Metrological Protocol for Comparison of digital and analogic Articulators for complete Dentures

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Abstract. This paper proposes a methodology to compare the trajectories from different articulators - both physical and digital - during lateral and protusive movements. In the case of digital articulators, the articulated models are digitally moved and exported in position; in the case of mechanical articulators, the models are locked into position and 3D scanned. The digital models in position, both digital and scanned, are aligned to a common reference system and a maxilla-based reference system is tracked. The trajectories are defined as interpolating splines through the maxilla-based reference system origins. A Gerber mechanical articulator and an "Artex CR adjustable" virtual articulator were compared. The repeatability of the mechanical trajectory is found to be less than 184 microns. The resting position of the two articulators is found significantly different meaning that a bias is introduced by the operator in the analogic protocol. The trajectories have significantly different shapes as expected coming from two different articulator models. The proposed methodology proved to be a valid means to compare different articulators.

Keywords: Complete Dentures, Articulators, Trajectory Reconstruction, 3D Scanners.

1 Introduction

During the last years, CAD-CAM procedures have been introduced in many fields of dentistry, in particular, digital workflows are now used to produce also complete dentures with remarkable advantages: increased biomechanical properties, reduced working times and costs, and fewer appointments at the office [1–4].

Among other digital design tools, digital articulators were introduced aiming to provide an alternative to the current golden standard analogic (mechanical) articulators [5]. A widely used mechanical articulator for the design of complete dentures is the Gerber semi-adjustable articulator, for which a set of specific intermaxillary occlusal registrations, measured from the patient, can be set to approximate a correct occlusion [6].

The use of digital articulators is still not completely independent, and some analogic clinical steps are necessary in digital workflows and cannot be substituted by digital steps so far, for example, the initial impressions, the gothic arch tracing, or the use of a facebow [7]. Nonetheless, the digital protocol allows for fewer steps and, therefore, should concatenate fewer uncertainty sources leading to a better design. Moreover, nowadays, the use of the digital facebow is a promising option for the evolution of such measurements.

There are still not many insights regarding digital articulators in the literature. Some studies looked at the influence of different parameters on the behaviour of digital articulators, such as the vertical dimension [8], or the inclination of the sagittal condylar path [9]. Another study compare the maximum intercuspal between classically articulated casts and digitally articulated ones [10], and the effect of the different settings for the digital articulator was tested on the occlusal morphology of restoration done with CAD/CAM technologies [11]. These results, with some limited disagreements, confirm the virtual articulator as a reliable tool to design denture bases.

However, these studies consider cases of patients with natural teeth; with edentulous cases, it is not trivial to define reliable landmarks on which to base the comparison. Moreover, to the best of our knowledge, there are no studies that specifically investigated if the simulation of occlusion of the digital articulator is comparable to the one from the semi-individual mechanical articulators, specifically for edentulous cases.

To fill this gap, this study aims to provide a methodology to compare the different simulations of occlusion given by different articulators for completely edentulous cases. The comparison is based on the actual trajectory of the casted or digital model during three movements: left and right lateral, and protusive movement. The procedure can work both digital vs analogic, digital vs digital or analogic vs analogic articulators. In this contribution, the comparison between an analogic and a digital articulator is provided.

2 Materials and methods

The overall workflow used for the study can be seen in **Fig. 1**. Starting from the same impression and intermaxillary occlusal registrations, obtained from a simulated completely edentulous patient, two parallel clinical workflows are followed, the digital one obtaining the digitally articulated STL models, and the analogic one obtaining the plaster model mounted and articulated in the Gerber articulator.

For both cases, the trajectory of the maxilla is recorded by mapping a reference system built on the maxilla from a second common reference system built on the mandible. The trajectories are then compared to assess whether the twos are the same or are significantly different.

Three different movements are analyzed: left and right lateral and protrusive movements.

