10	−0.14	0.01	0.01	
Vestibular +/− (mm)							0.51	1.44	0.25	0.54	−0.45	0.88	0.02			
Occlusal +/− (mm)								−0.01	−0.40	−0.30		0.02	0.33	0.40	0.10	

Mandible																
Tooth*	48	47	46	45	44	43	42	41	31	32	33	34	35	36	37	38
Mesial IPR (mm)																
Distal IPR (mm)																
Inclination (degrees)		−40.50	−38.40	−33.20	−27.60	−9.10	−8.60	−4.50	−1.70	−6.20	−8.40	−19.90	−24.80	−31.20	−36.10	
Inclination +/− (degrees)						0.40	−0.50		0.10	−0.10						
Angulation (degrees)		7.70	14.30	8.70	8.00	3.50	−5.60	0.30	−0.80	−3.00	1.80	−1.90	5.70	19.00	11.80	
Angulation +/− (degrees)				0.10	0.20	−1.80	−1.90	−0.90	−1.70	−0.50	0.10	0.50	0.30			
Rotation +/− (degrees)				0.20	0.60	−10.50	−5.80	−1.80	0.90	4.20	2.00	1.20	0.40			
Mesial +/− (mm)				−0.20	−0.40	−0.42	−0.14	−0.13	−0.73	−1.02	−0.83	−0.85	−0.36	0.05	0.01	
Vestibular +/− (mm)				−0.04	0.07	−0.58	−0.38	−0.78	−1.65	−0.42	−0.67	−0.05				
Occlusal +/− (mm)				−0.03	−0.08	−0.04	−0.21	−0.10	−0.30	−0.23	−0.10	−0.13	0.29	0.45	0.10	

Maxilla														
Tooth*	17–16	16–15	15–14	14–13	13–12	12–11	11–21	21–22	22–23	23–24	24–25	25–26	26–27		Total
Amount of IPR (mm)	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00		
Total (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
Distance (mm)	0.00	0.00	0.00	0.00	0.06	−0.20	−0.18	−0.19	−0.39	−0.26	−0.10	−0.10	0.05		−1.31

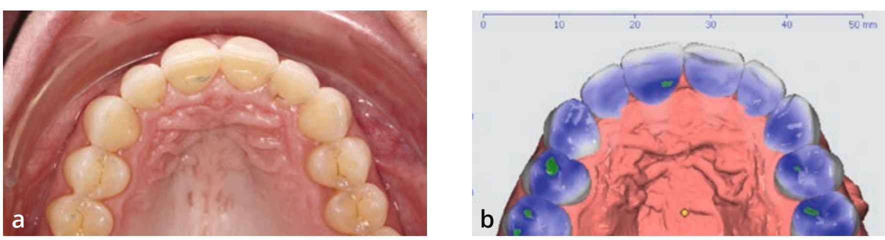
Mandible														
Tooth*	47–46	46–45	45–44	44–43	43–42	42–41	41–31	31–32	32–33	33–34	34–35	35–36	36–37		Total
Amount of IPR (mm)	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00	0.00 + 0.00		
Total (mm)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
Distance (mm)	0.00	−0.19	−0.18	−0.21	−0.15	−0.16	−0.24	−0.19	−0.36	−0.29	−0.45	−0.41	−0.02		−2.85

