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A semi-automated tool for digital and mechanical articulators comparative analysis of condylar path elements

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ABSTRACT

Digital workflows have revolutionized dentistry, especially when it comes to fabrication of complete dentures through Computer-Aided Design and Computer-Aided Manufacturing (CAD-CAM) procedures. Digital articulators manage to simulate mandibular movements and are emerging as alternatives to mechanical articulators like the Gerber semi-adjustable model. Despite being a promising tool, digital articulators require refinement in order to grant consistent functionality and effective occlusal balance. The aim of this research is to present a semi-automated MATLAB tool designed to compare trajectories from different articulator types—digital versus analog—used in dental practice. Validation of the MATLAB tool compared to existing data demonstrates its reliability and effectiveness. Sensitivity analyses assess the tool's robustness under various settings. Results suggest optimal input parameters and settings ensuring precision. Future developments may include integrating anatomically-based reference systems and advanced metrics for rotational analysis of condylar path elements (CPEs), thereby enhancing digital dentistry potentialities. Ultimately, the semi-automated MATLAB tool represents a significant step towards improving dental occlusal analysis, bridging the gap between analog and digital methodologies and enabling comparison among these tools.

1. Introduction

Over the recent years, CAD-CAM procedures have found wide application in dentistry. Specifically, digital workflows are now employed in the creation of complete dentures, offering notable benefits such as enhanced biomechanical properties, shortened work durations, cost reduction, and a decreased number of in-office visits [1–4].

Among various digital design tools, digital articulators have been introduced as an alternative to the traditional analog (mechanical – physical) articulators, which still serves as the gold standard [5]. Mechanical articulators, traditionally used in denture design, enable clinicians to simulate patient's jaw movements and bite dynamics. These devices primarily consist of semi-adjustable models, which rely on average anatomical values alongside specific intermaxillary occlusal registration to approximate mandibular movements [6]. On the one hand they provide a practical approximation of occlusion, on the other hand their reliance on generalized parameters rather than patient-specific data can limit their accuracy. Conversely, fully adjustable articulators offer a higher level of customization by incorporating detailed patient-specific measurements. This results in a more accurate simulation of jaw dynamics, such as condylar inclination and lateral movements, enhancing the fit and functionality of prosthetic devices through a more precise replication of the patient's specific jaw movements.

Despite advancements in digital workflows, it is still not possible to lay aside analog procedures, especially for edentulous patients. Some of the analog steps technique, such as initial impressions, gothic arch tracing, or the application of a facebow, remain essential [7]. Nevertheless, the digital protocol streamlines the procedure, reducing the number of steps and, consequently, minimizing sources of inaccuracy,

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ultimately contributing to an enhanced design. Furthermore, the contemporary utilization of the digital jaw motion tracking device presents a promising tool for advancing these measurements. This system can be used to convert the data coming from the actual patient movements into a list of settings for the articulator that duplicate patient's condylar path elements (CPEs). Indeed the final occlusal balance of the prothesis aims to equilibrate a new intermaxillary position for the patient instead of equilibrating the patient's existing dysfunctional occlusion [7]. The occlusal scheme of a prothesis is challenging in the best case scenario [8]; in the worst case scenario, it can introduce further issues that could lead to increased dental problems [9]. Apart from poor hygiene, non-functional occlusion can be considered the primary cause of dental related pathologies. With advancing age, dental occlusion related problems tend to increase due to tooth wear, break or loose which leads to the need for dental implants or prothesis to restore the lost occlusion. In some cases such prosthetic devices do not improve the patient's condition: the reason can be found in the inadequate patient-specific dental occlusal scheme used for the design of the prosthetic devices [10]. Moreover, osseointegrated implants can fail if problems related to CPEs and occlusal contacts are not considered [11, 12].

Analog articulators allow to prevent the catastrophic failure of the prothesis, thus avoiding articular (Temporomandibular Joint) disfunction and the need of a re-manufacture. However, clinical experience has shown that regardless of the workflow and the articulator used, perfect occlusal balancing, which involves adjustments to the teeth to achieve a proper occlusion, cannot be consistently obtained [9,13].

If a virtual articulator ever succeeds in perfectly simulating the patient-specific jaw cinematics, together with CAD-CAM technologies, it could treat bite-related disease in a predictable way, lowering cost and improving patient satisfaction. Nonetheless, if we consider clinical experience and user feedback, digital tools are still far from allowing the design and production of a fully functional device without the need for re-tooling and/or occlusal balancing.

Literature provides several insights into digital articulators. Many studies have examined the impact of various parameters on digital articulator behavior, including investigations into the influence of the vertical dimension [14] and the inclination of the sagittal condylar path [15]. Another study compared the maximum intercuspal relationship between traditionally articulated casts and digitally articulated ones [16]. Furthermore, the effects of different settings on the digital articulator were assessed to analyze the occlusal morphology of restorations created using CAD/CAM technologies [17]. While some discrepancies exist in these findings, all of them confirm the reliability of the virtual articulator as a valuable tool for denture base design.

However, these investigations focus on cases involving patients with natural teeth. These were used as landmarks to compare the behavior of different articulators in fixed positions.

For edentulous patients, establishing reliable landmarks for comparison is challenging [18]. Furthermore, to our knowledge, no studies have specifically explored whether the simulated occlusion of a digital articulator is comparable to that of semi-individual mechanical articulators, particularly in the context of edentulous patients, and moreover, no study investigated the difference between a digital articulator set to semi-adjustable values and a digital one set to fully adjustable values.

In order to fill this gap, a recent study [19] proposed a methodology for comparing different occlusion simulations produced by various articulators for fully edentulous cases. This comparison involves assessing the actual pathway of either casted or digital models during three CPEs: left and right lateral movements, and protrusion. This procedure performs a comparison between digital and analog articulators, digital and digital articulators, or analog and analog articulators. At the same time, it is suitable for both edentulous cases and cases with natural teeth, as it relies on comparing trajectories rather than natural landmarks on the palatal tissue/teeth. Although this procedure presents a good degree of flexibility, it has a considerable turnback, the fact that is completely manual. This means that the operator needs to manually perform the comparison setting one by one the reference point coordinates. The result is that the procedure is highly prone to operator-dependent errors that can be difficult to find and correct. Moreover, the possibility to update the comparison strategy, for instance defining further measurands or improving the computation of approximated quantity, is limited and requires restarting the process all over again.

For this reason, this study aims to introduce a semi-automated MATLAB-based tool for comparative analysis of digital and mechanical articulators. The proposed methodology addresses limitations in previous fully manual procedures by embedding trajectory comparison in an automated framework, significantly improving accuracy, repeatability, and user-friendliness. Through validation using existing datasets and sensitivity analyses, the tool is demonstrated to reliably assess condylar path elements of edentulous and dentate patients. This work does not aim to propose a new type of articulator, it rather offers a comparison among different existing tools, highlighting their possible implementation, performance and differences in evaluating the mandibular pathways.

