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Investigation of the precision of a novel jaw tracking system in recording mandibular movements: A preliminary clinical study

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ABSTRACT

Objectives: This preliminary study aimed to clinically assess the precision of a novel optical jaw tracking system (JTS) in registering mandibular movements (MMs) of protrusion and mediotrusion.

Methods: Twenty healthy participants underwent recordings using Cyclops JTS (Itaka Way Med) for functional MMs of protrusion and laterotrusion by two trained clinicians. Each subject performed five registrations at different times according to a standardized pattern within one-month period. The angulations of protrusive and mediotrusive functional paths within the first 2 mm from the maximal intercuspal position (MIP) were calculated for each trace, using a data software for angle measurements. Descriptive statistics were used to assess the repeatability of the recordings for each participant and MM. Additionally, inferential statistics were carried out on standard deviation values obtained (α=0.05).

Results: The overall precision for all the patients was 7.07±3.37° for the protrusion angle, 5.24±2.24° for right laterotrusion and 5.14±3.06° for left laterotrusion angles. The protrusion angle ranged from 3.08° to 13.57°, while the right and left laterotrusion ranged from 1.82° to 9.42° and from 1.58° to 10.59°, respectively. No statistically significant differences were observed between different functional MM types and gender ($p > 0.05$).

Conclusions: Recordings functional MMs of mediotrusion and protrusion using Cyclops JTS showed consistent repeatability, regardless of gender and functional MM type. The results revealed non-negligible variations that may be due to the patients' abilities to precisely reproduce jaw movements or to the operator's ability to consistently connect the kinesiograph.

Clinical significance: Capturing functional MMs digitally and importing the data into dental CAD software is essential for virtual waxing in prosthetic rehabilitations to design a functionalized adapted occlusion. Establishing the repeatability of MM recordings by a JTS is a crucial step in better understanding this novel JTS in the market. This process could facilitate the interpretation of cusp angles, aid in CAD dynamic technical modeling, and enhance clinical data communication between clinicians and technicians in a modern workflow.

1. Introduction

Traditionally, mandibular movements (MMs) were captured by kinesiograph systems, which required a writing stylus to record mandibular path [1]. Kinesiographs enabled the assessment of 3D mandibular border movements and their analysis during chewing and speeching [2,3]. However, limitations in correlating MMs with teeth contacts during clenching and parafunction, coupled with speculative aims, have resulted in decreased interest in prosthodontics [4].

The advent of digital jaw tracking systems (JTSs) has introduced safe and non-invasive techniques for recording MMs [5,6]. These systems utilize various technologies such as stereophotogrammetry [7],

Abbreviations/acronyms: JTS, Jaw tracking system; MMs, mandibular movements; MIP, maximal intercuspal position; CAD, Computer Aided Design.

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optoelectronics [8], ultrasound [9], and electromagnetic waves [10]. Modern dental software's capability to integrate data from cone beam computed tomography, intraoral scanner, face scanner and digital JTSs offers the potential to create a 4D virtual patient [11–14]. This represents the initial step in planning and designing complex prosthetic rehabilitations, such as complete arch implant prostheses or restorations for severely worn dentitions [15–17]. This non-invasive digital plan can be easily shared through network-mediated communication tools, facilitating simultaneous discussions between clinicians and technicians. Adjustments can then be made based on patient's aesthetic preferences [11–13]. Nowadays, the main clinical expectation of digital JTSs is to capture maxillomandibular relationship and MMs during functional tasks. This facilitates the fabrication of functionalized dental prostheses with adapted occlusion and articulation [18–22]. Functionalized occlusion could play a crucial role in prosthodontics, potentially reducing errors during CAD and manufacturing phases of prosthetic devices [21]. Accurately replicating MMs in a virtual environment depends on factors such as best-fit alignment data, which minimizes occlusal adjustments after restoration delivery [23,24]. This accuracy is crucial for ceramic and new hybrid materials, preserving their mechanical and aesthetic integrity [25,26].

