Condylar motion analysis - a controlled, blinded clinical study on the interindividual reproducibility of standardized evaluation of computer- recorded condylar movements

M. Oliver Ahlers (Ahlers@UKE.de)
University of Hamburg, University Hospital Hamburg-Eppendorf, Center for Dental and Oral Medicine, Department of Prosthetic Dentistry

Tim Petersen
CMD Center Hamburg-Eppendorf

Lukasz D. Katzer
CMD Center Hamburg-Eppendorf

Jens C. Türp
University Center for Dental Medicine Basel UZB University of Basel

Holger A. Jakstat
University of Leipzig, Center for Dental and Oral Medicine, 4 Department of Prosthetic Dentistry, Dental Materials and Special Care, Germany

Research Article

Keywords: diagnosis, computer-assisted, temporomandibular disorders, mandibular condyle, jaw relation record, Diagnostic Criteria for Dysfunction

Posted Date: November 3rd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2156434/v1

Abstract

Objectives

The present study investigated to what extent systematic evaluation of electronic condylar motion recordings based on the Diagnostic Criteria for Dysfunction (DCD) leads to reproducible results in different examiners.

Methods

The study was based on the anonymized condylar motion recordings of 20 patients. These were recruited consecutively from the examinations in a center specializing in diagnosing and managing craniomandibular/temporomandibular disorders (CMD/TMD). Four trained practitioners independently evaluated the identical movement recordings of all patients after calibration. The evaluation was based on the previously published evaluation system. The CMDtrace software was used to record the results. The findings were then compared, and the matching values were determined (Fleiss' Kappa).

Results

The evaluation, according to Fleiss' Kappa, showed that the consistency of the assessment of the findings among the examiners is excellent (mean value 0.88, $p < 0.00001$).

Conclusion

The study shows that calibrated dentists achieved reproducible results using this evaluation system and computer-assisted reporting.

Clinical Relevance

Good reproducibility confirms the reliability of clinical motion analysis. The ambiguities uncovered and eliminated in the study should avoid misunderstandings in the future. Both factors establish the prerequisites for applying condylar motion analysis in clinical practice.

Introduction

Methods for recording condylar/mandibular movements pursue the goal of using the information obtained to reproduce these movements as accurately as possible in mechanical or virtual articulators. This “articulator programming” allows individual reproduction of static and dynamic occlusion for the analog or digital design and fabrication of removable dentures and fixed restorations. The rationale for using motion data for articulator settings is based on the consequence that even relatively small changes in movement trajectories can significantly affect the design of the occlusal surfaces [1].

Historically, the instruments for recording mandibular motion were initially based on analog recording methods [1]. Computerized methods were not available until the 1970s [2–6]. In the 1990s, electronic recording instruments were introduced for dental practice [7, 8]. The earlier recording of movement data on graph paper was replaced by the voltage division method (Fig. 1), ultrasonic measurement technology (Fig. 2), and optoelectronic systems [9].

As part of articulator programming, devices from all manufacturers use electronically recorded spatial motion data for geometric evaluation. In this process, the condylar/mandibular movement patterns are assigned to the geometries of mechanical articulators, and the corresponding setting angles.

Software-based “virtual” articulators have been developed for the CAD/CAM-based production of dental restorations [10–14]. In these virtual articulators, the movement capabilities of mechanical articulators are digitally simulated [7]. For this purpose, the setting values determined from the mandibular motion recording are entered in a user interface for “programming” the selected virtual articulator [15]. The available study results on the quality of these movement simulations revealed good reliability in visualizing dynamic space and contacts, comparable to a mechanic articulator [15–17], but also determined the heterogeneity of the different analog and digital systems [18].

Independent of articulator programming s, another application has evolved based on the analysis of condylar/mandibular movements. This assessment includes (a) pattern recognition of condylar movements to clarify possible temporomandibular joint (TMJ) dysfunctions/disorders (for example, disc displacement with and without reduction, limitations of mandibular movements, and condylar hypermobility), and (b) a velocity curve analysis of condylar movements to assess movement coordination.

Pattern recognition of condylar movements to elucidate TMJ dysfunction dates to the work of Farrar in the 1970s [19, 20]. Based on the evaluation of arthrographies, he described the relationship between the timing of TMJ sounds associated with condylar movements and the displacement of the articular disc. Subsequently, other authors included changes in movement velocity and range of motion in the evaluation [21], which allowed for the assignment of typical movement patterns to individual TMJ dysfunctions [22–27]. This velocity curve analysis of condylar movement coordination is based on the evaluation of computerized condylar motion recordings and initially assessed movement capacity [2, 28] and coordination [29, 30]. Recently, this has been supplemented by evaluating the movement velocity using computer-assisted path-time diagrams [31].

The technical prerequisites for these applications are electronic registrations of the condylar/mandibular movements and the possibility of analyzing the recordings later on a PC with the appropriate software. Whereas in articulator programming, only the angular deviation from the reference plane and the curvature of the sagittal and horizontal condylar path are evaluated geometrically, condylar motion analysis assesses spatial motion and changes in movement velocity [31].

Condylar motion analysis was initially based on uniformly defined instrumental functional findings. These were developed at a consensus conference of the German Society for Functional Diagnosis and Therapy (Deutsche Gesellschaft für Funktionsdiagnostik und -therapie, DGFDT) in 2012 and published internationally as the “Diagnostic Criteria for Dysfunction” (DCD) [32]. Based on the DCD, a concept for parameterization and evaluation findings from functional movements analysis was developed [31, 33]. The contents of this work have been integrated into the DGFDT guideline on instrumental functional analysis [34].

Studies on the reproducibility of these evaluations are still a desideratum. Therefore, the present multicenter study aimed to investigate the reproducibility of individual findings for condylar motion analysis parameterized based on the concept mentioned above.

Material And Methods

Patients

The study was based on the anonymized findings of 20 consecutively recruited patients from a center specialized in diagnosing and managing craniomandibular/temporomandibular disorders (CMD/TMD) (inclusion criterion). All patients recruited for this study were diagnosed with one or more TMD. The registrations were made during everyday activities under practice conditions.

Before the motion recordings, all patients underwent a jaw-related clinical, functional analysis, and a manual structural analysis in a separate appointment. The findings were recorded in the corresponding modules (CMDstatus 4 and CMDmanu 4) of the software CMDfact 4 for Windows (dentaConcept Verlag, Hamburg, Germany) [35].

Instruments

Condylar movements were recorded using the Cadiax compact II system (see Fig. 1) and Gamma Dental Software for Windows, version 8.0.4, module Cadiax Analysis (Gamma Gesellschaft für medizinisch wissenschaftliche Fortbildungen, Klosterneuburg, Austria). All recordings were performed at least twice, as described in the DGFDT guideline [34].

Clinical procedure for movement recording

The mandibular bow was paraocclusally attached to the contour of the vestibular surface of the mandibular teeth, bearing electronic transmitters that indicated the condylar movements to the recording devices connected laterally to the maxillary facebow. A procedure published earlier was used, which made it possible to eliminate the need for luting cement or adhesives and to ensure that no material used to attach the mandibular bow covered the occlusal surfaces [36].

The starting point of the motion recording was the mandibular position currently determined by the habitual occlusion. During initial calibration at the beginning of instrumental motion recording, it was noted whether the zero point was maintained, whether a deviation from the zero point was deliberately maintained, or whether the system was recalibrated after identifying a variation. This information is relevant for the dental assessment of the mandibular position after recordings.

Dynamic mandibular movements were performed unguided with and without tooth contact to allow conclusions about the influence of occlusal contacts on the course of condylar/mandibular movements.

Since the condylar movement patterns in the fossa-disc-condylar complex depend on the velocity of the mandibular closing movement and the head posture, the recordings were performed with a physiological lordosis of the cervical spine. For this purpose, the examinations were carried out on a dental chair with a headrest that could be fully adjusted (Finndent FD 7000 patient chair, Finndent Oy, Helsinki, Finland). The back section was set to approximately 120° between the back and the legs. The headrest was adjusted manually to avoid excessive reclination or inclination until patients confirmed their perception of a natural head position. Furthermore, the closing velocity was kept as constant as possible at about 1 Hz [32]; this was previously practiced with the patient. By the specifications of the underlying recommendations, [31, 33] deviations of more than 0.3 mm from the starting point were interpreted as unstable.

After the recordings were made, the results obtained were anonymized. For this purpose, the records were copied from the practice data, and the first and last names, as well as the dates of birth, were deleted from the copies. Thus, the records were identified only by a patient number, which could not be traced back to the study participants [37].

Investigators

The patients were independently evaluated for the study after a calibration meeting. Four trained practitioners analyzed the motion recordings from two specialized institutions in Hamburg (M.O.A., T.P., L.K.) and Leipzig (H.A.J.). The Hamburg-based examiners worked in a Center specializing in CMD/TMD diagnosis and therapy from which the data originated. In contrast, the Leipzig-based examiner worked in a university dental clinic where he was responsible for the CMD/TMD consultations. The agreement among the examiners' findings was determined by calculating Fleiss' Kappa [κ].

Evaluation system

Before evaluating the motion recordings, the study director (M.O.A.) presented each patient based on the patient´s history and anonymized findings from the clinical functional analysis and the manual structural analysis. For this purpose, the results from the CMDfact 4 software module CMDstatus were printed out in the anonymized form as findings sheet “Clinical Functional Status” and from the CMDfact 4 software module CMDmanu as findings sheet “Manual Structural Analysis.”

The four examiners evaluated the clinical protocols of all patients. For this purpose, the CMDfact4 software module CMDtrace was used as the digital counterpart of the “Condylar Motion Analysis" findings sheet (dentaConcept Verlag) (Fig. 3).

The previously published evaluation system served as the basis for evaluation [31, 33]. The recorded motion data were evaluated within the Cadiax Software on a screen at 100% magnification in specific spatial directions (frontal, sagittal, horizontal). All available recordings were considered; this was done for the right and left TMJ, respectively. The following variables were examined (Table 1):

Table 1
Variables examined in the study.