2. Materials and methods

This section outlines the semi-automated protocol developed for analyzing trajectories from various articulator types. It begins with a detailed description of manual clinical procedures which is essential for data acquisition (see subsection 2.1), followed by the steps for processing analog and digital inputs into a standardized format (see subsection 2.2 and subsection 2.3). This enables automated comparison via a MATLAB code, which computes trajectory deviations, repeatability, and bias across articulators (see subsection 2.4). Validation and sensitivity analyses ensure methodological robustness, optimizing parameters for clinical reliability (see subsection 2.5).

2.1. Clinical protocols

The primary clinical goal in creating a complete denture is to give the dental technician an accurate and reliable intermaxillary records of the patient's occlusion, capturing both anatomical details (edentulous arch structure) and functional aspects (mandibular movements and intermaxillary relationships). This begins with impressions of the edentulous arches, typically made using irreversible hydrocolloid materials rather than digital scans, which often fail to accurately capture functional anatomy.

These impressions, either analog or digital, are then used to create models. Analog models are made by pouring plaster into the impressions, while digital models are created through direct scanning or importing digital impression files. Analog models can also be scanned obtaining digital model to be used in the digital protocol.

Next, the technician needs the definitive impression and intermaxillary records in order to mount the relative models on either an analog or digital articulator. For edentulous patients, accurate intermaxillary records and parameters are necessary, often requiring a face-bow for semi-individual articulators. For fully adjustable articulators, advanced digital devices are used to gather all specific patient parameters, replicating complex mandibular movements: digital systems like the Jaw Motion Analyzer or Optic face-bow capture allow to transmit these movements to the lab, providing a comprehensive record of the patient's mandibular function for setting the digital articulator.

2.2. Data acquisition

The data acquisition phase differs depending on whether the starting point is an analog articulator or a digital one (i.e. Zebris). The aim of this in vitro study is to obtain the same data set from different inputs, as illustrated in Fig. 1. The output is a digital representation of both articulated models in specific positions along each movement that needs to

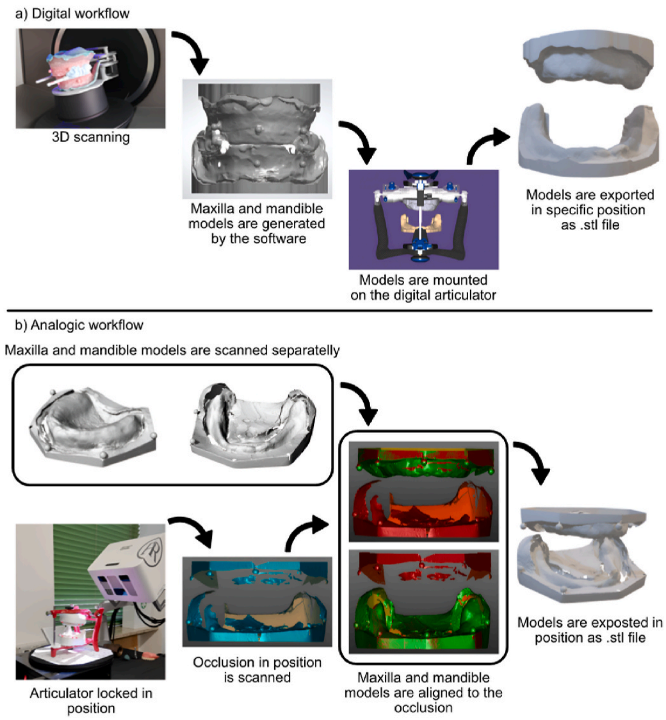

Fig. 1. Data acquisition phase.

be studied.

2.2.1. Analog articulator

In order to digitize an analog articulator, each pathway endpoint is sampled along with several intermediate points. The articulator, stabilized with a resin splint, is scanned in 3D for each position. Since the models are very close together, it's difficult to directly capture the internal geometry. To address this, the models are scanned individually, subsequently a scan of the articulated models' external surfaces is performed in order to align the scans accurately. Moreover, spherical landmarks are used to enhance precision. This procedure results in a series of 3D scans in various positions, saved as STL files, functioning like frames in a film.

2.2.2. Digital semi-adjustable articulator

Unlike analog articulators, digital ones (Arman Girbach, Exocad GmbH, Darmstadt, Germany) don't have fixed movement endpoints, allowing the operator to set any desired displacement value. The operator defines a maximum displacement and selects a number of intermediate points. The subsequent data elaboration, subsection 2.4, handles length discrepancies during comparisons. Once positioned, the digital models can be exported as STL files, yielding similar outputs as with analog articulators.

2.2.3. Digital fully-adjustable articulator

The procedure is almost identical to the previous one. The only difference is that the length of each movement is determined by the patient registration and the articulator is set with individual values, as a fully-adjustable articulator.

2.3. Data pre-processing

The acquired data consist of homogeneous STL files but differ in reference systems. This discrepancy arises because the reference system in analog articulator scans is set by the 3D scanner, while in digital articulators, it's embedded in the software. The goal of the preliminary processing is to standardize the reference system across all files, establishing it on the mandibular model.

In order to track the articulated maxilla's position, three fixed points are used to define a Cartesian reference system, reconstructing the rigid body trajectory of the occlusion. Simplified bases with three spherical markers are employed (refer to Fig. 2). The CAD reference system of the lower base serves as the common reference for alignment, carried out in GOM Inspect. The aligned models, all with the same origin and orientation, are then exported.

Each aligned file is then re-imported into GOM Inspect, where the upper base is aligned with the mucosa, and the three spheres' positions are exported as a CSV file.

2.4. Data elaboration methodology

The comparison among the articulators is automatically performed in MATLAB through a dedicated code. The main sections of the code are depicted in Fig. 3.

The process begins by setting input parameters, including patient details, file names, movements for analysis, sample numbers, and repetitions, alongside key plotting specifications. Then, data preliminarily processed in GOM Inspect are imported from CSV files to establish a local maxilla reference system. The reference system is then computed, with the origin set at the centroid of three spheres, while the x-y plane aligns with these spheres and the y-axis points towards the frontal sphere.

The script then calculates "intermediate splines," which interpolate the imported data points, representing the trajectory and versor heads that define the local reference system. If multiple repetitions are provided, corresponding splines for each repetition are generated. Final splines are derived next: without repetitions, intermediate splines directly become final ones. With repetitions, average trajectories are computed by resampling points evenly along each path. Since averaging may distort orthogonality in the reference system, an orthogonal reference system is optimally fitted to the computed one while maintaining a fixed origin.