The repeatability of mandibular motion and the range provided by the patient during the registration phase with JTSs are crucial for CAD prosthetic design [27–30]. Among the various MMs, the first 2 mm of the mediotrusion and protrusion, evaluated in frontal and sagittal planes, are particularly interesting for digitally projecting the inclination, length, position, and thickness of tooth cusps and pits [3,31,32]. In individuals with healthy dentition, this portion of the functional MMs appears to be influenced more by the opposing tooth surfaces than by the anatomy of the temporomandibular joint [3]. A recent study [21] demonstrated that occlusal design based on patient-specific motion was more effective in restoring natural anterior tooth guidance. However, precision in MMs registrations remains unaddressed. Given the influence of the neuromuscular system on functional MMs [32], assessing their repeatability is clinically significant. Previous studies have evaluated the repeatability of MMs during masticatory cycles [30] and mandibular border movements [3,28,29] finding significant variability across participants.

However, to the best of author's knowledge, no one has evaluated the precision in recording functional MMs using Cyclops© optical JTSs (ITAKA Way Med, Venice, Italy). This device employs a camera to track the position of markers attached to the patient's mandible in relation to additional markers placed on a patient's head mounter. In this manner, the JTS can map MMs and make measurements based on image analysis through marker tracking methods [33]. This preliminary study aimed to investigate the repeatability (precision) of recordings of functional MMs (protrusion and mediotrusion) in healthy subjects using this novel JTS.

2. Material and method

2.1. Study design

Thirty-two participants were initially recruited between February 2021 and June 2023. Within this initial sample, twenty subjects were ultimately enrolled in the study ($n = 20$). Participants were recruited on a voluntary basis from students and dentists within the dental clinic of our University. All participants were informed about the study procedures, and informed consent was obtained and signed. This study followed the principles laid down by the World Medical Assembly in the Declaration of Helsinki of 2008 regarding medical protocols and ethics. Each enrolled patient was assigned a consecutive number to ensure anonymity, and their data were securely stored in a computer chart. Specific inclusion and exclusion criteria were employed to select the patient sample for the study. The inclusion criteria for the study were:

- voluntary healthy patients (ASA 1) aged between 18 and 65 years;
- absence of any history of craniofacial trauma, no presence of congenital or acquired craniofacial anomalies;
- no temporomandibular disorders;
- not requiring any prosthetic, conservative, gnathological rehabilitation;
- completely dentate patients with a stable maximal intercuspal position (MIP).

Exclusion criteria were:

1. patients who had undergone underwent to prosthetic and conservative therapies on the posterior teeth and/or gnathological therapy;
2. presence of deep bite and overbite > 3 mm;
3. patients with second or third molar and canine Angle class and with restricted range of mandibular motion.

Twelve patients were excluded after the first visit because they did not meet the inclusion criteria (Table 1). So, the final sample size consisted of 100 tracings from twenty patients (10 men and 10 women). The method adopted consisted in a first clinical phase conducted by the two expert operators (FG, SP) that performed all the patient recordings with one optical JTS followed and a second phase of data processing conducted by a blinded operator (LL).

The same two trained operators in JTS recordings (FG, SP) performed all the registrations using Cyclops© (ITAKA Way Med, Venice, Italy) which is a photometric JTS. In order to standardize the recordings and to reduce the influence of external factors, all the recordings were performed under the same environmental conditions: 23 °C with 45 % of humidity and a room artificial lighting conditions of 1000-lux measured with a digital light meter (Digital light meter LX1010BS; Dr. Meter) and a white spectrum color temperature (4100 K) which reflects the clinical room lighting conditions defined by the ISO [34].

An image summarizing the study design is shown in Fig. 1.

2.2. Optical tracking recording using Cyclops©

This JTS consists of two components: hardware and software. The hardware measuring system is composed by a capture source provided of stereo-vision cameras and by several accessories provided of sensors

Table 1
Inclusion and exclusion criteria.

