Doctoral Dissertation

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Digital registration of intermaxillary relationship through a novel digital system for robotic simulation of human motion

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Summary

Introduction: Fully adjustable articulators and pantographs record and reproduce individual mandibular movements. Although these instruments are accurate, they are operator-dependent and time-consuming. Pantographic recording is affected by inter and intra operator variability in the individuation of clinical reference points and afterwards in reading pantographic recording themselves. Finally only border movements can be reproduced.

Methods. Bionic Jaw Motion system is based on two components: a jaw movement analyzer and a robotic device that accurately reproduces recorded movements. The jaw movement analyzer uses an optoelectronic motion system technology made of a high frequency filming camera that acquires 140frames per second and a custom designed software that recognizes and determines the relative distance at each point in time of markers with known geometries connected to each jaw. Circumferential modified retainers connect markers and do not cover any occlusal surfaces neither obstruct occlusion. The recording process takes 5 to 10 seconds. Mandibular movement performance requires six degrees of freedom of movement, 3 rotations and 3 translations. Other robots are based on the so-called delta mechanics that use several parallel effectors to perform desired movements in order to decompose a complex trajectory into multiple more simple linear movements. However, each parallel effector introduces mechanical inter-component tolerances and mathematical transformations that are required to transform a recorded movement into the combination of movements to be performed by each effector. Bionic Jaw Motion Robot works differently, owing to three motors that perform translational movements and three other motors that perform rotations as a gyroscope. This configuration requires less mechanical components thus reducing mechanical tolerances and production costs. Both the jaw movement analyzer and the robot quantify the movement of the mandible as a rigid body with six degrees of freedom. This represents an additional advantage as no

mathematical transformation is needed for the robot to reproduce recorded movements.

Results. Based on the described procedure, Bionic Jaw Motion provide accurate recording and reproduction of maxillo-mandibular relation in static and dynamic conditions.

Conclusion. This robotic system represents an important advancement compared to available analogical and digital alternatives both in clinical and research contexts for cost reduction, precision and time saving opportunities.

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Contents

Chapter 1

1. Introduction

Dental treatments such as full-mouth reconstruction and occlusal correction by selective grinding can be very extensive and complicated procedures. These complex treatments require accuracy and precision in the methods involved in the diagnosis and treatment of the dental patient. In these types of cases, it is best practice for the clinician to determine the proper equipment and measuring methods to collect the necessary data and apply the principles of occlusion to achieve accurate results.

1.1. Articulators.

An articulator in a mechanical device that simulates the movements of the mandible. The principle employed in the use of articulators is the mechanical replication of the paths of movement of the posterior determinants, the temporomandibular joints. The instrument is then used in the fabrication of dental restorations and oral rehabilitation in all field of dentistry that are in harmony with those movements. The outer limits of all excursive movements made by the mandible are referred to as border movements. All functional movements of the mandible are confined to the three-dimensional envelope of movement contained within these borders[1]. The border movements are of significance in discussing articulation because they are limited by ligaments. As such, they are highly repeatable and useful in setting the various adjustments on the mechanical fossae of an articulator. The more nearly the articulator duplicates the border movements, the more nearly it will simulate the posterior determinants of occlusion. As a result, the harmony between the restoration fabricated and the posterior determinants, ie, the temporomandibular joints, will be improved.

The need of perfecting the registration and transfer of jaw relations starts with the development of complete removable dentures. The first system that allowed to evaluate stone models statically at a given vertical dimension of occlusion (VDO) was described by Gariot in 1805.[2,3] Since then, a constant progression led to the development of modern dental articulators and facebows. Daniel T Evens (1840) introduced protrusive and lateral movements, while Bonwill (1858), a mathematician, built the first mean value articulator. William Earnest Walker (1856), developed the "clinometer", the first example of kinematic facebow to reproduce condylar inclination, and the first semi adjustable articulator. Gysi-Muller (1896-1899) constructed an articulator mimicking the form of the condyle and glenoid fossa.[4,5] During the first half of the XX century articulators had a rapid development (Table 1) reproducing more and more accurately the individual border movements.