Variability metrics are calculated, expressed as standard deviation when repetitions are involved (Gaussian bivariate distribution with equal standard deviation in all directions is assumed). If none are defined, repeatability is null. The revised method uses normal planes at movement start points to measure variability, correcting inaccuracies from prior research. If necessary, splines extend tangentially to find intersections, which are then used to compute variability.

Initial bias between trajectories is determined as a rigid difference, attributed to manual operator input, and calculated using a roto-translation matrix. Current implementation supports only rigid translations based on starting points, with median points used in case of multiple repetitions. Future enhancements may include rotational bias. The defined rigid transformation is applied to the "second" articulator trajectories for comparison.

The script then compares these splines by resampling the shortest trajectory and measuring distances between the resampled point to the second trajectory along the normal plane to the reference trajectory. Geometric errors and vectorial deviations are saved for statistical analysis. Finally, the tool generates various plots to facilitate understanding: these illustrate intermediate and final splines, translated splines, and, if repetitions exist, variability along trajectories. A deviation plot shows differences between trajectories, with vectorial deviations also visualized.

2.5. Validation and testing for the elaboration methodology

To validate the code's numerical computations against the results of a previous manual and analytical tool, the same dataset from prior research was used [19]. Results are detailed in subsection 3.

Sensitivity analyses were then performed to optimize tool performance and parameter settings.

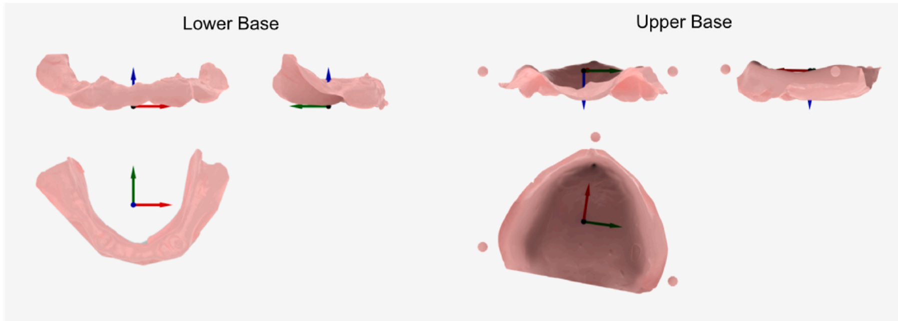

Fig. 2. Simplified bases with markers.

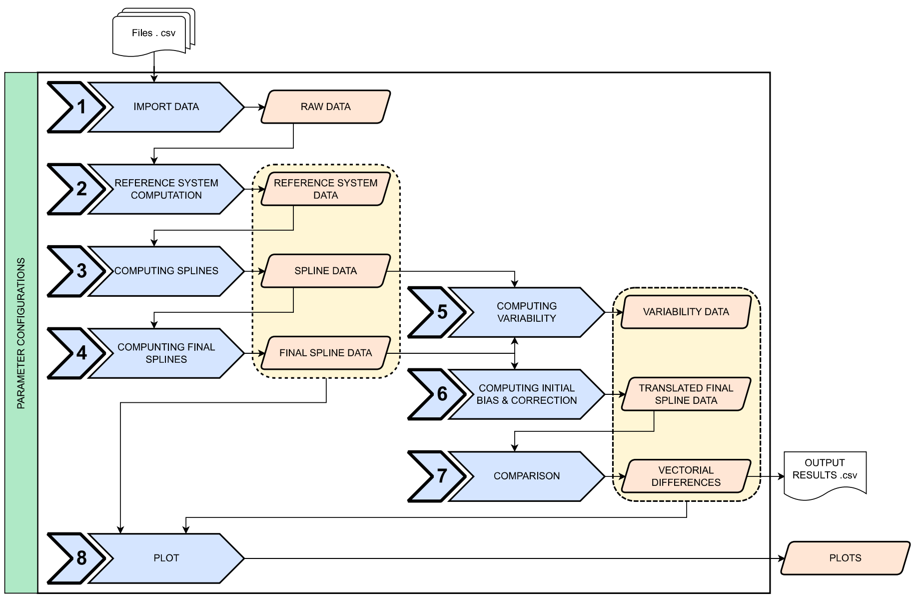

Fig. 3. Code architecture.

2.5.1. *Sensitivity to the number of acquisition points*

The first analysis examined the number of acquisition points required for accurate trajectory reconstruction. A 3D spline is constructed based on sampled points, as more points are sampled the reconstructed trajectory converges to the actual one. However, adding points also increased manual workload. The same trajectory was sampled using three to six points and compared to one sampled with eight points, considered the most accurate. Errors were evaluated using thresholds of 0.1 *mm* (maximum error) and 0.05 *mm* (average error). Both semi-adjustable and fully adjustable articulators were tested, with the former showing fewer smooth trajectories and greater errors. Results are presented in subsection 3.1.

2.5.2. *Sensitivity to the spherical marker position on the reference base*

The second analysis tested sensitivity to the positioning of spherical marker on the reference base (Fig. 2), which defines the mandibular CPEs. Starting with an initial sphere location, new positions were randomly selected within spherical domains of $S\varnothing 20$ *mm* and $S\varnothing$ 40 *mm*. A total of 100 random position within the predefine domains are tested, and standard deviations were calculated to measure repeatability. Smaller deviations indicated less influence from sphere positioning, with results detailed in subsection 3.2.

2.5.3. *Sensitivity to the resampling*

Furthermore, sensitivity to resampling density was analyzed. Although resampling frequency doesn't affect point-specific error, low densities can underestimate global error due to aliasing [20]. Using the digital vs. analog data, resampling densities from 5% to 45% of the shortest trajectory (in 5% increments) were tested, with endpoints set to 90% of the trajectory length. Errors were recorded and compared to denser resampling. The same method was applied to repeatability (standard deviation), with tolerances set at 10 μm for maximum error and 5 μm for average error. Results are presented in subsection 3.3.

2.5.4. *Sensitivity to the location of the acquisition points*

Finally, the sensitivity of acquisition point location along the trajectory was evaluated. For analog articulators, this factor is already accounted for in the standard deviation due to variability across repetitions. For digital articulators, the same points can be exported repeatedly. To assess the influence of point location, the articulator was sampled four times, slightly shifting the acquisition points each time while maintaining consistent start and endpoints. Eighteen points were acquired per movement, resulting in 256 combinations. The standard deviation of the average trajectory across these combinations was computed for semi-adjustable and fully adjustable articulators. Results are outlined in subsection 3.4.

3. Results

In the following section will be presented the results obtained from the various validation analyses.

The results from the validation test are summarized in Figs. 4 and 5.

