*applied sciences*

MDPI

*Article*

# Correlations Between Mandibular Kinematics and Electromyography During the Masticatory Cycle: An Observational Study by Digital Analysis

**Alessandro Nota [1,*], Laura Pittari [1,2], Francesco Manfredi Monticciolo [1], Alessia Claudia Lannes [1] and Simona Tecco [1]**

[1] Department of Dentistry, Dental School, Vita-Salute San Raffaele University, IRCCS San Raffaele Hospital, 20132 Milan, Italy; laura_pittari@hotmail.it (L.P.); francesco.manfredi.monticciolo@gmail.com (F.M.M.); a.lannes@studenti.unisr.it (A.C.L.); tecco.simona@hsr.it (S.T.)

[2] MeSVA Department, University of L'Aquila, 24100 L'Aquila, Italy

* Correspondence: nota.alessandro@hsr.it

**Abstract:** The analysis of the masticatory cycle plays a fundamental role in studying the functions of the stomatognathic system and evaluating temporomandibular dysfunctions (TMD). The primary objective of this study is to investigate the complex interplay between mandibular kinematics and surface electromyography (sEMG) activity during the masticatory cycle using advanced 4D dentistry technology in 22 healthy subjects (without TMD). By employing electromyography, it becomes feasible to capture the electrical activity of the masticatory muscles throughout the chewing process. The BTS TMJOINT (© 2023 BTS Bioengineering, Garbagnate Milanese, MI, Italy) electromyograph was utilized in this study. Mandibular tracking, on the other hand, allows for recording the movements of the mandible during chewing and condylar slopes. This latest technology (ModJaw®, Tech in motion™, Villeurbanne, France) utilizes motion sensors placed on the jaw to accurately track three-dimensional movements, including jaw opening, closing, and lateral movements. Nowadays, in clinical gnathology, it is common practice to examine masticatory function by analyzing mandibular kinematics and muscle contraction as distinct entities. Similarly, the results obtained from these analyses are typically assessed independently. The investigation of a correlation between electromyography data and mandibular kinematics during the masticatory cycle could provide several advantages for clinicians in diagnosis and lead to a combined analysis of muscle activities and intraarticular dynamics. In conclusion, it can be inferred from the results obtained in the present study that the chewing cycle with a greater vertical movement results in increased masseter muscular activity, and condylar slopes are positively correlated to an increase in temporalis muscle activation. This comprehensive approach can provide valuable insights into the relationship between muscle activity and mandibular movement, enabling clinicians to gain a deeper understanding of the functional dynamics of the stomatognathic system.

**Keywords:** chewing cycle; digital dentistry; electromyography; jaw-tracking; masticatory system; temporo-mandibular disorders

check for updates

**Citation:** Nota, A.; Pittari, L.; Monticciolo, F.M.; Lannes, A.C.; Tecco, S. Correlations Between Mandibular Kinematics and Electromyography During the Masticatory Cycle: An Observational Study by Digital Analysis. *Appl. Sci.* **2024**, *14*, 9996. https://doi.org/10.3390/app14219996

Academic Editor: Bruno Chrcanovic

Received: 30 July 2024
Revised: 24 October 2024
Accepted: 25 October 2024
Published: 1 November 2024



## 1. Introduction

In current clinical practice, when the patient needs dental rehabilitation, it is necessary to assess every aspect of their stomatognathic system, especially in rehabilitations that involve modifications to the occlusal area, in order to restore physiology.

Among these analyses, the evaluation of mandibular kinematics and muscle activity plays a strategic role.

Over the past two decades, the advancement and widespread adoption of digitized methods for evaluating stomatognathic function has significantly simplified the entire rehabilitation process [1–4]. One of the advantages is the possibility to digitally simulate the desired outcome of rehabilitation before implementing it on the patient, enabling better planning and delivering consistent outcomes [2,5–7]. Digital methods are realities that dentistry can no longer ignore; their field of application covers all disciplines of the dental industry, from data acquisition to treatment planning. Digital methods are also designed to be able to evaluate the information of clinical relevance through digital systems in a fast, accurate, and comparable way.