Condylar stability: Start/end point displacement
Analysis of the presence of a breakpoint during the closing movement
Condylar motion sequence: path length, path shape
Functional coordination: movement or velocity over time; condylar coordination

Basic evaluation data

In the first step, the diagnostic indication for the examination was introduced. Furthermore, the recorded settings were studied, which formed the basis for the subsequent evaluations and findings.

The settings included the registration systems used (see above) and the determination of the posterior reference points. In the further course of the study, the position of the maxillary face-bow with the recording devices attached to it was arbitrarily applied according to the system defaults of the Cadiax Compact 2 registration device.

In case of deviations of the start or end position from the initial calibrated start position during the various recordings, the respective displacement direction of the starting point or end point was determined (cranial, caudal, posterior, anterior), whereby different approaches could be combined (e.g., retral + cranial). The evaluation was primarily based on the jaw *opening curves*, alternatively on the protrusive and retrusive movements with tooth contact.

Analysis of condylar stability

In the condylar stability section, the reproducibility with which the condyles assume the initially calibrated position at the beginning of the movement (starting point shift, Fig. 4) and return to this position at the end of the closing movement (endpoint shift, see Fig. 5). was evaluated. In addition, it was checked whether an intermediate stop in the jaw-closing movement of the condyles (incursion) could be detected [31], i.e., a short interruption of this movement, whereby the movement velocity increased again (Fig. 6).

Analysis of the condylar motion sequence

For the analysis of the condylar motion sequence, the condylar/mandibular movements between the start and end points were parameterized regarding movement capacity and form. For evaluation, the movements opening/closure and protrusion/retrusion were each sampled twice. In case of doubt, the review was based on the non-occlusally guided condylar/mandibular movements in the vertical direction (opening/closure).

The parameters for evaluating the movement capacity (track/path length) were based on the extent of movement. The classifications relied on corresponding study results [8, 28]. Accordingly, the path lengths during opening and closing were classified as follows (Fig. 7):

- Conspicuous/noticeable shortening: movement ranges of < 6 mm path length.
- Normal (physiological) length: movement ranges between 6 mm and 12 mm path length.
- Conspicuous/noticeable extension: movement ranges > 12 mm path length.

The movement's most significant deviation from the reference point was the beginning.

The geometry of the movement form (path form) was evaluated using the following feature definitions:

- Concave anterior trajectories are rounded in the caudal direction (Fig. 8, left and right condyles).
- Caudal convex trajectories are rounded cranially (Fig. 8, right condyle).
    - Straight condylar trajectories differ from curved trajectories by the curvature index (K) of the trajectory [38], formed by the length ratio of the secant (d) by the starting and end point of the trajectory, and the maximum deviation of the trajectory from the constructed secant (a). The ratio $\kappa = a/d$ thus describes the curvature of the trajectory, with straight lines characterized by values $\kappa < 0.05$ (Fig. 8, left condyle).
    - Erratic or 8-shaped movements are present when the signal corresponds to the course of a flat number “8” (Fig. 9, right condyle).
- Irregular movements (Fig. 9, left condyle) differ from the previously mentioned possibilities [32].

Analysis of functional coordination

In the “coordination” section of the study, parameterized findings were made concerning the variables “velocity curve” and “condylar coordination.” The results were also based on the DCD [32] and their design in the published examination and evaluation concept [31, 33].

Time-distance diagrams (“time curves”) were used to assess movement velocity over time between start and finish. A second diagram showed the movement velocity at each time along the path (Fig. 10). Based on the shape of the velocity diagram, this was then classified as

- - single-peaked,
- - two-peaked, or
- - multi-peaked.

Regarding condylar coordination during jaw opening and closure, axial diagrams were first displayed in the top and frontal views as overviews and then viewed twice over time at normal velocity. The line diagrams were examined for parallelism during jaw opening and closure (Fig. 11). Three possibilities were distinguished:

- - (extensive) uniformity
- - slight unevenness (slight non-parallelism)

- significant unevenness (clear non-parallelism)

Asymmetries were geometrically represented as line compressions expressing a temporarily lower velocity in one of the two TMJs (Fig. 12).

Statistical evaluation

For the mathematical evaluation, the collected findings were exported from CMDfact 4 to Excel (Microsoft 365, Microsoft, Seattle/WA, USA), where they were formatted and prepared.

The statistical analyses were carried out with the program package SigmaStat 4.0, and the graphical representations of the results were performed with SigmaPlot 13 (Systat Software GmbH, Erkrath, Germany). The data were compared, and the agreement values were determined (Fleiss' Kappa [κ] method). The statement on the quality of the agreement was derived from Fleiss' κ: the more Fleiss' κ approaches 1, the more likely it is that the different investigators will arrive at consistent diagnoses [39]. κ values > 0.4 are considered “moderate agreement”, > 0.6 a “substantial agreement”, and > 0.8 “almost perfect agreement” [40].

In addition, a test for normal distribution was performed using the Shapiro-Wilk test. Normally distributed data were analyzed parametrically with Student´s t-test. In contrast, non-normally spread data were evaluated non-parametrically with the Mann-Whitney U-test for the presence of significant differences to determine if the agreement among investigators was significantly better than expected by chance ($p < 0.05$).

Null hypothesis

The study was based on the null hypothesis that the examiner’s agreement could be explained by chance alone.

Results

The evaluations, according to Fleiss' κ, showed the following results:

Overall agreement

The overall analysis of all findings across the four examiners yielded a κ of 0.88 ($p < 0.00001$).

When the evaluation was restricted to the three examiners from the practice, the κ value was 0.91 ($p < 0.00001$). Both values correspond to an almost perfect agreement. Since these values were so close, only the individual values for all four examiners were subsequently determined (Table 2).

Table 2
Overall reproducibility of findings evaluated according to Fleiss' kappa.

Evaluation	Fleiss´ κ (rounded)	p
Overall agreement / 3 raters	0.91	< 0.00001
Overall agreement / 4 raters	0.88	< 0.00001

Condylar stability

Evaluation of the agreement in the assessment regarding a starting point shift resulted in a κ-value of 0.90 ($p < 0.0000001$). The agreement regarding the existence of an endpoint shift was even higher (κ = 0.92, $p < 0.00001$) (Table 3).

Table 3
Reproducibility of single findings according to Fleiss' kappa.

Findings	Fleiss´ κ (rounded)	p
Starting point	0.90	< 0.0000001
Breaking point	0.67	< 0.00001
Endpoint shift	0.92	< 0.00001
Track/path length	1.00	< 0.0001
Track/path form	0.88	< 0.00001
Velocity curve analysis	0.86	< 0.00001
Functional coordination	0.62	< 0.00001

Breakpoint in the closing movement

In comparison, an agreement was lower for the detection of a breakpoint (κ = 0.67, $p < 0.00001$) but still substantial (Table 3).

Condylar motion path

When evaluating movement capacity (track/path length) for deviations, complete agreement ($\kappa = 1$, $p < < 0.0001$) was achieved. The evaluation of the geometry of the movement form (path form) yielded an almost perfect agreement ($\kappa = 0.88$, $p < 0.00001$) (Table 3).

Functional coordination

The agreement was almost perfect when evaluating the velocity curve ($\kappa = 0.86$, $p < 0.00001$). The evaluation of condylar coordination was more heterogeneous ($\kappa = 0.62$, $p < 0.00001$) but still reached a remarkable agreement (Table 3).

Refutation of the null Hypothesis

The null hypothesis that the investigators’ agreement could be explained by chance was refuted in all individual findings.

Discussion

The general conditions are essential in assessing the significance of the results from this study.

Experimental design

Patients

It should be noted that the movement records were obtained from a center of excellence for CMD/TMD diagnosis and management, which almost exclusively cares for patients who could not be successfully managed elsewhere and were therefore referred. Hence, more abnormal findings were expected in this patient population compared to patients in an average dental office. However, for this investigation – to examine the reproducibility of the diagnostic conclusions – patients with an exceptionally high number of clinical signs were helpful.

The study’s results are externally valid because patients were not purposively selected but were recruited consecutively without exception, and the motion recordings were made under practice conditions.

Investigators

The four examiners were specialized dentists with many years of expertise in evaluating condylar motion recordings. This requirement was intended to ensure that the study results reflected the findings’ reproducibility rather than differences in the qualifications of the investigators. However, as with all skill-based examinations and techniques, dentists with less experience may produce more heterogeneous results, with a higher proportion of noise and bias.

The selection of the four examiners from two locations, with distribution among three examiners working closely together at one place and one examiner who had no contact with the other examiners in practice, was designed to show whether regular cooperation and coordination strongly influenced outcomes. The results refuted this hypothesis; there was little difference among the scores.

Instruments

The computerized registration system used in the study was selected because it has been in practice for many years and because the associated software (Cadiax Analysis) fully enables the display of condylar/mandibular movements for functional movement analysis if the user interface is appropriately set.

The analysis system is completely manufacturer-independent [31, 33]. Thus, other computerized condylar registration systems that meet these requirements could have been used – especially since different systems ensure the technical and diagnostic validity and reliability of the motion data with their signal quality [22]. However, this requires suitable display software. A new software module, "CMDfact Interactor," for the Jaw Motion Analyzer (JMA; Zebris Medical, Isny, Germany, and Schütz Dental, Rosbach vor der Höhe, Germany) was developed specifically for this purpose.

Evaluation system

The evaluation system is based on the DCD to evaluate instrumental registrations [32]. Their parameterized transfer into a graphical user interface formed the basis for developing the software module CMDtrace, which was used in this study to record findings. The study aimed to test the suitability of the evaluation system for use with the diagnostic reporting system employed here. The high agreement values have confirmed this suitability.