b

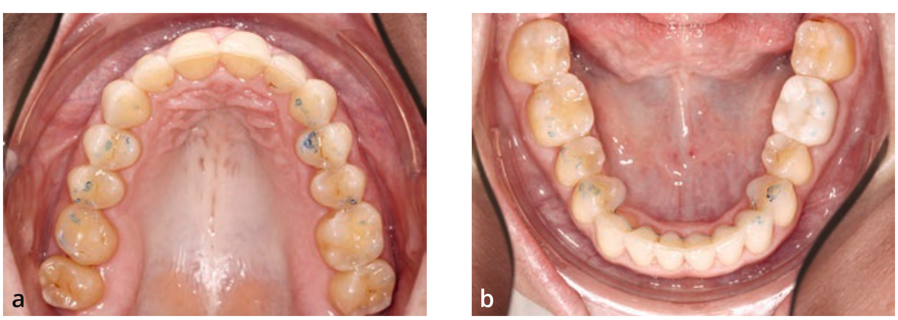
Conclusions

With regard to digital joint recording, it is important to consider that a rotation axis cannot be determined exactly, especially not if a translation is included, but a condylar path can be. The track is arthrogenic and myogenic and is stable and reproducible in the digital recording. The condylar position is determined and fixed "on the path". It is only possible to determine the condylar position on the path by means of digital recording. To do this, prior determination of the axis of rotation is not required. The established condylar position on the path is the axis of rotation. A condylar position and thus a physiological joint space are determined. The starting point of the trajectory is the given but possibly pathological position of the condyles in the joint space. If it is pathological, a new physiological condylar position on the path is determined. Most often, TMD is caused by a pathological joint position and the joint space being constricted in habitual intercuspation. There is no physiological end feel in the joint play. This is almost always consistent with the CBCT analysis. The new starting point is the specific condylar position, which renders the discussion

Figs 30a-e Final intraoral situation with aligned anterior arches.



Figs 31a-b Occlusal contact in the final intraoral situation and in the VTS. The planned contact palatal of the maxillary right central incisor was present exactly as shown in the treatment simulation.

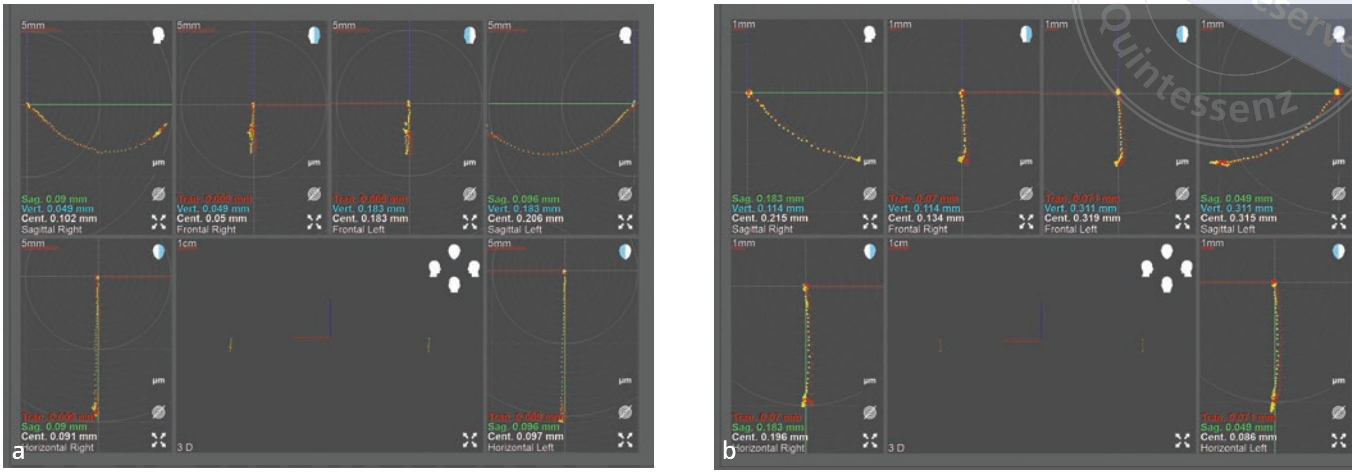


Figs 32a-b After 16 weeks of treatment, contacts were present on all molars and premolars. In the maxilla, the patient inserted the last aligner for retention at night. In the mandible, a lingual retainer was bonded from the mandibular left first premolar to the right first premolar.

about a hinge axis obsolete. In patients without TMD, the practitioner begins from habitual intercuspation and defines a point at the start of the path as the axis that is transferred to the VTS. Orthodontic treatment can only be considered successfully completed if the occlusion corresponds to a physiological condylar position.

Declaration

The authors declare no conflicts of interest relating to this study.



Figs 33a-b (a) Final opening and **(b)** final protrusion. At the end of treatment, the tracks of opening and protrusion were both of sufficient length, with a concave shape and without jumps or rebounds during opening and closing movements. The tracks were on top of each other. In contrast to the tracks at the beginning of the treatment, no pathology was visible.

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