Huberty articulator	1901	**Hanau** model H110 articulator	1926
Kerr articlator	1902	**Philips** student articulator (Model C)	1926
Christensen's articulator	1905	**Hanau** model H110 modified articulator	1927
New century **George Snow**	1906-1907	**House** articulator	1927
The Acme articulator	1906	The **Stansberry** tripod instrument	1929
Gysi adaptable articulator	1910	**Gysi Truebyte** articulator	1930
Luce articulator	1911	**Terrell**'s precision co-ordinator	1930
Eltner articulator	1912	**Hanau** crown and bridge articulator	1934
Gysi simplex articulator	1914	The **Phillips** occlusoscope	1938
Alligator-Rubert Hall	1915	The **McCollum** gnathoscope	1939
Hall's anatomic articulator	1915	**Stephan** articulator modified	1940
Gysi Dreipunkt articulator	1917	**Stephan** articulator model P	1940
Monson-maxillomandibular instrument	1918	The **Fournet** articulator	1940
Hagman balancer	1920	**Dentatus** articulator ARH model	1944
Stephan articulator	1921	**Johnson-Oglesby** articulator	1950
Hanau articulator	1921	**Moyer** articulator	1950
Hanau model M **kinoscope**	1923	**Coble** articulator	1950
The **Homer** relater	1923	**Bergstorm** articulator	1950
Wadsworth articulator	1924	**The Galetti articulator**	1950-1960

Table1. Table summarizing the main examples of articulators and their evolution through time.

During the Sixties the first fully adjustable articulators and pantograph facebows appeared, among which the most used and known systems were Hanau 130-21,[6,7] Stuart's articulator[8] that was called the gnathological computer, and Denar D5A.[4,9] They presented components that could be adjusted to reproduce individual condylar movements as a main innovation compared to semi adjustable that presented standardized flat tracks and planes.[10] Unfortunately, fully adjustable articulators require more complex records (i.e. pantographic and stereographic tracings) and therefore need more time to be programmed.[11] Notwithstanding their precision, these devices are hindered by several limitations. The first possible source of error is the ability of the clinician to measure articulator settings from the pantographic tracings.[12] Other limits are linked to the difficulty of the mechanical components to reproduce movements generated by complex three dimensional structures like the ones of the condyle and the glenoid fossa.[13,14] Other issues possibly preventing the optimal reproduction of border movements could be:

a) the identification of the correct location of the reference plane angle,[15]

b) the assumption that at least in the first millimeters the mandible makes a pure rotation around its hinge axis,[16]

c) the interoperator and intraoperator variability of measurements.[12]

A substantial improvement regarding intra and inter operator agreement of recorded values was achieved with the introduction of the digital pantograph Denar Cadiax Compact (Teledyne Waterpik)[17] and Arcus Digma (KaVo America)[18] that is a jaw motion analyzer that uses multiple ultrasonic to record mandibular movements. Besides, movements that can be recorded and reproduced are stereotyped and they do not reflect dynamicity of functional movements.

1.2. Robotic systems for the registration of the intermaxillary relationship

Since the 1990s there has been growing interest to overcome the aforementioned limitations with jaw robots.[19,20]

One of the most common definitions of a robot is characterized *"as a machine, especially programmable by a computer, capable of automatically performing a complex series of actions"*.[21]

With the technological progress that characterizes our era, robots have begun to spread in various sectors, from manufacturing companies to medicine. In the latter field in particular, the best example is represented by the " Da Vinci " robot[22]. This robot is used in complex surgeries, often to reach areas that are difficult to access. This robot act as a so called ''master-slave'' system, in which the robot is controlled by a remote surgeon and it is able to exactly reproduce the commands it receives. It has been estimated that 7 million surgeries were performed with the help of the Da Vinci robot in 2019. [23, 24]

Although robots are regularly used in medicine, the development and diffusion of robots in dentistry is still in its infancy. One of the most well-known robots is the SureSmile orthodontic system, which was introduced in 2001. [25] Since then, various robots have been proposed in different areas of dentistry, such as prosthodontics[26] and implantology[27]. However, their practical use is rather limited.

To my knowledge, there are only two systems in dental literature that tried to register and reproduce individual mandibular movement for clinical purposes but are limited to digital simulation of individual mandibular movements within a virtual environment.[28] The first one uses a CAD software called Adams to analyze data about mandible position that is obtained using an optoelectronic motion capturing system (370 frames per second) that records the light reflected from six point of reference whose position in relation to the mandible is known. The proposed method follows a geometrical study of the subject's mandibular and maxillary teeth. It records chewing paths using an optoelectronic motion-tracking technology.[29] These devices were originally developed to record tongue and mouth movements for speech research.[29,30] The second one uses a facial scanner target tracking. Eight targets are positioned on both maxillary and mandibular incisors to record mandibular movements. Mandibular movements are reconstructed after having eliminated head parasite movements that are the ones recorded from the maxilla. A computer software (Exocad, GmbH) allows to evaluate occlusal contacts.

Chapter 2

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2. Aim of the study:

The objective of my PhD research was to devise a robotic tool that would streamline cases to be more time-efficient, accurate, and reliable in the registration of the intermaxillary relationship.

The study was divided into three main phases with the following goals:

1) Collaborate with engineering for initial testing and validation to help develop a new robotic system for digitally recording the intermaxillary relationship.

