Original Article
Determination of mandibular border and functional movement protocols using an electromagnetic articulograph (EMA)

Ramon Fuentes[1], Pablo Navarro[1], Aldo Curiqueo[2,3], Nicolas E Ottone[1,4]

[1]Research Centre in Dental Sciences (CICO), Dental School, Universidad de La Frontera, Temuco, Chile; [2]Master Program on Dentistry, Dental School, Universidad de La Frontera, Temuco, Chile; [3]Universidad Adventista de Chile, Temuco, Chile; [4]Doctoral Program on Morphological Sciences, Medicine School, Universidad de La Frontera, Temuco, Chile

Abstract: The electromagnetic articulograph (EMA) is a device that can collect movement data by positioning sensors at multiple points, measuring displacements of the structure in real time, as well as the acoustics and mechanics of speech using a microphone connected to the measurement system. The aim of this study is to describe protocols for the generation, measurement and visualization of mandibular border and functional movements in the three spatial planes (frontal, sagittal and horizontal) using the EMA. The EMA has transmitter coils that determine magnetic fields to collect information about movements from sensors located on different structures (tongue, palate, mouth, incisors, skin, etc.) and in every direction in an area of 300 mm. After measurement with the EMA, the information is transferred to a computer and read with the Visartico software to visualize the recording of the mandibular movements registered by the EMA. The sensors placed in the space between the three axes XYZ are observed, and then the plots created from the mandibular movements included in the corresponding protocol can be visualized, enabling interpretation of these data. Four protocols for the obtaining of images of the opening and closing mandibular movements were defined and developed, as well as border movements in the frontal, sagittal and horizontal planes, managing to accurately reproduce Posselt's diagram and Gothic arch on the latter two axes. Measurements with the EMA will allow more exact data to be collected in relation to the mandibular clinical physiology and morphology, which will permit more accurate diagnoses and application of more precise and adjusted treatments in the future.

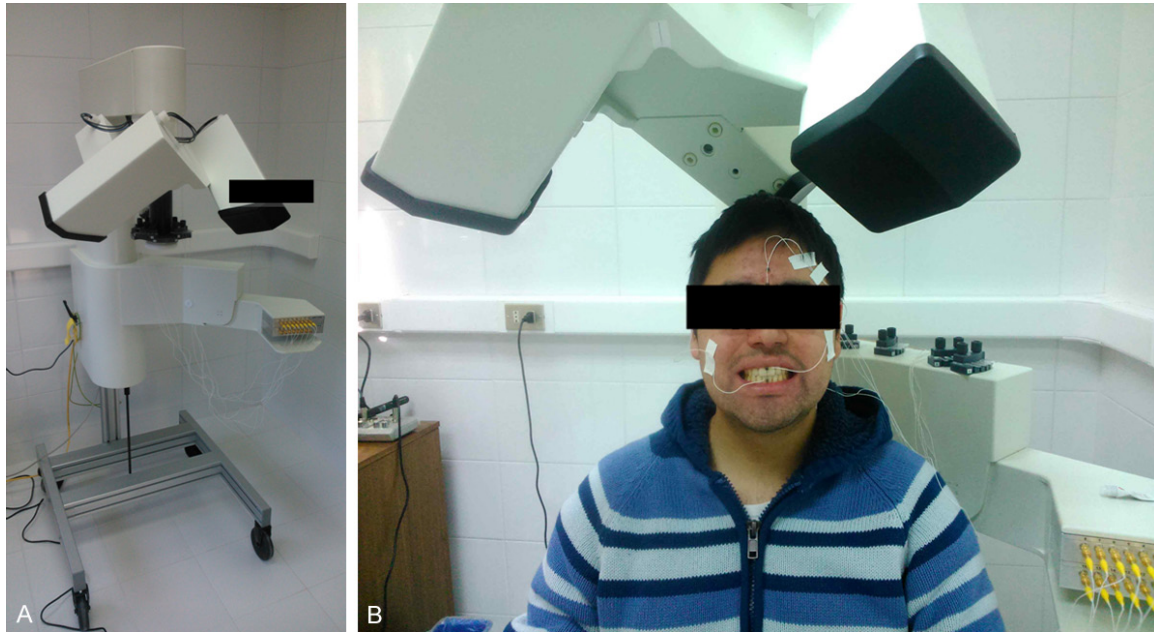**Keywords:** Electromagnetic articulograph, EMA, mandibular movements, protocols

Introduction

Understanding mandibular movement patterns has been of great interest in clinical dentistry due to the importance of knowing the behavior of the jaw during function and rest, and of describing reference studies that make it possible to analyze pathological situations. Therefore, the study of oral physiology and more specifically mandibular movement patterns is a topic of great importance in current dental practice.

Defining the different mandibular movement patterns accurately will enable more rigorous diagnoses and thus customized treatments.

The movement of the mandible is exerted in the three spatial planes; it is a three-dimensional movement, but the classic studies that describe the movement analyze it in one plane.

In 1957 Posselt [1] designed a gnathothesiometer, an instrument with which he could record mandibular border and non-border movements in the sagittal plane, describing the well-known "Posselt's diagram". From that moment, attempts began at achieving greater precision in the recording of mandibular movements for the definition of patterns. The cinefluorograph was introduced [2] but the high radiation levels it emitted prevented continuation of its use. Then less invasive forms were sought, such as

Figure 1. A. Articulograph electromagnetic (EMA). B. Patient under EMA.

cineradiographic observations implemented in 1959 by Berry & Hofmann [3], with the use of films intensified electronically [4, 5]. In 1966, Gibbs et al. [6] developed their studies on a gnathic replicator. In 1975, magnet-based technologies came into use, such as Jankelsson et al. with the kinesiograph [7]. In 1988, Pröschel & Hofmann [8] created the sirognathograph. The electrognathograph was introduced to the field of the dentistry by Bodin & Abjean in 1989 [9]. In 1994, three-dimensional studies began with the JAWS 3D system [10]. For their part, Nishigawa et al. [11], in 1997, produced works that allowed the measurement taken to be related to the use of an electromyograph and mandibular movements.

