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Accuracy of a new photometric jaw tracking system in the frontal plane at different recording distances: An in-vitro study / Valenti, C.; Massironi, D.; Truffarelli, T.; Grande, F.; Catapano, S.; Eramo, S.; Tribbiani, G.; Pagano, S.. - In: JOURNAL OF DENTISTRY. - ISSN 0300-5712. - 148:(2024). [10.1016/j.jdent.2024.105245]

Publisher:
Elsevier

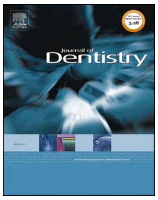
Published
DOI:10.1016/j.jdent.2024.105245

Journal of Dentistry 148 (2024) 105245

Contents lists available at ScienceDirect

Journal of Dentistry

journal homepage: www.elsevier.com/locate/jdent



Accuracy of a new photometric jaw tracking system in the frontal plane at different recording distances: An in-vitro study

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ARTICLE INFO

Keywords:
Kinesiography
Motion tracking analysis
Functional mandibular movement
Photometric jaw tracking system
Jaw movement recording

ABSTRACT

Objectives: To evaluate the accuracy of a new photometric jaw tracking system (JTS) in recording linear vertical movements in the frontal plane at different distances.

Methods: A mandibular plaster cast of a patient was placed on a simulation machine capable of linear movements along two spatial axes. Cyclops JTS (Itaka) was adapted to the plaster cast, while the head frame was attached to the simulation machine. The latter performed five linear movements from 20 to 40 mm in the y-axis; each movement was repeated five times at five different recording distance (380 to 420 mm). The recorded movements were measured and compared with those obtained with a laser Doppler vibrometer (LDV) for accuracy analysis. Data were statistically processed ($\alpha = 0.05$).

Results: No statistically significant differences were found between Cyclops and LDV measurements on the y- and z-axes ($p = 0.5$). Changes in linear vertical motion and distance positions did not affect the accuracy, which remained relatively constant with similar trends and values less than 1 % for each parameter variation. The best condition observed was linear vertical movement of 30 mm at 420 mm (0.010 ± 0.023 mm).

Conclusions: Cyclops has proven to be an accurate JTS in recording linear vertical movements in the frontal plane at different recording distances. For optimal recordings, the scanner should be placed as close as possible to the markers; excessive vertical movements decreased the accuracy. However, this study has limitations and requires in-vivo confirmations.

Clinical significance: The tested JTS proved accurate in recording linear vertical movements in the frontal plane. However, given the limitations of the study, further investigation under real conditions is needed to support prosthetic and gnathological rehabilitations.

1. Introduction

Mandibular motion tracking has evolved significantly over the years from 2D to advanced 3D/4D motion tracking systems. This evolution marks a fundamental change in both the accuracy and applications of such technologies for diagnostic purposes and treatment planning. Jaw motion tracking began with analog condylography, which required a number of steps, including the use of facebows, dental articulators, and impressions to record the spatial relationship of the maxillary arch to the temporomandibular joints [1].

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https://doi.org/10.1016/j.jdent.2024.105245
Received 21 May 2024; Received in revised form 6 July 2024; Accepted 15 July 2024

2D devices like electromagnetic Cadiax Diagnostics or Compact represented early digital innovations, using electronic sensors to capture jaw movements, and improving condylography precision, making the process more efficient and accurate [2,3].

The development of 3D and 4D motion tracking systems brought a new level of detail and accuracy to jaw motion analysis, with advanced sensors and software to capture complex movements, often in real-time, offering a comprehensive analysis of mandibular function. Ultrasonic devices, like Jaw Motion Analyzer (JMA) by Zebris Company, ARCUSdigma II by KaVo, or Axioquick Recorder by SAM Präzisionstechnik, employ ultrasonic sensors to track jaw movements in 3D, providing real-time data on jaw positioning. While Modjaw allows 4D analysis, capturing dynamic sequences of jaw movements, with optical sensors and advanced algorithms. SDI Matrix optical system instead combine 3D imaging with motion capture technology, with a blend of magnetic and optical sensors to ensure precise tracking. This system can be integrated with intraoral scanners (IOS) and CAD software, facilitating comprehensive treatment planning and simulation. The synergy of IOS and CAD technologies with 3D/4D motion tracking systems ensures a complete digital workflow from diagnosis to treatment, improving accuracy and efficiency of dental interventions, resulting in personalized and effective patient care [4].

Jaw tracking systems (JTS) have both diagnostic and design purposes. The former involves recording a patient's mandibular motion and analyzing the movements, while the latter allows the movement to be exported to Computer-Aided Design (CAD) software for designing prostheses and adapted occlusal devices [5].

Numerous are thus the advantages of applying JTS. The CAD design of complex and accurate restorations with improved comfort and function, reduced design time, and simplified processes are also combined with the possibility of having additional data for diagnosis and treatment of temporo-mandibular joint disorders (TMDs). JTSs capture detailed motion data, allowing a comprehensive analysis of jaw function. This is critical for accurately diagnosing of TMDs. In addition, more effective treatment plans can be developed, resulting in better patient outcomes. It is also to be noted how JTSs eliminate the need to use physical facebow and articulators by providing digital alternatives, reducing the complexity of steps and the use of bulky and uncomfortable instrumentation for patients, simplifying workflows [4,6].

A recent systematic review evaluated the accuracy of digital systems for mandibular motion analysis and the physiological and device-related factors that affect their accuracy. This review concluded that realistic variations in device accuracy ranged from 50 to 330 μm among digital systems, with very low inter-operator reliability observed for motion tracking from photographs [7].

Photometric devices use one or more cameras to track the position of markers attached to the jaw, supplemented by additional markers on the patient's face. These devices have been found to be affected by marker size and video frame rate: smaller markers perform worse than devices with higher frame rates [8]. However, other factors may influence their accuracy.

A novel photometric JTS for clinical data acquisition is Cyclops (ITAKA Way Med, Venice, Italy) [9]. This device tracks mandibular movements using image analysis based on marker tracking. A specific algorithm is then applied to acquired images to detect and record the position of the markers [10]. By repeating this process for all frames, the movement of the markers can be measured, and the mandibular path can be retrieved by the software [11,12]. Cyclops can map the motion of specific markers placed on the patient through a camera system and highlight the dynamic maxillomandibular relationship in dental CAD systems when combined with intraoral scan data.

The accuracy of digital medical devices is expressed by trueness and precision [13,14]. Trueness relates to the level of agreement between the average value of a large number of test results and the real or accepted reference value. Precision reports on the degree of agreement between test results [15]. In particular, considering JTSs, Trueness refers to the device's ability to reproduce a mandibular movement as close as possible to its actual movement, while precision (reproducibility) indicates the degree to which mandibular movements acquired from repeated recordings under the same conditions are identical.

Mandibular movements are determined by a complex kinematic system that includes muscles, teeth, and joint components. There are two basic mandibular movements: hinge axis movement, defined as a rotation of the mandible around the horizontal transverse axis passing through the heads of the mandibular condyles, and translatory or sliding movement, which is a body movement in the anteroposterior and/or mediolateral direction. In most cases, translation occurs simultaneously with rotation, resulting in high complexity. However, they can be separated along the three axes (x-, y-, and z-axis). JTSs can record all mandibular movements, allowing their individual analysis along the three axes.