2) Record the intermaxillary relationship on a large sample of patients to be able to quantify the precision.

3) Test the robot in a real prosthodontics rehabilitation condition to manufacture the prosthesis and adjusting the occlusal contact points on the robot before delivering it to the patient.

Due to the Covid-19 pandemic that became widespread in March 2020, it was only possible to clinically test the procedure on a limited number of patients and consequently, only phase 1 was able to be completed.

2.1. Methods Presentation

The presented system is called Bionic Jaw Motion (BJM Bionic Technology, Vercelli, Italy) and it is composed of a Jaw movement analyzer and a robotic articulator.

The acquisition system is similar to the aforementioned ones. It uses a technology, based on high frames-per-second filming, that through an artificial vision system is capable to achieve higher precision because it is capable of computing a high amount of information. In particular, it can dimension and quantify the spatial position of known geometries applied to markers. The recording process of each acquisition last from 5 to 10 seconds depending on clinical requirements. More than one acquisition can be performed but is not always required. Square markers with peculiar geometries on them are placed at a known position (Fig.1,2) from each other and from maxillary and mandibular teeth, to which they are connected using a designed jig through respectively a maxillary and a mandibular circumferential retainer that do not interfere with occlusion and function (Fig.3).

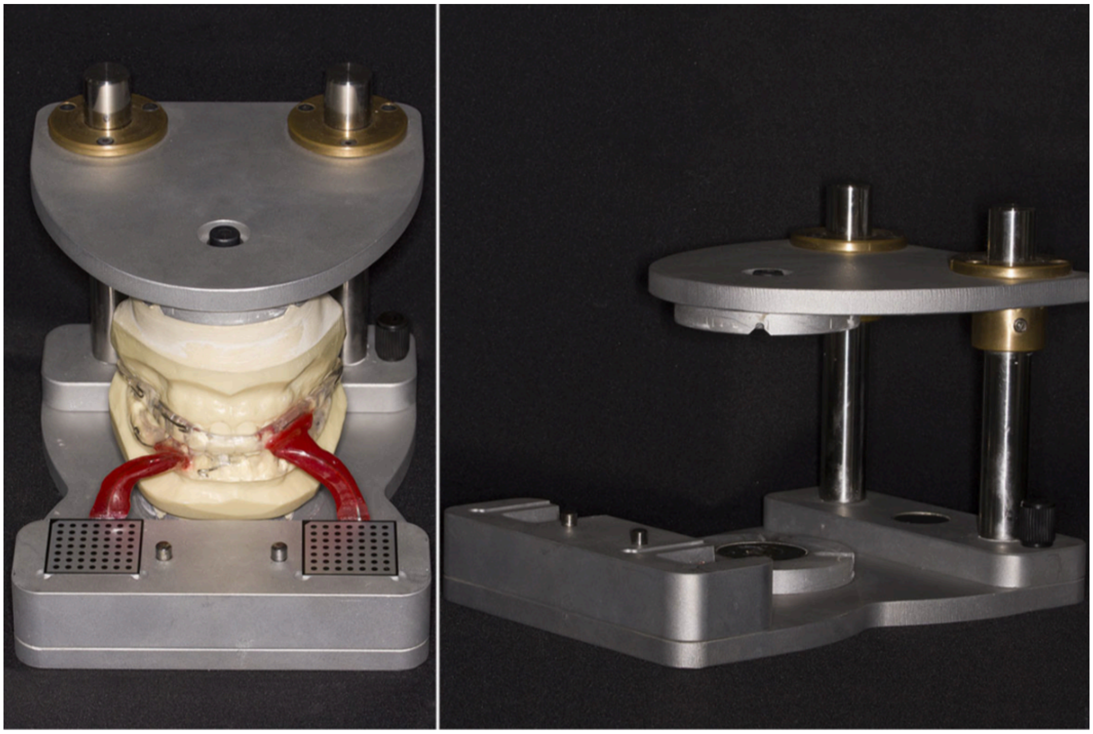

Fig.1. Installation aid. The Installation aid is a device meant to position the markers in a known position in relation to each jaw: on the right side the installation aid without the casts, on the left side the casts mounted on the installation aid with maxillary and mandibular retainers

Fig.2. Maxillary and mandibular retainers.

Fig. 3 Intraoral check of the retainers. It is necessary to check there are no occlusal contacts on the retainers during function. The picture depicts the contact points of the patient in the 4th quadrant. No contact points should be present on the splint surface

They need to have occlusal clearance. This design is suitable in absence of severe deep-bite. The resin vestibular to the 5th sextant and lingual to the 2nd sextant is removed in patients with severe deep-bite to allow maximum intercuspation and eccentric movements with no interference

The artificial vision system (Fig 4) is capable of recognizing the geometric landmarks of the markers was developed by the automotive industry to plot the planarity of car components and adapted for dental purposes.