But as can be deduced from all these devices, although they could vary in the accuracy of the measurements, some presented great interference in the findings due to their inadequate size, to causing real interference when the movements were being performed or perhaps also due to the great invasiveness that determined their use at the time of application.

In recent years, with the use and evolution of the electromagnetic articulograph (EMA), measurement of a large number of functions has been achieved in the three planes and in real time, related to phonetics, speech disorders, coordination of motor activity of the lips during

the articulation of words, combined tongue-mandible movements, speech analysis in people with dentures, among others. The first publication in this area was by Schönle et al. in 1987 [12], who later applied the EMA in investigations of the vocal tract and in 1989 Engelke et al. [13] applied the EMA to the study of orofacial movements. Horn et al. [14] took the first measurements of swallowing with the EMA. Then Bourdiol et al. [15] used the EMA to assess swallowing, defining three patterns related to the movements of the tongue and the swallowing of saliva. It is currently possible to carry out 3D determinations, although data analysis and interpretation has increased in complexity. Unlike other phonetic research techniques, such as radiology, magnetometry is not detrimental to the speaker's health.

The aim of this article is to describe a protocol for the generation, measurement and visualization of mandibular border and functional movements in the three spatial planes (frontal, sagittal and horizontal) with the use of the EMA.

Materials and methods

The electromagnetic articulograph (EMA) is a device with three transmitter coils that can detect magnetic fields to collect movement data at multiple points, enabling measurement in real time of the movements of the structures
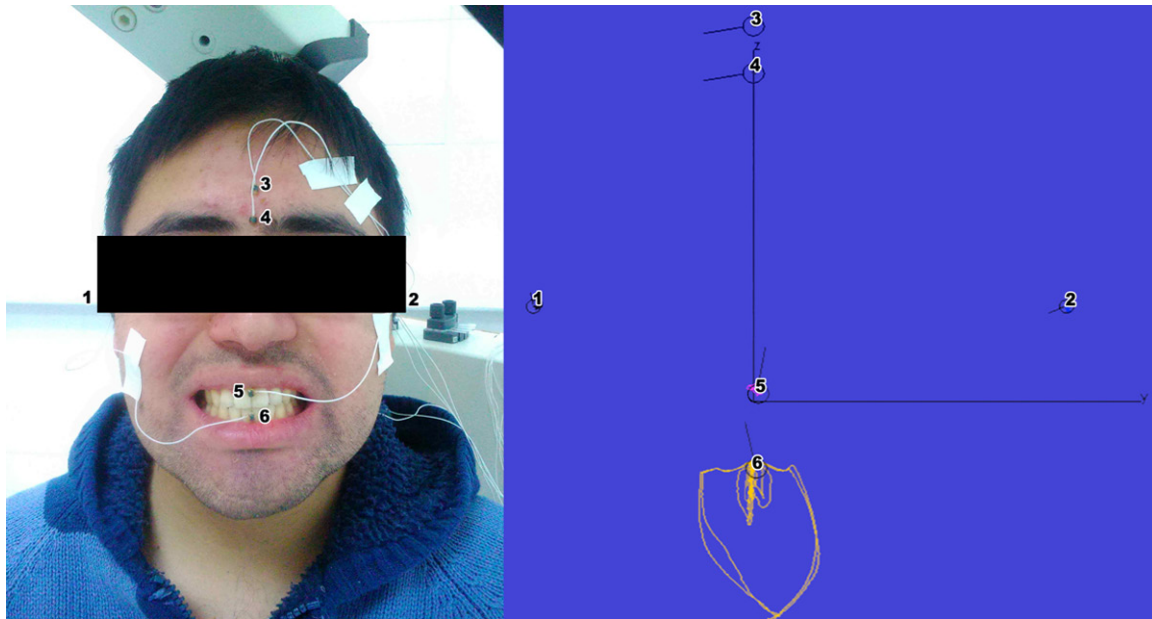
Figure 2. Site of placement of sensors. 1. Right mastoid process (reference sensor); 2. Left mastoid process (reference sensor); 3. Glabella (reference sensor); 4. Nasion (movement sensor); 5. Upper incisor (between the two upper incisors) (movement sensor); 6. Lower incisor (between the two lower incisors) (movement sensor).

connected to the sensors, as well as the acoustics and mechanics of speech using a microphone connected to the measurement system. The movements are measured, plotted and stored on a computer. The sensors can be placed in all positions and all directions within an area of 300 mm. The device is accompanied by software that configures the data analysis, so that the user can access the data obtained from the sensors that can be placed in different sectors, such as the tongue, palate, mouth, incisors, skin, and other anatomical locations (**Figure 1**). Once the measurement is taken with the EMA, the information is extracted from the computer connected to the EMA and transferred to a second computer, where the data is read through the Visartico software, which visualizes the mandibular movements recorded on the EMA (**Figure 2**). In Visartico, the sensors placed in the space between the three axes XYZ can be observed, from which the data provided by the EMA can be interpreted.

In terms of the sensors, each produces an alternating magnetic field at different frequencies. This field induces an AC voltage in the sensors located on the subject, like in a transformer, and enables the distances from each sensor to be ascertained. Next, it is possible to calculate the XYZ coordinates, so that the positions

of the sensors can be measured, stored and visualized.