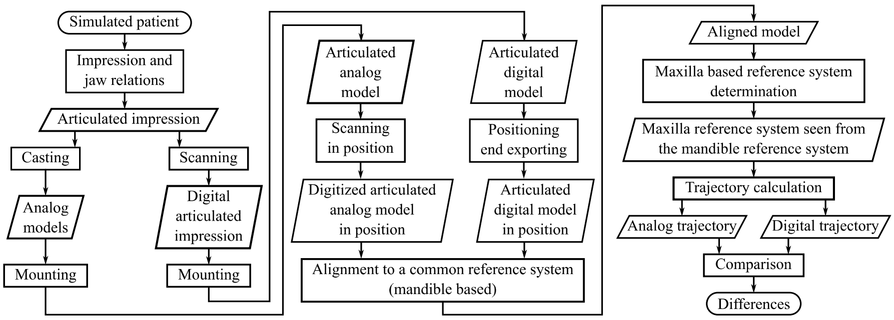

Fig. 1. Overall workflow of the study.

2.1 Clinical protocol

A completely edentulous patient is simulated using two edentulous plaster models already mounted in a mechanical articulator, considered as the patient's oral cavity. The standard protocol to obtain the final impressions and the intermaxillary occlusal registrations for edentulous patients is followed. The intermaxillary occlusal registrations are set as the clinical average value for all settings, these values are used for both protocols. The final results are the articulated impressions, which were scanned using a E3 scanner obtaining a digital articulated impression used in the digital protocol, and then were cast with type IV plaster obtaining the physical model used in the Gerber articulator. The digital articulator "Artex CR Adjustable" in the Exocad software is used for the digital protocol. The digitally articulated impressions are imported. The software creates the two digital models already in position. The models, together with the digitally articulated impressions are aligned using the information contained in the intermaxillary occlusal registration following the standard clinical protocol. The plaster models are mounted into the Gerber articulator following the standard clinical procedure that involves the separation between the upper and lower impression and their recombination once the mandible model is fixed in position with the use of the face bow. Further details about the clinical protocol and the parameters available in analog and digital articulators can be found in [12].

2.2 Movement mapping

To map the movement described by the maxilla in the articulator three incremental points were sampled per each movement plus the common resting position. Thus, each movement is characterized by a total of four points.

The digital articulator has no physical end to each movement: the operator can choose whatever displacement value for each movement and the maxilla is moved into position. Once in position, the two digital models can be exported into an STL file. The three incremental points were chosen to be 3mm apart from one another.

The Gerber articulator has a physical endpoint for each movement that is chosen as the last point to be sampled; two intermediate points were then sampled. Once locked in position the articulator was scanned as described in the following.

The scanning procedure is needed since a physical mechanical articulator is considered, **Fig. 2**. Since the two casted models are close to each other, it is impossible to acquire the actual oral cavity.

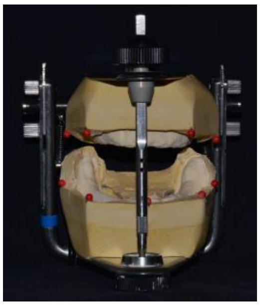

Fig. 2. Gerber articulator ready to be scanned.

To address this issue, a strategy commonly used with oral scanners is used: the two models are individually scanned, and then the articulated models are scanned obtaining mainly the external surface which is used to correctly align the individual scans. Five spherical landmarks were added to each model to increase the alignment accuracy.

To test the reproducibility of the workflow applied to the physical articulator, each position was scanned ten times, thus obtaining ten trajectories.

To compare the two articulators the same reference system was established on the mandibular model and the position of the articulated maxilla model was tracked through the position of three fixed points reconstructing the rigid body trajectory of the simulated occlusion. The three points define a cartesian reference system.

Starting from the digital models, two simplified bases were defined and three spherical markers were added, **Fig. 3**. The CAD reference system of the lower base was used as a common reference system for the comparison, therefore the scanned model or the exported model were first aligned to this base in GOM Inspect obtaining the aligned model that was exported.

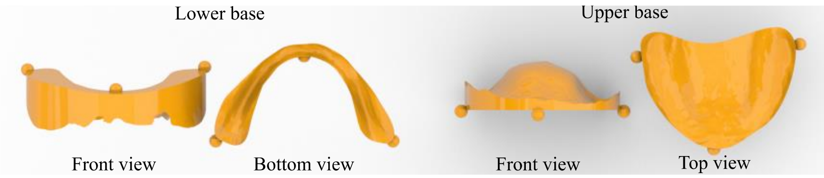

Fig. 3. Simplified bases with markers.