Fig. 4 Bionic Jaw Motion Movement Analyzer. The jaw movement analyzer is composed of a high-speed recording camera and a software running on a computer. The software recognizes the known geometries of the markers and their optical deformation during movement registration thus reconstructing mandibular movement. It is mandatory to check whether the artificial vision software is able to locate reciprocal position of the markers during all opening phases before performing the actual recording.

Despite modern high-speed cameras can reach 2000 fps, the acquisition system is set to 140 fps to quantify movement. This choice was made after empirical laboratory data and previously published data on mandibular velocity.[31] Highest mandibular velocity in opening/closing phases ranges between 10-13cm/s approximately.[31,32] The system's dimensions have been designed to guarantee precision with an accuracy to less than a tenth of a millimeter. The markers known position allows it to reach high precision during movement registration. A software elaborates data from markers position and digitalizes movements, that can be visualized as kinesiographic tracings and as three-dimensional relationship between virtualized models during recorded movements. Current available instrumentation has limitations regarding its capability of reproducing complex trajectories determined by irregular geometries of the condyles and glenoid fossae and coherence of reference system between the patient and the mechanical instrument.[33] To the authors' knowledge, BJM is the first system to have an integrated software designed to reproduce the recorded functional movements on a robotic jaw simulator (Fig. 5).

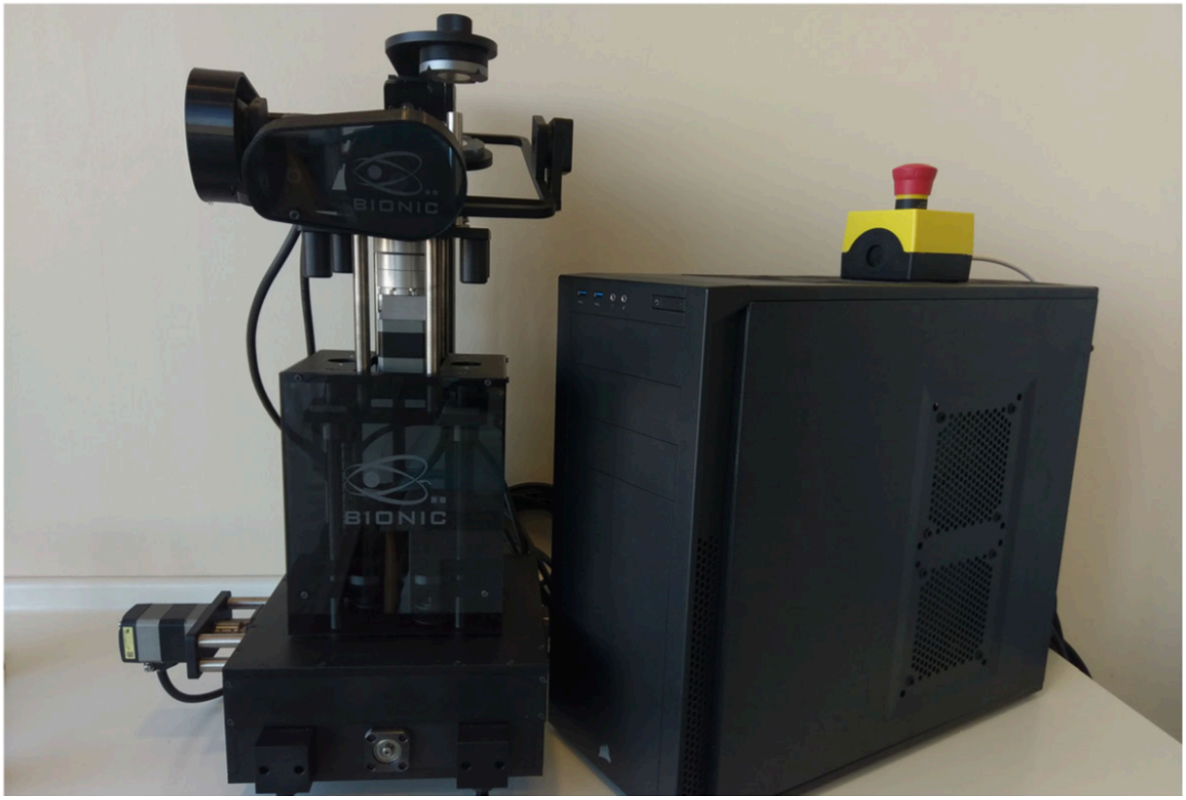

Fig. 5. Bionic Jaw Motion robot. The robot with its computer unit that controls the motors and makes the robot move.