The EMA can install 24 channels to which the sensors connect. Our device has 16 channels, and can therefore connect a total of 16 sensors. According to the tests conducted to develop the protocols in this study, we defined the use of 6 sensors per individual. This way, 12 sensors can be prepared which can be used on two subjects, thereby reducing the experiment time.

The sensors to be used in the experiment must be calibrated to ensure the movements performed during the experiment are recorded. The calibration process lasts approximately 20 minutes and is only necessary at the beginning prior to taking the measurements. In all cases, the 16 sensors are calibrated, of which 12 are then selected, as explained previously.

The sensors can be classified for reference or movement. The operator will indicate which will be the reference sensors and which the movement sensors. Three reference sensors must be selected. This selection is made on the EMA computer before beginning the experiment. The reference sensors, of which there must be three, are static sensors and will be identified by the EMA as sensors that can identify the
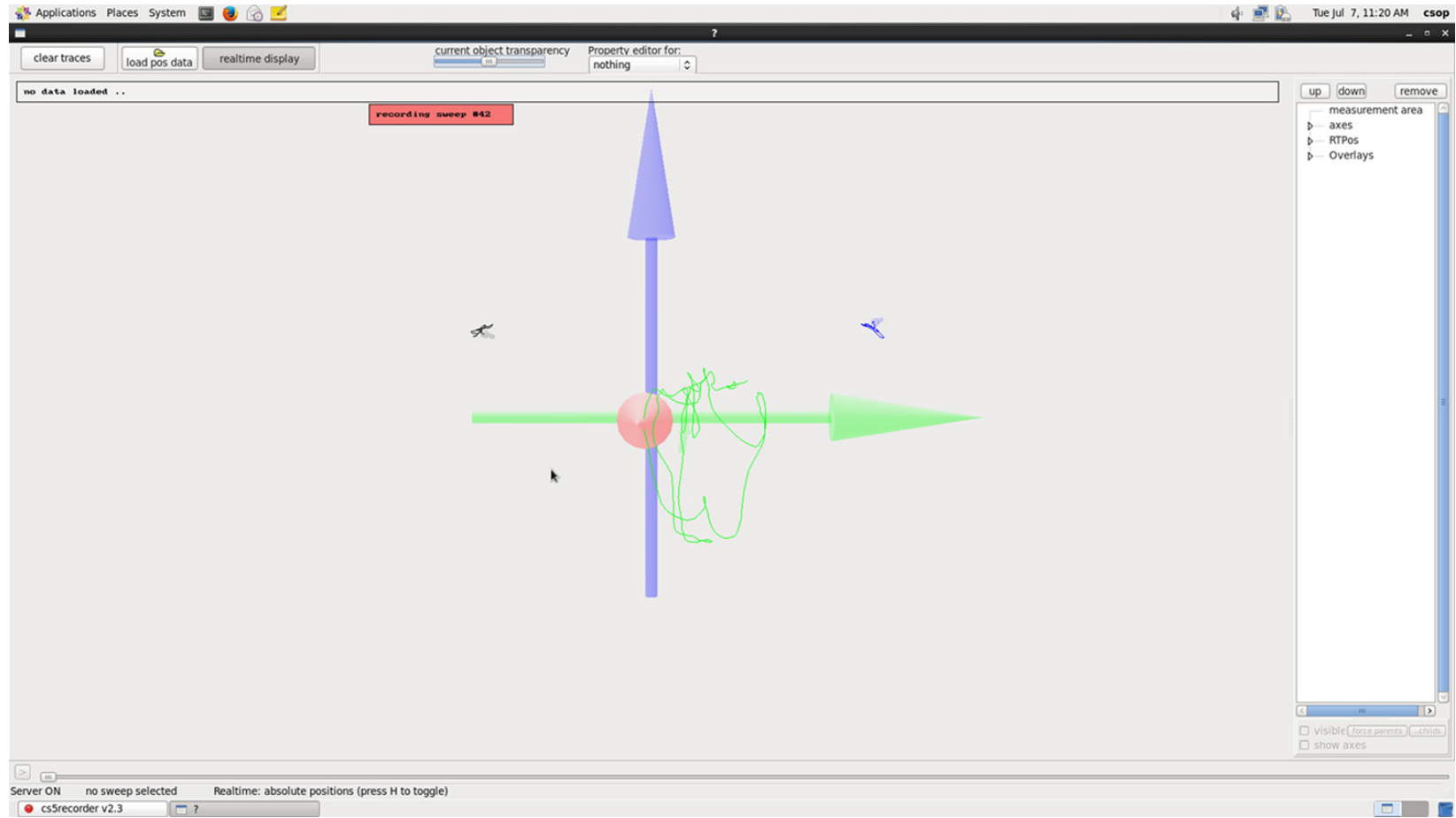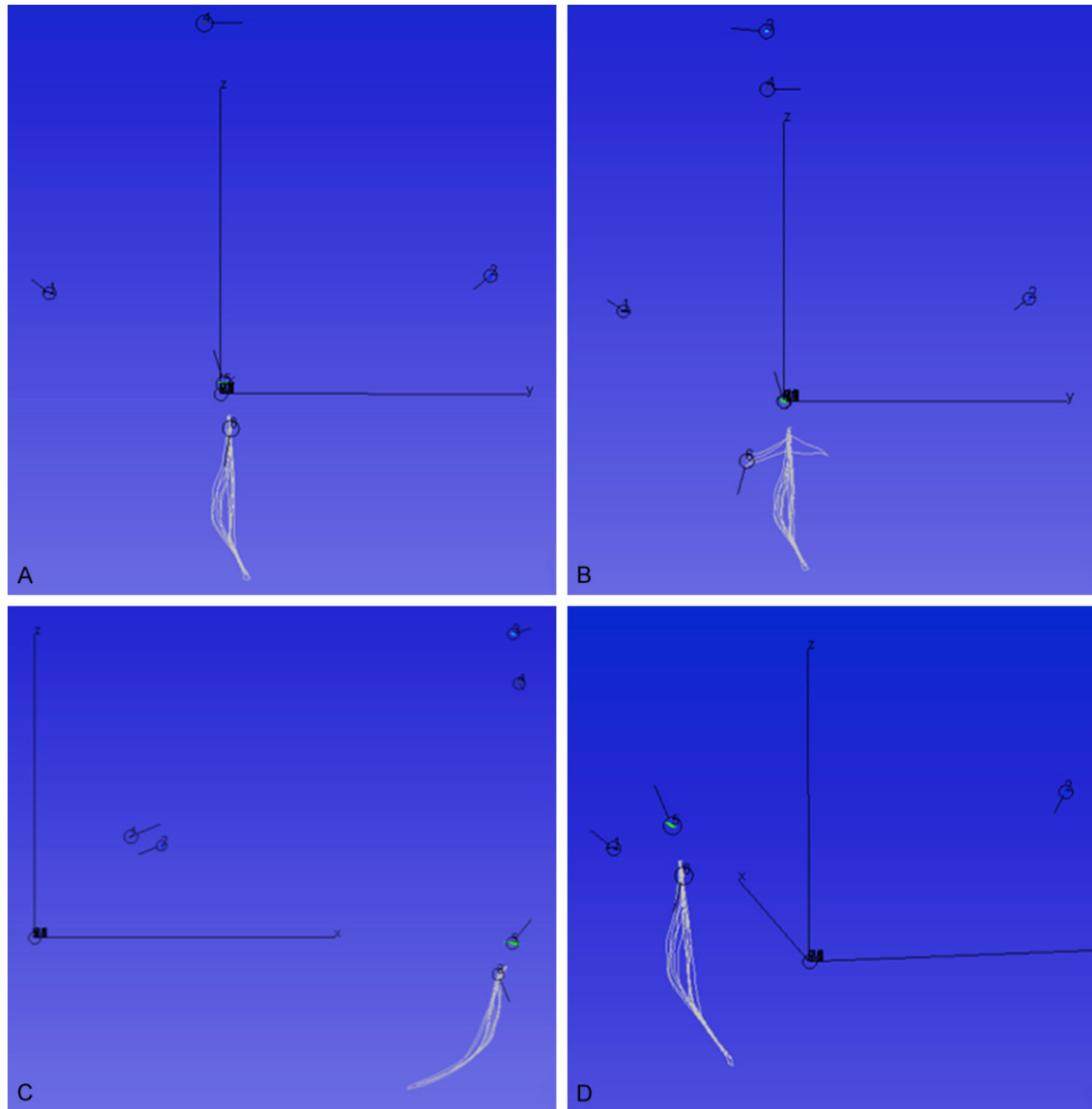
Figure 3. 3D visualization of the sensors and movements in EMA computer.