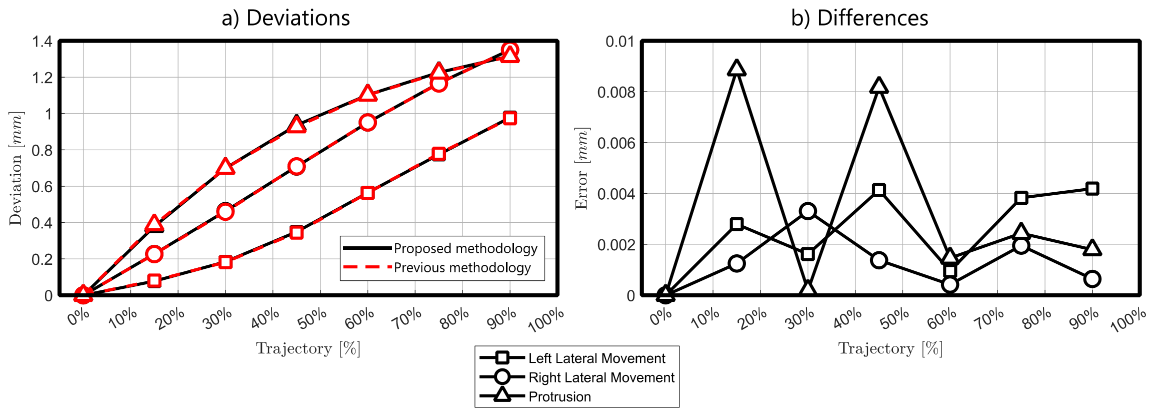

Fig. 4. Comparison between the deviations obtained with the previous manual method and the proposed semi-automated method.

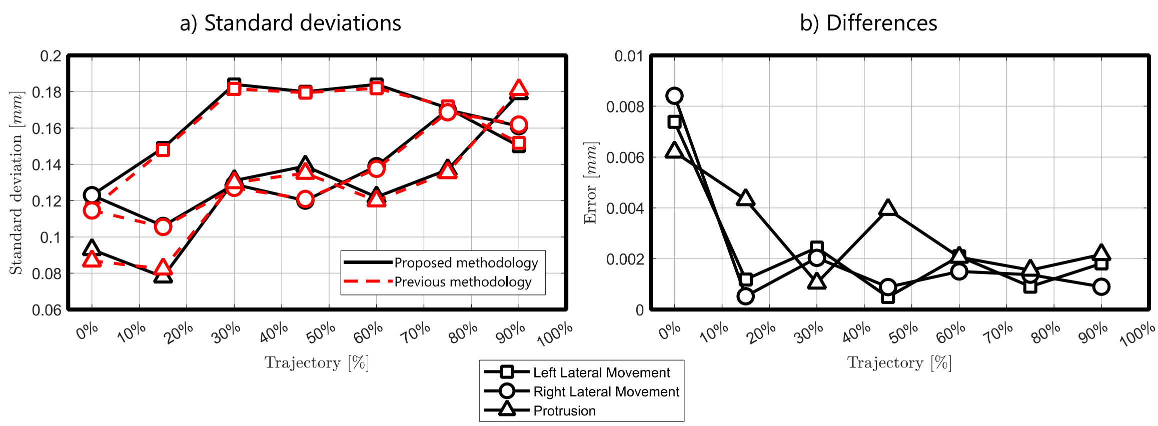

Fig. 5. Comparison between the standard deviations obtained with the previous manual method and the proposed semi-automated method.

Fig. 4 shows the result relative to the deviations coming from the analog articulator. The curves representing the deviations (Fig. 4a) are almost perfectly overlapped. By looking at Fig. 4b, where the error can be seen, it can be noted that the difference is always below 0.01 *mm* (or 10 μm). The biggest error can be found for the protrusion for two points (15 % and 45 % of the trajectory) where the error is higher than 8 μm. If these two points are excluded, the remaining errors are below 5 μm.

The comparison between the standard deviation (repeatability) result obtained for the analog articulator with the previous manual and the proposed procedure is shown in Fig. 5.

A good overlapping between the two curves sets can be seen for all points except for the starting point, Fig. 5a. The computation of the repeatability of the starting point was updated, therefore, a different result was expected. By looking at the errors between the two curves sets, Fig. 5b, the error for the initial point is between 6 μm and 9 μm which is less that 10 % relative error. The error for the other point is

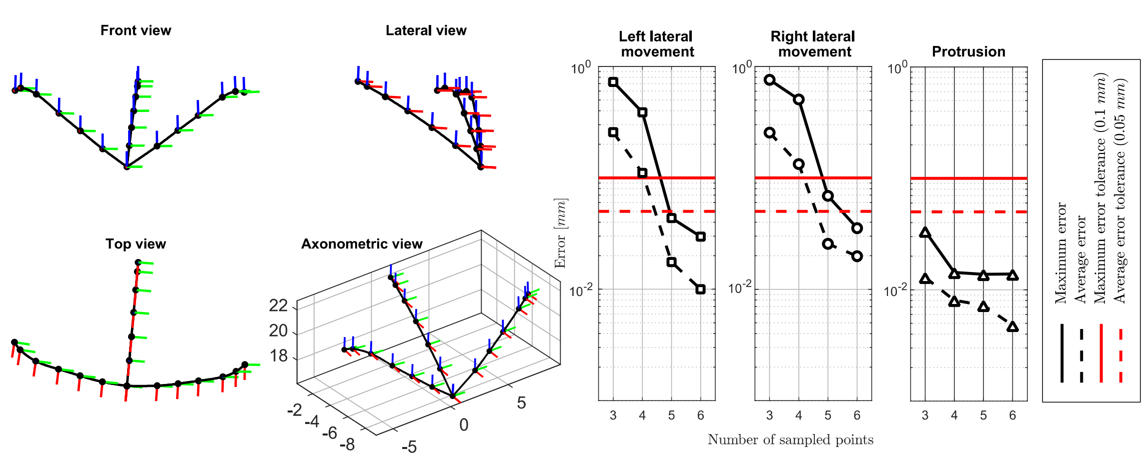

Fig. 6. Errors for different sampling point applied to the semi-adjustable articulator trajectories.

always below 5 μm.

3.1. Sensitivity to the number of acquisition (sampling) points

The results from the sensitivity analysis regarding the number of acquisition points for a semi-adjustable articulator are displayed in Fig. 6. Both errors progressively decrease with a higher number of acquisition points. This trend is similar for both lateral movements, as the two trajectories are nominally identical.

Fig. 7 illustrates the errors for the fully adjustable articulator with different sampling. The trend is similar to that for the semi-adjustable articulator for both lateral movements. Also in this case, with five sampling points, the error is below the threshold except for the maximum error for the left movement, which is 0.108 mm, therefore 8 μm above the threshold.