In order to reproduce anatomical movements accurately, robots ought to have 6 degrees of freedom of movement, 3 translations and 3 rotations, with high movement accuracy.[34] The first prototypes of robots for clinical purposes were built using delta mechanics also called parallel robots.[35] Among their favorable characteristics one may enumerate the limited volume and fast operation modalities. On the other hand, their mechanics are complex. The numerous connections between each component demand a production system enabling particularly low mechanical tolerances, which is very expensive. To overcome delta mechanics limitations, BJM uses a different mechanical configuration. Complex effectuators are substituted by a simplified system comprised of three motors that work in translation and three motors that work in rotation as a gyroscope converging on the rotor that is the lower model holder. All rotations and all translations converge on the lower model holder thus conferring to it six degrees of freedom of movement.[36] Since even the acquisition system quantifies movement homogeneously through relative position of maxillary and mandibular markers, no mathematical transformation is needed to move the robot. This does not happen in robots designed with delta mechanics because mathematical transformations are required to break down movement in every effector axis.[35] These characteristics allow to obtain an excellent precision and to contain prices for robot production.

2.2. Demonstration case.

The volunteer whose reports were included in this study signed a written informed consent to undergo the examination and to eventually make his examination available for research purposes.

A 53 year old male patient (Fig.6), voluntarily underwent the recording of his jaw movements with the Bionic Jaw Motion.

Fig.6. Close up images of patient's lower and upper arches.

The phases for the jaw movement recordings are as follows:

- Silicon impressions of the arches were acquired, and resin models were created.

- Mandibular and maxillary retainers were created, and square markers were fixed with designed jig on the retainers in the second premolar area. The installation aid was used to place the markers in a known position (Fig.7).

Fig.7. Placement of the markers guided by the installation aid.

- Retainers with the square markers were allocated to the arches with particular attention to ensure that no contact points were presented on the splint surface. Wherever there was a contact point on the splint area, the area was modified accordingly (Fig.8).

Fig.8. Intraoral occlusal check of the lower retainer.

- Resin models were set in the robot cast holder (Fig.9).

Fig. 9. Models set in the cast holders. Close up image of the upper and lower resin models in the robot cast holders

- Patient was asked to sit in a natural position, with his head facing straight and directed at a fixed point.

- Bionic Jaw Motion Movement Analyzer was placed in position in front and above the patient head and connected to the computer.

- The artificial vision software was checked before performing the actual recording to confirm its ability to locate reciprocal position of the markers during all movement phases.

- The recording was performed. During this phase the patient was asked to perform jaw open-close movements, right/left laterotrusion, and protrusive/retrusive movements. (Fig.10)

