Protet Stomatol, 2023; 73(1): 18-28 www.protetstomatol.pl
DOI: 10.5114/ps/162663

Jaw motion tracking systems – literature review

Systemy śledzenia ruchów żuchwy – przegląd literatury

Sylwia Jakubowska[1], Marcin Piotr Szerszeń[2], Jolanta Kostrzewa-Janicka[2]

[1] **Studenckie Koło Naukowe, Katedra Protetyki Stomatologicznej, Warszawski Uniwersytet Medyczny**
Students' Research Group, Department of Prosthodontics, Medical University of Warsaw

[2] **Katedra Protetyki Stomatologicznej, Warszawski Uniwersytet Medyczny**
Department of Prosthodontics, Medical University od Warsaw,
Head: prof. dr hab. n. med. *Jolanta Kostrzewa-Janicka*

KEY WORDS:
mandibular movement analysis, jaw motion tracking system, MODJAW, 4D CBCT, SICAT, JMT

HASŁA INDEKSOWE:
analiza ruchu żuchwy, System śledzenia ruchu żuchwy, MODJAW, 4D CBCT, SICAT, JMT

Summary

Mandibular movement analysis is an integral part of the diagnosis and therapeutic processes in the fields of prosthodontics, orthodontics, or maxillofacial surgery and for many years has remained a subject of studies. For the stomatognathic system to work physiologically, during mastication, swallowing, and speaking, stability and proper dynamics of movement are crucial. The TMJ's intricate anatomy and biomechanics require complete harmony in order to be healthy and functional. A major implication might result from any problem or malfunction that impacts even one of the system's components, eventually triggering the onset of a temporomandibular disorder. Six degrees of freedom (6 DOF) – three translational and three rotational, which correspond to all conceivable motion axes of a rigid body in a three-dimensional space - are used to biomechanically describe the mandibular kinematics. Pure rotation or translation in TMJ function is a rare occurrence. For many years, in the field of traditional prosthodontics workflow, instrumentation in the form of mechanical articulators and face bows has been used. However, due to the articulator's basic design and, in some cases, the inability to

Streszczenie

Analiza ruchów żuchwy jest niezbędną i integralną częścią procesów diagnostycznych i leczniczych w dziedzinie protetyki, ortodoncji, chirurgii szczękowo-twarzowej czy ortognatycznej i pozostaje przedmiotem badań od wielu lat. Aby układ stomatognatyczny funkcjonował w sposób fizjologiczny, podczas żucia, połykania i mówienia, stabilność i prawidłowa dynamika ruchu są cechami kluczowymi, a nawet niezbędnymi. Skomplikowana anatomia i biomechanika stawu skroniowo-żuchwowego (TMJ) wymagają pełnej koherencji, aby były zdrowe i funkcjonalne. Poważne implikacje mogą wynikać z jakiegokolwiek problemu natury anatomicznej lub nieprawidłowego działania, które mają wpływ nawet na jeden z elementów systemu, ostatecznie mogąc być początkiem zaburzeń skroniowo-żuchwowych. Do biomechanicznego opisu kinematyki żuchwy wykorzystuje się sześć stopni swobody (6 DOF) – trzy translacyjne i trzy obrotowe, które odpowiadają wszystkim osiom ruchu obiektu sztywnego w przestrzeni trójwymiarowej. Czysta rotacja lub translacja w funkcji TMJ jest rzadkim zjawiskiem. Od wielu lat w obszarze tradycyjnej protetyki stomatologicznej pojawia się oprzyrządowanie w postaci mechanicznych artykulatorów oraz *perform patient-specific movement modeling, there are still unavoidable limitations of their use. Today, in the era of digital dentistry, innovative and efficient instruments for treatment planning and diagnostics in orthodontic and prosthodontic workflow, as well as in gnathological research, are jaw motion tracking systems (JMT). The aim of this literature review was to describe digital protocols and to characterize methods and instruments that enable individualized treatment of patients in the scope of complex mandibular movements.*

łuków twarzowych. Jednak ze względu na konstrukcję artykulatora i niekiedy brak możliwości modelowania ruchu specyficznego dla pacjenta, nadal wymieniane są ograniczenia wynikające z jego wykorzystywania. W dobie stomatologii cyfrowej, innowacyjnym i skutecznym narzędziem do planowania leczenia i diagnostyki w pracy ortodontycznej i protetycznej, a także w badaniach gnatologicznych są systemy śledzenia ruchów żuchwy (JMT). Celem niniejszego przeglądu piśmiennictwa było opisanie protokołów cyfrowych oraz scharakteryzowanie metod i instrumentów, które umożliwiają zindywidualizowanie cyfrowego postępowania w zakresie rejestracji złożonych ruchów żuchwy.