Initially recruitment between February 2021 and June 2023: 32 patients	
Inclusion criteria	**Exclusion criteria**
Good systemic health status	Deep bite
No previous diagnosis of Temporo Mandibular Disorders (TMDs)	< 18 years old
Presence of all teeth groups (incisive, canines, premolars and molars)	> 65 years old
Willingness to understand the procedure and give informed consent	Rehabilitated with a removable total/partial denture
First molar and canine class	Ongoing orthodontic treatment (finished treatment >6 months)
	Acute oral health issue (caries, odontogenic abscess, odontogenic phlegmon)
	Acute/chronic pain of masticatory and facial muscles
	Primary headaches
	Chronic pain (pain >3 months) neck, shoulders or back
	Previous brain injuries
	Facial cleft lips/palate
	Impaired salivary flow because of drugs or systemic conditions
	Neurological disorder with impaired motor capabilities and affecting cranial nerves
Final patients sample basing on inclusion and exclusion criteria: 20	

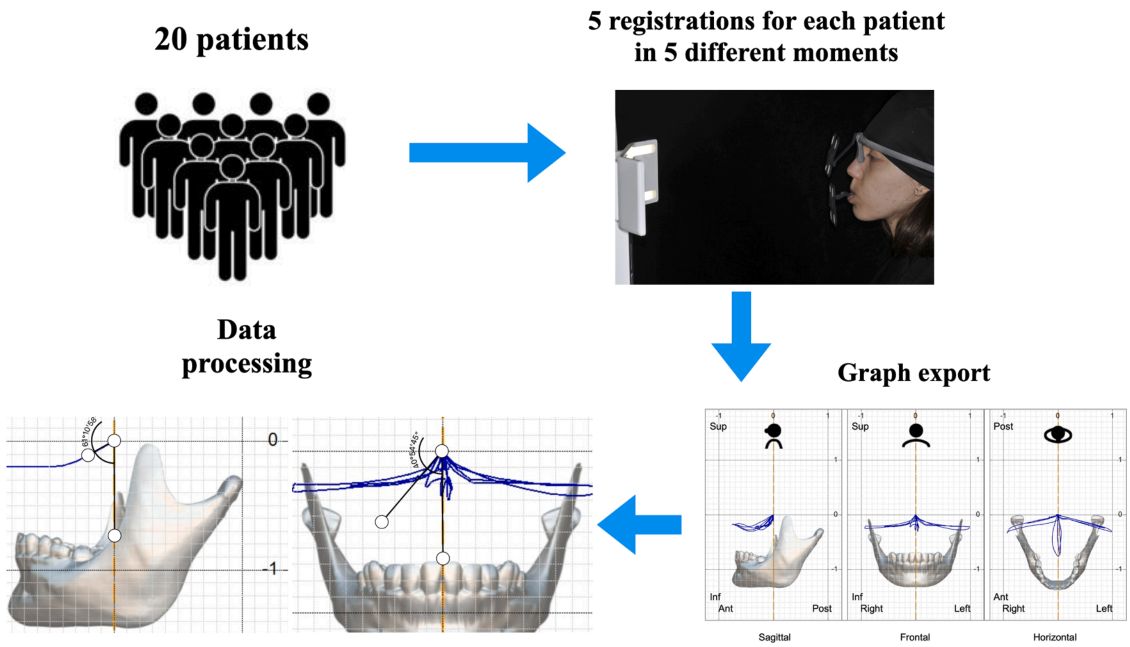

Fig. 1. Graphical representation of the study design.

that are reported as follow:

The hardware measuring system is composed of a capture source provided with cameras and several accessories provided with sensors, as follow (Fig. 2):

- A lower fork called "mandifork" which was adapted to the vestibular surfaces of mandibular teeth with bisacrylic resin (Acrytemp, Zhermack, Badia Polesine, Italy) and used as the mandibular tracker (Fig. 2a);
- A "Triskel" that was hooked by magnets to the "mandifork", "bytefork" and "upper positioner" (Fig. 2b);
- An "upper positioner" that was fixed to the subject head as the head frame (Fig. 2c);
- A "bytefork" that was adapted to the occlusal surfaces of the maxillary teeth using a polyvinylsiloxane material (Hydrorise Medium Body, Zhermack, Badia Polesine, Italy) only for the maxillary position recording;

The stabilization of the "mandifork" to the teeth and the absence of pre-contact or interferences with the antagonist during the MMs were checked.