Figure 4. Display of protocol 1 in different planes. A, B. Frontal plane. C. Sagittal plane. D. Lateral and inferior view.

location/direction of the head in the three spatial planes. By contrast, the movement sensors are those recognized by the EMA as the sensors that will record the study movements, with the reproduction in the form of trajectory lines, which will enable point-by-point visualization of the mandibular movements, according to our investigation.

Once calibrated, the 12 sensors are covered with liquid silicone, which dries adequately in 30 minutes. Sensors covered with silicone cannot be calibrated, because the silicone does not allow a good mounting of the sensors in the

adapter used for the calibration, as they are at a 45° angle in the calibration adapter.

The EMA is adapted to take the measurements with the patient seated. Therefore, before beginning the recording, and with the patient already seated, the operator will explain the movements to be made during the experiment, which will be reproduced by the patient before the sensors are placed. This training will take about 10 minutes. In relation to this training, we consider it important to have, in this stage of experimentation, subjects with a good knowledge of the mandibular movements to be made;
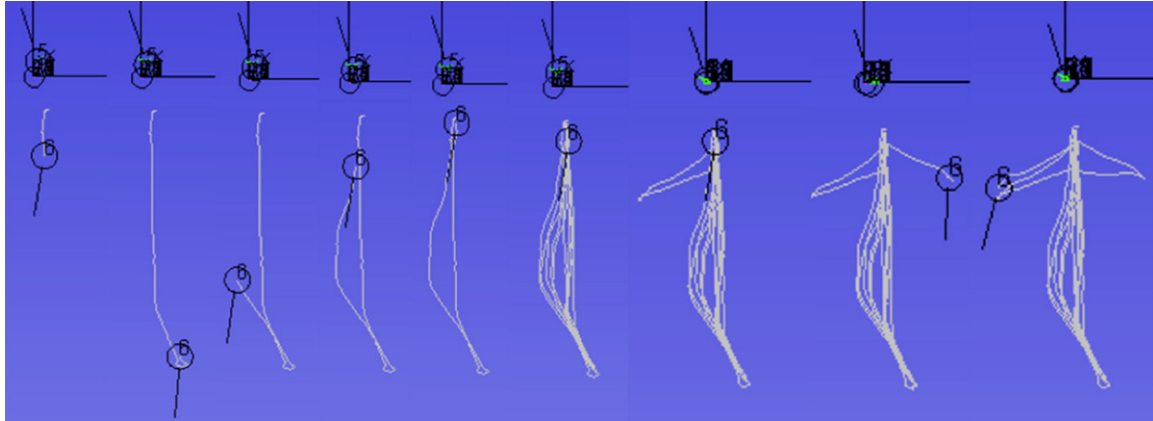
Figure 5. Generation and evolution of Protocol 1 from the frontal plane.

therefore, student dentists will be the best to carry out these protocols. We recommend that the detailed description of the movements and the training be done at another time, particularly for patients with no previous knowledge of these protocols.