Introduction

For decades now, mandibular movement analysis has been an inherent and crucial element of diagnosis and treatment process in the fields of prosthodontics, orthodontics, maxillofacial or orthognathic surgery. Stability and physiological dynamics are the fundamental or even necessary features in order to perform the natural and automatic stomatognathic system's functions such as biting, swallowing, speech without disturbances or interferences.[1,2] The complexity of anatomy and biomechanics of TMJ dictates the need for utter harmony between them to maintain health and function. As a consequence of any disorder or dysfunction affecting even single one of the system's elements, a serious implication may occur, eventually leading to the emergence of a temporomandibular disorder (TMD).

The majority of physiological mandibular movements constitute a resultant of related rotational and translational shifts in three-dimensional directions. Moreover, despite the fact that TMJ is known to be a bilateral joint and that both sides cannot work entirely independently of one another, they rarely perform the same movements simultaneously. Mandibular kinematics is biomechanically characterized by six degrees of freedom (6DOF) that refer to all the possible motion axes of a rigid body in a three-dimensional space. During movement, each motion axis is independent, yet it never changes its position in relation to the other axes. 6DOF of temporomandibular joint consist of three translational and three rotational movements.

Rarely can one observe pure rotation or translation in the TMJ function. Furthermore, the concept of the initial pure rotation was questioned by *V.F. Ferrario* et al. in 1996. Kinesiograph proved that rotation and translation are always combined, and the localized reference axis changed during motion. Therefore, hinge axis theory seems invalid since pure rotation did not occur around the intercondylar axis.[3] As a result, highly complex, spatial movements are challenging to analyze, and it can only be achieved in 3D projections. *J.P. Okeson* demonstrates the issue by describing the simple lateral mandible shift as a resultant of movements in three spatial planes (sagittal, horizontal, frontal) during which each axis pivot adapting to the movements appearing around other axes to maintain their constant relation.[4]

Mandibular movements ranges are not only determined by ligaments, articular surfaces, morphology of dental arches and teeth anatomy, but are also controlled by brain stem's superior neurons called CPG (central pattern generator) stimulated by numerous sensory receptors.

A simple, approximated, and schematic depiction of 3D mandibular kinematics is 1952s *Posselts'* Envelope – a spatial solid with its shape determined by border movements of an incisal point. With the combination of border movements in all three planes it portrays the 3D space within which each movement is possible.[4]

Literature Research Methods

A literature research approach was chosen to most effectively provide background information on the progress of digital methods of mandibular kinematics registration. A search of the literature was performed from September to November 2022 using four databases: PubMed/Medline, PMC, Web of Science, EMBASE and ResearchGate. Only articles published within the last 30 years were considered. In addition, a search using major Internet search engine (Google) was conducted, and books in the thematic scope of this article were used. Both English- and Polish-language papers were reviewed. The literature search employed various keyword combinations: "jaw tracking," "jaw tracking device," "jaw motion tracking," "jaw tracker," "mandibular movement," "jaw movement registration," "virtual articulator," "digital patient," "TMJ motion analysis," "optoelectronic tracking," "ultrasonic tracking". Articles were screened by title and abstract, and subsequently, full texts of the selected articles were examined. Articles that were irrelevant to the scope of this review were excluded. Additional literature was identified from the reference lists cited in the initially identified articles.

Digital solutions in mandibular kinematics registration

Jaw motion tracking devices (JMT) are innovative and valuable tools for treatment planning and diagnostics in prosthodontics and orthodontic workflow or even in gnathological research.[5] JMT technology contributed to extending the knowledge about the masticatory system. *E. M. Wilson* et al. reported using optical motion tracking system to study the developmental course of early chewing in a group of children, which led to better understanding of childhood feeding and swallowing disorders.[6]

Until now, TMD diagnosis has been generally entrusted in physical and clinical examination and imaging that require experienced clinician and specialist knowledge. In 2022, systematic review and meta-analysis by *Scolaro* et al. confirmed the importance of TMJ kinematic parameters on mandibular function assessment, but stressed the necessity of data standardization and future case-control studies to deliver evidence and establish the gold standard.[7] According to *Riise* and *Sheikholeslam* from Karolinska Institute healthy condition of TMJ is secondary to physiological occlusion. Hence, acknowledging "how" and "why" some anatomical surfaces pathologically changed comes from understanding the functional genesis.[8,9] In 2019 *E. Moriuchi* et al. and *Yasuda* et al. conducted a study on masticatory function and mandibular movements to explain neuromuscular control mechanisms of mastication and to investigate the etiology of oral motor disorders. They compared the parameters of function of normal mice and those of genetically modified mice with oral behavioral dysfunctions by means of jaw-tracking system (which consisted of two high-speed cameras and reflective markers) and micro-CT of mice anatomy.[10,11]