JTS use various technologies to capture key reference positions such as hinge axis, a key element to understand rotational movements of the jaw, and centric relation, critical for designing restorations and diagnosing TMDs. These systems include calibration procedures to ensure that these reference positions are captured consistently and predictably, guiding the patient through specific movements while the system records the data. Data registration is integrated with CAD software, allowing for precise alignment of digital models [16].

It is crucial to understand the accuracy of these systems in recording different mandibular movements to define their reliability and clinical utility [17]. To date, few studies have evaluated the accuracy of mandibular motion recording with these new JTSs [18-22].

The purpose of this study was to evaluate the accuracy (trueness and precision) of the Cyclops system in the y-axis (vertical up/down direction), considering variations in instrument placement on the z-axis, and to compare it with a laser doppler vibrometric system (LDV), typically used in metrology applications as a reference.

The null hypothesis was that there were no statistically significant differences between Cyclops recordings and LDV measurements.

2. Materials and methods

A simulation machine capable of reproducing standardized linear motion along all three spatial axes was built by incorporating parts of the structure and electronic components of an Ender 3 Pro 3D printer (Creality, Shenzhen, China). The 3D printer's stepper motors, along with dedicated control drivers, were assembled to enable machine motion. Linear movements were automatically defined using dedicated G-code motion commands stored on a microSD memory card.

The base of the instrument was 3D printed using polylactic acid (PLA) material with a 60 % fill rate (Fig. 2). The 3D printer build plate, which serves as the machine base, was movable along the y- and z-axes, allowing the distance between the tool and the scanner reference point to be adjusted. Movements were standardized using G-code functions and repeated at a rate of 30 frames per second (fps).

The Cyclops system includes a camera and two recording devices: an upper positioner head frame attached to the patient's head, and a lower fork called a "Mandyfork," which is adapted to the mandibular arch. Both devices have magnets that connect to a reference tool containing four white markers, which are tracked and recorded by the camera during mandibular movements. The upper positioner serves as a fixed reference for the scanner, while the Mandyfork is movable. The system translates the movements into marker points, which represent an approximation of mandibular movement. In this experiment, the upper device with four markers was magnetically placed on a stand that simulate the position of the patient's head, while the Mandyfork was attached to a mandibular plaster cast using self-curing bisacrylic resin (Acrytemp, Zhermack SpA, Rovigo, Italy).

An LDV served as a reference to measure the vertical motion of the Mandyfork in the constructed mechanical system [23,24]. The LDV measures surface motion remotely using optical interferometry techniques, allowing displacements much smaller than the wavelength of light to be measured (Tables 1 and 2). The vibrometer system consists of two basic functional blocks, the interferometer or optical sensor head OFV-303 (Polytec GmbH, Waldbronn, Germany) and the controller OFV-3001 (Polytec GmbH, Waldbronn, Germany), an electronic signal processor, that powers the measuring head and processes the vibration signal, which contains information about the pure Doppler frequency shift. The optical head uses light from a continuous wave 2 mW Helium-Neon (He-Ne) laser source projected onto the surface under test through a system of variable focus lenses, which return the collected light to the interferometer, that performs an optical phase comparison of the recovered light with an internal reference beam. A Pico 5000USB data acquisition system (Pico Technology Ltd., St Neots, United Kingdom) was used to acquire the sensor output voltage by connecting it to a PC. A laser triangulation sensor measured the distance positions of a target from the scanner.

The experiment was conducted in a laboratory with standard environmental conditions: humidity rate at 40 %, illumination of 500 lux, and temperature of 25 °C. Before each test, the simulation machine was calibrated to ensure accurate positioning and motion control.

The protocol involved setting up sequences of linear movements along the y-axis with five different amplitudes (20, 25, 30, 35, and 40 mm). Each sequence included downward and upward linear movements in the frontal plane. Five different distance positions of the plaster cast from the Cyclops scanner (380, 390, 400, 410, and 420 mm) were considered for each vertical motion, with movements replicated five times for each group. Five main groups were then created based on the linear vertical motion, with five subgroups added to each main group corresponding to the distance positions (Fig. 1):

- Groups with linear vertical movement of 20 mm: at 380 mm (group 1A), 390 mm (group 1B), 400 mm (group 1C), 410 mm (group 1D), and 420 mm (group 1E) distance from the scanner;
- Groups with linear vertical movement of 25 mm: at 380 mm (group 2A), 390 mm (group 2B), 400 mm (group 2C), 410 mm (group 2D), and 420 mm (group 2E) distance from the scanner;
- Groups with linear vertical movement of 30 mm: at 380 mm (group 3A), 390 mm (group 3B), 400 mm (group 3C), 410 mm (group 3D), and 420 mm (group 3E) distance from the scanner;
- Groups with linear vertical movement of 35 mm: at 380 mm (group 4A), 390 mm (group 4B), 400 mm (group 4C), 410 mm (group 4D), and 420 mm (group 4E) distance from the scanner;
- Groups with linear vertical movement of 40 mm: at 380 mm (group 5A), 390 mm (group 5B), 400 mm (group 5C), 410 mm (group 5D), and 420 mm (group 5E) distance from the scanner.

Each subgroup was subjected to five repeated movements, for a total of 125 recordings (5 groups x 5 subgroups x 5 repetitions = 125 recordings). Through a statistical analysis of random errors, the uncertainty of measurement was performed by calculating the standard deviation of the mean over N repeated measurements of the same physical measurement, according to the ISO reference [25].

During the experimental analysis, measurements were conducted simultaneously using both Cyclops and LDV (Fig. 3), with synchronized signals. The output signals obtained from both devices were analyzed. Data recorded by Cyclops were acquired in the ".IMD" file format and then converted to ".txt" format for analysis. LDV measurements were recorded in PicoLog data logging software and compared with Cyclops data (Fig. 4).

Table 1
Selected parameters for vibrometer and displacement signal acquisition.

Laser doppler vibrometer (LDV) parameters	
Optical sensor head He-Ne laser wavelength	633 nm
Tracking Filter	Slow
Velocity Range [mm/s/V]	HF 125
Velocity Filter [MHz]	Off (1.5)
Displacement Range [μm/V]	5120
Displacement signal acquisition parameters	
Range [V]	± 5
Sampling Rate [Hz]	60
Resolution [bit]	14

Table 2
LDV Displacement Decoder Specifications and calibration accuracy.

Measurement Range	Full Scale Output (Peak-to-Peak)	Resolution[1]	Max. Vibration Frequency	Max. velocity
μm/V	mm	μm	kHz	m/s
0.5	0.008	0.002	25	0.06
2	0.032	0.008	75	0.25
8	0.13	0.032	75	1.0
20	0.32	0.08	250	1.6
80	1.3	0.32	250	1.6
Calibration accuracy	+ 2% of reading + 1 step (up to 100 kHz) (1 step corresponds to the resolution limit of the selected range)			

1The resolution is defined as one digit of the fringe counter output.