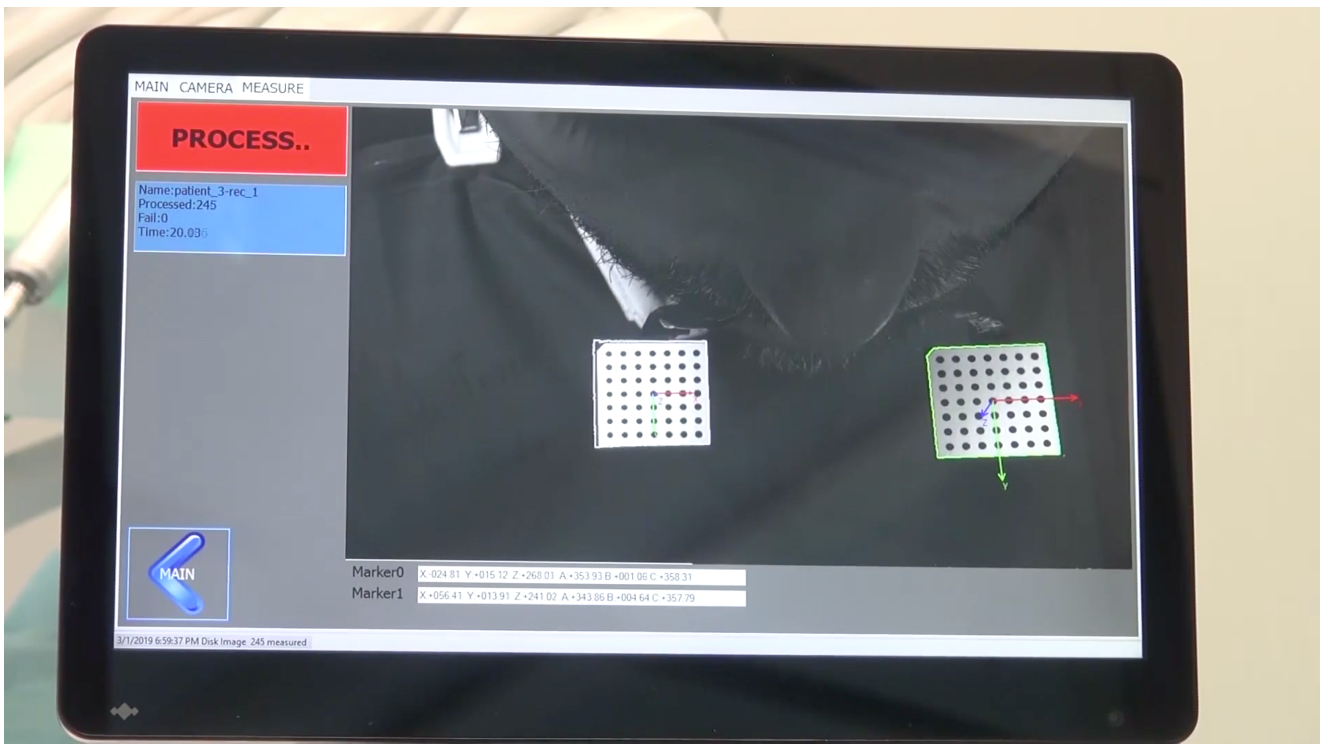

Fig.10. Recording phase during patient's movements.

- The software immediately analyzed the data that was recorded and subsequently created the three dimensional relationship of the jaws. By clicking ''start simulation'' it was already possible to observe all the movements recorded (Fig.11). It was also possible to observe the kinesiographic tracings (Fig.12).

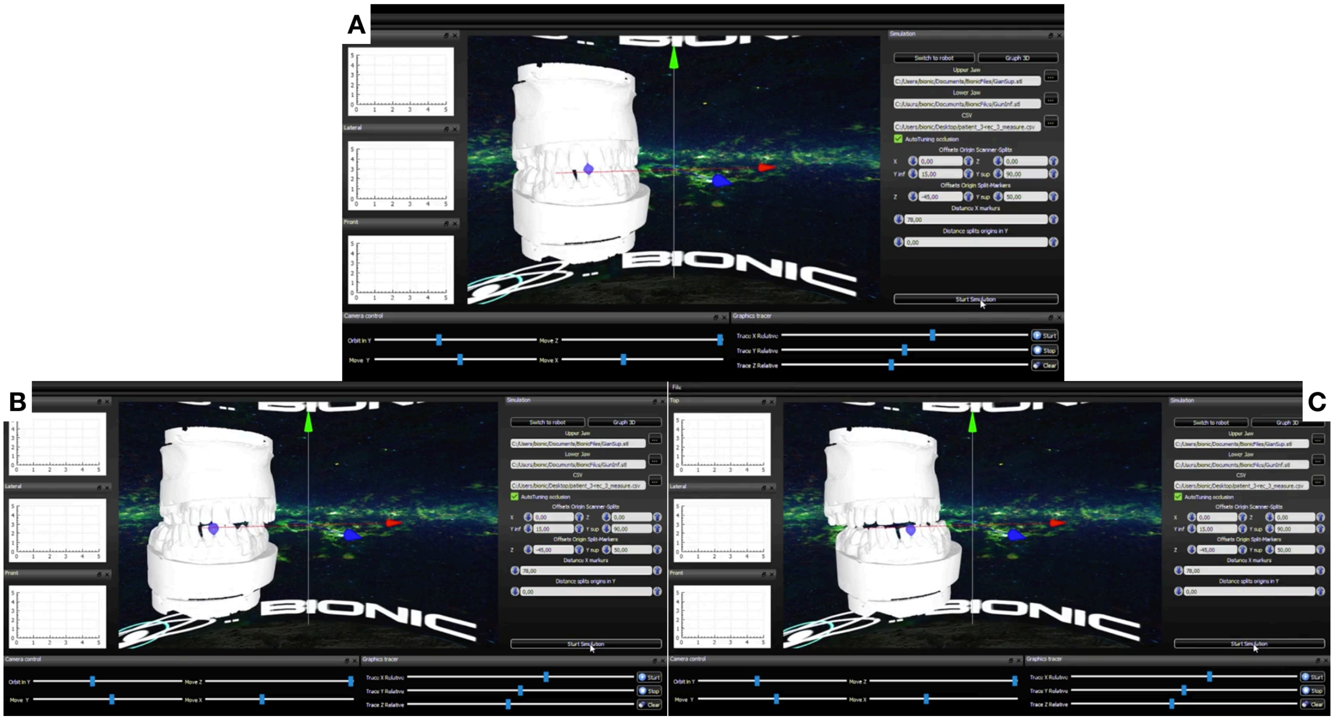

Fig.11. Virtual three dimensional relationship created by the software. **A.** Intercuspidal relation. **B.** Right laterotrusion. **C.** Left laterotrusion.