In oral surgery, JMT facilitates pre-operational implantological planning such as implant location, shape and distribution of mastication forces.[12] Maxillofacial and orthognathic surgery commonly use JMT as a tool for pre-operative and post-operative function analysis and comparison. Several studies evaluating pre- and post-orthognathic operation TMJ mobility have been described in literature. Using 4D JMT technology, *Aslanidou* et al. evaluated TMJ function in the control group in comparison to the group of post-operative orthognathic patients. No significant differences in function were observed, however, some clinical symptoms were still present.[13] According to *M. Akashi* et al. 4D-computed tomography has proved its value in post-op evaluation in patients after mandible resection and reconstruction. 4D-CT revealed that operated on patients showed limited mouth-opening in comparison with the control group, although duration of mastication act did not change.[14] *E. Baltali* et al. effectively implemented 3D-JMT technology to compare mandible kinematics of a patient with osteoarthritis before and after unilateral joint replacement with a special implant and *F. Rahman* et al. report positive results of post-operational functional assessment with JMT ultrasonographic device in the case of total joint replacement with an individual prosthesis.[15,16]

The CAD/CAM systems prevalence in clinical prosthodontics practice was followed by the development of virtual articulators' software. In the present era of digital dentistry, the main goal and future direction focuses on the development of single, holistic virtual environment for gathering and merging data. Storage of intra-oral scans, CBCT imaging, JMT registration, virtual articulator and CAD/CAM software would not only allow projecting a comprehensive digital patient image, but also operating entirely digitally at each step of the workflow protocol.[17] Currently it is the most case-individualized and prospective concept that does not base on any population-averaged parameters. Furthermore, 4D kinematic imaging fills the gap in modern diagnostics and planning. While the virtual environment offers various possibilities, e.g. virtual waxing, modifications of tooth morphology, etc. in terms of the advantage of articulation and occlusion, it seems that the combination of VA (virtual articulators), JMT and the CAD/CAM systems would be the gold standard of the purely digital era of dentistry. From the bigger perspective, virtual articulator might become the essential tool facilitating interdisciplinary treatment that requires the holistic approach.[18]

Review of contemporary jaw motion tracking systems

Most common JMT systems operate on a few technological principles, whose pros and cons have been scrutinized in clinical research and described in systematic reviews, although the need for further studies is continuous and would add reliable and repeatable values. Systematic review of 2020 published by *S. C. Woodford* et al. from University of Zurich describes comprehensively available 3D or 4D jaw motion tracking devices and their principles of operation.[19] Among the most common are ultrasonographic devices, electromagnetic sensors, video analysis such as cinematography, optoelectronic imaging, radiographic video x-ray fluoroscopy and 4D computed tomography (4D CBCT).

Ultrasonographic appliances emit ultrasonic pulsations from the lower mandibular face bow to sensors located on the upper head face bow. Mandibular movement is measured by computerized calculation of pulse-travel-time between emitters and sensors. Good example in this category is Jaw Motion Analyzer (JMA, Zebris,Germany). Ultrasonographic JMA devices were used among others by *B. Kordass* et al. in population-representative baseline study (SHIP).[20] Among others, *Hugger* et al. proved the ultrasonographic JMA effectiveness in 2001 clinical trial claiming its 0.1mm precision, and implying the benefits of using the device in clinical practice.[21-24] At the International Dental Show (IDS 2019) in Cologne the new version of the device was presented, namely oJMA, which is based on optical technology making the elements lighter and smaller. The goal of development was to optimize the product for CAD/CAM appliances and to improve precision in motion detection, circa. 50 to 100 µm in the close range of occlusion, according to the manufacturer's specifications.[25]