Areas with conspicuously lower agreement

Given the overall high agreement, two values were conspicuously lower in comparison:

- Analysis of condylar stability: break in the closing movement (incursion). This was defined as a short interruption of a closing movement during which the motion velocity increased again. In TMJ arthropathies, this course may indicate that a physiological TMJ position is adopted that prevents dysfunctional displacement, especially in the retral and cranial direction [41].
- Analysis of functional condylar coordination. Here, a review of the causes of the comparatively low agreement showed that the definition is open to different interpretations. A distinction should be made between no, slight, and marked nonparallelism, whereby the mandibular opening and closure findings were recorded together.

Definition of the criteria and adjustment of the findings matrix

Because of the results, the differently interpreted records were reevaluated – this time openly – after the completion of the study evaluation. This new analysis revealed misunderstandings in the definition of the respective findings as the cause of the selectively lower agreements. The following adjustments are therefore necessary for improvement:

- We propose to define a stopping not as a *point* where the movement stops absolutely with a sudden velocity drop towards zero but as an *area* where the condyle in question slows down abruptly during the mandibular closing movement with a noticeable velocity drop, followed by a subsequent increase of the movement velocity.
- Furthermore, we advocate distinguishing only between even or asymmetrical/nonparallel in condyle coordination. For more transparency, each finding is recorded separately for jaw opening and closing. This avoids inconsistent evaluations when combining these two condylar/mandibular movements.

In addition, the available evaluation revealed the following possible sources of ambiguous findings:

- Multiple selections were previously possible when evaluating trajectory shape. This did not lead to an improvement in the 20 patients examined. Therefore, only *one* option should be selectable.
- Multiple selections were also previously possible for the movement velocity findings to be able to image different states of jaw opening and closure. Here, too, only one option should be selectable.

Classification of the values

Other studies on the reproducibility of findings in instrumental motion analysis examined the reproducibility of trajectories in registration systems with arbitrary and kinematic hinge axis localization. They achieved an intra-class correlation (ICC) of > 0.8 for the Cadiax compact II registration system, also used in our study. They found strong similarities in the characteristics of the motion paths [8]. Comparable data were obtained from a multicenter study with five trained and calibrated examiners using the JMA ultrasound measuring instrument (Zebris Medical) for sagittal condylar track inclination (ICC 0.87–0.91) and sagittal and lateral anterior guidance (ICC 0.88–0.99). This reproducibility of unguided and guided Bennett movement alone was significantly lower (0.44–0.62) [42]. Our results complement these findings with the values for functional motion analysis and show that a similarly high reproducibility was achieved with the evaluation system used.

In clinical functional analysis, corresponding investigations were performed for the Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) [43]. The reliability achieved in the clinical evaluation in connection with the DC/TMD criteria for pain related CMDs was excellent, with a κ value ≥ 0.85 [43]. The agreements in this study, apart from the two exceptions mentioned above, were of the same order of magnitude and, in some cases, even higher, indicating that the system developed for the evaluation of instrumental functional motion analysis meets the requirements of functional analysis.

Perspectives

...for the practice

The results determine that the condylar motion analysis is a reliable tool for functional analysis, at least for dentists trained in this technique, and helps evaluate clinical situations based on the findings. The improvements to the evaluation system developed in this study were implemented directly into a digital version of the earlier form (CMDfact4 software module CMDtrace, dentaConcept, Hamburg) to translate the results from research into practice (Fig. 13). Of course, the systematics verified in this study is completely independent of this and condylar movements can be recorded with any documenting system, as long as the condylar motion analysis data provide the required data and the respective instrument´s dedicated software illustrates the corresponding findings.

... for science

In the future, it would also be helpful to repeat the present study on the reliability of the findings with trained, but clinically inexperienced investigators. This would allow testing the extent to which less experienced examiners can correctly assess the results of functional movement analysis.

It would also be beneficial to investigate the reliability of diagnoses based on the motion recordings. A study on the reliability of diagnoses based on the examination techniques of clinical functional analysis and manual structural analysis showed that the results were significantly more consistent in the case of computer-assisted diagnosis [44]. Computer-assisted diagnosis following function-oriented motion analysis would continue this technological leap. The conditions for this are in place, given the results obtained in the present study.

Declarations

Ethical Approval

The study was approved by the Ethics Committee of the Hamburg Medical Association (WF-062/21). The study was also conducted following the latest version (2013) of the Declaration of Helsinki of the World Medical Association. Informed consent was obtained from all participants in this study.

Competing interests

The authors declare that they have no conflict of interest. Two of the authors were amongst the authors of the paper and the form the study was based upon, but the methodology is completely independent of that.

Authors' contributions

- M. Oliver Ahlers developed the study conception and design.
- M. Oliver Ahlers, Tim Petersen, and Lukasz Katzer performed the condylar motion recordings.
- Tim Petersen identified the consecutive recordings in the CMD Centre´s data and collected and anonymized all material.
- M. Oliver Ahlers, Tim Petersen, Lukasz Katzer, and Holger A. Jakstat evaluated the condylar motion records and later discussed the results.
- Holger A. Jakstat calculated the data and performed the statistical evaluations.
- M. Oliver Ahlers performed the drawings that illustrate the findings investigated in the study.
- M. Oliver Ahlers also wrote the manuscript.
- Lukasz Katzer and Holger A. Jakstat corrected the Manuscript.
- Jens C. Türp revised the manuscript, translated it into English, and revised the manuscript repeatedly, together with M. Oliver Ahlers.
- All authors read and approved the final manuscript.

Funding

The study was researcher driven and was not funded by a third party or grant.

Availability of data and materials

The original raw data will be uploaded along with the paper as related files and are thus accessible. Other materials the authors will be happy to provide upon request.

References

1. Lundeen HC, Shryock EF, Gibbs CH (1978) An evaluation of mandibular border movements: their character and significance. J Prosthet Dent 40:442–452. https://doi.org/10.1016/0022-3913(78)90130-0
2. Kordaß B, Hugger A, Bernhardt O (2012) Correlation between computer-assisted measurements of mandibular opening and closing movements and clinical symptoms of temporomandibular dysfunction. Int J Comput Dent 15:93–107.
3. Knapp JG (1983) Computer graphic representation of mandibular movements in three dimensions: the method. J Oral Rehabil 10:295–305. https://doi.org/10.1111/j.1365-2842.1983.tb00124.x
4. Mack PJ (1989) A computer analysis of condylar movement as determined by cuspal guidances. J Prosthet Dent 61:628–633. https://doi.org/10.1016/0022-3913(89)90290-4
5. Roedema WH, Knapp JG, Spencer J, Dever MK (1978) Computer-graphic representation of mandibular movements in three dimensions. Part I. The horizontal plane. J Prosthet Dent 39:378–

383. https://doi.org/10.1016/s0022-3913(78)80152-8

6. Salomon JA, Waysenson BD, Warshaw BD (1979) Computer-monitored radionuclide tracking of three-dimensional mandibular movements. Part II: experimental setup and preliminary results – Posselt diagram. J Prosthet Dent 41:463–469. https://doi.org/10.1016/0022-3913(79)90045-3
7. Pelletier LB, Campbell SD (1991) Comparison of condylar control settings using three methods: a bench study. J Prosthet Dent 66:193–200. https://doi.org/10.1016/s0022-3913(05)80047-2
8. Bernhardt O, Küppers N, Rosin M, Meyer G (2003) Comparative tests of arbitrary and kinematic transverse horizontal axis recordings of mandibular movements. J Prosthet Dent 89:175–179. https://doi.org/10.1067/mpr.2003.10
9. Kordaß B, Ruge S, Ratzmann A, Hugger A (2013) Current technologies for functional diagnostics and CAD/CAM. Int J Comput Dent 16:163–71.
10. Gärtner C, Kordaß B (2003) The virtual articulator: development and evaluation. Int J Comput Dent 6:11–24.
11. Kordaß B, Gärtner C, Söhnel A, Bisler A, Voss G, Bockholt U, Seipel S (2002) The virtual articulator in dentistry: concept and development. Dent Clin North Am 46:493–506. https://doi.org/10.1016/s0011-8532(02)00006-x
12. Ruge S, Kordass B (2008) 3D-VAS - initial results from computerized visualization of dynamic occlusion. Int J Comput Dent 11:9–16.
13. Ruge S, Quooss A, Kordass B (2011) Variability of closing movements, dynamic occlusion, and occlusal contact patterns during mastication. Int J Comput Dent 14:119–127.
14. Bisler A, Bockholt U, Kordass B, Suchan M, Voss G (2002) The virtual articulator. Int J Comput Dent 5:101–6.
15. Maestre-Ferrín L, Romero-Millán J, Peñarrocha-Oltra D, Peñarrocha-Diago M (2012) Virtual articulator for the analysis of dental occlusion: an update. Med Oral Patol Oral Cir Bucal 17:e160-3. https://doi.org/10.4317/medoral.17147
16. Hsu MR, Driscoll CF, Romberg E, Masri R (2019) Accuracy of Dynamic Virtual Articulation: Trueness and Precision. J Prosthodont 28:436–443. https://doi.org/10.1111/jopr.13035
17. Úry E, Fornai C, Weber GW (2020) Accuracy of transferring analog dental casts to a virtual articulator. J Prosthet Dent 123:305–313. https://doi.org/10.1016/j.prosdent.2018.12.019
18. Yee SHX, Esguerra RJ, Chew AAQ, Wong KM, Tan KBC (2018) Three-Dimensional Static Articulation Accuracy of Virtual Models – Part I: System Trueness and Precision. J Prosthodont 27:129–136. https://doi.org/10.1111/jopr.12723
19. Farrar WB (1972) Differentiation of temporomandibular joint dysfunction to simplify treatment. J Prosthet Dent 28:629–36.
20. Farrar WB (1978) Characteristics of the condylar path in internal derangements of the TMJ. J Prosthet Dent 39:319–323. https://doi.org/10.1016/s0022-3913(78)80103-6