Then, each participant was dressed wore a black cap and sheet to prevent interference with the recording sensor caused by white clothing or hair, based on the instructions provided by the manufacturer. The participant seated at approximately 40 cm in front of the camera and MMs were recorded in natural head position (Fig. 2d).

Before each recording, participants were instructed to perform free, quick and repeated MMs for 10–15 s with maximum excursion avoiding any uncertainty in both contactless and tooth contacts. This was done to prevent misperception and ensure self-awareness and individual recordings free from operator conditioning or manipulation.

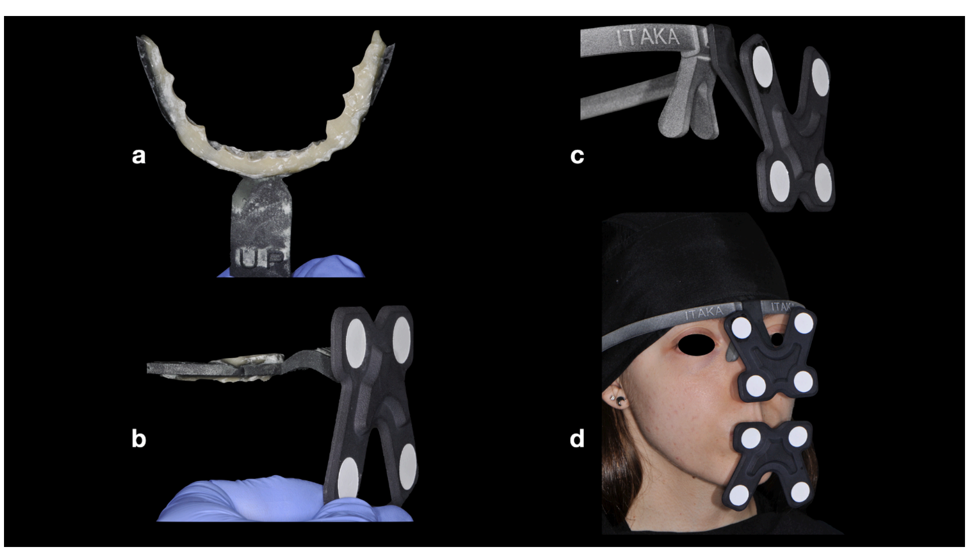

Fig. 2. a) The Mandyfork of the Cyclops system adapted to the vestibular surfaces of mandibular teeth with bisacrylic resin. b) The Mandyfork connected with the markers reference (Triskel). c) The upper positioner of Cyclops system connected with its markers reference. d) Patient dressed and in position for functional mandibular movements recordings.

Subsequently, five recordings were taken at five different times for each participant over a period of one month. The setup time for each procedure was approximately five minutes. During each recording, participants performed brief pro-retrusion and mediotrusion movements starting from the maximal intercuspal position (MIP) to design the corresponding tooth guidance.

Following the recording, the JTS software (ITAKA Way Med Software, Itaka) provided the traces of the markers points recorded along the three spatial planes (coronal, sagittal and frontal) (Fig. 3).

All data registered and saved were then exported to measurement software as a JPEG graph image for further processing.

2.3. Data processing

The JPEG images of the movement tracing graphs were imported into a software for angle measurements (Angle Meter 360, software App) (fig. 4). Three different angles were measured on two different movements trace graphs for each registration. Two angles (on the right and on the left side) on the frontal view graph of the mediotrusion movement were measured and referred to as "laterotrusion angles" (Fig. 4a). One angle on the sagittal view of the protrusion movement was measured and referred to as "protrusion angle" (Fig. 4b).