Regarding the gnathology field, in modern clinical practice, various tools are commonly employed. These include smartphone apps, software programs, accelerometers, posture–stabilometric platforms, electromyographs, intraoral scanners, devices for analyzing mandibular kinematics, facial scanners, and digital cephalometry analysis tools [1,7–13]. In the past, analogical instruments such as articulators were employed to simulate the patient's stomatognathic function and assess the relationship between dental arches during mandibular movements on the base of mechanical values [6,13,14]. However, with the advancement of digital technologies in dentistry, it is now possible to achieve a more precise evaluation by directly capturing the actual movements of the patient's mandibular condyles without relying on statistical data [1,4].

During dental rehabilitations that involve modifications to the occlusal area, monitoring changes in mandibular kinematics and muscular activity is crucial, especially in detecting the correlation between joint movements and electromyographic activity. For this purpose, the digitalization of actual condylar paths and muscular masticatory cycles can help in assessing the correlation between the parameters. However, there is still a lack of comprehensive studies in the scientific literature that provide data on such variations using digital instrumentation, as muscle activations and joint movements are generally measured and studied independently. In clinical practice, it is common to examine masticatory function by analyzing mandibular kinematics and muscle contraction as distinct entities. Similarly, the results obtained from these analyses are typically assessed independently by measuring masticatory direction as a function of muscle activation in patients with malocclusions [15–17].

Today, thanks to innovative technologies for data acquisition with stereophotogrammetry, it is possible to trace the real condylar path along with the ability to capture joint movements and muscle activations. Also, studying the associations and correlations between variables related to muscle activation and those related to condylar pathways during a chewing cycle has become increasingly possible.

Therefore, the primary objective of this study is to investigate the correlation between electromyography data and mandibular kinematics recorded during the masticatory cycle in subjects who did not exhibit pathologies of the temporomandibular joint.

Correlating the results of both examinations on healthy subjects would allow for an integrated analysis of muscle activities and intraarticular dynamics of electromyography data and mandibular kinematics during the masticatory cycle. This comprehensive approach could provide valuable insights into the relationship between muscle activity and mandibular movement, enabling clinicians to gain a deeper understanding of the functional dynamics of the stomatognathic system.

## 2. Materials and Methods

Twenty-two Dental students attending Vita-Salute San Raffaele University in Milan (11 F, 11 M, average age 25 ± 2.88) voluntarily underwent a recording of the masticatory cycle. The participants had complete and healthy dentition with at least 28 teeth, showed no limitations in mouth opening, did not experience any pain or disorders in the temporomandibular joint, and reported no chewing impairment. These subjects did not suffer from temporomandibular disorders (TMD) according to DC/TMD criteria [18].

This study was approved by the ethics committee of IRCCS San Raffaele Hospital (Milan, Italy) with the document "parere09/int/2023".

During this experimental clinical study, small savory biscuits (Gullòn, Ctra. Burgos, Km 1.5, 34800 Aguilar de Campoo, Palencia, Spain) were used as test food. This food test allowed the recording of condylar paths and electromyographic activity for 15 s.

Each volunteer underwent digital scanning of their dental arches using IOS iTERO (© 2023 Align Technology, Inc.; San Jose, CA, USA) (Figure 1). The obtained dental scan data were exported and imported into the TWIM™ software (ModJaw®, Tech in motion™, Villeurbanne, France) for the analysis of mandibular movements with ModJaw devices (Figure 2).

(**a**) (**b**)

**Figure 1.** (**a**) iTERO intraoral scanner device; (**b**) Dental scan frontal view iTERO iOS.

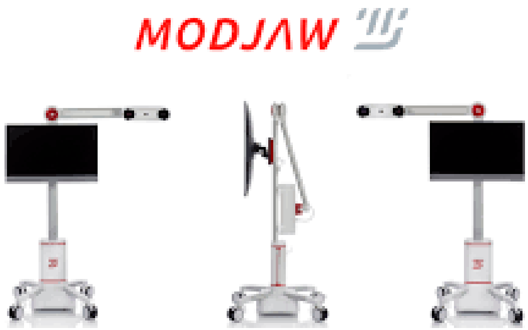



**Figure 2.** Jaw-tracking device ModJaw®.

This device is based on 3D stereophotogrammetry technology: the optical sensors are placed on the jaw and head of the patient to capture data. Modjaw® captures movements of the hinge axis of the patient during functional jaw movements and transfers them, along with the personal reference plane of the patient, to the TWIM™ software (version 3.5).