At this point, each newly exported model shares the same origin and orientation. This file is imported in GOM Inspect and the upper base is aligned to the mucosa. The locations of the three spheres are recorded and elaborated in Excel to define the maxilla-based reference system. The origin is defined as the centroid of the spheres, the x-y plane as the plane through the spheres, and the x-axis point towards the central sphere and z-axis pointing upwards.

This procedure was performed per each sampled point in the analogic and digital protocol. The trajectories are calculated in a mathematical graphical tool: GeoGebra. This tool was chosen since it allows real-time testing and modification of the procedure. The details of the maxilla-based reference systems were imported into the 3D space and the trajectories are defined as cubic interpolating splines through the origins. For the digital articulator, only one repetition was done since the exporting is by definition perfectly repeatable. At the same time, the scanning procedure of the mechanical articulator introduces variability due to the 3D Scan itself and due to the alignment. For this reason, the Gerber articulator was mapped ten times to determine the repeatability.

Among the ten trajectories derived from the mechanical articulator, the average trajectory had to be defined to define the repeatability. The intermediate points that were sampled cannot be considered repeatable because of the uncertainty in the looking of the articulator, but the length of the trajectory is theoretically the same. Therefore, congruent points along the trajectories were defined as points at the same percentual distance from the resting position, and points at 0%, 30%, 60%, 90%, and 100% of the trajectory length were sampled. The average trajectory was defined by averaging the position of these points. The dispersion of the mechanical articulator is defined by the distance of each trajectory to the average one, the distance is defined, point by point, in the plane normal to the average trajectories, **Fig. 4**.

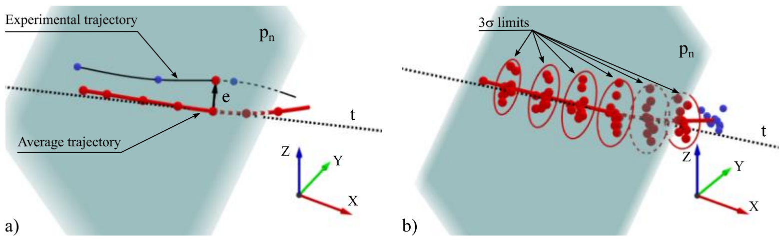

Fig. 4. Analog trajectories error definition (a) and dispersion (b).

The dispersion was sampled at steps of 15% of the average trajectory length excluding the resting position. Assuming a bivariate normal distribution with the same dispersion in each direction for the sampled trajectories, and therefore a Rayleigh distribution for the distances (radial component), the standard deviation of the bivariate distribution is defined by:

$$\sigma = \sqrt{\frac{2}{\pi}}\,\frac{\sum_{i=1}^{n} d_i}{n}$$

The dispersion of the resting position is divided into two contributions. For the lateral movement, the aforementioned formula is applied to the projection of the resting position point into the sagittal plane (lateral plane, x-z); for the protusive movement, the projection into the frontal plane (y-z) is considered instead.

2.3 Movement comparison

The differences between the digital and analogic trajectories are defined by the distance between the average analogic trajectory - including its dispersion - and the digital one. Since the analogic trajectory ended up being shorter than the digital one, it was used as the baseline.

First, the baseline error, define as the distance between the resting positions is calculated and represents the initial bias between the two trajectories.

The digital trajectory is translated of the quantity defined as the baseline error to check for differences excluding the initial bias.

The distance between the two trajectories is calculated at steps of 15% of the analogic trajectory as the distance in the plane normal to the baseline trajectory.

3 Results and discussion

Regarding the mechanical articulator, the ten trajectories that were sampled and the average trajectory, with its associated standard deviation, can be seen in **Fig. 5**.a). The repeatability test, applied to the mechanical articulator, shows a maximum standard deviation of 184 microns for the left lateral movement, see **Fig. 5**.b).

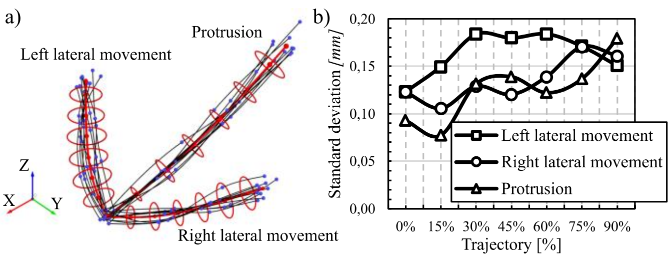

Fig. 5. Result of the ten trajectories sampled with the Gerber articulator (black lines), the average trajectories (red lines), and the standard deviation along the three movements.