Cyclops accuracy was calculated as the difference ΔD from the LDV recordings (taken as 100 % reference) (Fig. 5) [26], considering the variation of the linear vertical movement and of distance positions of the scanner parameters during the experimental tests (Supplementary Fig. 1–4, available online). For each measurement group, ΔD values were identified (Fig. 6) and the mean and standard deviation (SD) were calculated. Accuracy was determined for each combination by dividing the SD obtained by the square root of the number of points ($N = 5$). Trueness and precision were evaluated for all groups.

Data analysis was performed using Python software program with a $p = 0.05$ significance level. One-way parametric analysis of variance (ANOVA) was used to test the normality of data distribution (Supplementary Fig. 5). Student's t-test was performed to detect any significant differences between Cyclops and LDV measurements.

3. Results

A total of 125 recordings were taken. Analysis of the raw data revealed a consistent vertical shift between the records of the two instruments, attributed to a systematic uncertainty of the simulation machine. This shift was averaged and removed from the records, after which an ANOVA analysis was conducted, showing that the distribution of the data was normal, and then the p-value was calculated. One-way ANOVA analysis of variance indicated no statistically significant differences between the Cyclops and LDV recordings ($p = 0.5$). Trueness values (mean ± SD) for each combination of recordings taken in quintuplicate are shown in Table 3, while Fig. 7 presents a graphical representation of the measured trueness and precision among the groups tested by boxplots.

Fig. 8 illustrates the accuracy values of the JTS considering the SDs of the means. The results for parameter influence indicate that variations in linear vertical movement and distance positions did not significantly affect the accuracy of the instrument, showing consistent trends in all combinations. It is evident that accuracy remains relatively constant for each variation in the parameters tested.

4. Discussion

The objective of this in vitro study was to evaluate the accuracy of a new photometric JTS in the frontal plane at various scanner recording distance positions. The null hypothesis was confirmed, as no statistically significant differences were observed between the recordings obtained with Cyclops and those with the LDV ($p = 0.5$). Consequently, disparities in measurements between the two instruments were considered not significant.

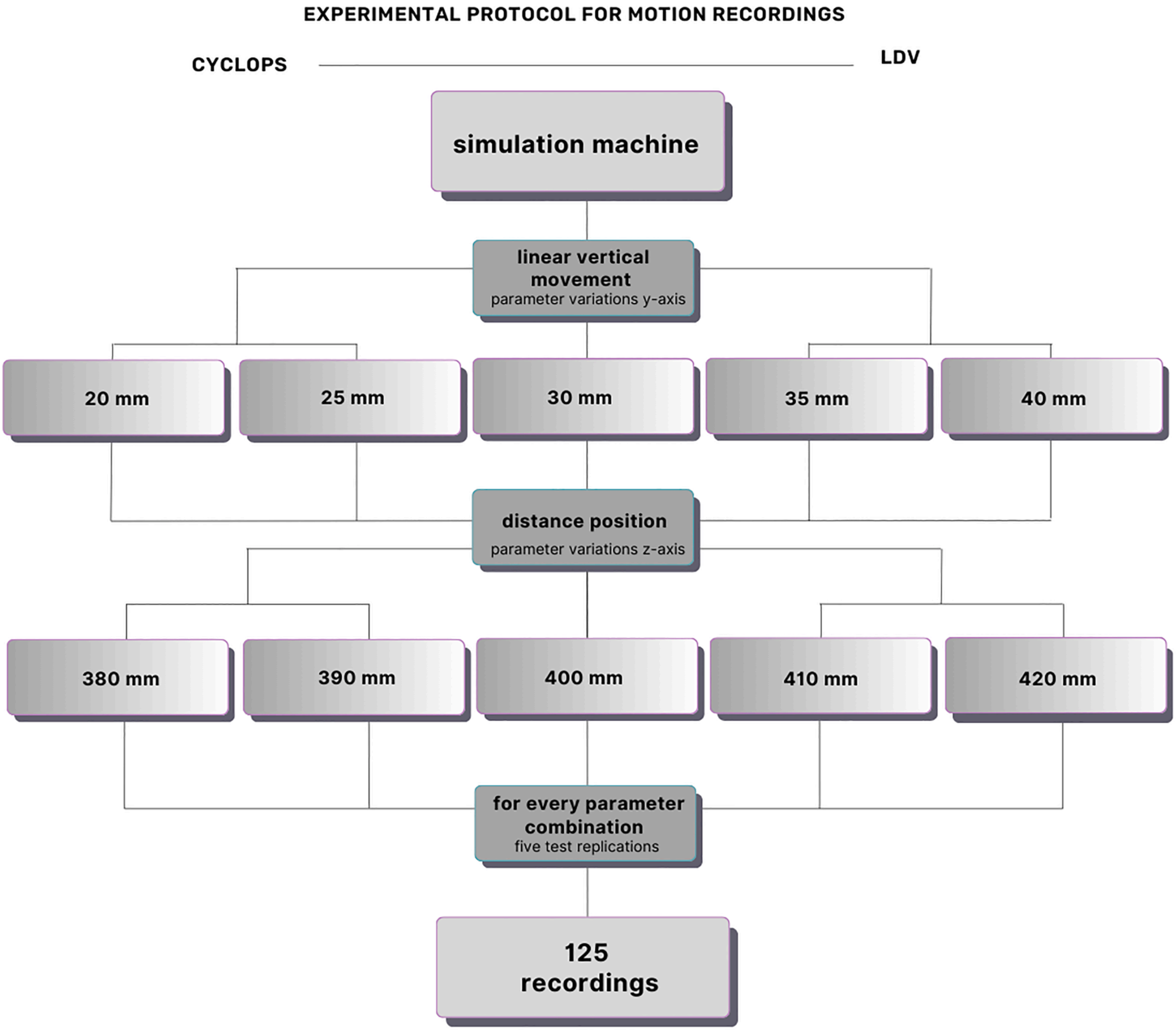

Fig. 1. Experimental protocol.

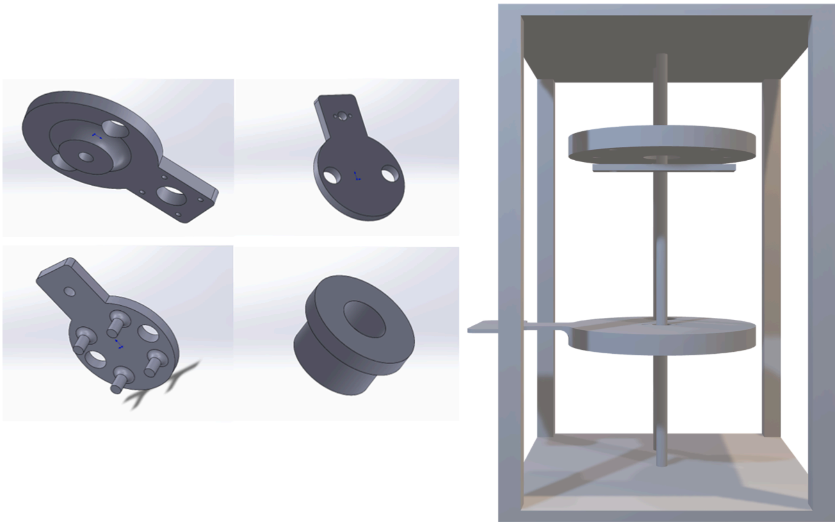

Fig. 2. 3D printed parts used to create the simulation machine.