The devices are also integrated with an HD camera for high precision and high frequencies for real-time 4D visualization, a touch screen PC, and a rotative arm and stable cart with a locking system [5].

The delay time of the Modjaw® system is minimal, typically within 10 ms, which ensures near-instantaneous capture of mandibular kinematics. This low latency is crucial for real-time 4D visualization and accurate dynamic movement tracking during functional activities such as chewing, talking, and swallowing. According to recent studies by Bapelle et al., the repeatability of recordings was good to excellent in healthy subjects. The Modjaw® device also offers a high level of reliability in recording mandibular kinematics with excellent precision [4,5].

For mandibular kinematics recording, the volunteer assumed an upright position on the dental chair, with their back straight and head raised, not resting on the backrest (Figure 3).

(**a**) (**b**)

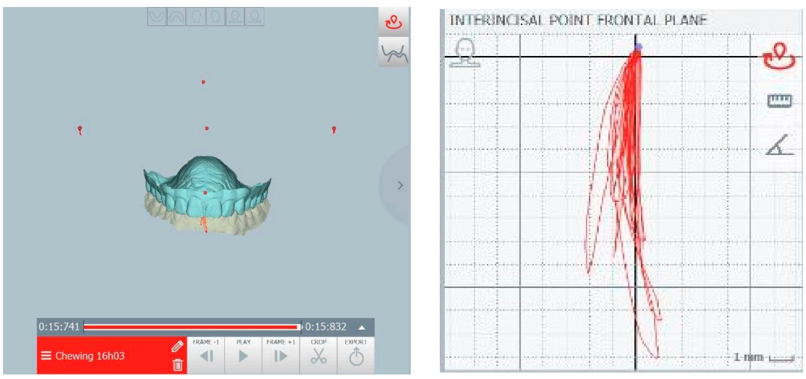
**Figure 3.** (**a**) Lateral view of a volunteer student wearing tiara and fork; (**b**) Volunteer performing chewing movements.

After the ModJaw® device calibration, the markers (Fork and Tiara) were then positioned on the volunteer's jaw and head (Figure 3). Calibration of the Modjaw® system is a fundamental step to ensure the accuracy of measurements of mandibular kinematics and occlusal dynamics. The Modjaw® system requires the definition of an "individual reference plane" for the patient as a reference for jaw movements. This is done through the acquisition of anatomical reference points related to the position of the head using the optical markers on the tiara and the "interincisal point," the most anterior point between the lower incisors, using the optical markers on the wand. During calibration, it is also essential to identify the "hinge axis" of the jaw by marking both the condylar lateral poles of the patient. All volunteers were instructed to perform movements before registration and the experimenter monitored upon the correct execution of procedures. Before the masticatory test, the volunteer was also instructed to place a biscuit on the tip of their tongue and to start every test with their teeth initially closed.

Upon receiving a vocal command from the experimenter, the volunteer commenced chewing unilaterally for a duration of 15 s. In this study, the volunteers were asked to begin with right-sided unilateral chewing.

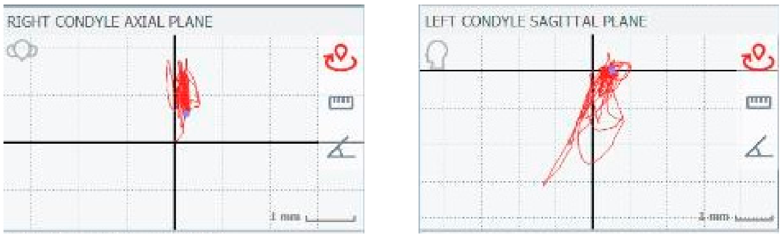
Data on unilateral chewing on both the right and left side were recorded, along with right and left laterotrusion to measure the Bennet angle, and protrusion-retrusion to measure condylar slopes angle. These were recorded and analyzed.

Figure 4 shows an example of a right masticatory cycle recorded by Modjaw®, the software represents the traces of the right and left condyle recorded from the points located on the right and left condyles and the tracing of mandibular movements recorded from the interincisal point during the 15 s of recording.