The reparability of the rest position is 123 microns in the sagittal plane and 93 microns in the frontal plane. On average the repeatability decrease (higher standard deviation) the further from the resting position; indeed the locking in position adds a level of uncertainty to the procedure.

The comparison between the two articulators' trajectories can be seen in **Fig. 6**.a). At first glance, the difference in length between the two trajectories can be noted. Nonetheless, this does not imply an actual difference because the shorter trajectory can still represent the first part of the longest one.

The first real difference that can be recorded is the initial bias between the two articulators, the resting positions are 1,373 mm apart. Considering the dispersion of the resting position for the mechanical articulator this difference is considered significant. This means the bias is not due to the measuring uncertainty but is based on an actual difference. The reason behind this deviation can be traced back to the analogic clinical protocol when the articulated impressions need to be separated for the alignment in the Gerber articulator. Maxillary and mandibular casts are then fixed again thanks to the gothic arch plates and the bite registration during the clinical protocol. This step may introduce a shift between the two impressions therefore it is the main candidate to explain the bias.

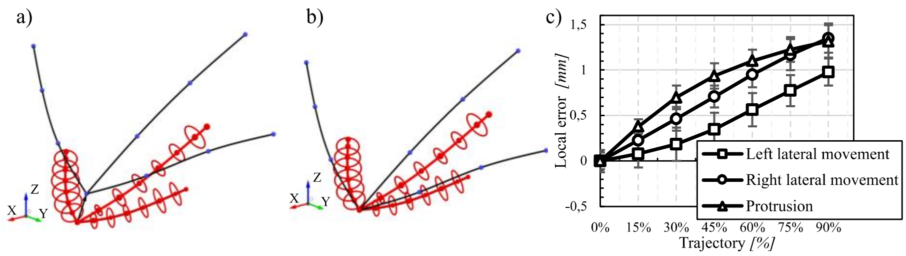

Fig. 6. Comparison between the analogic and digital trajectories.

To evaluate the actual differences between the two trajectories, excluding the bias, the digital trajectories are rigidly translated to share the same resting position with analogic ones, **Fig. 6**.b). Comparing the two trajectories, taking into consideration the standard deviation associated with the analogic trajectory, it can be said that the trajectories are significantly different. The local error along the trajectories can be seen in **Fig. 6**.c).

The local error increase as the distance from the resting position increase meaning that the two trajectories diverge. Looking at **Fig. 6**.b) it can be seen that this divergence is not due to an alignment issue but it come from the trajectories having different shapes; for instance, the mechanical articulator has a shallow angle between the two lateral movement when compared to the digital one. The maximum recorded difference is 1.350 mm for the right lateral movement.

It must be noted that this study does not want to conclude that any of the tested articulators is better than the other. Differences were expected since the type of articulators is different. The same protocol may be used to check whether a digital articulator simulating a specific mechanical model and the actual physical counterpart coincide.

4 Conclusions

This paper aims to propose a methodology to compare the dynamic movements of different articulators used in dentistry. The methodology is designed having in mind to give the possibility to compare mechanical vs mechanical, mechanical vs digital, and digital vs digital articulators. To prove its usability the methodology was tested by comparing a mechanical articulator (Gerber) to a digital one (Artex CR Adjustable" in the Exocad). Therefore differences were expected.

As expected significant differences were found proving the overall methodology to be a valid means to compare different articulators. A far more interesting comparison for future works will be the study of corresponding digital and mechanical articulators to test whether the digital articulator can provide a precise replica of the, so far, standard clinical procedure based on mechanical articulators.

The late development of digital face bows capable of tracking the actual 3D jaw movement of the patient without any approximation (needed using an articulator both digital or mechanical based on a set of values) opens the possibility to compare the actual patient movements to the one approximated by the articulators.

Further studies will also be necessary to automate the procedure and test a clinically significant population to provide clinicians with useful data to improve dentures design.

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