21. Gsellmann B, Schmid-Schwap M, Piehslinger E, Slavicek R (1998) Lengths of condylar pathways measured with computerized axiography (CADIAX) and occlusal index in patients and volunteers. J Oral Rehabil 25:146–152. https://doi.org/10.1046/j.1365-2842.1998.00198.x
22. Bernhardt O, Kordaß B, Meyer G (2014) The diagnostic values of computerized jaw tracking for arthrogenous temporomandibular disorders (TMDs). /Der diagnostische Wert von computergestützten Kieferbewegungsaufzeichnungen bei arthrogenen kraniomandibulären Dysfunktionen. J Craniomandib Funct 6:39–50.
23. Klett R (1986) Zur Biomechanik des Kiefergelenkknackens. III: Ätiologie der zentrischen und exzentrischen Diskusluxation. Dtsch Zahnärztl Z 41:684–692.
24. Kordaß B (2003) Computer-assisted instrumental functional diagnostics - state of development, possibilities, and limits. Int J Comput Dent 6:249–269.
25. Kordaß B (1996) Kopplung der Kernpintomographie des Kiefergelenkes mit computergestützten Aufzeichnungen der Kondylenbahn. Neue Aspekte für die funktionsorientierte Kiefergelenkdiagnostik und -therapie. Quintessenz, Berlin
26. Marpaung CM, Kalaykova SI, Lobbezoo F, Naeije M (2014) Validity of functional diagnostic examination for temporomandibular joint disc displacement with reduction. J Oral Rehabil 41:243–249. https://doi.org/10.1111/joor.12130
27. Kobs G, Bernhardt O, Kocher T, Meyer G (2005) Critical assessment of temporomandibular joint clicking in diagnosing anterior disc displacement. Stomatologija 7:28–30.
28. Kordaß B, Bernhardt O, Ratzmann A, Hugger S, Hugger A (2014) Standard and limit values of mandibular condylar and incisal movement capacity. Int J Comput Dent 17:9–20.
29. Piancino MG, Roberi L, Frongia G, Reverdito M, Slavicek R, Bracco P (2008) Computerized axiography in TMD patients before and after therapy with 'function generating bites'. J Oral Rehabil 35:88–94. https://doi.org/10.1111/j.1365-2842.2007.01815.x
30. Piehslinger E, Bigenzahn W, Celar A, Slavicek R (1995) The effect of occlusal splint therapy on different curve parameters of axiographic TMJ tracings. Cranio 13:35–41. https://doi.org/10.1080/08869634.1995.11678040
31. Ahlers MO, Bernhardt O, Jakstat HA, Kordass B, Türp JC, Schindler HJ, Hugger A (2015) Motion analysis of the mandible: guidelines for standardized analysis of computer-assisted recording of condylar movements. Int J Comput Dent 18:201–223.
32. Hugger A, Hugger S, Ahlers MO, Schindler HJ, Türp JC, Kordaß B (2013) Movement function of the mandible: A concept for structuring criteria for analysis and for standardizing computer-assisted recordings (Expert statement for developing Diagnostic Criteria for Dysfunction). J Craniomandib Funct 5:41–53.
33. Ahlers MO, Bernhardt O, Jakstat HA, Kordaß B, Türp JC, Schindler HJ, Hugger A (2014) Motion analysis of the mandible: concept for standardized evaluation of computer-assisted recording of condylar movements. J Craniomand Funct 6:333–352.

34. Utz K, Hugger A, Ahlers MO, Seeher W (2016) S2k Guideline, Instrumental Functional Analysis in Dentistry. J Craniomand Funct 8:185–236.
35. Ahlers MO, Jakstat HA (2002) Computer assistance in clinical functional analysis. Int J Comput Dent 5:271–284.
36. Ahlers MO (2009) The attachment of a paraocclusal tray adapter to the lower arch for axiography – an improved procedure. J Craniomandib Funct 1:241–250.
37. Ahlers MO, Jaeger D, Jakstat HA (2010) Concept of computer-assisted clinical diagnostic documentation systems for the practice with the option of later scientific evaluations. Int J Comput Dent 13:233–250.
38. Kobs G (2003) Differentialdiagnostische Aspekte bei der Beurteilung von Funktionsstörungen des stomatognathen Systems mittels elektronischer Achsiographie und Magnetresonanztomographie. Dissertation, Ernst-Moritz-Arndt-Universität Greifswald
39. Fleiss JL (1971) Measuring nominal scale agreement among many raters. Psychol Bull 76:378–382. https://doi.org/10.1037/h0031619
40. Landis JR, Koch GG (1977) The measurement of observer agreement for categorical data. Biometrics 33:159–174.
41. Trulsson M, Essick GK (2004) Mechanosensation. In: Miles TS, Nauntofte B Svensson P (eds) Clinical Oral Physiology. Quintessence, Copenhagen:190–194
42. Hugger A, Hugger S, Niedermeier W, Morneburg T, Weßling W, Jakstat HA, Verde P, Bollmann F (2005) Reliability of computer assisted determination of articulator related functional parameters. Poster (P14), 24th Biannual Conference of the Society of Oral Physiology, Reykjavik
43. Schiffman E, Ohrbach R, Truelove E, Look J, Anderson G, Goulet JP, List T, Svensson P, Gonzalez Y, Lobbezoo F, Michelotti A, Brooks SL, Ceusters W, Drangsholt M, Ettlin D, Gaul C, Goldberg LJ, Haythornthwaite JA, Hollender L, Jensen R, John MT, De Laat A, de Leeuw R, Maixner W, van der Meulen M, Murray GM, Nixdorf DR, Palla S, Petersson A, Pionchon P, Smith B, Visscher CM, Zakrzewska J, Dworkin SF (2014) Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) for Clinical and Research Applications: recommendations of the International RDC/TMD Consortium Network and Orofacial Pain Special Interest Group. J Oral Facial Pain Headache 28:6–27. https://doi.org/10.11607/jop.1151
44. Becker K, Jakstat HA, Ahlers MO (2018) Quality improvement of functional diagnostics in dentistry through computer-aided diagnosis: a randomized controlled trial. Int J Comput Dent 21:281–294.

Figures

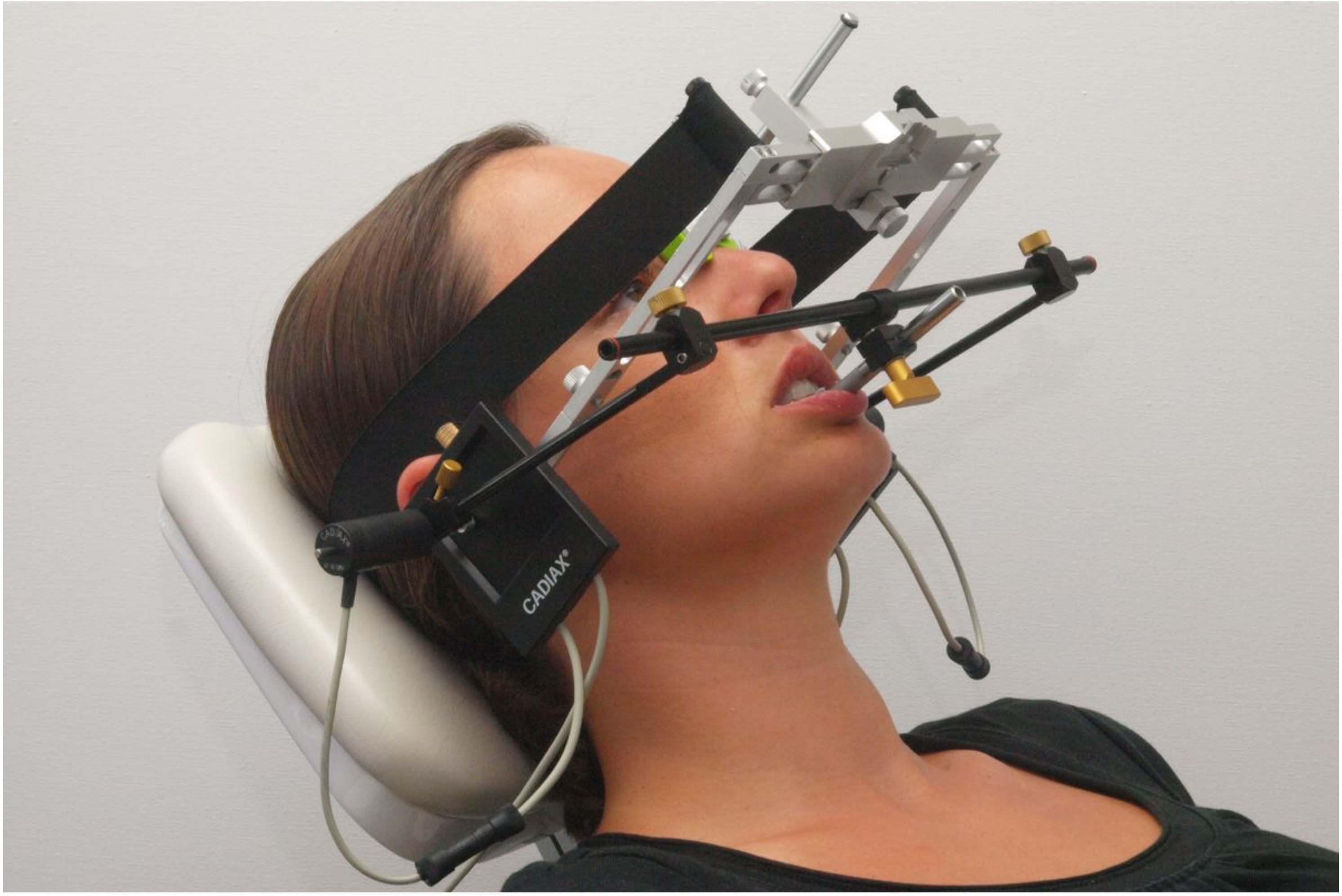
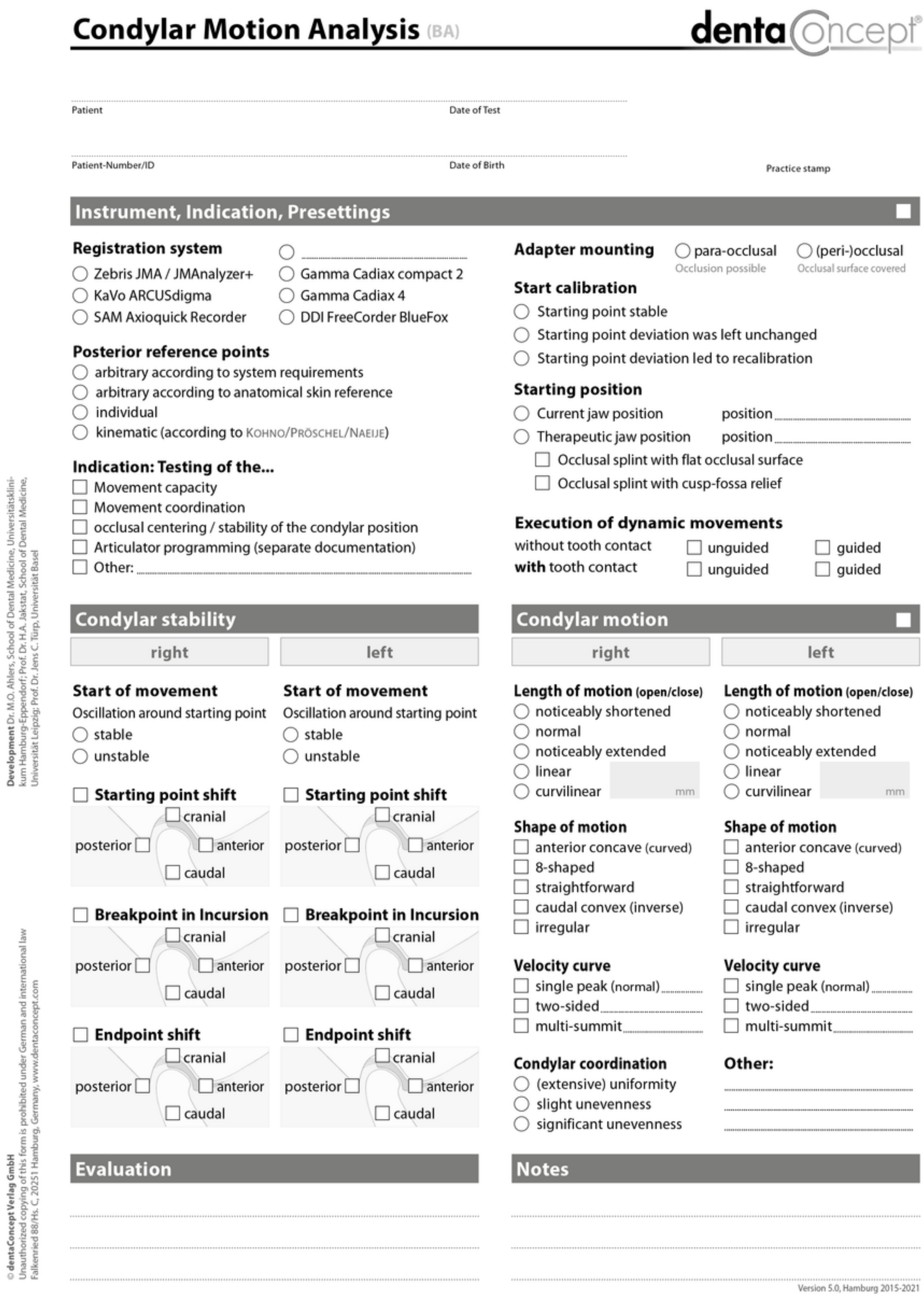