(**a**) (**b**)

**Figure 4.** *Cont.*

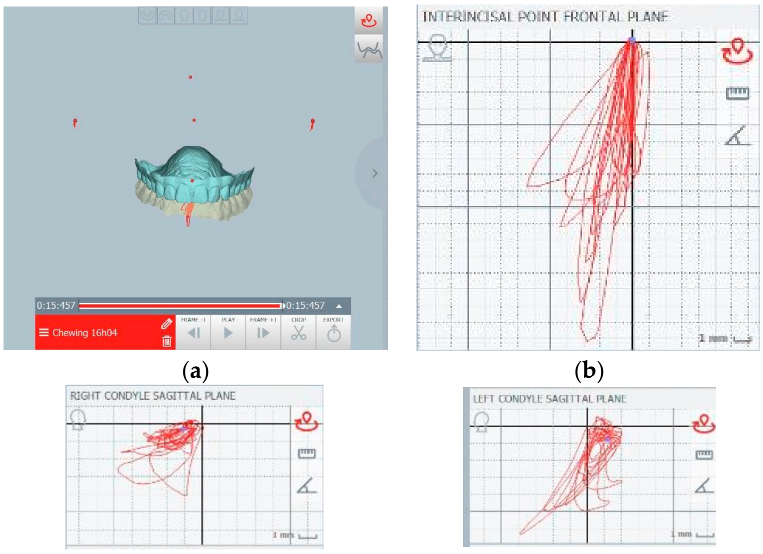



(**c**) (**d**)

**Figure 4.** (**a**) Chewing recording with ModJaw® Right Trial; (**b**) Right masticatory cycle from an interincisival point of view frontal plane; (**c**) Right condyle path on the axial plane during unilateral chewing on the right side; (**d**) Left condyle path on the sagittal plane during unilateral chewing on the right side.

Similarly, the volunteer again positioned the biscuit on the tip of their tongue. Upon receiving the voice command, they commenced unilateral chewing on the left side for 15 s.

Figure 5 shows similar recorded data during masticatory cycle on the left side.




(**c**) (**d**)

**Figure 5.** (**a**) Chewing recording with ModJaw® Left Trial; (**b**) Left masticatory cycle from an interincisival point of view; (**c**) Right condyle path on the sagittal plane during unilateral chewing on the left side; (**d**) Left condyle path on the sagittal plane during unilateral chewing on the left side.

Electromyography was recorded using TMJoint sEMG device (© 2023 BTS Bioengineering, Garbagnate Milanese, MI, Italy) with the software Dental Contact Analyzer (Version 4.0.43.2).

After the examination with Modjaw®, the experimenter removed the markers and prepared the volunteer's skin by cleaning it with ethanol on the masseter and anterior temporal muscles to enhance electrode adhesion and reduce impedance (Figure 6a,b).

Before the start of the examination, in order to place the electrodes, the volunteer was asked to clench their teeth while the experimenter palpated the position of the masseter and temporalis muscles with their finger (Figure 6c–f) and placed the TMJoint® sensors accordingly on the muscle bellies parallel to the muscle fiber (Figure 6d–f).

Following the instructions in the manufacturer's user guide, the first pre-operative test was registered and consisted of recording a maximum voluntary contraction (MVC) of the teeth by interposing 10 mm cotton rolls for 5 s on the mandibular second premolar to standardize the sEMG potential (Figure 7).