Electromagnetic methods calculate spatial target location by sensing changes in the surrounding magnetic field. Originally, the method stems from biomechanical studies on spine and knee joint.[26,27] To avoid occlusal interferences, micro-sensors were developed, which are put on the labial surface of the incisors. Electromagnetic JT-3D (BioResearch Associates Inc., Milwaukee, WI, USA), magnetic K7 CMS (Myotronics, Kent, WA, USA) or The Dental Motion Decoder system (DMS-System Ignident, Ludwigshafen am Rhein, Germany) work on this principle.[28,29] There have been attempts to use magnetic microsensores in devices tracking parafunctional activities among bruxers. Their micro size and patient comfort are the main advantages that enable longer diurnal and nocturnal observation period.[30] In 2020, *J. Goob* et al. confirmed reliability and repeatability of sagittal condylar inclination angle and Bennet angle measurements made by DMD-System both *in vitro* and *in vivo*.[31]

Optoelectronic systems are based on emission of infrared light by markers located in certain positions on the face. Two or more high-speed cameras that register up to 2,000 frames per second and computer software register the light impulses and convert them into the movement displayed on the interface. Prime example is Bionic Jaw Motion (BMJ; Bionic Technology, Vercelli, Italy) with software that recognizes and simultaneously locates the markers non-stop during function, thereby accurately reconstructing free mandibular movements (target-tracking device).[32-34] Moreover, BMJ is the first system that integrates a software designed to reproduce the recorded jaw movements on a robotic simulator without the need for its arbitrary regulation and with no mathematical transformations.[35] The downside of target tracing devices seems to be univocal determination of extra-oral landmarks and possible skin artifacts because of markers instability. Therefore, *Revilla-Leon* et al. suggested using a modified custom device with optical jaw tracking system rather than extra-oral markers.[36] 3D scanning works by applying markers to the labial surface of lower incisors and "target" tracing during motion. Such a method is described by *Kwon* et al. as simple to implement in everyday practice considering time and cost. In the study they combined 3D scans with the CBCT scan of the mandible to show accurate condyle movements.[37] According to *Wang* et al. and *Park* et al. integration of 3D scans, intra-oral scans, CBCT, JMT and face scans may offer positive results for occlusion analysis, digital smile design, full-mouth rehabilitation and TMD diagnostics followed by proper treatment.[38,39]

Technology based on 3D fluoroscopy was introduced by *Chen* et al. in 2013 and 2020 in publications claiming that results were promising for mandibular kinematics quantitative assessment, although additional research needed to be carried. Fluoroscopy origins from knee joint imaging. Projection is obtained by joining CT image with dynamic, two-dimensional fluoroscopic registration and therefore creating three-dimensional jaw movement.[40] Contrary to target tracing systems, fluoroscopy eliminates the risk of skin artifacts. However, total radiation dose during a 10-second examination (without CT) reaches approx. 135 microSv. Another concern is measurement reliability, especially during dynamic movements, since speed of registration is about 7.5 frames per second.[19] *Ghanai* et al. reported similar computer-assisted planning for dysgnathia treatment. By merging 3D laser scans of the models, lateral and PA cephalometric X-rays with markers they managed to create a realistic 3D image and virtually reposition the jaws with success.[41]

4D-CBCT technology makes it possible to directly measure and reconstruct mandibular kinematics in virtual environment by means of merging JMT registration with the CBCT image. The application of this method has proven useful in various clinical research, e.g. surgical and orthognathic post-op evaluation of the TMJ function in patients with osteoarthritis, mandible or joint reconstruction. Major disadvantage is the ethical problem of radiation exposure during CBCT affecting both joints and the upper and lower jaw. In a publication by *Akashi* et al. radiation dosage during a 15-second examination is approximately 3.58 mSv with 7.5 frames per sec. and FOV 220 mm. However, the authors strongly believe that 4D-CBCT has a great potential to become "the gold standard" in the future mainly because of ease of use, light instrumentation, elimination of skin artifacts and impact of intra-oral splints or heavy face bows on occlusion and function.[14,19] At the moment of writing this paper the most comprehensive solutions are offered by two 4D-CBCT systems, SICAT (SICAT, Sirona, Bonn, Germany) and Planmeca 4D Jaw Motion (Planmeca, Helsinki, Finland). CBCT enables 3D imaging of bony structures in different layer-thickness and under lower radiation dose comparing to CT. SICAT Function Software integrates registration from ultrasonographic JMT+ (Sicat, Bonn,Germany), intra-oral scans (Cerec Omnicam system, Sirona), CBCT image in DICOM format (Galileos CBCT, Sirona, Germany). After merging the data, system presents final, realistic, and dynamic 3D jaw movement simulation related to the patient's individual anatomy. Ranges of the movement can be easily assessed and the gap between glenoid fossa and condyle can be measured during movement and at rest, meaning compression or stretch. Additionally, SICAT software measures forces of jaw movement and include them in an overall final analysis.[42,43] Due to the publications by *Kühnöl* et al. and *Hannsen* et al. SICAT is the valuable tool in treating cases of TMD that require rehabilitation e.g. occlusal or repositioning splints. It allows the doctor to precisely determine the most therapeutic mandibular and condylar position and transfer it directly to a compatible CAD/CAM program.[44,45] General sequence of steps in SICAT system is described: intra-oral scan, single silicone impression of the maxilla and the mandible on FusionBite tray, CBCT with FusionBite tray, JMT registration. Software merges the obtained data and segments the CBCT image to locate both jaws and condyle in a single layer. The final file is formatted as .DXD (Diogenes Extended Document) and transferred to CAD/CAM, jaw motion simulation is displayed as a video sequence. Sagittal condyle inclination angle, Bennet angle, ISS parameters can be used to regulate external articulator, however the comprehensive workflow that SICAT offers eliminates the need for mechanical or another virtual articulator. *Kurbad* in the 2018 publication extensively described the entire SICAT digital workflow for prosthetic treatment and splint manufacturing, confirming its satisfactory results.[46] Researchers consensually declare that this technology brings great value in TMD diagnostics and studies on occlusion. *Aslanidou* et al. delivered such evidence in the 2017 clinical case report. For the 46 y.o. female patient after pharmacological therapy, with pain and clicking in TMJ, they designed a therapeutic splint in a fully digital SICAT workflow. Digitally designed and fabricated custom-made splint was accurate, adjustment time as well as doctor's time was reduced, and the patient reported immediate relief from TMJ symptoms.[42]