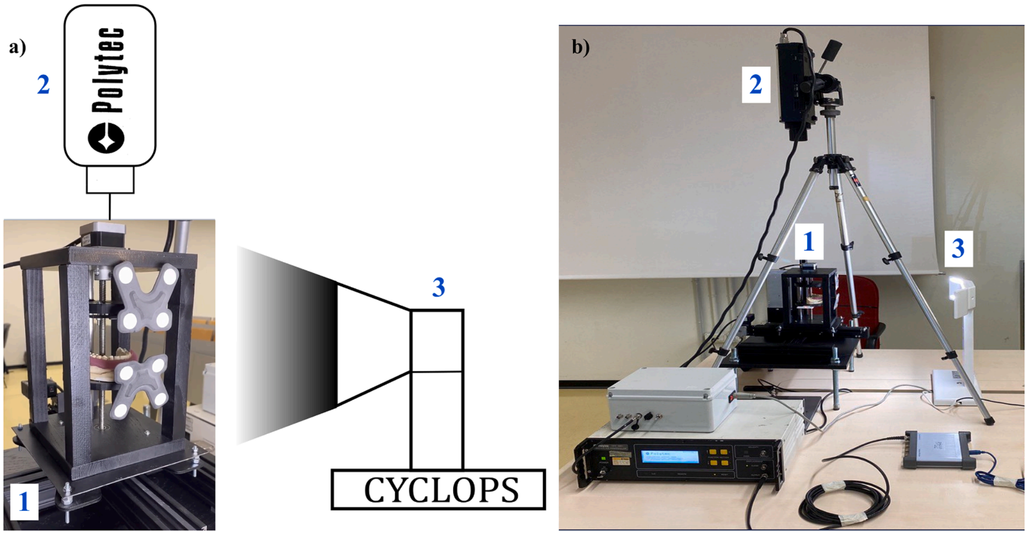

Fig. 3. setting of the test bench: schematic setup (a) and real test bench (b); 1) excursion system for linear vertical movement, 2) LDV reference system, and 3) Optical JTS under examination.

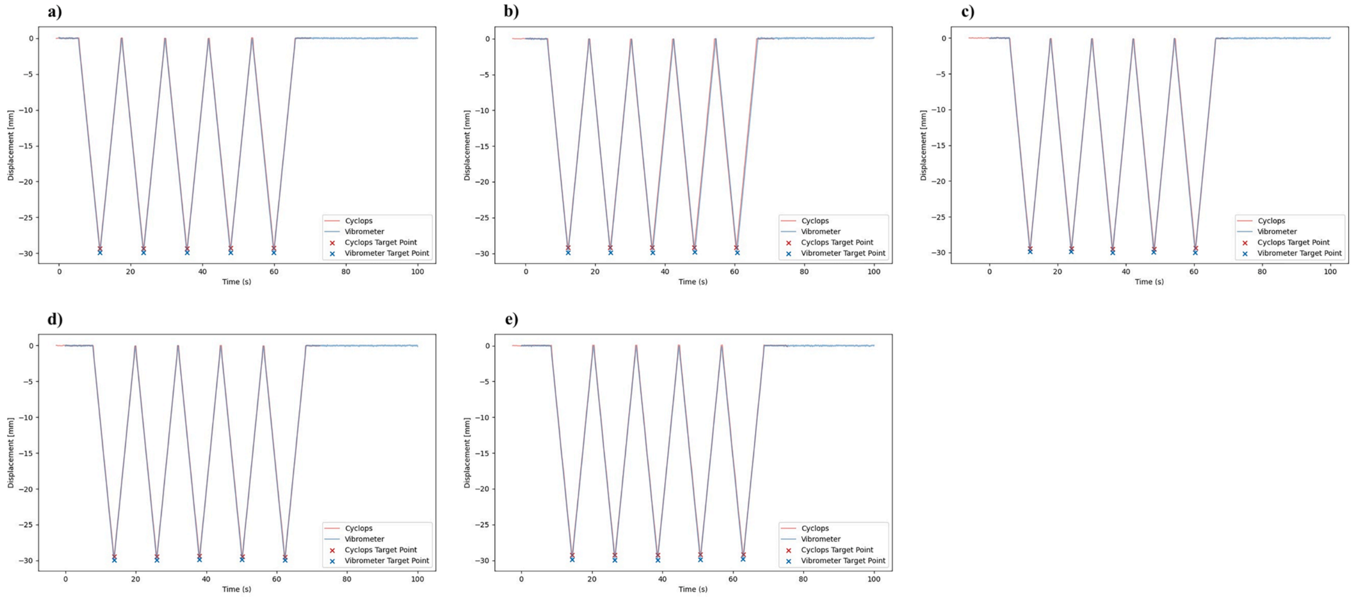

Fig. 4. Overlap and comparison between the tracks obtained from LDV reference (blue) and CYCLOPS® (red) for groups: a) 3A, b) 3B, c) 3C, d) 3D, and e) 3E.

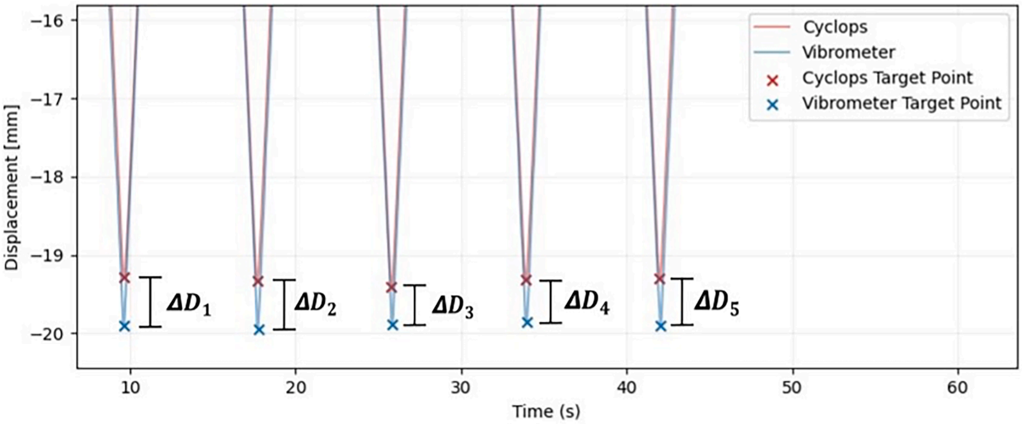

Fig. 5. Difference ΔD evaluated on the maximum displacement between the signals obtained with the JTS and with the reference LDV.