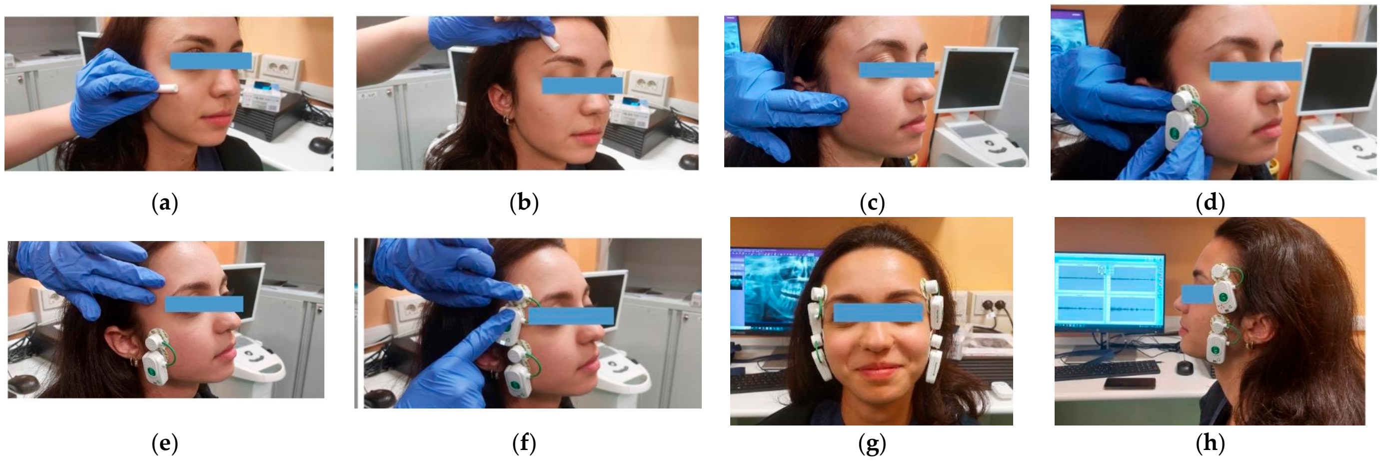



**Figure 6.** Skin detersion of the temporalis and masseter muscle area; (**a**,**b**) Palpation of the temporalis and masseter muscle region; (**c**–**e**), TMJoint® electrodes placement on masseter and temporalis muscle; (**d**–**f**), front and side view (**g**,**h**).

**Figure 7.** Volunteer performing MVC interposing cotton rolls.

Afterwards, the masticatory test was performed, during which the volunteer was instructed to place a biscuit on the tip of their tongue, as during the jaw-tracking recording, and to start every test with their teeth initially closed.

Upon receiving a vocal command from the experimenter, the volunteer performed chewing unilaterally for a duration of 15 s. Also, during sEMG test the volunteer was asked to begin with right-sided unilateral chewing. Similarly, for the left side, the volunteer again positioned the biscuit on the tip of their tongue. Upon receiving the voice command, they commenced unilateral chewing on the left side for 15 s.

The following Parameters were extracted from the Dental contact Analyzer® software data:

- SMI: The symmetry muscular index (SMI, %) is a measure that evaluates the balance and coordination of muscle activation during chewing. It quantifies the symmetry between the right and left sides of the masticatory muscles. The SMI is expressed as a percentage, with 100% representing perfect symmetry. Values lower than 100% indicate asymmetry, with one side exhibiting greater muscle activity than the other. This index is valuable for assessing muscular imbalances and functional issues in the masticatory system, as well as monitoring the effectiveness of treatment interventions aimed at improving chewing function and restoring muscle balance. An example is represented in Figure 8.
- Frequency (bps) is the number of masticatory acts per second expressed in bps or bytes per second.

- Modmed (measured in percentage between right and left cycles, %) is the distance from the center of the graph and the center of the ellipse of the right and left chewing cycles. (ModmedR and ModmedL, of the right and left chewing cycles.)
- TA IMPACT (%) is an index of the work done by the anterior temporal muscles during the test. (TAIR and TAIL, of the right and left chewing cycles.)
- MM IMPACT (%) It is an index of the work done by the masseter muscles during the test. (MMIR and MMIL, of the right and left chewing cycles.)