In March 2019, MODJAW Tech in Motion (Modjaw, Villeurbanne, France), the latest technology for real-time jaw motion registration was presented. MODJAW's unique software merges all patient data, including 3D models, 4D movements, and CBCT and facial scans to establish the complete digital replica of the patient. It is believed to be the most prospective and promising solution that is devoid of problems of previous devices. High quality cameras record markers location on the lower face bow and scan certain face areas to deliver the computer stereovision and replicate real-time jaw movements. The patient is not continuously exposed to radiation, and the instrumentation is light and comfortable. It is possible to immediately detect any static or dynamic occlusion interference, occlusal guidance or TMJ disturbances. In 2021, *M. Bapelle* et al. analyzed precision and repeatability of MODJAW measurements by taking into consideration TSI (transversal sagittal inclination) and SCI (sagittal condylar inclination) in asymptomatic patients. Quality and reliability have been satisfactory or excellent, and the authors drew conclusions that MODJAW was an effective tool to treat patients in a specific, most habitual mandibular position.[47]

Conclusions

In the current era of digital dentistry one can witness a rapid development of new technologies and updates on the market. *Greven* et al. correctly emphasized the increasing awareness of high-quality dentistry by patients and the subsequent demand for better longevity of their dental therapies, which should encourage dental community to take a fresh look at modern innovations.[48] Brand-new solutions facilitate doctor-patient communication, gathering and storing loads of data, more precise diagnostics and possibility to design and fabricate the prosthodontic and esthetic restorations in a fully digital environment. To integrate every essential step in the digital workflow subsequent must-have devices are being presented that complicate the process and take time to learn. According to the creator of Digital Smile Design (DSD) Protocol, developing a simple, integrated and complex digital system is a superior goal of modern dentistry that would allow its common useand further development.[49] Because of relatively short time of follow-up and high costs of new technologies, the majority of clinicians stay with solutions like axiography or ultrasonographic JMT, which are prone to risk of error in determining inter condylar axis, occlusal interference of heavy instrumentation, etc. Often, intercondylar axis point is approximately determined somewhere on the mandibular head, which according to *Gallo* et al. usually differs circa 4.5 - 10 mm from the actual axis.[50] Therefore, it seems more reasonable to consider measurements from e.g. 3D JMT devices that use CT or joint anatomy imaging, but again expose patients to radiation. Optoelectronic systems may be burdened by error of skin artifacts. Another downside of many aforementioned devices is incompatibility with the CAD/CAM software and transfer or different file formats. Currently this can easily be achieved in SICAT system (.jmtxd to Cerec, inLab), Zebris and MODJAW (.xml to for example Exocad). Gradual digital integration of subsequent steps in full-mouthrehabilitation gives promise of creating a complete and consistent protocol in the near future that considers detailed diagnostics, fast and effective data gathering, direct virtual designing and precise fabrication of restorations by milling machines or 3D printers. This could supposedly eliminate downsides of analogue, conventional prosthodontics such as operator inaccuracy, limitations of articulators or additional adjustments. Moreover, real-time, 4D technologies for mandibular kinematics assessment may be valuable solutions for TMJ analysis in cases that require understanding of the etiology of a specific disorder and applying proper treatment.