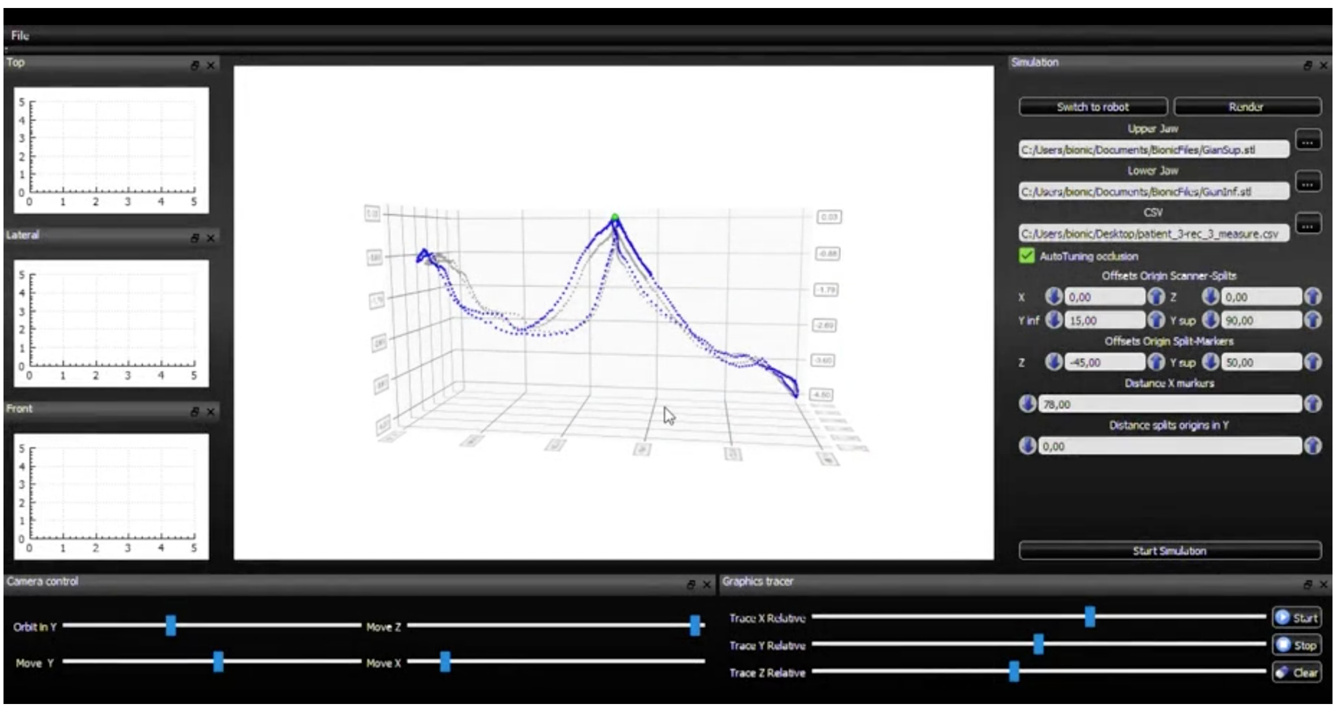

Fig.12. Kinesiographic tracing.

- The computer was then linked to the robot. The robot was observed moving the models reproducing all the patient's movements that were recorded (Fig.13).

Fig.13. Patient's resin models moved by the robot reproducing all the movements recorded. **A.** Left laterotrusion. **B**. Protrusion. **C.** Right laterotrusion.

- Articulating papers were used on both the patient arches and the models on the robot to visually check the movements **(Fig.14).**