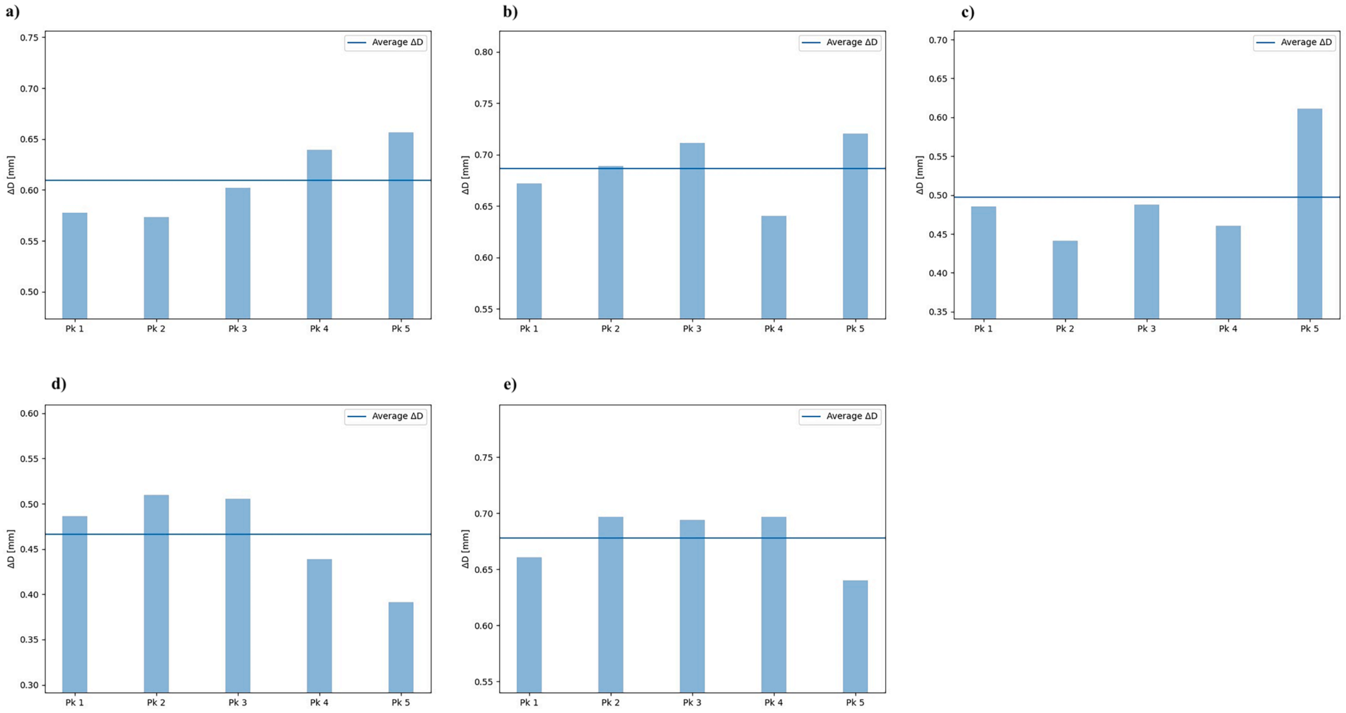

Fig. 6. sine wave amplitude difference ΔD, for groups: a) 3A, b) 3B, c) 3C, d) 3D, and e) 3E.

Table 3

Trueness values (mean and SD) of the recordings taken in quintuplicate for the 5 amplitude values (20, 25, 30, 35, and 40 mm) at the 5 different distances considered (380, 390, 400, 410, 420 mm), for groups 1(A-E), 2(A-E), 3(A-E), 4(A-E), and 5(A-E).

Displacement [mm]	Distance [mm]									
	380		390		400		410		420	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
20	0,568	0,050	0,422	0,043	0,378	0,052	0,544	0,042	0,628	0,057
25	0,633	0,042	0,567	0,045	0,708	0,084	0,540	0,062	0,589	0,050
30	0,610	0,033	0,686	0,029	0,497	0,060	0,466	0,045	0,678	0,023
35	0,855	0,051	0,708	0,042	0,800	0,064	0,723	0,031	0,643	0,056
40	0,803	0,044	1019	0,062	0,989	0,084	0,764	0,030	1015	0,047

None of the parameters examined affected the accuracy of recordings with Cyclops JTS. Higher accuracy was observed at distances of 380 mm and 420 mm for linear vertical movements of 30 mm, that aligns with the average physiological opening value, while lower accuracy was found for movements of 25 mm and 40 mm at the manufacturer-recommended conditions of 400 mm distance from the scanner, still within the micron range. However, similar trends in instrument trueness and precision were evident when the selected registration parameters were considered. This may be attributed to the placement of the markers at the edges of the scanner's camera field of view in relation to the patient's degree of opening. Therefore, it is advisable to position the scanner as close to the patient as possible during recordings to improve marker detection, while also taking into account the extent of the patient's opening.

Comparing our results with those of other studies in the literature is difficult because of variations in JTSs, methodologies, and settings. In addition, the existing literature on JTSs evaluates various aspects, including accuracy in recording edentulous maxillomandibular relationships, voluntary mandibular movements, trueness and precision of maxillomandibular relationships in centric relation position, and condylar inclination analysis.

A recent study conducted an in vitro evaluation of an optical JTS, measuring edentulous maxilla and mandible models with complete dentures mounted on an articulator. The authors highlighted that the accuracy of the device was clinically acceptable considering the maxillomandibular relationship in the recordings of protrusion, left and right laterotrusion, and small opening positions. The mean displacement values were less than 200 μm in the mandible [18].

The same research group evaluated the accuracy of a customized JTS in recording the edentulous maxillomandibular relation using a direct digital method [27]. There were in vivo recordings of the habitual mandibular opening-closure trajectory and mandibular resting position. The authors showed that by combining the individual trajectories obtained from the developed JTS with 3D scanning and surface reconstructions, it becomes possible to establish a digital method to determine and record maxillomandibular relationships in edentulous patients, including the physiological position of the jaw and maximum repeatability of mandibular movement.

On the other hand, Morikawa et al. tried to simplify the measurements of jaw motion, as existing devices on the market are currently large, wired, and may not detect physiological movements [28]. The authors investigated the effectiveness of a new JTS with six degrees of freedom as a portable device, with the aim of not compromising the patient's occlusal status or restricting head movement. Using a microelectromechanical system (MEMS) orientation sensor, this technique allows the measurement of voluntary mandibular movements with a simple and compact system in three-dimensional orientation and position, without restricting the patient's movements by attaching a jig to the tooth surface.