Figure 1

Electronic motion recording system used, which is based on the voltage division method (Cadiax Compact 2, photo: Ahlers).

Figure 2

Example of a computer-aided motion recording system based on ultrasonic measurement technology (Jaw Motion Analyzer, photo: Ahlers).



Condylar Motion Analysis (BA)

dentaConcept®

Patient .... Date of Test ....

Patient-Number/ID .... Date of Birth ....

Practice stamp

Instrument, Indication, Presettings

Registration system
- ○ Zebris JMA / JMAnalyzer+
- ○ KaVo ARCUSdigma
- ○ SAM Axioquick Recorder
- ○ ....
- ○ Gamma Cadiax compact 2
- ○ Gamma Cadiax 4
- ○ DDI FreeCorder BlueFox

Posterior reference points
- ○ arbitrary according to system requirements
- ○ arbitrary according to anatomical skin reference
- ○ individual
- ○ kinematic (according to KOHNO/PRÖSCHEL/NAEIJE)

Indication: Testing of the...
- ☐ Movement capacity
- ☐ Movement coordination
- ☐ occlusal centering / stability of the condylar position
- ☐ Articulator programming (separate documentation)
- ☐ Other: ....

Adapter mounting ○ para-occlusal (Occlusion possible) ○ (peri-)occlusal (Occlusal surface covered)

Start calibration
- ○ Starting point stable
- ○ Starting point deviation was left unchanged
- ○ Starting point deviation led to recalibration

Starting position
- ○ Current jaw position — position ....
- ○ Therapeutic jaw position — position ....
  - ☐ Occlusal splint with flat occlusal surface
  - ☐ Occlusal splint with cusp-fossa relief

Execution of dynamic movements
- without tooth contact ☐ unguided ☐ guided
- **with** tooth contact ☐ unguided ☐ guided

Condylar stability

right	left
Start of movement	**Start of movement**
Oscillation around starting point	Oscillation around starting point
○ stable	○ stable
○ unstable	○ unstable
☐ **Starting point shift** ☐ cranial, posterior ☐, ☐ anterior, ☐ caudal	☐ **Starting point shift** ☐ cranial, posterior ☐, ☐ anterior, ☐ caudal
☐ **Breakpoint in Incursion** ☐ cranial, posterior ☐, ☐ anterior, ☐ caudal	☐ **Breakpoint in Incursion** ☐ cranial, posterior ☐, ☐ anterior, ☐ caudal
☐ **Endpoint shift** ☐ cranial, posterior ☐, ☐ anterior, ☐ caudal	☐ **Endpoint shift** ☐ cranial, posterior ☐, ☐ anterior, ☐ caudal

Condylar motion

right	left
Length of motion (open/close)	**Length of motion (open/close)**
○ noticeably shortened	○ noticeably shortened
○ normal	○ normal
○ noticeably extended	○ noticeably extended
○ linear	○ linear
○ curvilinear ... mm	○ curvilinear ... mm
Shape of motion	**Shape of motion**
☐ anterior concave (curved)	☐ anterior concave (curved)
☐ 8-shaped	☐ 8-shaped
☐ straightforward	☐ straightforward
☐ caudal convex (inverse)	☐ caudal convex (inverse)
☐ irregular	☐ irregular
Velocity curve	**Velocity curve**
☐ single peak (normal)	☐ single peak (normal) ....
☐ two-sided	☐ two-sided ....
☐ multi-summit	☐ multi-summit ....
Condylar coordination	**Other:**
○ (extensive) uniformity	....
○ slight unevenness	....
○ significant unevenness	....

Evaluation

....

Notes

....

Version 5.0, Hamburg 2015-2021

Development Dr. M.O. Ahlers, School of Dental Medicine, Universitätsklinikum Hamburg-Eppendorf; Prof. Dr. H.A. Jakstat, School of Dental Medicine, Universität Leipzig; Prof. Dr. Jens C. Türp, Universität Basel

Figure 3

Findings sheet "Instrumental motion analysis" (dentaConcept, Hamburg)

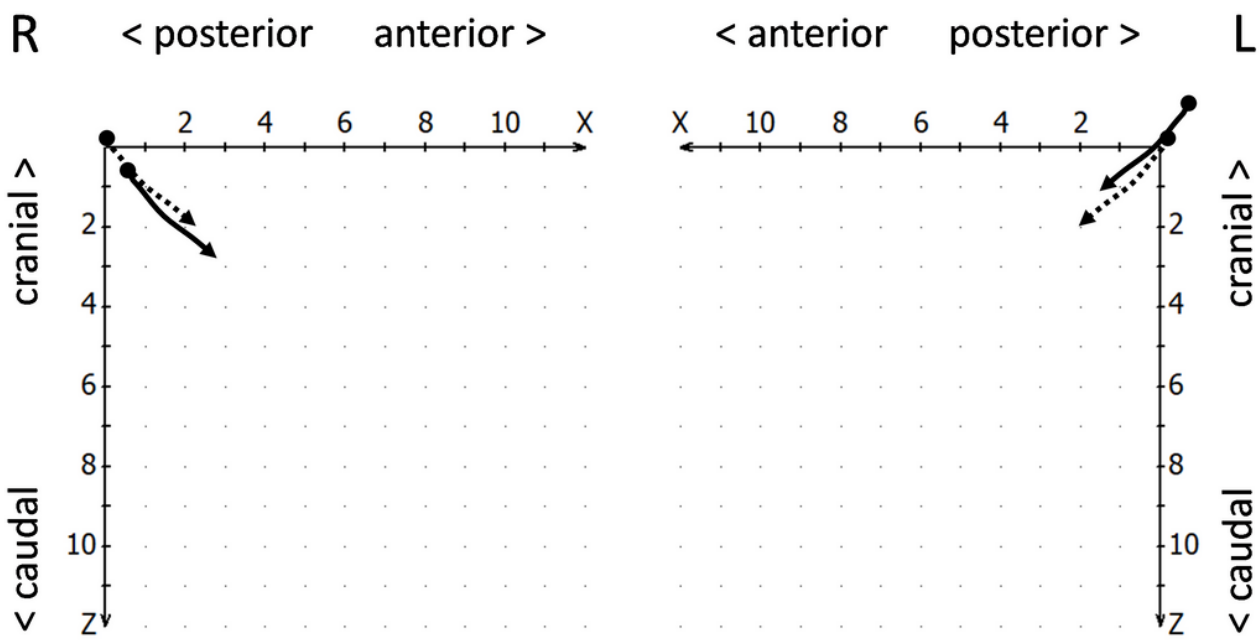


Figure 4

Schematic drawing of a starting point shift to anterior-caudal (right, continous line) and to retro-cranial (left, continous line), both compared to normal movement paths (dotted).