The measurements were taken on the first 2 mm of trace registered from the MIP, which indicate the movement inclination from the maximal intercuspation to anterior and lateral left and right edge-to-edge positions. When different traces, corresponding to different angles, were found in the same graph for the same movement, the choice was to take the most external trace (the black one) (Fig. 4c).

2.4. Statistic analysis

Descriptive statistics were used to assess the repeatability (precision) of the recordings for each patient and for each MM (protrusion and medio-laterotrusion right and left movements). The overall repeatability of the data for each angle was assessed by calculating the mean of the standard deviation values obtained from the recording of the 20 patients (Fig. 5).

Inferential statistics were used to evaluate significant differences between the laterotrusion and protrusion angles, as well as between male and female groups, with a significance level set at $p < 0.05$.

3. Results

Twenty participants were involved in the study, ten males and ten females, with a mean age of 27.2 years old. For each patient, five registrations at five different time points were taken. The raw values of the angles (protrusion and laterotrusion angles) calculated for this study were summarized in table 2. For each participant and for each angle, a descriptive analysis indicating the range, the median, the variance, the mean, the standard deviation and the interquartile range was carried out (Table 3).

The overall precision calculated for all the patients was 7.07±3.37° for the protrusion angle, and 5.24±2.24° and 5.14±3.06° for the laterotrusion angles. The protrusion angle ranged from 3.08° to 13.57° while the right and left laterotrusion ranged from 1.82° to 9.42° and from 1.58° to 10.59° The overall precision for men were 6.60±4.03°, 4.94 ±2.1° and 3.99±2.33° for the protrusion, right laterotrusion and left laterotrusion angles respectively. The same for the woman were 7.54 ±2.68°, 5.54±2.45° and 6.29±3.31°

Figs. 5 show the histograms of the mean±st.deviation related to each participant of the protrusion, right and left laterotrusion angles, respectively.

Kolmogorov-Smirnov Test revealed that data in each group of movements were not normally distributed. The Kruskal Wallis non parametric test did not demonstrate statistic significant differences between the laterotrusion and protrusion groups ($p = 0.52$) and between male and females ($p = 0.83$).

4. Discussion

The purpose of this study was to investigate the precision in recordings of three functional MMS (pro-retrusion, right and left mediotrusion) captured by using a novel optical JTS, named Cyclops©, at five distinct time points within a one-month period. The descriptive statistical analysis is the only available method that can facilitate an insightful investigation.

In this study, the authors chose to measure the angles of MMs traces in the first 2 mm in tooth contact because they are considered the most interesting from a prosthetic point of view [19,21,31]. The relative precision values of the three functional MMs angles are not so high, but they are comprised in different ranges. This means that, in the subsequent CAD dynamic modeling phase, the dental technician should consider a certain degree of imprecision in designing the adapted functionalized occlusion.