References

1. *Soboļeva U, Lauriņa L, Slaidiņa A*: Jaw tracking devices – historical review of methods development. Part I. Stomatologija 2005; 7: 67-71.
2. *Soboļeva U, Lauriņa L, Slaidiņa A:* Jaw tracking devices--historical review of methods development. Part II. Stomatologija 2005; 7: 72-76.
3. *Ferrario VF, Sforza C, Miani A, Serrao G, Tartaglia G*: Open-close movements in the human temporomandibular joint: does a pure rotation around the intercondylar hinge axis exist? J Oral Rehabil 1996; 23: 401-408. doi:10.1111/j.1365-2842.1996.tb00871.x
4. *Okeson JP*: Management of Temporomandibular Disorders and Occlusion, 8th ed. Elsevier: St. Louis MI, USA, 2020.
5. *Adel S, Zaher A, El Harouni N, Venugopal A, Premjani P, Vaid N*: Robotic Applications in Orthodontics: Changing the Face of Contemporary Clinical Care. Biomed Res Int 2021; 2021: 9954615. doi:10.1155/2021/9954615
6. *Wilson EM, Green JR*: The development of jaw motion for mastication. Early Hum Dev 2009; 85: 303-311. doi:10.1016/j.earlhumdev.2008.12.003
7. *Scolaro A, Khijmatgar S, Rai PM, Falsarone F, Alicchio F, Mosca A, Greco C, Del Fabbro M, Tartaglia GM*: Efficacy of Kinematic Parameters for Assessment of Temporomandibular Joint Function and Disfunction: A Systematic Review and Meta-Analysis. Bioengineering 2022; 9: 269. doi:10.3390/bioengineering9070269
8. *Riise C, Sheikholeslam A*: The influence of experimental interfering occlusal contacts on the postural activity of the anterior temporal and masseter muscles in young adults. J Oral Rehabil 1982; 9: 419-425. doi:10.1111/j.1365-2842.1982.tb01031.x
9. *Sheikholeslam A, Riise C*: Influence of experimental interfering occlusal contacts on the activity of the anterior temporal and masseter muscles during submaximal and maximal bite in the intercuspal position. J Oral Rehabil 1983; 10: 207-214. doi:10.1111/j.1365-2842.1983.tb00114.x
10. *Moriuchi E, Hamanaka R, Koga Y, Fujishita A, Yoshimi T, Yasuda G, Kohara H, Yoshida N*: Development and evaluation of a jaw-tracking system for mice: reconstruction of three-dimensional movement trajectories on an arbitrary point on the mandible. Biomed Eng Online 2019; 18: 59. doi:10.1186/s12938-019-0672-z
11. *Yasuda G, Moriuchi E, Hamanaka R, Fujishita A, Yoshimi T, Yamamoto K, Hayashida K, Koga Y, Yoshida N*: Visualization of mandibular movement relative to the maxilla during mastication in mice: integration of kinematic analysis and reconstruction of a three-dimensional model of the maxillofacial structure. BMC Oral Health 2021; 21: 527. doi:10.1186/s12903-021-01879-4
12. *Chkhikvadze TV, Roschin E, Bekreev V*: Comparative analysis of the application of virtual and mechanical articulators in functional diagnostics. RUDN Journal of Medicine 2020; 24: 38-51. doi:10.22363/2313-0245-2020-24-1-38-51
13. *Aslanidou K, Xie R, Christou T, Lamani E, Kau CH*: Evaluation of temporomandibular joint function after orthognathic surgery using