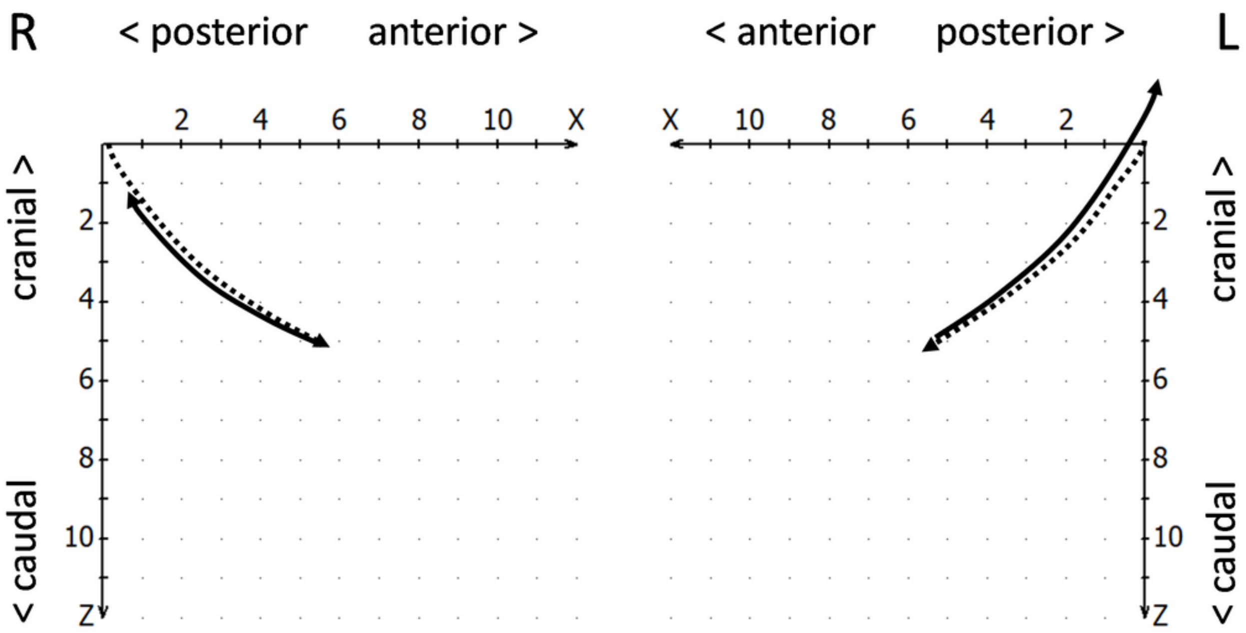


Figure 5

Schematic drawing of an endpoint shift (continous lines), right anterior-caudal and left retro-cranial, as compared to normal movement paths (dotted).

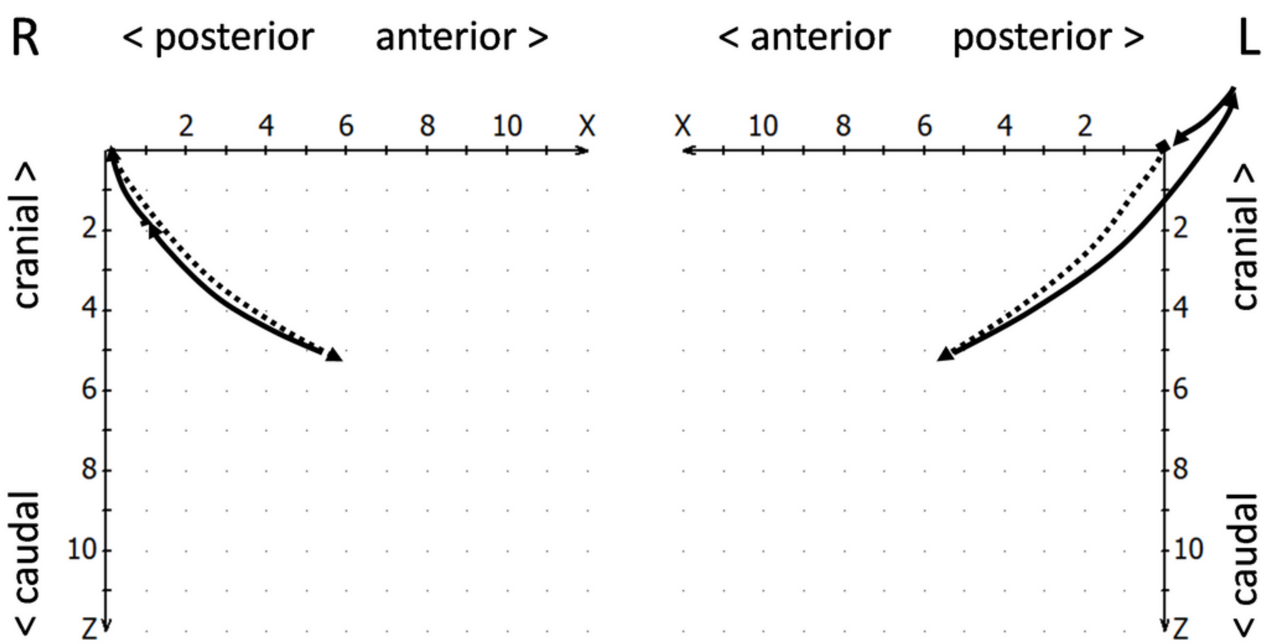


Figure 6

Schematic drawing for a breakpoint in incursion (continous lines), right anterior-caudal and left retro-cranial (as compared to dotted normal movement paths).

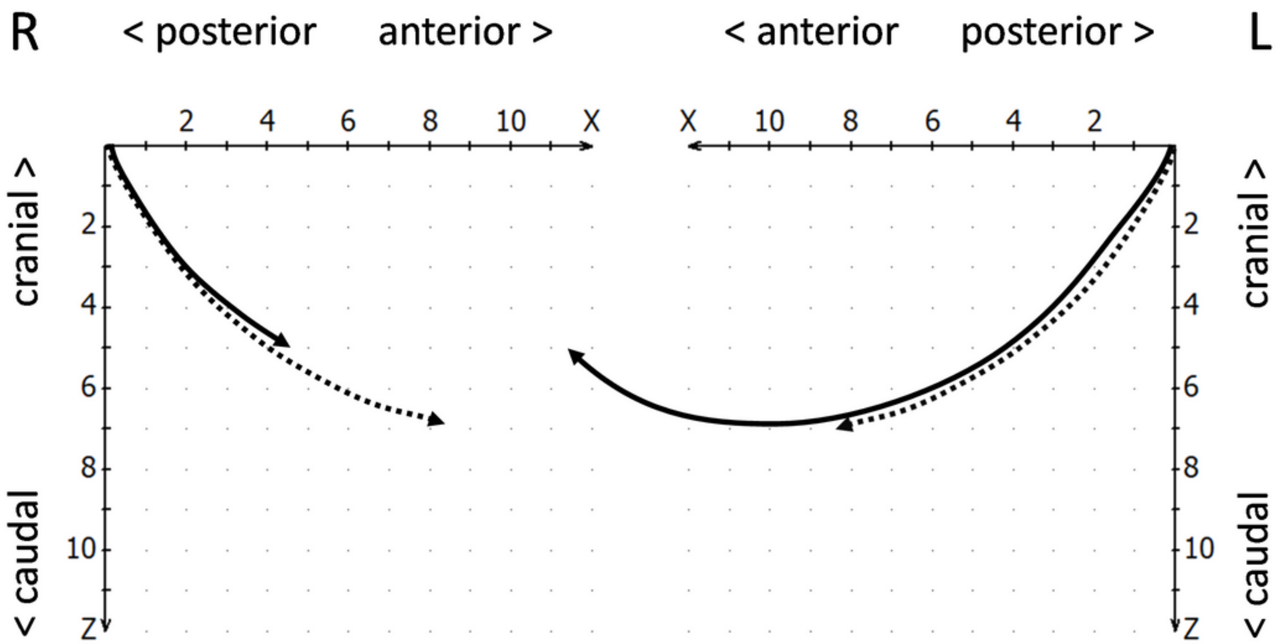


Figure 7

Schematic drawing of a conspicuously shortened movement path (continous line, right side) and a conspicuously lengthened movement path on the left side of the jaw (normal movement paths dotted, for comparison).