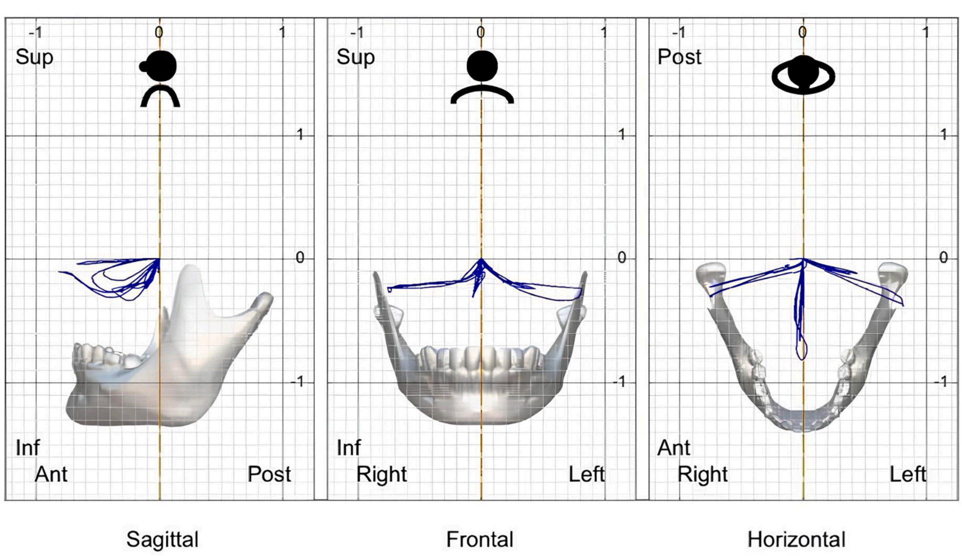

Fig. 3. Report of mandibular movements graphs generated by Cyclops system.

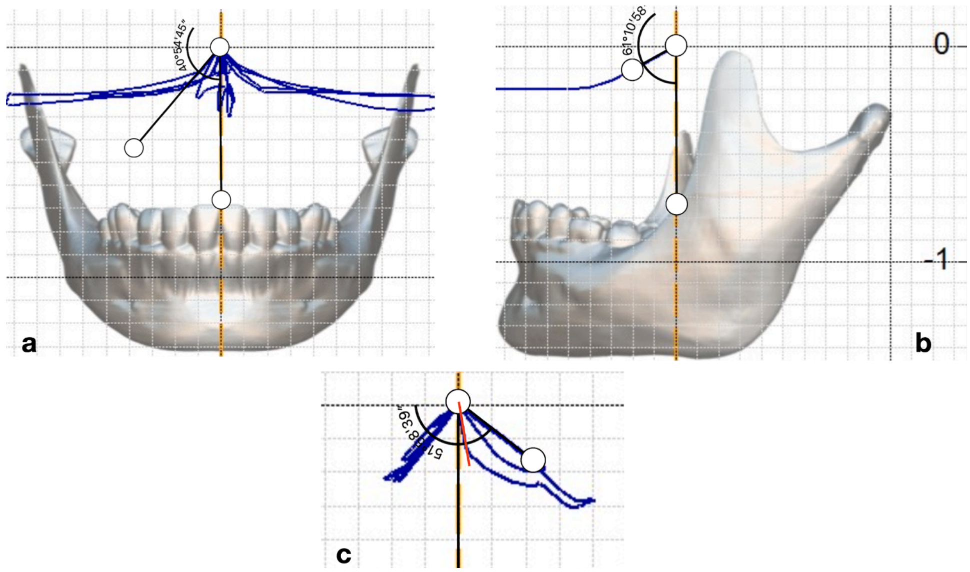

Fig. 4. a) Example of right laterotrusion angle measurement. b) Example of protrusion angle measurement. c) Selection of the external trace: authors opt for the black line when multiple angles of the same movement were present on the same graph. The red line indicates the most internal trace in the graph representing the left laterotrusion movement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