a jaw tracker. J Orthod 2020; 47: 140-148. doi:10.1177/1465312520908277

14. *Akashi M, Shibuya Y, Takahashi S, Hashikawa K, Hasegawa T, Kakei Y, Negi, N, Sekitani T, Komori T*: Four-dimensional computed tomography evaluation of jaw movement following mandibular reconstruction: A pilot study. J Craniomaxillofac Surg 2016; 44: 637-641. doi:10.1016/j.jcms.2016.01.027.
15. *Baltali E, Zhao KD, Koff MF, Durmuş E, An KN, Keller EE*: A method for quantifying condylar motion in patients with osteoarthritis using an electromagnetic tracking device and computed tomography imaging. J Oral Maxillofac Surg 2008; 66: 848-857. doi:10.1016/j.joms.2008.01.021
16. *Rahman F, Femiano F, Louis PJ, Kau CH*: An Evaluation of Jaw Tracking Movements in Patients with Total Joint Replacements versus a Control Group. Medicina (Kaunas) 2022; 58. doi:10.3390/medicina58060738.
17. *Cywoniuk E, Sierpińska T.* Wykorzystanie technologii cyfrowych w wykonawstwie uzupełnień protetycznych na podstawie piśmiennictwa. Protet Stomatol 2019; 69(2): 207-216. doi:10.5114/ps/109361
18. *Lepidi L, Galli M, Mastrangelo F, Venezia P, Joda T, Wang HL, Li J*: Virtual Articulators and Virtual Mounting Procedures: Where Do We Stand? J Prosthodont 2021; 30: 24-35. doi:10.1111/jopr.13240
19. *Woodford SC, Robinson DL, Mehl A, Lee PVS, Ackland DC*: Measurement of normal and pathological mandibular and temporomandibular joint kinematics: A systematic review. J Biomech 2020; 111: 109994. doi: 10.1016/j.jbiomech.2020.109994
20. *Kordass B, Hugger A, Bernhardt O*: Correlation between computer-assisted measurements of mandibular opening and closing movements and clinical symptoms of temporomandibular dysfunction. Int J Comput Dent 2012; 15: 93-107.
21. *Hugger A, Bölöni E, Berntien U, Stüttgen U*: Accuracy of an ultrasonic measurement system for jaw movement recording. In Proceedings of the Continental European Division 35th Annual Meeting, Montpellier, France, September 23-25, 1999. J Dent Res 2001; 80: 1194-1255. doi: 10.1177/00220345010800040401
22. *Baltrusaityte A, Surna A, Pileicikiene G, Kubilius R, Gleiznys A, Zilinskas J*: The relationship between unilateral mandibular angle fracture and temporomandibular joint function. Stomatologija 2014; 16: 87-93.
23. *Enciso R, Memon A, Fidaleo DA, Neumann U, Mah J*: The virtual craniofacial patient: 3D jaw modeling and animation. Stud Health Technol Inform 2003; 94: 65-71.
24. *Rzewuska A, Kijak E, Halczy-Kowalik L*: Rehabilitation in the treatment of mandibular condyle fractures. Dent Med Probl 2021; 58: 89-96. doi:10.17219/dmp/128092
25. *Kordaß B, Behrendt C, Ruge S*: Computerized occlusal analysis - innovative approaches for a practice-oriented procedure. Int J Comput Dent 2020; 23: 363-375.
26. *Hill AM, Bull AM, Dallalana RJ, Wallace AL, Johnson GR*: Glenohumeral motion: review of measurement techniques. Knee Surg Sports Traumatol Arthrosc 2007; 15: 1137-1143. doi:10.1007/s00167-007-0318-8
27. *Lezcano MF, Dias FJ, Chuhuaicura P, Navarro P, Fuentes R*: Symmetry of mandibular movements: A 3D electromagnetic articulography technique applied on asymptomatic participants. J Prosthet Dent 2021; 125: 746-752. doi:10.1016/j.prosdent.2020.01.020
28. *Girouard P*: Biometrics: digital technology as a clinical aid to dental examination and diagnosis. Gen Dent 2019; 67: 32-36.
29. *Yamashita A, Kondo Y, Yamashita J*: Thirty-year follow-up of a TMD case treated based on the neuromuscular concept. Cranio 2014; 32: 224-234. doi:10.1179/0886963413z.00000000020