A different trend can be observed for the protrusion, which is significantly above the thresholds.

3.2. Sensitivity to the spherical marker position on the reference base

The results from the sensitivity to the spherical marker position on the reference base considering a variability of $S\varnothing 20\ mm$ is shown in Fig. 8. On the left side, the sampled sphere location is displayed along with the reference system origin. On the right side, the standard deviation of the computed differences is plotted. The variability in the differences increases in a linear mode towards the end of the trajectories for all movements. The maximum standard deviation is found for the right lateral movement with a value of approximately 0.15 mm.

Considering a variability of $S\varnothing 40\ mm$ on the spherical marker location, the results are found in Fig. 9. The maximum variability reaches approximately 0.275 mm for the left lateral movement. A linear increase in standard deviation is found for the protrusion and the left lateral movement. The Right lateral movement shows a linear behavior up to 65 % of the trajectory length followed by a plateau.

3.3. Sensitivity to the resampling

In this subsection, the results for the sensitivity to resampling are presented. Fig. 10 shows, as an example, the comparison between the standard deviation and the deviation obtained with a resampling every 5 % and 25 % of the trajectory length. The differences between the two curves are shown in Fig. 11.

The lobes in the differences graph show that the actual points sampled at lower rates have correct values, but the graphical representation lacks accuracy between sampled points. For this reason, it is important to define a resampling rate that allows an accurate representation of the error. To achieve this, the maximum error and the average error are plotted in Fig. 12. It can be observed that in both cases (deviation and standard deviation), the maximum and mean error decreases as the resampling rate increases.

3.4. Sensitivity to the location of the acquisition points

The results for the sensitivity to the location of the acquisition points are presented below.

Fig. 13 shows the results from the semi-adjustable articulator. On the left, the actual position of the exported points is shown. On the right, the standard deviation associated with the average trajectory is depicted. It can be observed that the variability of the protrusion is uniform along the entire trajectory and well below 10 μm. The variability for the lateral movements is below 10 μm up to 60% of the trajectory length, and then a sudden increase in variability can be seen, reaching its maximum around 90% of the trajectory.

Fig. 14 shows the results from the fully-adjustable articulator. It can be observed that the variability for all movements is below 10 μm up to 50% of the trajectory length, then the protrusion has a sudden increase in variability with a maximum around 65% of the trajectory length slightly below 30 μm. The left lateral movement start ramping up around 60% of the trajectory length reaching its maximum at 75% of the trajectory length. The right laterality has a spike at 90% of the trajectory length slightly above 30 μm.

4. Discussion

The results from the sensitivity analyses provide valuable insights into the behavior and performance of the proposed method, as well as its practical implications. For the number of acquisition points, it was observed that errors decrease progressively with an increasing number of points, confirming that a higher sampling density improves accuracy (Fig. 6 and 7). Notably, while five sampled points were sufficient to keep errors below the threshold for most movements, specific cases, such as the protrusion in the fully adjustable articulator, displayed higher errors due to the particularly curved nature of the trajectory (Fig. 7). This geometry-dependent variability highlights the need for careful consideration of patient-specific factors in practical applications, such as extreme curvatures that are not anticipated in all cases. Similarly, the sensitivity to the spheres' position on the reference base showed a predictable increase in variability with larger positional domains. For instance, the maximum variability reached approximately 0.275 mm for the left lateral movement with a ∅40 mm domain, as shown in Fig. 9.

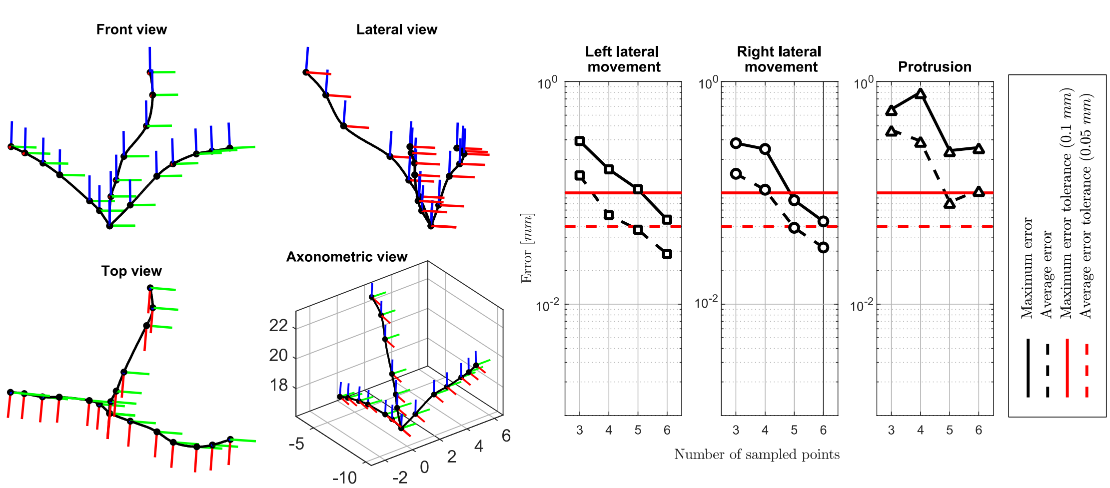

Fig. 7. Errors for different sampling point applied to the fully adjustable articulator trajectories.

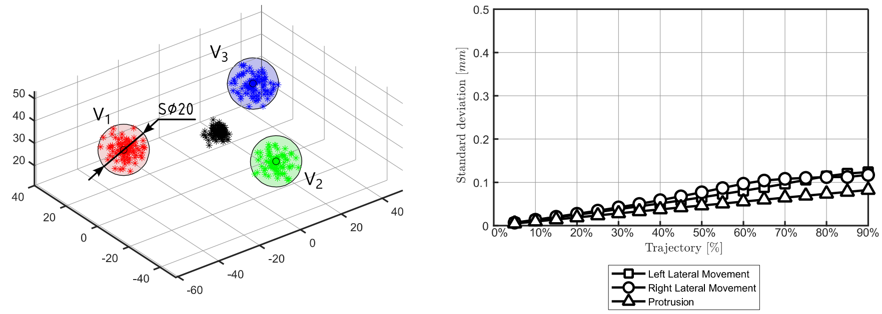

Fig. 8. Sensitivity to the spherical marker position on the reference base considering a $S\varnothing20$ *mm* variability.