Once the training of the movements is complete, and with the sensors already covered with liquid silicone, the sensors are then positioned on the patient, which are fixed to the patient with glue. In addition, a special tape is used to fix the sensor cables to the patient's skin, and thus to ensure adequate arrangement of the cables so the experiment can run without interference.

The sensors are placed on the following anatomical points (**Figure 2**).

1) Right mastoid process (reference sensor). 2) Left mastoid process (reference sensor). 3) Glabella (reference sensor). 4) Nasion (movement sensor). 5) Upper incisor (between the two upper incisors) (movement sensor). 6) Lower incisor (between the two lower incisors) (movement sensor).

Then, the coil system is lowered to 2 cm from the top of the patient's head. The patient is told to look to the front and adopt the position of the head defined in the protocols, which in these cases is the postural position.

Once the patient is in the postural position, he/she is told to remain completely still, and recording of the measurements of the mandibular movements with the EMA begins. The corresponding calibration is selected on the EMA

computer to ensure that the movements are being recorded correctly. Then, the sensors must be selected that will be used in the experiment (from 1 to 6). In this step, 3 reference sensors must be selected, which will be needed so the EMA can interpret the right location for the remaining movement sensors. The reference sensors will be 1, 2 and 3. Sensors 4, 5 and 6 are for movement. Once this has been done, the head is "corrected", which will allow the reference and movement sensors to be defined among the sensors selected in the previous step. From this point, recording of the mandibular movements can begin.

Before beginning, the 3D visualization of the movements is activated (**Figure 3**) so the patient's movements can be visualized and checked in real time.

Next recording of the mandibular movements begins. Before beginning each of the protocols, the individual is asked to place their jaw in the starting position defined for each protocol, thereby avoiding the recording of movements that generate plots that will later interfere with the trajectory recorded during the experiment.

Four protocols were defined to record and later analyze the mandibular movements in the frontal, sagittal and horizontal planes.
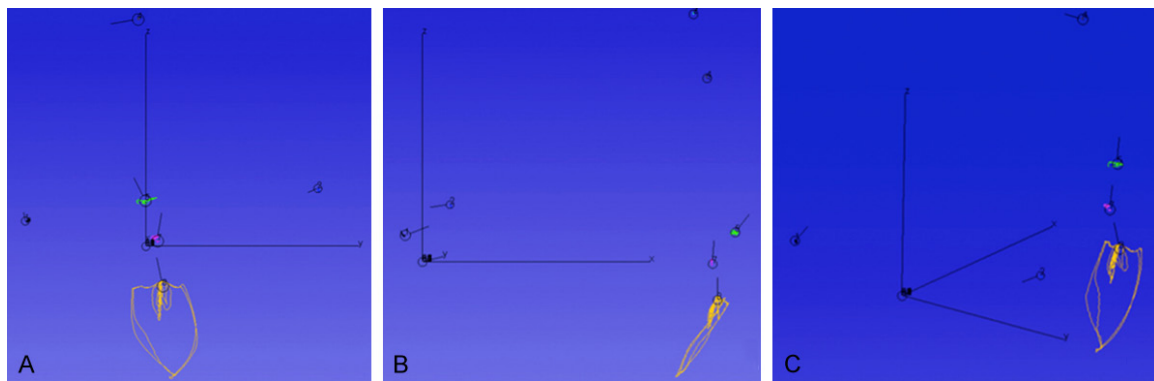
Protocol 1. Indications to generate the maximum opening and closing movement and non-contact side (**Figures 4** and **5**).

Protocol 2. Indications to generate the border movement in the frontal plane (**Figures 6** and **7**).
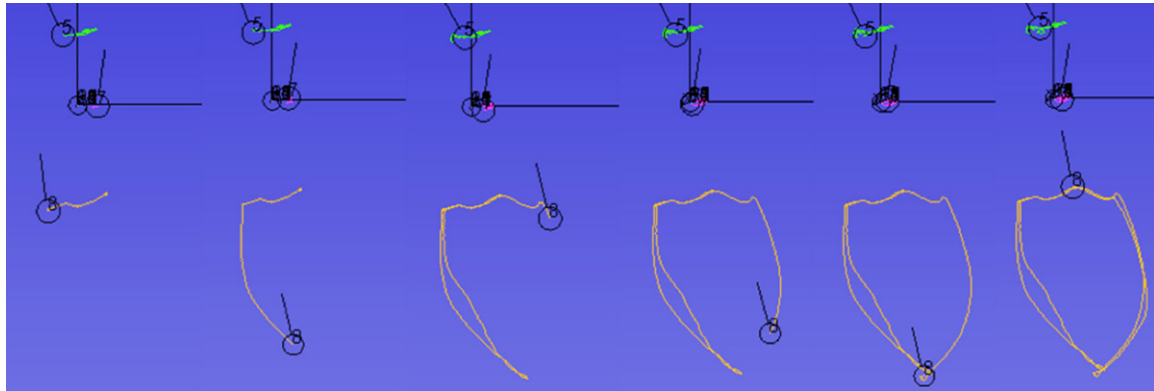
Figure 6. Border movements in frontal plane from Protocol 2.

Figure 7. Border movements in different planes of space generated from protocol 2. A. Frontal plane. B. Sagittal plane. C. Lateral and inferior view.

Protocol 3. Indications to generate the border movement in the sagittal plane "Posselt's Diagram" (**Figures 8** and **9**).

Protocol 4. Indications to generate the border movement in the horizontal plane "Gothic Arch" (**Figures 10** and **11**).

Each of the movements in the protocols is repeated 5 times.