Revilla-León et al. conducted an in vivo study [19] on trueness and

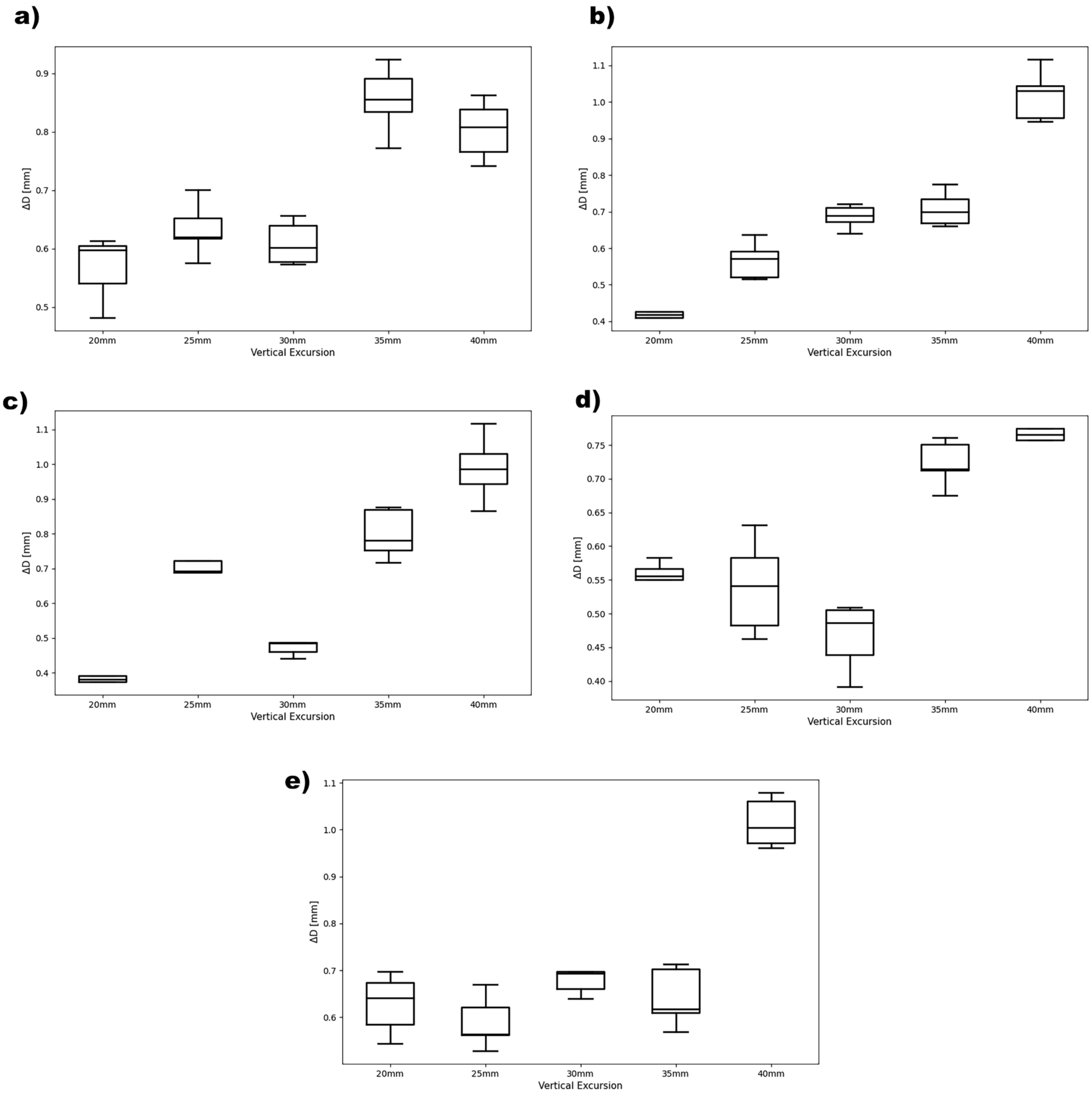

Fig. 7. Boxplots representing trueness, as the mean of ΔD (center line in the boxplots) and precision, standard deviation, measured among groups tested with recordings at: a) 380 mm (groups 1–5A); b) 390 mm (groups 1–5B); c) 400 mm (groups 1–5C); d) 410 mm (groups 1–5D); and e) 420 mm (groups 1–5E).

precision of 3 different intraoral scanners with or without correlated JTS, considering maxillomandibular relationship recordings in centric relation position. The Modjaw JTS was found to improve the trueness compared with the intraoral scanners.

Other authors have focused on condylar inclination analysis with different JTSs [20,29]. Celar et al. evaluated the accuracy of the Cadiax compact electronic hinge axis tracking device in measuring horizontal condylar inclination and Bennett angle [29]. In this study hinge axis movement was simulated with an articulator to which a hinge axis tracer was applied. The authors pointed out that Cadiax is accurate for clinical application in anteriorly guided restorations because of the small range of the maximum measuring error. Ma et al. also pointed out that clinicians should take into account the accuracy of the virtual articulator and JTS during prosthetic treatment, although the sagittal condylar inclination measurement error may be acceptable within a certain range [29]. Other authors highlighted that Zebris JTS demonstrated comparable accuracy to Cadiax 4 in recording sagittal condylar inclination [30].

A recent study evaluated the accuracy of the new Modjaw JTS using typodontic models in a phantom head to replicate various maxillomandibular relationships [31]. The study concluded that the JTS is accurate, comparable to industrial scanners and superior to traditional methods, with a trueness of 11 μm, similar to that of high-end digital dental devices. However, the accuracy decreases slightly with higher intermaxillary ratios, and future in vitro studies should incorporate simulation of movements outside the centric relationship, such as protrusion or laterotrusion, to provide a more comprehensive analysis [31]. The authors also reported how the use of an IOS can worsen the accuracy of Modjaw, as has been highlighted in the literature. Therefore, it would also be interesting to evaluate the contribution of different error sources, such as IOS, in the clinical inaccuracy of the optical device we selected in our study. Nagy et al. [31] also identified important limitations, such as the lack of measurement of maximum intercuspation, which was not achievable with dental models with typodontic teeth because they cannot be occluded in a stable position by not grinding together. Another limitation concerned the clinical accuracy of Modjaw, which

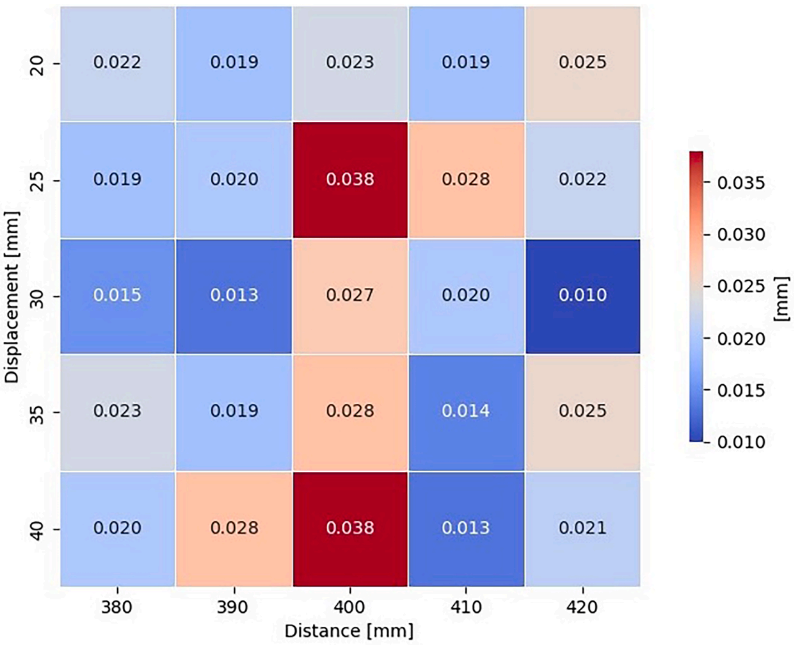

Fig. 8. Parameters-related accuracy: heat map of the standard deviations (SDs) of the means of the recordings taken in quintuplicate for the 5 amplitude values (20, 25, 30, 35, and 40 mm) at the 5 different distances considered (380, 390, 400, 410, 420 mm), for groups 1(A-E), 2(A-E), 3(A-E), 4(A-E), and 5(A-E).