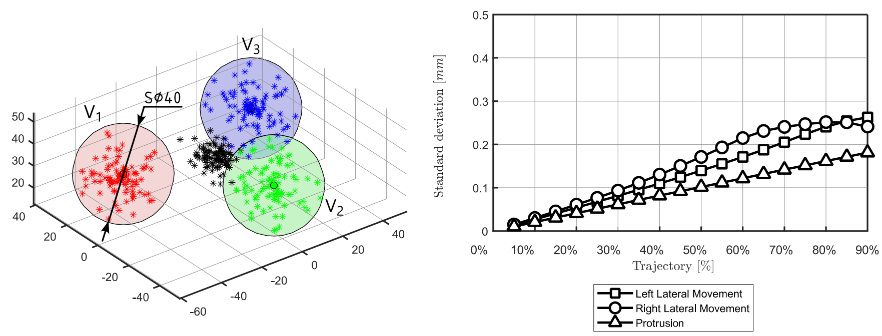

Fig. 9. Sensitivity to the spherical marker position on the reference base considering a $\varnothing40$ *mm* variability.

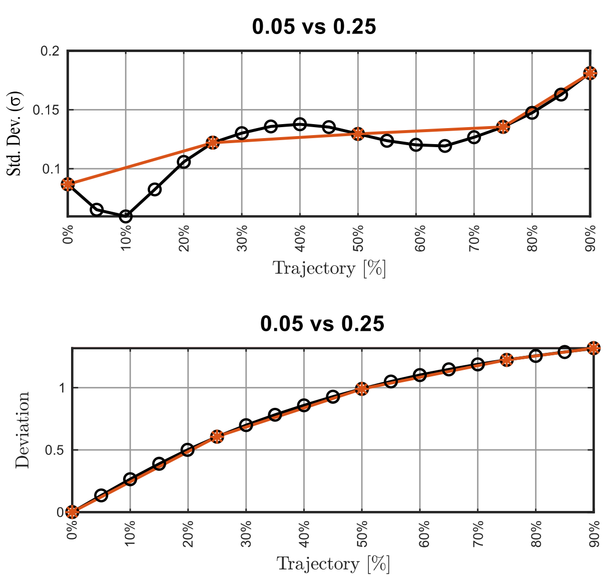

Fig. 10. Protrusion comparison between 5 % and 25 % resampling: standard deviation (top) and trajectory deviation (bottom).

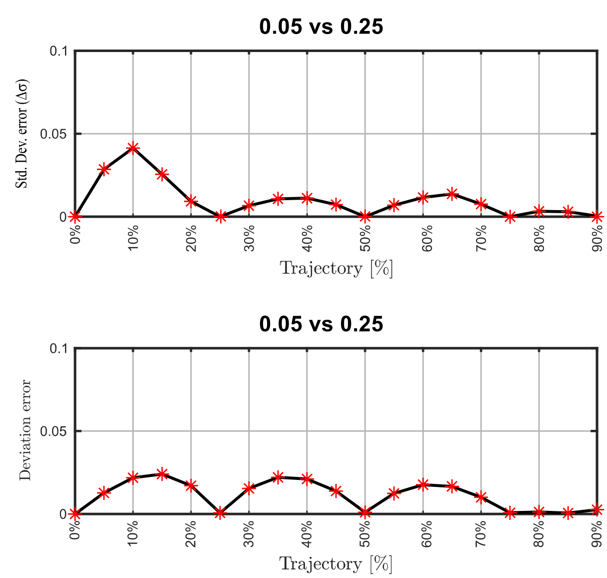

Fig. 11. Protrusion differences between 5 % and 25 % resampling: standard deviation (top) and trajectory (bottom).

This finding demonstrates that the manual placement of the spheres can significantly influence the results, especially in regions with greater trajectory curvature, underscoring the importance of ensuring precise and consistent placement of the reference spheres during measurement.

For resampling sensitivity, the results revealed that lower resampling rates introduce larger deviations, particularly in standard deviation errors, due to the aliasing effect, which prevents higher frequencies in the data from being accurately captured. This phenomenon was less prominent in trajectory error analysis due to the smoother nature of the curve. Based on the results (Fig. 12), a resampling rate of 10 % of the trajectory length was identified as optimal to respect error thresholds, although 15 % may suffice for average error considerations. Furthermore, the sensitivity to the location of acquisition points highlighted how trajectory geometry affects variability (Figs. 13–14). Points located near regions of high curvature, such as the end of the lateral movements or specific protrusion segments, exhibited the highest variability,

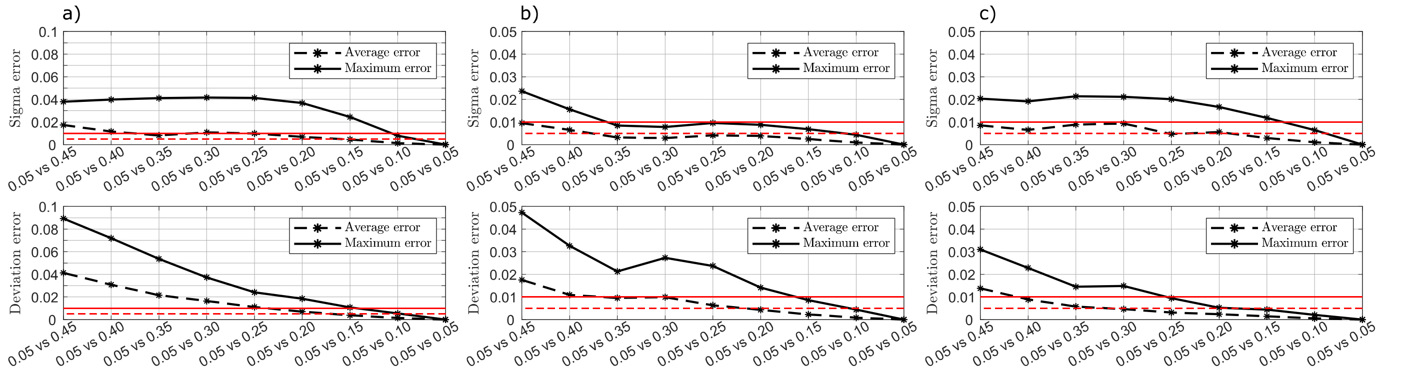

Fig. 12. Sensitivity to the resampling, a) Protrusion, b) Left laterality, c) Right laterality.

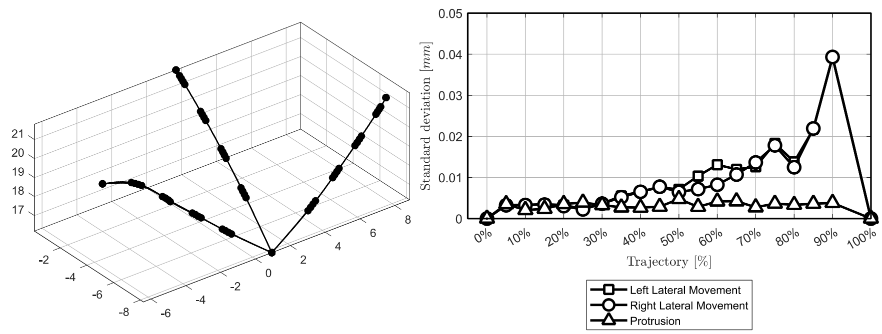

Fig. 13. Sensitivity to the location of the acquisition points for the semi-adjustable articulator.