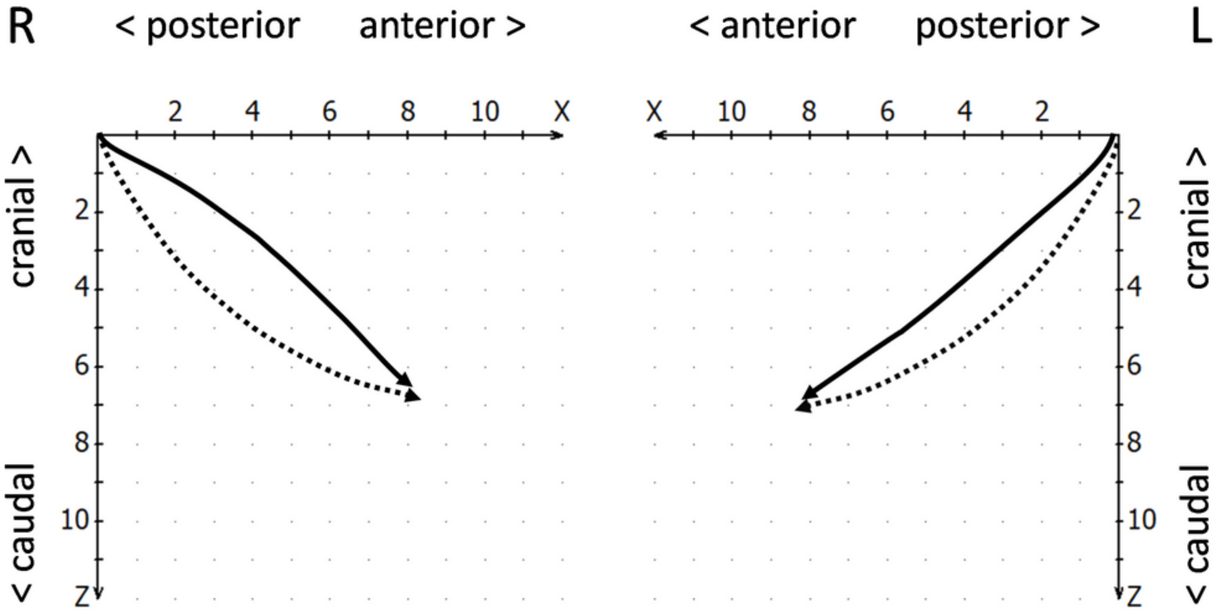


Figure 8

Schematic drawing of caudal convex movement paths (dotted) and anterior concave (continous, right) and straight movement path (continous) on the left side of the jaw.

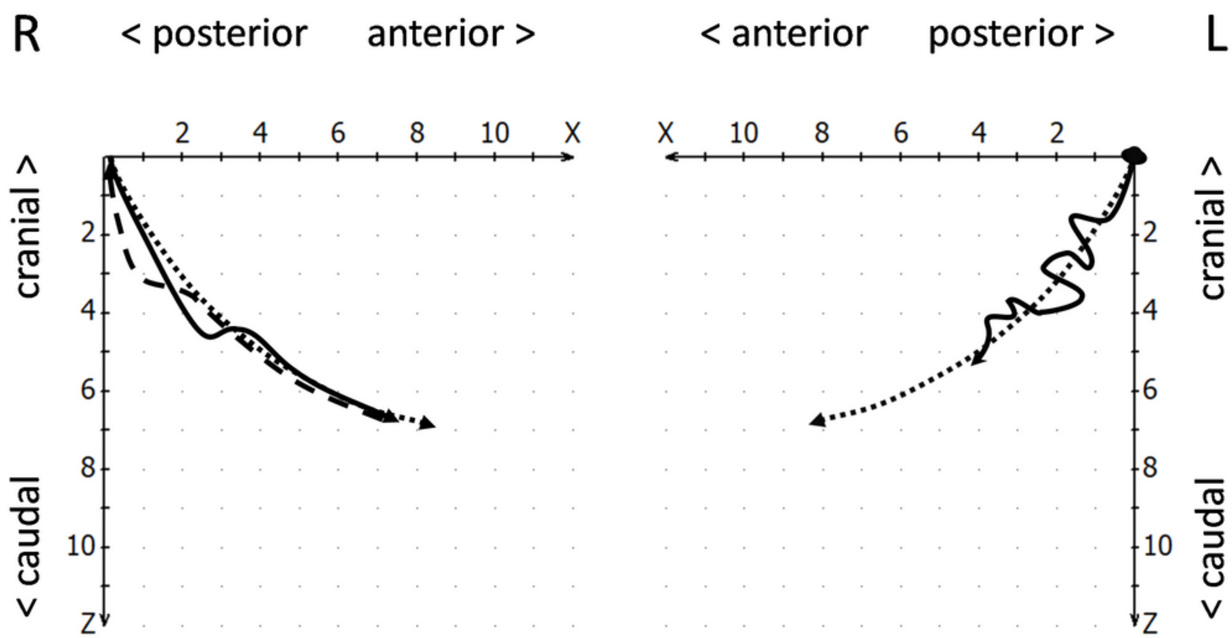


Figure 9

Schematic drawing of an erratic (8-shaped) movement pattern on the right (excursion continous, incursion dashed) and an irregular movement pattern (continous) on the left side of the jaw.

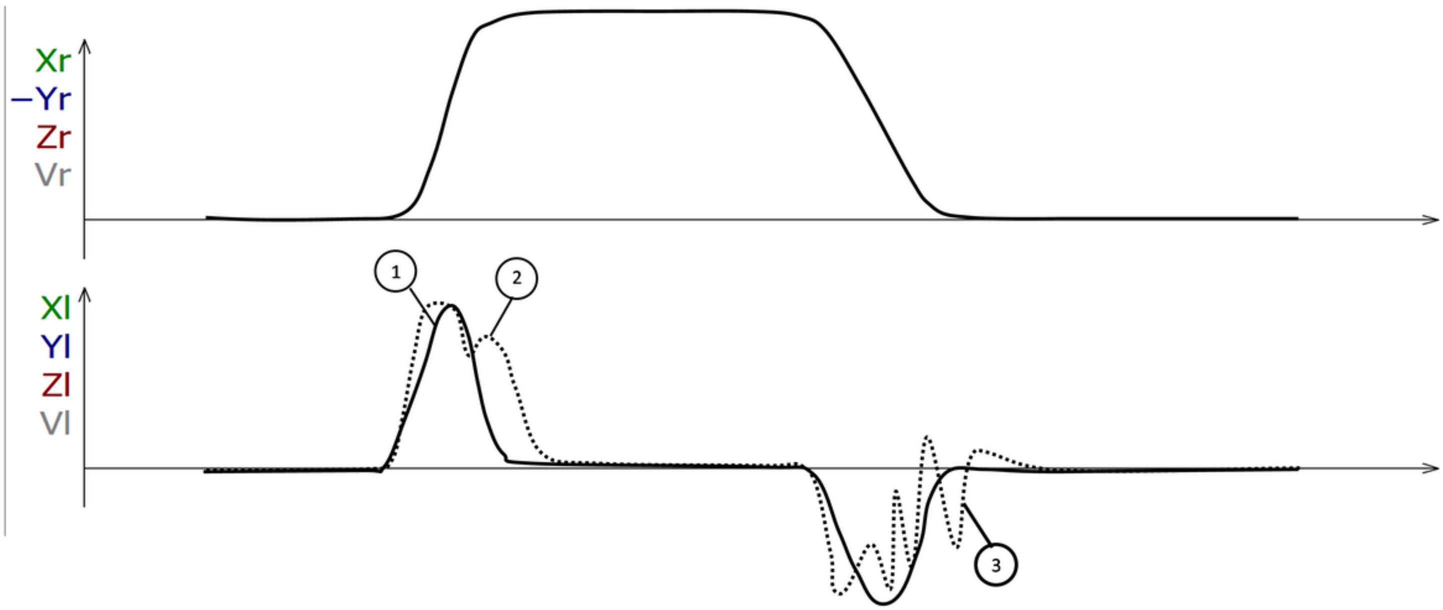


Figure 10

Schematic drawing of a time-distance diagram (upper plot) and a time-speed-diagram (bottom plot) with a single-peaked (continousm arked “1"), a dotted line featuring a double-peaked velocity curve in the opening phase (dotted, marked “2") and a multi-peaked velocity curve in the closing phase of movement (dotted line, marked “3”)

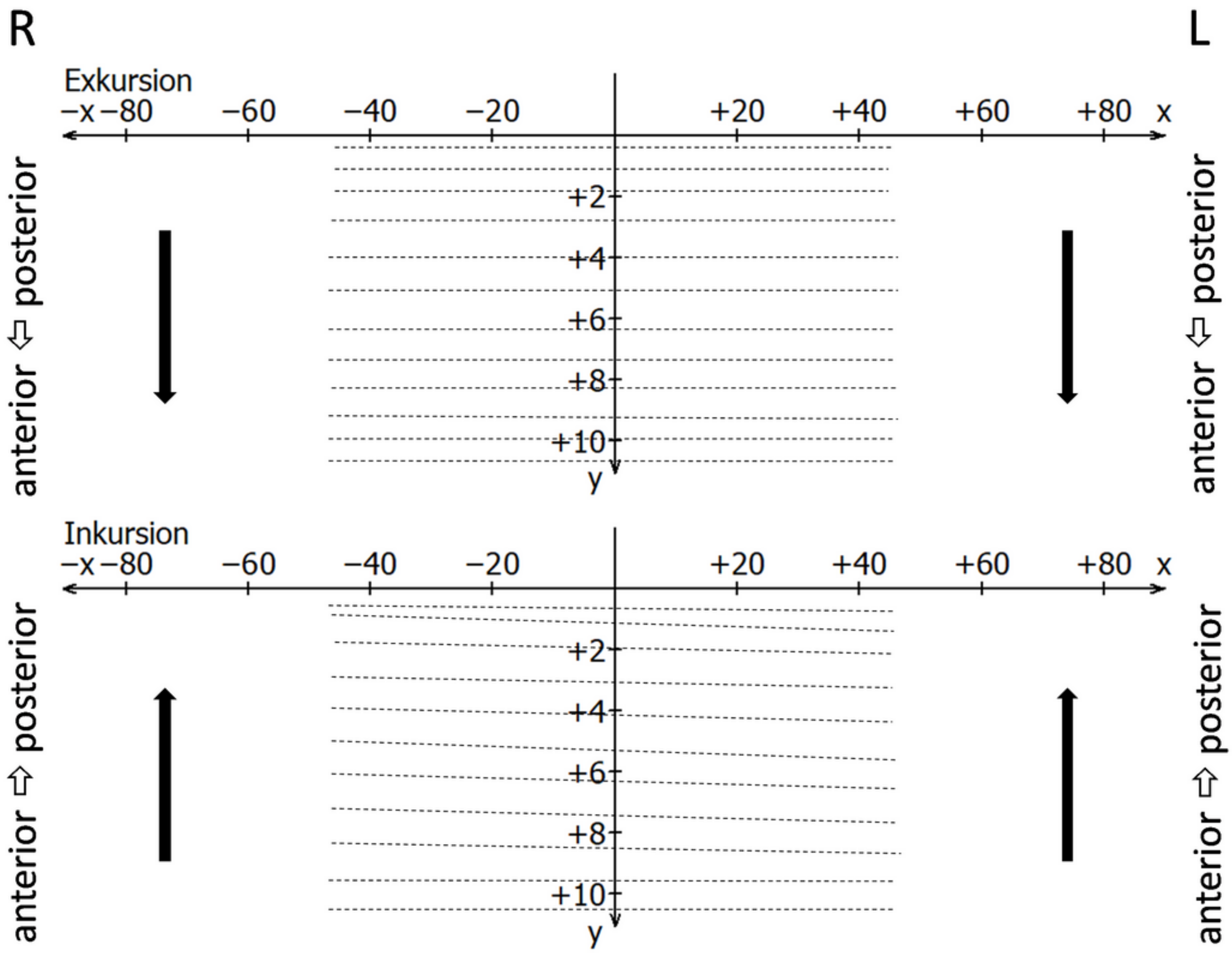


Figure 11

Schematic drawing of an essentially uniform condylar coordination during jaw opening (excursion, upper plot) and jaw closing (incursion, bottom plot) in top view.