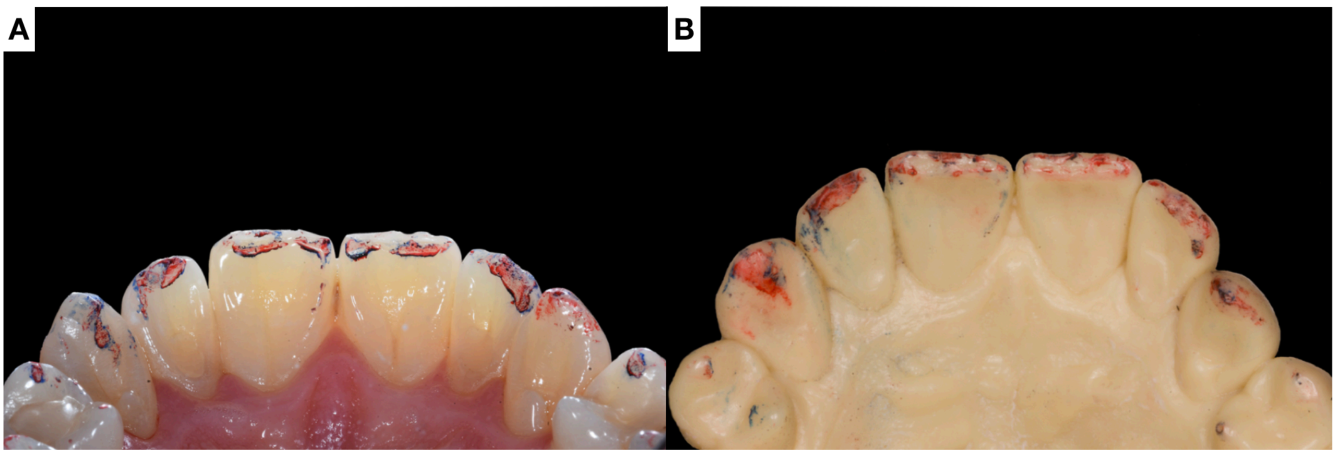

Fig.14. Check of contact points. **A.** Intraoral check of contact points during patient's right laterotrusion. **B.** Check of contact points during right laterotrusion on the models moved by the robot.

2.3. Result

Based on the described procedure, Bionic Jaw Motion provide accurate recording and reproduction of maxillo-mandibular relation in static and dynamic conditions.

Chapter 3

3. Discussion

Although the diffusion of robots in dentistry began 20 years ago, their diffusion and practical use is still rather limited. Most of the systems documented in the literature focus on teaching or research purposes, but a method that has been clinically validated on the patient is still absent.[37,38] This can be mainly attributed to the fact that the cost of much of the equipment is still very expensive. Consequently, this results in limited access to equipment for research purposes.[38] Based on the widespread prevalence of the robotics systems in medicine, research is encouraged to continue investigating both current and new methodologies in order to provide a useful robotic system in dentistry in the upcoming decades. This may only be possible with a close collaboration between dentistry, engineering, and industry.

The Yomi robot (Neocis, Miami, Florida, USA) is currently available in the market for implantology purposes, but its clinical use is documented in literature with only a case report[39].
In prosthodontics, the robotic systems that are presented are limited to mechanism to automatically place artificial teeth into a dental arch to manufacture complete dentures based upon the patient's arch size[40,41].

The results from my PhD research are promising and favors us to advance with the study.
With this novel robot, we aimed to precisely identify the individual movements of the subjects in addition to both the static and dynamic occlusal contacts. If the precision in reproducing the individual movements is validated, the clinical application of this methodology may offer the possibility to check and modify the occlusal surface of

the prosthesis directly on the robot prior to delivery on the patient. As a result, the time needed to the adjustment the occlusal contacts inside the mouth will decrease and also contribute to a reduction in costs. Nevertheless, it could also have positive implications in research fields on mandibular and condylar movements.

BJM differs from other digital robotic systems for acquisition and reproduction of mandibular movement because it is the first, at least to my knowledge, that is capable to quickly record individual functional movement, analyze data, and reproduce it on a robot. Most published prototypes focus only or on movement recording or on robotic movement reproduction, usually using data arbitrarily inserted in a software and trying to reproduce them at best on a robot. [28] The technology of BJM allows to reproduce mandibular kinematics without being limited to stereotyped movements. It uses intraoral landmarks to quantify movement not being influenced by an external reference system (hinge axis) such as facebow- articulator systems, or by alteration of motion of the condyles, i.e. Articular Disc Displacement. It has an optimal intra- and inter-operator repeatability and reproducibility as the human factor is reduced as low as reasonably achievable. Another advantage is the shorter chair time and consequently lower cost for individual registration compared to pantographic tracings and articulator setting (few seconds vs several minutes or hours). Compared to other systems like Arcus Digma, BJM is considerably lighter and comfortable for the patient. It could represent a novel valuable tool for prosthetic, gnathological and orthodontic application both for clinical and for research purposes. For instance, this new method could provide easy and quick jaw movement recording in patients that need to undergo prosthetic rehabilitation and accurate jaw movements reproduction during laboratory phases. It could also prove itself useful in the study and diagnosis of tempo-mandibular disorders. It can be helpful in studying mandibular kinematics during speech and during other functional activities that are of interest, for example, as orthodontic research topic to study the relation between different jaw movement patterns and the development of alterations in maxillofacial growth.

Chapter 4

4. Conclusion

Whithin all the limitations of the present study, BJM quickly records and reproduces individual mandibular movements and overcomes many of the limitations of traditional pantograph-individual articulators systems. An intraoral reference system is adopted to avoid any possible mistake in clinical identification of extraoral landmarks whose univocal determination is nearly impossible. BJM also allows the recording of functional movement besides border movements.

Further experiments are required to clinically validate the procedure.

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