cannot be predicted without motion during recordings, contrary to what we hypothesized in our work by inserting a motion simulation machine. These results are consistent with those of our study, although we evaluated the entire vertical movement rather than just the static position of maxillomandibular relationship.

In particular, another recent study analyzes the precision of Cyclops in vivo, showing that the device was accurate in recording mediotrusion and protrusion movements, regardless of the type of functional mandibular movement performed by the subjects. However, the authors pointed out that further studies are needed, considering the repeatability and standardization of the recordings, as wide clinical variations in the tracings were shown during the execution of the movements [22].

JTS devices thus represent a breakthrough in clinical dental practice especially since they can also integrate information from intraoral and facial scanners, and cone-beam computed tomography, virtually and faithfully replicating the patient [1]. The planning of complex treatments and rehabilitations, either of indirect restorations in conservative dentistry or in the case of prosthetics or implant prosthetics is consequently simplified for both the clinic and the dental laboratory. The fabrication of functionalized and individualized restorations allows shorter time frames, greater patient compliance, and fewer occlusal adjustments after delivery [32].

The accuracy of JTS recordings is related to both the distance between the markers and the camera and the position of the markers [21]. To achieve optimal digital kinesiographic recordings, standardized and appropriate clinical examination protocols are essential. The position of the markers must be perpendicular to the camera to reduce radial and angular measurement errors [21]. Through a stereo camera system, Cyclops can record a pathway for mandibular movement. However, ensuring the precise position and angle of each camera is complex. During clinical examinations, recordings should be as standardized as possible. The patient's head and clothing should be covered with dark cloths to effectively recognize the markers. The scanner should be placed at the same height and distance, under appropriate lighting conditions, and the Mandyfork should be properly stabilized. To obtain optimal digital kinesiographic recordings, the target, while maintaining a constant position, should be no more than 1 meter from the scanner, thus reducing the parallax phenomenon [33,34].

Although optical JTS appear to be a valid alternative for recording and integrating the patient's mandibular movement, this preliminary study has some limitations. This in vitro study did not consider confounding factors such as the patient's involuntary head movements. In addition, the movement assessment focused only on the frontal plane and did not consider mixed frontal-sagittal movement, such as jaw opening. More importantly, no matter how meticulous the realization of the motion simulation device was and allows for predictable and replicable movements thanks to the motion programming code, such a device cannot reliably represent real, physiological jaw movements, which are in any case more complex than those made by the simulation machine.

Another major limitation of the study is the fact that the literature is lacking in studies conducted in vitro on such devices to analyze their metrological characteristics and accuracy before using the device on patients under real-world conditions, which consider a number of errors and confounding factors related to the operator and the patient themselves. Thus, this study did not have a solid base from which to start preliminary research.

Furthermore, there are no uniform clinical protocols or studies in the literature that consider digital instruments for recording mandibular motion compared with other traditional kinesiographic measurement techniques with a large sample size. Another limitation of the study is the lack of comparisons with other devices due to the absence of instruments similar to the selected digital kinesiograph.

5. Conclusions

Neither linear vertical motion nor scanner distance positions affected the accuracy of the recordings with the JTS tested. Accuracy remained constant for each change in parameters, with values ranging from 0.010 mm, with 30 mm of linear vertical motion at a distance position of 420 mm, to 0.038 mm with 25 mm and 40 mm of linear vertical motion at a distance position of 400 mm. These data correspond to inaccuracies of 0.2 % on a full scale. However, the potential of digital kinesiographic technology needs to be further clinically validated with a larger patient sample size; future studies are needed to evaluate its application under realistic conditions, considering not only the physiological opening/closing movement, but also laterality and protrusion, determining whether the degree of patient opening has a greater influence than the distance at which the scanner is placed, and the optimal recording conditions.

CRediT authorship contribution statement

Chiara Valenti: Writing – original draft, Investigation, Formal analysis, Data curation. **Domenico Massironi:** Writing – review & editing, Project administration, Conceptualization. **Tiberio Truffarelli:** Writing – original draft, Formal analysis, Data curation. **Francesco Grande:** Writing – review & editing, Validation, Investigation. **Santo Catapano:** Supervision, Conceptualization. **Stefano Eramo:** Writing – original draft, Supervision. **Giulio Tribbiani:** Software, Methodology. **Stefano Pagano:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Acknowledgements

The authors sincerely thank Dr. G.A. Boyd for English revision.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jdent.2024.105245.

References

[1] M. Revilla-Leon, D.E. Kois, J.M. Zeitler, W. Att, J.C. Kois, An overview of the digital occlusion technologies: intraoral scanners, jaw tracking systems, and computerized occlusal analysis devices, J. Esthet. Restor. Dent. 35 (5) (2023) 735–744, https://doi.org/10.1111/jerd.13044.

[2] M. Revilla-León, J.M. Zeitler, J.C. Kois, Digital maxillomandibular relationship and mandibular motion recording by using an optical jaw tracking system to acquire a dynamic virtual patient, J. Prosthet. Dent. (2022), https://doi.org/10.1016/j.prosdent.2022.05.012.

[3] M.O. Ahlers, O. Bernhardt, H.A. Jakstat, et al., Motion analysis of the mandible: guidelines for standardized analysis of computer-assisted recording of condylar movements, Int. J. Comput. Dent. 18 (3) (2015) 201–223.

[4] J. Shen, The chance and challenge of creating virtual patients in prosthodontics, Hua Xi Kou Qiang Yi Xue Za Zhi 42 (1) (2024) 1–11, https://doi.org/10.7518/hxkq.2024.2023317.

[5] S. Jakubowska, M.P. Szerszeń, J. Kostrzewa-Janicka, Jaw motion tracking systems – literature review, Prosthodontics 73 (1) (2023) 18–28, https://doi.org/10.5114/ps/162663.

[6] M. Revilla-León, J.M. Zeitler, J.C. Kois, Digital diagnostic occlusal equilibration combining an intraoral scanner, optical jaw tracking system, and dental design program: a dental technique, J. Prosthet. Dent. (2024), https://doi.org/10.1016/j.prosdent.2023.12.004.