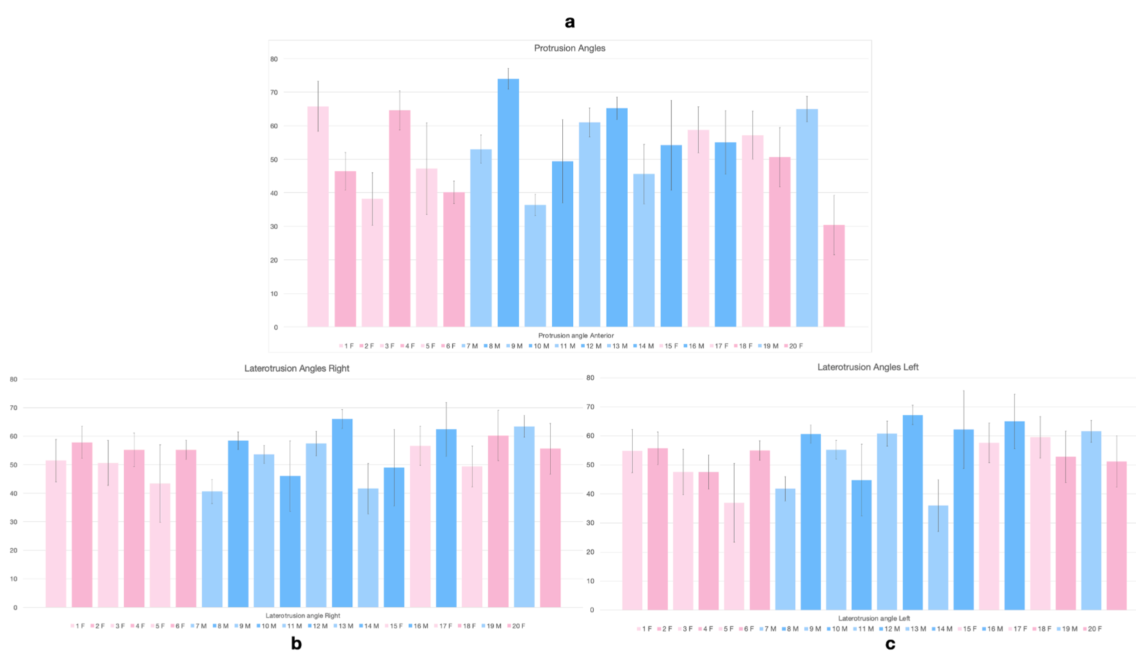

Fig. 5. Histograms of the mean and standard deviation related to each participant of the protrusion (a), right (b) and left (b) laterotrusion angles.

Table 2
Raw values of the protrusion and laterotrusion angles calculated for each participant during each registration.

Patient	Age	Sex	Registration number	Angles			
1	24	F		Protrusion angle		Laterotrusion angles	
				Ant	Post	Right	Left
			1	77	0	47	52
			2	61	0	56	57
			3	70	0	49	55
			4	61	0	49	56
			5	60	0	56	54

Table 3
Descriptive analysis generated for each participant for protrusion and laterotrusion angles.

	Age	Sex	Registration number	Angles		
1	24	F		Protrusion angle	Laterotrusion angles	
				Ant	Dx	Sx
			Max value	77	56	57
			Min value	60	47	52
			Median	61	49	55
			Variance	55,7	18,3	3,7
			Mean	65,8	51,4	54,8
			Standard Deviation	7,46	4,28	1,92

No statistically significant differences were observed among the angles measured (protrusion, right and left laterotrusion). However, the protrusion angle group exhibited higher mean and standard deviation values than right and left laterotrusion angles. This may be attributed to the specific recording method used by the Cyclops© JTS. This system comprises hardware featuring a camera (capture source) positioned on the frontal plane relative to the moving object (accessories). Consequently, the observed difference could be associated with the "parallax phenomenon" or potential operator errors, leading to increased values in the sagittal plane [35,36].

However, this remains only a hypothesis as we lack a true reference for comparison. In fact it could also be possible that the reason of this difference is linked to a human factor, as the muscle groups activated for protrusion and laterotrusion movements differ [37–39].

Regarding the impact of human factors on functional MMs recordings with optical JTSs [5,27,40], the literature reported also the individual pattern or patient behavior during the acquisition procedure. In this study, although each participant received clear instructions multiple times on how to perform the MMs spontaneously and in uninduced way, it's important to note that the quality of MMs can vary between individuals due to differences in muscle and joint components [37–39]. It is established that mandibular movements involve the coordination of 20 muscle groups, constituting a complex kinematic system [37–39]. The activity levels of the masticatory muscle like masseter and temporalis groups decrease during lateral movements and is not always the same leading to differences in the eccentric MMs [37–39].