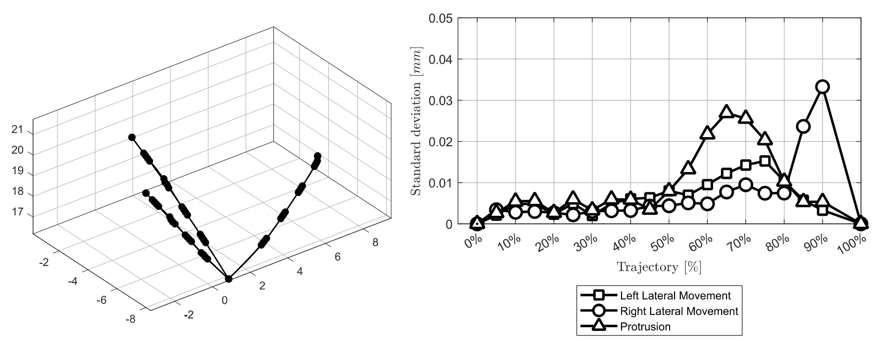

Fig. 14. Sensitivity to the location of the acquisition points for the fully-adjustable articulator.

emphasizing the need for accurate and consistent acquisition point selection. These findings collectively underline the influence of sampling density, reference base positioning, resampling frequency, and trajectory geometry on the overall accuracy and repeatability of the method. They also point to potential areas for improvement in standardizing protocols and minimizing variability in future applications.

4.1. Benefit of the automated procedure

This paper presents a semi-automated MATLAB tool that implements a metrological method to compare trajectories from different articulators, particularly useful for analyzing occlusal pathways in horizontal intermaxillary records. Designed with ease of use for clinicians, the tool runs all mathematical computations in the backend, requiring minimal manual input. Users simply select input files and desired outputs, a significant improvement over the previous manual approach [19] which required expert supervision and took hours to complete. The new tool reduces the comparison time to seconds while nearly eliminating the possibility of manual errors.

The tool also supports modular development, allowing for easy integration of add-ons and modifications. For example, the current version computes variability assuming a bivariate distribution independent of direction. However, Fig. 15 illustrates that this assumption is not ideal, as the maximum variability is along a specific direction relative to the trajectory's reference system. Future updates could incorporate direction-dependent variability, improving the representation of the uncertainty volume in 3D space.

Similarly, enhancements like angular bias correction and more refined computations for trajectory alignment beyond the current translational components can be seamlessly integrated, thanks to the tool's flexible architecture.

In summary, this semi-automated tool significantly improves the

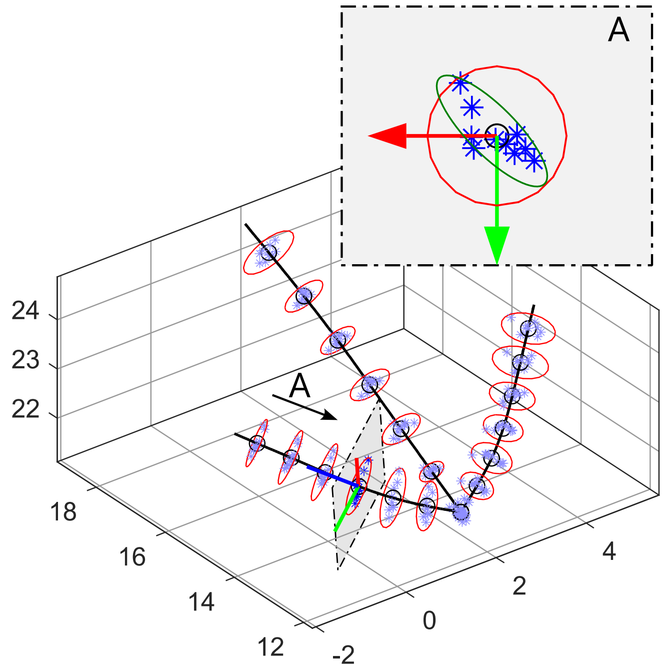

Fig. 15. Dispersion around the average trajectory of the actual trajectories from the analog articulator with a close-up of the dispersion from the third point along the Left Lateral Movement.

efficiency, accuracy, and extensibility of trajectory comparisons, making it a practical and robust solution for clinical and research applications.

4.2. Best settings for the implementation

Various settings influence the performance of the semi-automated procedure presented in this study, including the number of acquisition points along each trajectory and the density of resampled points used to compute differences.

The number of acquisition points significantly impacts the time required for the manual portion of the protocol on the analog articulator. To balance time and accuracy, sensitivity analyses were conducted (subsections 2.5.1 and 3.1). Results showed that increasing the number of acquisition points leads to convergence, as expected. Convergence occurs more quickly for linear movements, such as the protrusion of the semi-adjustable articulator, but is slower for the fully adjustable articulator, which exhibits irregular trajectories with abrupt changes in curvature. This highlights the importance of concentrating acquisition points in trajectory sections with higher curvature changes. For instance, in semi-adjustable articulators, sampling should focus on the trajectory's end, particularly for lateral movements (Fig. 6). This recommendation is generalizable to most traditional semi-adjustable articulators, given their typically consistent trajectory shapes.

Fully adjustable articulators present greater variability due to their non-uniform pathways, with curvature changes occurring unpredictably across patients. For these articulators, no universal sampling strategy can be prescribed. However, comparing results for lateral movements in both articulators shows similar convergence behaviors (Figs. 6 and 7), while significant differences arise for the protrusion. The fully adjustable articulator exhibits slower convergence for protrusion, likely due to its pronounced out-of-plane behavior, as illustrated in Fig. 7. Based on testing, using five acquisition points offers the best tradeoff, yielding a maximum error below 0.1 *mm* and an average error below 0.05 *mm* in most cases. It is worth noting that the clinical case selected for the fully adjustable articulator represented a worst-case scenario.

The density of resampled points also affects accuracy (subsection 3.3). While the underlying computation remains accurate, insufficient resampling can fail to capture sudden changes in deviations or standard deviations. A resampling rate of one point every 10% of the trajectory length ensures a maximum error below 10 μm, and one point every 15% results in an average error below 5 μm, both meeting acceptable thresholds. However, given the negligible impact on computational time, higher resampling densities are recommended. For optimal accuracy, a rate of one point every 5% of the trajectory length is suggested.