[7] T.H. Farook, F. Rashid, M.K. Alam, et al., Variables influencing the device-dependent approaches in digitally analysing jaw movement—a systematic review, Clin. Oral. Invest. 27 (2023) 489–504, https://doi.org/10.1007/s00784-022-04835-w.

[8] M. Farronato, G.M. Tartaglia, C. Maspero, L.M. Gallo, V. Colombo, In vitro and in vivo assessment of a new workflow for the acquisition of mandibular kinematics based on portable tracking system with passive optical reflective markers, Appl. Sci. 11 (9) (2021) 3947, https://doi.org/10.3390/app11093947.

[9] Itaka Way Med (2022). https://itakawaymed.com.

[10] F.J. Ramírez, R. Muñoz-Salinas, R.M. Carnicer, Speeded up detection of squared fiducial markers, Image Vis. Comput. 76 (2018) 38–47, https://doi.org/10.1016/j.imavis.2018.05.004.

[11] Q. Li, M. Bi, K. Yang, et al. The creation of a virtual dental patient with dynamic occlusion and its application in esthetic dentistry J. Prosthet. Dent.. 126 (1) (2021) 14–18.

[12] M.S. Bartlett, J.C. Hager, P. Ekman, T.J. Sejnowski, Measuring facial expressions by computer image analysis, Psychophysiology 36 (2) (1999) 253–263, https://doi.org/10.1017/s0048577299971664.

[13] J.R Taylor, An Introduction to Error Analysis: The study of Uncertainties in Physical Measurements, University Science Books, 2022. Third edition.

[14] International Organization for Standardization. ISO 20896-1: 2019. Dentistry digital impression devices part 1: methods for assessing accuracy. https://www.iso.org/standard/69402.html.

[15] International Organization for Standardization. ISO 5725-1: 2023. Accuracy (trueness and precision) of measurement methods and results — Part 1: general principles and definitions.

[16] M. Revilla-León, J.M. Zeitler, J.C. Kois, Implementing an optical jaw tracking system to locate centric occlusion: a dental technique, J. Prosthet. Dent. (January 6, 2024), https://doi.org/10.1016/j.prosdent.2023.11.016. Published online.

[17] 11 M. Carossa, D. Cavagnetto, P. Ceruti, F. Mussano, S. Carossa, Individual mandibular movement registration and reproduction using an optoeletronic jaw movement analyzer and a dedicated robot: a dental technique, BMC Oral Health 20 (1) (2020) 271, https://doi.org/10.1186/s12903-020-01257-6.

[18] W. Li, L. Li, Y. Wang, Y. Sun, Q. Xie, Accuracy of recording edentulous jaw relations by using an optical jaw tracking system: an in vitro study, Int. J. Prosthodont. 35 (3) (2022) 302–310, https://doi.org/10.11607/ijp.7126.

[19] M. Revilla-León M, L. Fernández-Estevan, A.B. Barmak, J.C. Kois, J.A. Pérez-Barquero, Accuracy of the maxillomandibular relationship at centric relation position recorded by using 3 different intraoral scanners with or without an optical jaw tracking system: an in vivo pilot study, J. Dent. 132 (2023) 104478, https://doi.org/10.1016/j.jdent.2023.104478.

[20] A.G. Celar, K. Tamaki, Accuracy of recording horizontal condylar inclination and Bennett angle with the Cadiax compact, J. Oral Rehabil. 29 (11) (2002) 1076–1081, https://doi.org/10.1046/j.1365-2842.2002.00951.x.

[21] Y. Feng, L. Max, Accuracy and precision of a custom camera-based system for 2-d and 3-d motion tracking during speech and nonspeech motor tasks, J. Speech. Lang. Hear Res. 57 (2) (2014) 426–438, https://doi.org/10.1044/2014_JSLHR-S-13-0007.

[22] F. Grande, L. Lepidi, F. Tesini, A. Acquadro, C. Valenti, S. Pagano, S. Catapano, Investigation of the precision of a novel jaw tracking system in recording mandibular movements: a preliminary clinical study, J. Dent. (2024), https://doi.org/10.1016/j.jdent.2024.105047.

[23] V.R. Meyer, Measurement uncertainty, J. Chromatogr. A 1158 (1–2) (2007) 15–24, https://doi.org/10.1016/j.chroma.2007.02.082.

[24] S. Baumgaertel, J.M. Palomo, L. Palomo, M.G. Hans, Reliability and accuracy of cone-beam computed tomography dental measurements, Am. J. Orthod. Dentofacial. Orthop. 136 (1) (2009) 19–28, https://doi.org/10.1016/j.ajodo.2007.09.016.

[25] International Organization for Standardization. ISO ENV 13005 "Guide to the expression of uncertainty in measurement (GUM)".

[26] T. Tocci, L. Capponi, G. Rossi, ArUco marker-based displacement measurement technique: uncertainty analysis, Eng. Res. Express 3 (2021) 035032, https://doi.org/10.1088/2631-8695/ac1fc7.

[27] W. Li, H. Chen, Y. Wang, Q. Xie, Y. Sun, Digital determination and recording of edentulous maxillomandibular relationship using a jaw movement tracking system, J. Prosthodont. 31 (8) (2022) 663–672, https://doi.org/10.1111/jopr.13529.

[28] K. Morikawa, R. Isogai, J. Nonaka, Y. Yoshida, S. Haga, K. Maki, A New Intraoral Six-Degrees-of-Freedom Jaw Movement Tracking Method Using Magnetic Fingerprints, Sensors 22 (22) (2022) 8923.

[29] L. Ma, F. Liu, J. Mei, J. Chao, Z. Wang, J. Shen, A comparative study to measure the sagittal condylar inclination using mechanical articulator, virtual articulator and jaw tracking device, J. Adv. Prosthodont. 15 (1) (2023) 11–21, https://doi.org/10.4047/jap.2023.15.1.11.

[30] L. Lepidi, F. Grande, G. Baldassarre, C. Suriano, J. Li, S. Catapano, Preliminary clinical study of the accuracy of a digital axiographic recording system for the assessment of sagittal condylar inclination, J. Dent. 135 (2023) 104583, https://doi.org/10.1016/j.jdent.2023.104583.

[31] Z. Nagy, A. Mikolicz, J. Vag, In-vitro accuracy of a novel jaw-tracking technology, J. Dent. 138 (2023) 104730, https://doi.org/10.1016/j.jdent.2023.104730.

[32] A. Bedrossian, E. Bedrossian, J.C. Kois, M. Revilla-Leo´n, Use of an optical jaw-tracking system to record mandibular motion for treatment planning and designing interim and definitive prostheses: a dental technique, J. Prosthet. Dent. (2022), https://doi.org/10.1016/j.prosdent.2022.08.036. S0022-39132200640–0.

[33] E. Adil, M. Mikou, A. Mouhsen, A novel algorithm for distance measurement using stereo camera, CAAI Trans. Intell. Technol. 7 (2022), https://doi.org/10.1049/cit2.12098, 177e186.

[34] H. Sarmadi, R. Muñoz-Salinas, M.A. Berbís, R. Medina-Carnicer, arXiv, 2021, https://doi.org/10.48550/arXiv.2103.09141.