30. *Jucevičius M, Ožiūnas R, Mažeika M, Marozas V, Jegelevičius D*: Accelerometry-Enhanced Magnetic Sensor for Intra-Oral Continuous Jaw Motion Tracking. Sensors (Basel) 2021; 21. doi:10.3390/s21041409
31. *Goob J, Erdelt K, Schweiger J, Pho Duc JM, Schubert O, Güth JF*: Reproducibility of a magnet-based jaw motion analysis system. Int J Comput Dent 2020; 23: 39-48.
32. *Carossa M, Cavagnetto D, Ceruti P, Mussano F, Carossa S*: Individual mandibular movement registration and reproduction using an optoeletronic jaw movement analyzer and a dedicated robot: a dental technique. BMC Oral Health 2020: 20: 271. doi: 10.1186/s12903-020-01257-6.
33. *Röhrle O, Waddell JN, Foster KD, Saini H, Pullan AJ*: Using a motion-capture system to record dynamic articulation for application in CAD/CAM software. J Prosthodont 2009; 18: 703-710. doi:10.1111/j.1532-849X.2009.00510.x.
34. *Shigeta Y, Suzuki N, Otake Y, Hattori A, Ogawa T, Fukushima S*: Four-dimensional analysis of mandibular movements with optical position measuring and real-time imaging. Stud Health Technol Inform 2003; 94: 315-317.
35. *Pietruski J*: Okluzja w praktyce, 1st ed. Kwintesencja, Warsaw, Poland, 2021.
36. *Revilla-León M, Zeitler JM, Gómez-Polo M, Kois JC*: Utilizing additively manufactured custom devices to record mandibular motion by using optical jaw tracking systems: A dental technique. J Prosthet Dent 2022. doi:10.1016/j.prosdent.2022.03.035
37. *Kwon JH, Im S, Chang M, Kim JE, Shim JS*: A digital approach to dynamic jaw tracking using a target tracking system and a structured-light three-dimensional scanner. J Prosthodont Res 2019; 63: 115-119. doi:10.1016/j.jpor.2018.05.001
38. *Wang C, Shi YF, Xiong Q, Xie PJ, Wu JH, Liu WC*: Trueness of One Stationary and Two Mobile Systems for Three-Dimensional Facial Scanning. Int J Prosthodont 2022; 35: 350-356. doi:10.11607/ijp.7746
39. *Park JH, Lee GH, Moon DN, Yun KD, Kim JC, Lee KC*: Creation of Digital Virtual Patient by Integrating CBCT, Intraoral Scan, 3D Facial Scan: An Approach to Methodology for Integration Accuracy. J Craniofac Surg 2022; 33: e396-e398. doi:10.1097/scs.0000000000008275
40. *Chen CC, Lin CC, Hsieh HP, Fu YC, Chen YJ, Lu TW*: In vivo three-dimensional mandibular kinematics and functional point trajectories during temporomandibular activities using 3d fluoroscopy. Dentomaxillofac Radiol 2021; 50: 20190464. doi:10.1259/dmfr.20190464
41. *Ghanai S, Marmulla R, Wiechnik J, Mühling J, Kotrikova B*: Computer-assisted three-dimensional surgical planning: 3D virtual articulator: technical note. Int J Oral Maxillofac Surg 2010; 39: 75-82. doi:10.1016/j.ijom.2009.10.023
42. *Aslanidou K, Kau CH, Vlachos C, Saleh TA*: The fabrication of a customized occlusal splint based on the merging of dynamic jaw tracking records, cone beam computed tomography, and CAD-CAM digital impression. J Orthod Sci 2017; 6: 104-109. doi:10.4103/jos.JOS_61_16
43. *Kordaß B, Ruge S*: On the analysis of condylar path versus real motion of the temporomandibular joint: application for Sicat Function. Int J Comput Dent 2015; 18: 225-235.
44. *Kühnöl C, Kordaß B*: Digital workflow for TMD diagnostics and bite alteration: description of a case treated using Sicat Function. Int J Comput Dent 2019; 22: 283-292.
45. *Hanssen N, Ruge S, Kordass B*: SICAT function: anatomical real-dynamic articulation by merging cone beam computed tomography and jaw motion tracking data. Int J Comput Dent 2014; 17: 65-74.
46. *Kurbad A*: Three-dimensional registration

of real jaw motion tracking data and its therapeutic consequences. Int J Comput Dent 2018; 21: 57-70.

47. *Bapelle M, Dubromez J, Savoldelli C, Tillier Y, Ehrmann E*: Modjaw® device: Analysis of mandibular kinematics recorded for a group of asymptomatic subjects. Cranio 2021; 1-7, doi:10.1080/08869634.2021.2000790.
48. *Greven MD, Landry AD, Carmignani AD*: Comprehensive dental diagnosis and treatment planning for occlusal rehabilitation: a perspective. Cranio 2016; 34: 215-217. doi: 10.1080/08869634.2016.1186880
49. *Coachman C, Sesma N, Blatz MB*: The complete digital workflow in interdisciplinary dentistry. Int J Esthet Dent 2021; 16: 34-49.
50. *Gallo LM, Airoldi GB, Airoldi RL, Palla S*: Description of mandibular finite helical axis pathways in asymptomatic subjects. J Dent Res 1997; 76, 704-713, doi:10.1177/0022034 5970760021201

Zaakceptowano do druku: 20.03.2023 r.

Adres autorów: 02-097 Warszawa, ul. Binieckiego 6.