4.3. Methodology performance

The performance of the proposed semi-automated procedure was evaluated against the previously manual method (subsection 3.1). Results showed that differences were below 5μm for all resampled points, except for two deviation points ($\sim$ 8μm), and the starting point of the standard deviation ($\sim$ 8μm). These differences in the standard deviation at the starting point were anticipated due to the refined computation implemented in the MATLAB code and, thus, do not compromise the methodology's overall performance.

Theoretically, differences at other points should have been zero, but the observed differences, although minimal, are acceptable as they are significantly smaller than the measured quantities. These variations can be attributed to numerical approximations used by the new tool, which solves the problem numerically rather than analytically as in the manual method. Additionally, differences in the implementation of interpolation splines may lead to slight trajectory variations between points.

As discussed earlier, trajectory reconstruction accuracy is influenced by the curvature of the trajectory and the distribution of sampled points. Optimal performance is achieved when sampled points are denser in regions of high and rapidly changing curvature. This adjustment must be made manually during the protocol. If a digital articulator is used, these areas can be visually identified by the physician for refinement.

Subsection 3.2 highlighted the impact of the sphere locations on deviations in the maxilla-based reference system. Since the spheres are manually positioned, perfect repeatability is not achievable. If the sphere locations vary within a spherical domain of $S\varnothing 20\,mm$, the maximum variability (expressed as standard deviation) is approximately 0.15 *mm* at the end of the trajectory. Its variability increases to nearly 0.30 *mm* for a $S\varnothing 40\,mm$ spherical domain. However, adhering to the recommended guidelines for sphere placement, on a plane parallel to the occlusion plane with V_1 near the last left molar, V_2 in front of the incisive, and V_3 near the last right molar, makes a $S\varnothing 40\,mm$ variability unlikely, while $S\varnothing 20\,mm$ represents a worst-case scenario. For the latter case, the variability remains acceptable and consistent with other contributing factors. To minimize the influence of sphere placement, their positions should be defined precisely according to guidelines and verified by clinicians if performed by an engineer. As noted in subsection 4.5, adopting a kinematic-based reference system could eliminate this variability altogether.

4.4. Clinical outcomes

Nowadays, from a clinical point of view, the digital recording of the intermaxillary relationship offers the possibility to replicate the actual movement of the mandible articulating in the glenoid fossa, without using a mechanical simulator of occlusion (articulator). This opportunity promises to perform a copy-and-paste of the precise movements of the mandible during its functioning, in the digital articulator, that becomes a fully-adjustable articulator. The use of a jaw motion tracking device automatically allows to calculate the CPEs, and visualize them, and also diagnose any potential Temporo-Mandibular Joint (TMJ) disfunction. Moreover, this digital technology enables the automatic checking and detection of the transverse horizontal hinge axis. The present study documented the elaboration of a metrological method to compare two or more different pathways of horizontal intermaxillary movements: this becomes particularly important when it comes to evaluating if the use of a fully-adjustable digital articulator is more accurate than an analogic semi-adjustable one when using a dynamic analog facebow in case of edentulous patients.

Several studies documented the use of the virtual articulator, and considerable improvements in registering intermaxillary records were experienced by different authors [5,21–29]. However, the practical use of the digital facebow and of the fully-adjustable digital articulator needs to be clinically tested on a case series prospective study, in order to investigate the accuracy improvements compared to traditional analogic intermaxillary recording of edentulous patients. For this reason, the methodology presented in this study is essential to compare the two workflows.

4.5. Outlook

Future advancements of the proposed methodology aim to increase accessibility and clinical relevance. One key development involves creating a graphical user interface to make the tool more user-friendly for researchers, thereby eliminating the need for direct interaction with the compiler. This step would pave the way toward a standalone application, reducing dependency on MATLAB software and licensing requirements.

Currently, the reference system is CAD-based and lacks physical, anatomical, or clinical significance. An important enhancement could involve adopting a kinematics-based reference system. By tracing lateral movements, it would be possible to register the center of pure rotation and the helicoidal movement axis of the condyles in the glenoid fossa. Using the condyle locations at the start of lateral movements, a sagittal plane could be defined as the symmetry plane between these points. This plane, together with the centroid of these points, could establish a Cartesian reference system.

In addition, future improvements should focus on developing more advanced metrics for trajectory comparisons. Currently, deviations are calculated as linear distances orthogonal to the shortest trajectory and projected along the main reference axes for directional deviations. However, rotational information—already available in the local reference system—is not yet utilized. Incorporating rotations and other complex metrics into the analysis could significantly enhance accuracy. The code's existing structure is flexible enough to accommodate these refinements, including improvements to the computation of initial bias and trajectory deviations.

To increase the clinical applicability of digital workflows, future studies should evaluate how the tool performs in different groups of patients, considering variables such as age, oral health, and mandibular disorders (e.g., TMJ dysfunction). Validation in younger patients with higher functional demands and older patients with compromised oral health would further demonstrate the tool's versatility. The proposed methodology allows to assess the accuracy of digital articulators in replicating the actual CPEs and detect limitations in current algorithms and guide future improvements.

5. Conclusion

This research has developed and validated a semi-automated MATLAB tool for comparing trajectories from different types of articulators used in dentistry. The real challenge of modern dental technology is represented by the transition from traditional analog procedures to digital workflows in complete denture fabrication.

The automated comparison methodology presented in this study addresses several critical aspects:

Accuracy and Efficiency: Automating the comparison process allows to significantly reduce manual errors and processing time and thus improve the MATLAB tool, which manages to perform detailed analysis of trajectory differences between gothic arch pathways.

Validation and Sensitivity Analysis: Validation using previous data and sensitivity analyses ensures the robustness of the MATLAB tool in different scenarios. Extensive sensitivity tests highlighted optimal parameters such as acquisition point density and resampling frequency, crucial for minimizing reconstruction errors and ensuring clinical reliability.

Future developments could enhance the tool's usability with a graphical interface and expand its capabilities with anatomically-based reference systems and advanced metrics for rotational analysis. These enhancements aim to further refine clinical practices and contribute to ongoing advancements in digital dentistry.

Overall, the semi-automated MATLAB tool represents a pivotal advancement in dental technology, facilitating more accurate and efficient comparisons between digital and analog articulators. This methodology not only allows the comparison of different solutions, highlighting strengths and limitations of various clinical protocols, but also sets a foundation for future innovations in dental occlusion analysis and diagnosis, facilitating the subsequent treatment planning.

CRediT authorship contribution statement

Mattia Maltauro: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elisa Vargiu:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Federico Tozzi:** Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Leonardo Ciocca:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Roberto Meneghello:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

Ethics statement

All data used in this study is either synthetic or derived from patients who followed a predetermined clinical workflow, authorized by the Ethics Committee under protocol Nr. 646/2021/OSS/AUSLBO.

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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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