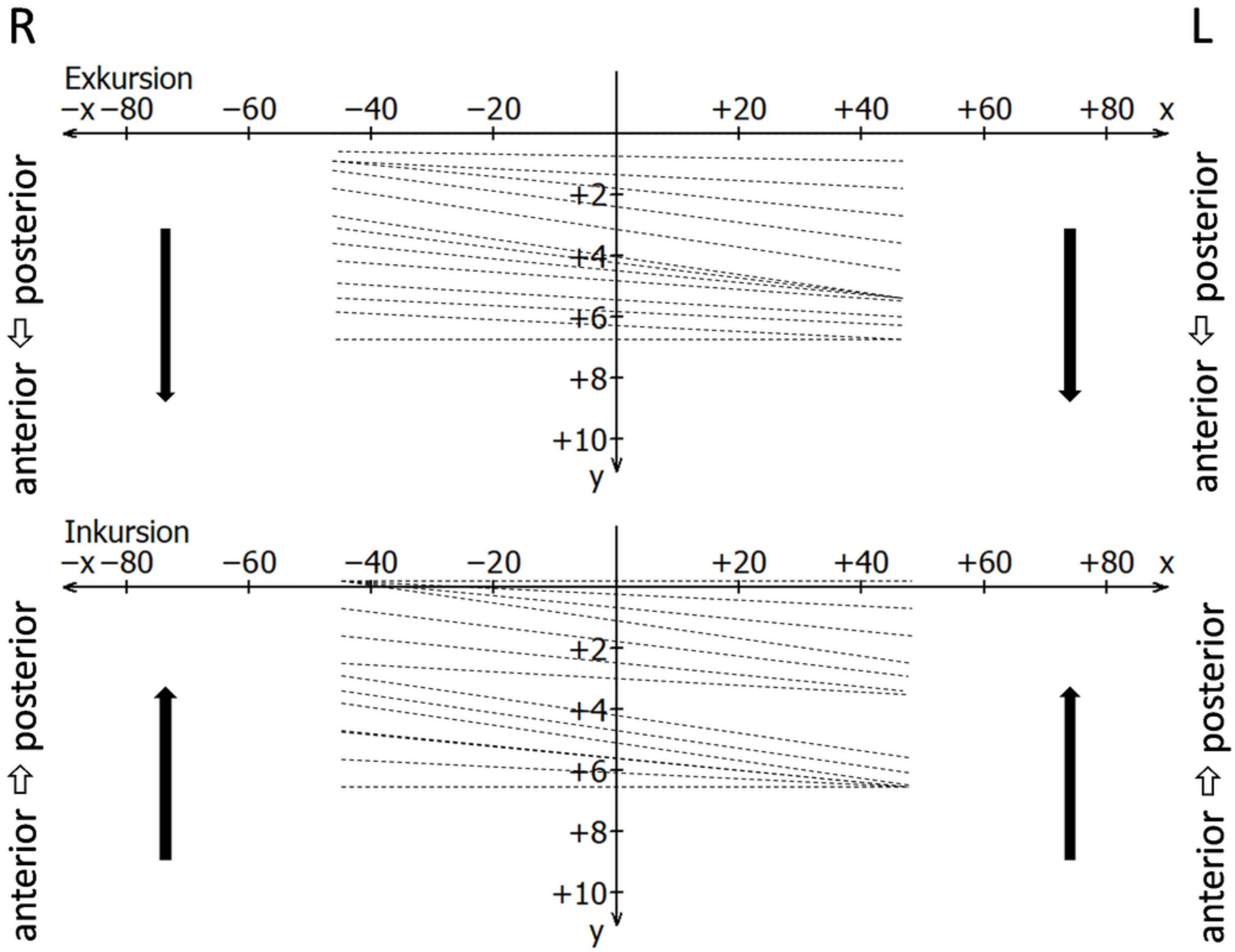


Figure 12

Schematic drawing of an asymmetrical condylar movement with unilateral line compression during jaw opening (excursion, upper plot) and jaw closing (incursion, bootm plot) in horizontal view.

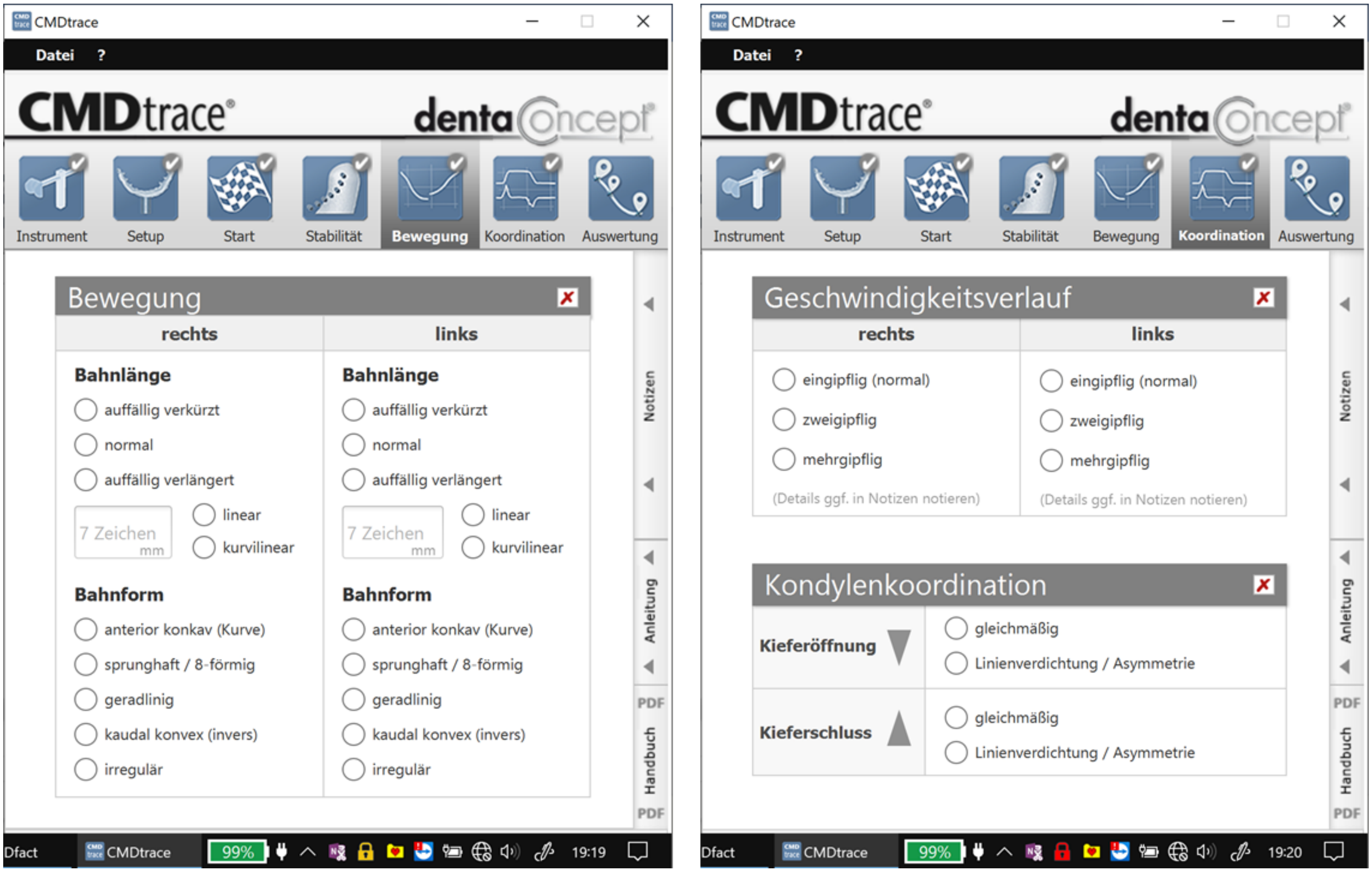


Figure 13

Software module CMDtrace as part of the software suite CMDfact 4 (dentaConcept Verlag) with revised user interface because of the study results for the condylar motion (a) and condylar coordination (b) sections. The options that can be selected in the German-language software CMDtrace are Fig. 13 a) Movement Path length conspicuously shortened | normal | conspicuously lengthened as well as path shape anterior concave (curve) | jumpy / 8-shaped | straight-line | caudal convex (inverse) | irregular; Fig. 13 b) Velocity curve single-peaked (normal) | double-peaked, multi-peaked and in the condylar coordination section at jaw opening and jaw closing respectively: even | line compression/asymmetry.