Then, the data are transferred from the EMA computer to a second computer on which the VisArtico software [16] is installed to visualize in the three spatial planes the movements recorded on the EMA and to obtain from it images and videos that make it possible to analyze the movements recorded on the EMA. Thus, the drawings of the mandibular movements in the frontal plane can be obtained and analyzed.

To implement this protocol, students were selected from the Dental School at the Universidad de La Frontera. They all read and signed the informed consent to be able to participate in this investigation.

The study took place in the Oral Physiology Laboratory of the Research Centre in Dental Sciences (CICO), Dental School at the Universidad de La Frontera. The study was approved by the Ethics Committee of Universidad de La Frontera.

Summary of the steps to operate the EMA:

1) Turn on the EMA and computer. a. Check connections (computer-EMA cable; microphone connection). 2) Place sensors in calibration device. 3) Calibrate. 4) Cover the sensors with silicone. 5) Turn on the EMA and computer. 6) Seat the patient underneath the EMA. a. Adjust the height of the EMA. b. Train the patient in the mandibular movements to perform. c. Place the sensors on the patient. d. Place the ground connector on the patient's ankle. e. Position the patient's head according to the protocol. 7) Check the status of the sensors on the com-
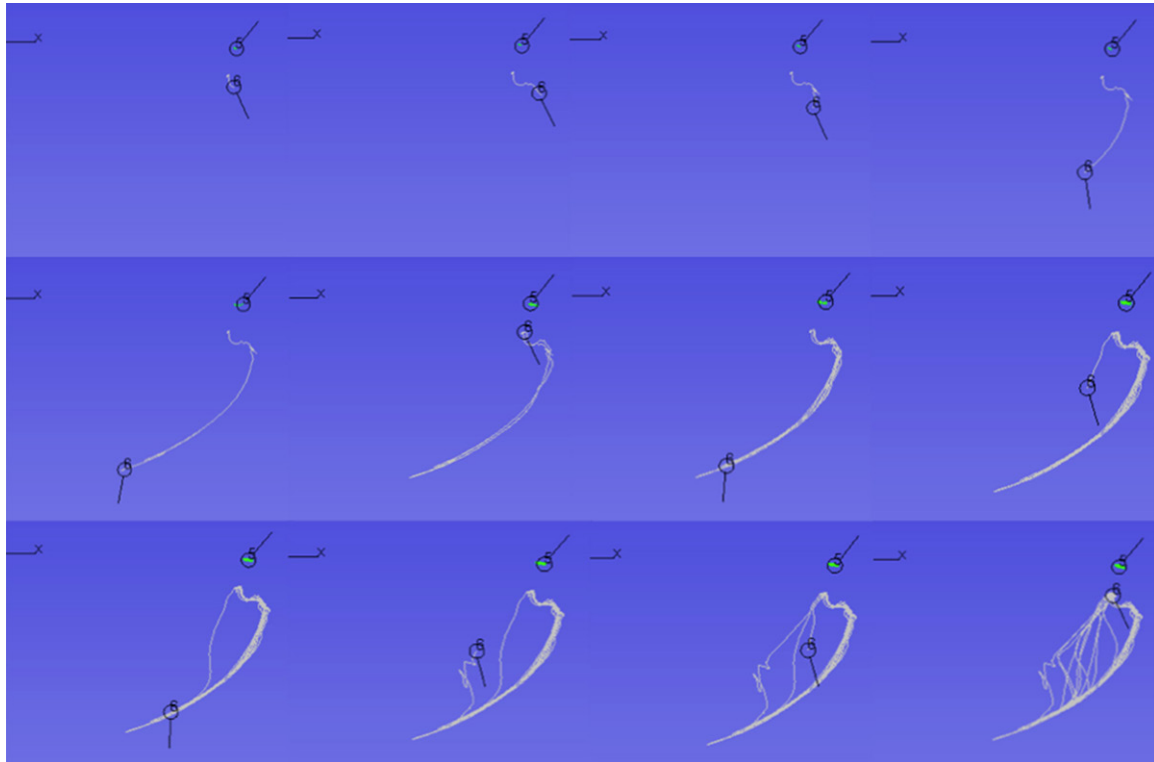
Figure 8. Posselt's diagram generation from protocol 3 in sagittal plane.
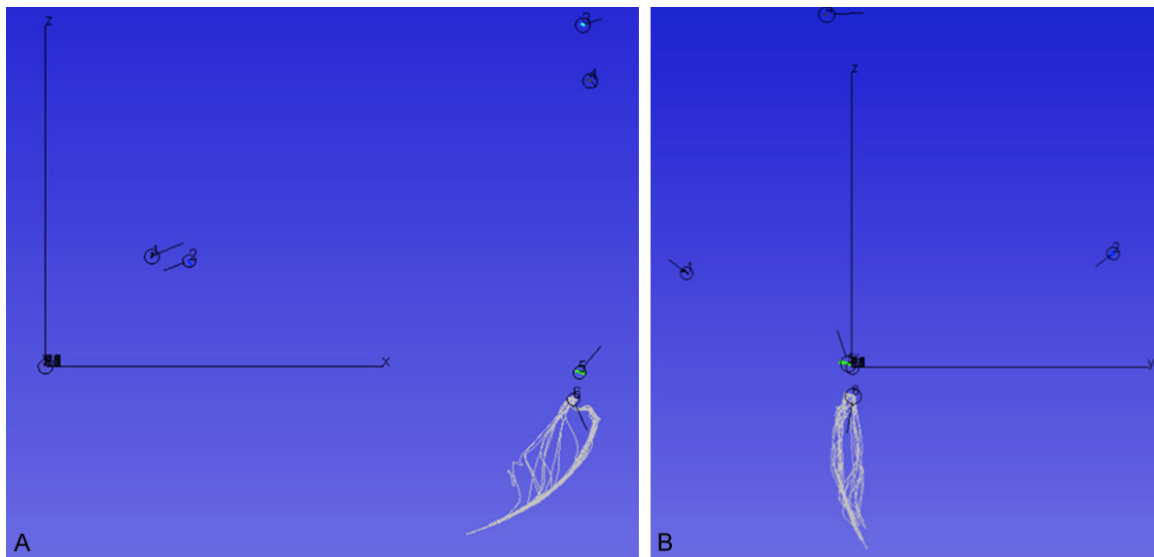
Figure 9. Display of Protocol 3 in different planes. A. Sagittal plane. B. Frontal plane.