Furthermore, the patient's head posture may have change during the recordings, potentially contributing to the inconsistency of the MMs [41,42]. Factors such as the patient's self-balance and visual righting reflexes may have also influenced the recordings, especially considering that the system emits a strong white light projected in front of the patient's face during the registration procedure [43,44].

MMs may also vary depending on the patient's emotional state [45]. We conducted the registrations over one month to minimize the time between recordings and prevent potential changes in the patient's mouth. However, we did not have information about the emotional state of the patients during the recordings. Additionally, it is the Authors opinion that participants may have experienced the 'white coat effect,' which could have introduced differences in the MMs [46].

The intraoperator variability in measuring the angle may have also played a role [47,48]. When different traces were found in the same graph for the same movement, the choice was to take the most external one to design the angle. This decision was based on our attempt to focus the angle exclusively on patient movements with teeth in contact. Consequently, when different traces were found, the choice leaned towards the outer trace indicating teeth in contact, while inner traces were interpreted as MMs in disclusion. However, this assumption by the authors may not necessarily be accurate.

Some environmental conditions may have influenced the registration process, such as the light source, ambient temperature, type of resin used to stabilize the mandifork and especially the patient-device distance [49]. While efforts were made to standardize these factors, fluctuations in the patient-device distance may have occurred during the recording of functional MMs. It is well-documented that for photometric systems, the distance between the cameras and the markers can significantly impact registration reliability, especially along the z-axis (x-axis: roll, y-axis: pitch, z-axis: rotation) [50]. For this reason, it's crucial that data recorded by the camera come from a source positioned perpendicular to the camera and at a constant distance from the object, no >1 meter away to minimize the "parallax phenomenon" [35,36].

Moreover, to achieve accurate recordings, it's necessary to stabilize the "mandifork" to avoid oscillations that could negatively impact patient perception and limit movements, thereby introducing potential data distortions [27]. For this purpose, we used a bisacrylic resin due to its ease of application for securing the fork on the vestibular surfaces of mandibular teeth, and its ability to be easily relined or removed if necessary. However, an additively manufactured mandibular fork may be employed to maximize stability during the MMs recordings [51].

The main limitation of the present study is the absence of a reference or control group, which makes impossible to fully assess the accuracy of this novel JTS. Due to the in vivo nature of this study, it is impossible to establish a reference specific to each patient's functional MM for the assessment of trueness. Furthermore, variations observed between values recorded at different temporal instances of MMs may arise from both instrument imprecision and inherent biological variability among individual patients. Therefore, this study can only be considered preliminary, highlighting the need for further comprehensive evaluations of the accuracy of this novel JTS.

Moreover, the study's potential was limited by the small sample size and the inclusion of only healthy participants. In fact, these JTSs are clinically used for patients undergoing oral rehabilitations. Clinical conditions such as temporomandibular joint disorders, neuromuscular kinematic dysfunction, variations in natural head position, parafunctions, unbalanced occlusal contacts, as well as difficulties in intraoral stabilization of the devices due to shortened arches, deep bite, tooth absence, and tongue movements, were identified as confounding variables [6,27].

Those points need to be assessed in further research studies.

5. Conclusions

Cyclops© JTS, as a digital kinesiograph, showed consistent precision registering mediotrusion and protrusion MMs, regardless of gender and functional MM type. The results revealed non-negligible variations that may be due to the patients' abilities to precisely reproduce jaw movements or to the operator's ability to consistently connect the kinesiograph.

Differences in functional MMs recorded at different times by using a JTS should be considered for dynamic CAD modeling. Further researches are necessary with a control group to fully assess the accuracy of this JTS.

CRediT authorship contribution statement

Francesco Grande: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Luca Lepidi:** Writing – original draft, Data curation. **Fabio Tesini:** Investigation. **Alessio Acquadro:** Investigation. **Chiara Valenti:** Investigation, Formal analysis, Data curation. **Stefano Pagano:** Validation. **Santo Catapano:** Writing – review & editing, Validation, Supervision, Project administration.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jdent.2024.105047.

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