puter. 8) Begin program to record data from the EMA. a. Select last calibration file generated. b. Perform head correction so that sensors to be used in the experiment can be selected. c. Select the reference sensors and movement sensors. 9) Open the 3D visualization on the EMA computer. 10) Check the sensors are working in the 3D visualization. 11) Begin the protocols.

Results

Measurements and records of the border and non-border movements were obtained to be analyzed in the three spatial planes.
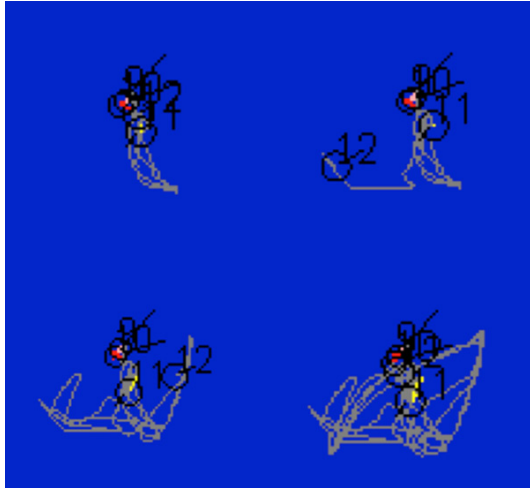
Figure 10. Protocol 4 and generation of Gothic Arch image (horizontal plane).

From the movements registered on the EMA with protocol 1, records of the movements are described in real time of the maximum opening and closing of the mouth, combined with movements of the non-contact side. And in **Figure 5**, the generation of the trajectories can be seen, step by step, in the frontal plane of visualization. **Figure 4** shows these trajectories in all the spatial planes.

The development of protocol 2 was used to obtain the plots that the border movement generates in the frontal plane (**Figure 6**), which can also be analyzed in the rest of the spatial planes (**Figure 7**).

By applying protocol 3, the border movement can be generated in the sagittal plane (Posselt's diagram), the visualization of which is in the sagittal plane (**Figure 8**). But the trajectories generated can also be analyzed in the three spatial planes (**Figure 9**).

Protocol 4 makes it possible to generate the layout to finally obtain the Gothic arch, which is seen in the horizontal plane of the space (**Figure 10**). As in every experiment, the movements produced can be visualized in the three spatial planes (**Figure 11**).

In addition, the VisArtico software can record the trajectory of the movements, being able to stop the recording at any point, among other data that can be extracted by applying this software to the recordings obtained with the EMA.
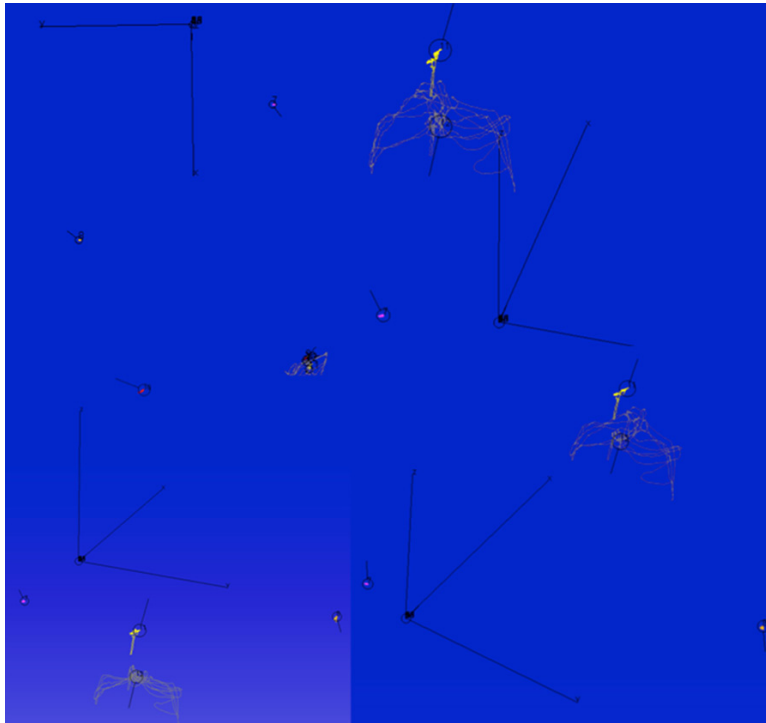
Discussion

Studies conducted with the EMA on temporal and spatial coordination of the tongue, jaw and soft palate during the implementation of different movements were carried out by Schönle et al. [17, 18], Engelke et al. [13], Engelke and Schönle [19], Schwestka-Polly [20] and Bourdiol et al. [15], fundamentally.

The development of measurement systems based on magnetic fields, like the EMA, has made it possible leave aside the use of other equipment, such as the cinefluorograph or the kinesiograph, due to their high risk to patient health (the former) or the difficulties in guaranteeing precise measurements (the latter). Thus, the EMA can take minimally invasive measurements and, which is fundamental in this case, it can take measurements without interference to the patient in terms of the equipment used, which does not cause the patient discomfort.

Every system of measurement endeavors to alter the patient's normal surroundings to the least extent possible during use. The transmitters coupled to the dental arches altered the mandibular movement during mastication and thus the measurements were faulty. As well, the positioning of the transducers on the skin, although a good initial alternative to the previous case, also caused great variations between the movement of the mandibular bone structure and soft tissues in the area. This is why reduction to the least interference possible is one of the most important advances provided by the EMA, in which the sensors used with a design similar to dental braces, makes them more physiological in terms of the comfort for the patient, being placed at the level of the lower incisors and recording mandibular movements without interference, with great precision and harmless to the patient.

In this same sense, fulfillment of all the indications related to avoiding interference during the implementation of the tests is of paramount importance: not using cell phones in the laboratory, correctly disinfecting and handling the transducers, keeping the temperature steady in the laboratory (20-22°C), using a voltage stabilizer, as well as fully reading the instructions of the protocols to the patient, so that everyone is subject to the same indications. It is essential, therefore, to follow the recommendations

utes. This way, before beginning each experiment, only 20 minutes are needed for training and positioning of the sensors. The implementation and recording of the protocols can begin.

Also, before beginning each measurement process, it is recommended that calibration of the status of the sensors be checked using the visualization in the software installed on the EMA computer in order to verify that the sensors remain calibrated for their use in the experiment.

In terms of the reproducibility of the measurements, this is ensured from the possibility of repeating on all the patients the measurement protocols stipulated for the visualization of the mandibular movements in the three spatial planes (frontal, sagittal and horizontal). Additionally, the software for the equipment allows for the simultaneous recording of the trajectories of movement and sound, from which not only complete images but also videos can be obtained.

Figure 11. Protocol 4 on the three planes of space.

established in the materials and methods section, and mainly, to the absence of the distractions that can cause alterations in the records acquired during the implementation of the protocols.

Included in the indications so the measurements are correct, it is important to allot sufficient time, as these measurements are not characterized as being fast. Therefore, first of all, we recommend the sensors be calibrated the day before the measurements are taken. This avoids the loss of at least one hour in this step, which is crucial for the correct operation of the EMA.

After calibration, and also the day before the experiment, the sensors must be covered with silicone. This can be done after calibration, on the same day or even another day, but in both cases we recommend they be done on days prior to implementation of the protocols.

Before beginning the experiment, the patient must be taught the movements to perform in the different protocols. This training period should not exceed 10 minutes. Finally, the patient is placed with the EMA and the sensors are positioned, which will take another 10 min-

It is very important to establish that although each border movement protocol produces the movement trajectory for visualization in a certain plane (for example, protocol 3, for the generation of Posselt's diagram, visualization occurs in the sagittal plane), each of the movements can be visualized in the remaining spatial planes thanks to the functions provided in the VisArtico software [16], thereby making it possible to accurately observe the trajectories obtained of the movements and to evaluate them from new perspectives. An example can be observed in protocol 1: when mandibular opening and closing is assessed, an anteroposterior movement is visualized in the sagittal plane, a movement that is not seen if the movement is only analyzed in the frontal plane.

From the experience acquired during our investigation, and for the correct implementation of the measurements on the EMA, we consider it

of primary importance to take the following indications into consideration.

The measurements must be taken in an environment with no distractions for the subject on whom the measurements are being taken, such as noise, conversations, annoying sounds, etc.

Do not use cell phones in the laboratory where the EMA is located to avoid interference in the recording of the measurements. For that reason, it is recommended that cell phones be turned off or not brought into the laboratory.

On the manufacturer's recommendation, the sensors must be placed with at a distance to each other equal to or greater than 8 mm.

The temperature in the laboratory must be kept between 20 and 21°C. To ensure this, it is important to have a digital thermometer that can measure room temperature, as well as heating devices (cold/heat) that can be regulated to maintain the temperature indicated.

There must equipment to stabilize the electrical current, which must be placed between the EMA and the electrical current connection in the laboratory. This will allow the EMA equipment to receive the electrical current steadily, avoiding exposure to variations in electrical voltage, which can also affect the recording of the measurements.

The Wi-Fi signal, difficult to avoid in education and research institutions, does not affect the normal operation of the EMA.

The sensors must be handled carefully, performing a correct disinfection after each experiment and before new application of silicone.

The use of silicone on the sensors is fundamental so they can be reused on each patient. This step protects the sensor, facilitating the elimination of the adhesive after the session and therefore helping to keep them clean, with a proper asepsis ensuring their use for each patient and prolonging their use at the same time.

The siliconization of the sensors the day before the measurements are taken is recommended, so that all the equipment is ready for the execution of the protocols. The preparation of 12 sensors will make it possible to analyze 2 subjects consecutively, with a minimum time delay.

The protocol instructions must be in writing so they can be read by the experimenter to the patient; this way, all the patients are subject to the same indications and there are no variations in their communication and interpretation.

Horn et al. [14] established in their study on the movements of the tip of the tongue, that there were intraindividual and interindividual variations, which determined a clear significance of interrelation with the underlying pathology, and this enabled precise identifications of these changes in mandibular functionality that could not be detected with other equipment.

In the future we consider it will be necessary to undertake reliability and validity studies of the measurements taken on the EMA, so that this system of measurement can continue to be applied to patients belonging to different skeletal classes and who could present non-functional, pathological movements. These measurements will allow more accurate data to be collected from these patients in terms of their mandibular clinical morphology, which will permit more accurate diagnoses and the application of more precise treatments adjusted to each patient according to their mandibular recordings on the EMA.

Disclosure of conflict of interest

None.

Address correspondence to: Dr. Ramon Fuentes, Facultad de Odontología, Universidad de La Frontera, Manuel Montt 112, Casilla 54-D, Temuco, Chile. Tel: 0056 045 2734153; E-mail: ramon.fuentes@ufrontera.cl

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