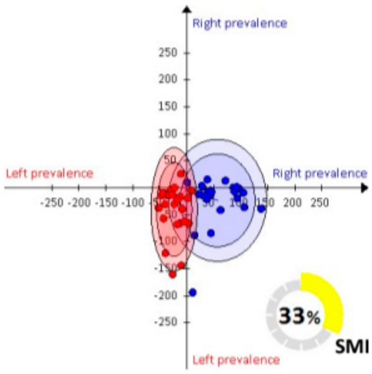
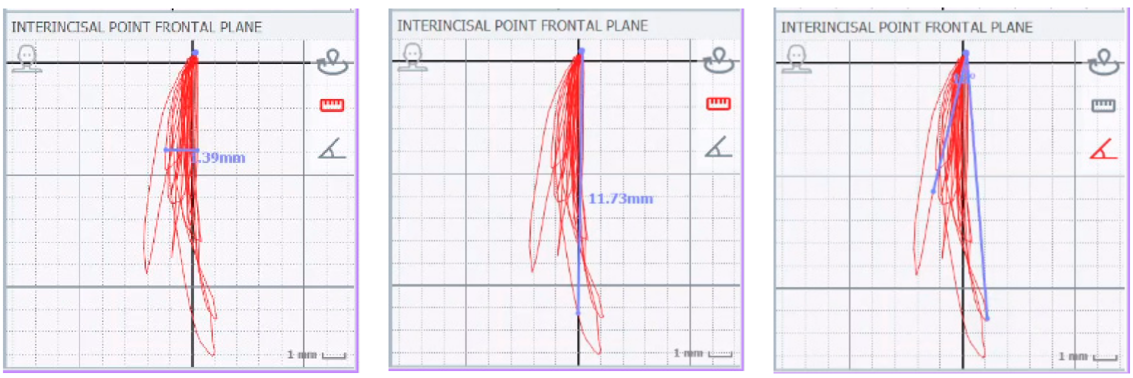



**Figure 8.** Representation of the SMI parameter: the red ellipse represents the left chewing cycle. The blue ellipse is the right one. SMI represents the amount of symmetry between the two cycles, which in this case is only 33%.

Chewing graphs extracted by the Modjaw® device were:

- CS: Condylar slopes during protrusion-retrusion movements (degree), named CSL and CSR for the left and right side, respectively.
- BA: Bennet Angle during lateral movements (degree), named BAL and BAR for the left and right side, respectively.
- MW: Masticatory Width on the masticatory interincisival graph (mm), named WR and WL for the right and left side, respectively (Figure 9a).
- MH: Masticatory Height on the masticatory interincisival graph (mm), named HR and HL for the right and left side, respectively (Figure 9b).
- MA: Masticatory Angle on the masticatory interincisival graph (degree), named MAR and MAL for the right and left side, respectively (Figure 9c).




(**a**) (**b**) (**c**)

**Figure 9.** (**a**) Example of MW masticatory width measurement taken on the graph of chewing movements marked by the interincisival point; (**b**) Example of MH masticatory height measurement taken on the graph of chewing movements marked by the interincisival point; (**c**) Example of MA masticatory angle measurement taken on the graph of chewing movements marked by the interincisival point.

The masticatory angle, with the vertex located at the lower interincisal point, can be described as the angle formed by the mandibular movements during mastication. In this configuration, the vertex of the angle coincides with the interincisal point (i.e., the interincisal point is located at the level of the lower central incisors and is used to mark the center of mastication and mandibular trajectories during functional movements.) while the sides of the angle represent the mandibular trajectories during the opening and closing phases of the mouth during unilateral chewing. The masticatory angle on the graphs was measured using the ruler and goniometer provided by the TWIM software, as shown in Figure 9.

In practice, this angle allows for the study of the dynamics of mastication, including the symmetry or asymmetry of movements, the smoothness of the chewing cycle, and potential dysfunctions or deviations from a "normal" chewing cycle. Then, to express the angular measurement as a linear measurement, the difference between the right and left masticatory angles was calculated, and a percentage value of $\frac{MAR}{MAL} \times 100$.

(The lesser divided by the greater multiplied by 100) was calculated. This variable was called angular percentage value $\frac{MAR}{MAL} \times 100$.

The sample size of the present study was calculated with an a priori power analysis performed on the basis of a pilot study with preliminary data obtained from the first 10 subjects of the present study. On this preliminary sample a correlation of r = −0.59 was found for SMI% that was considered as a primary outcome. A sample size a priori estimation conducted on the basis of previous references [19,20] showed that in order to achieve a power of 80% with an alpha of 0.05 on the primary outcome, a minimum sample of 20 subjects was necessary.

Data were analyzed with descriptive and inferential statistics. Descriptive statistics included the mean and standard deviation of all the variables for the whole sample.

For the inferential analysis, firstly, the Pearson correlation coefficient (r) was calculated to assess the correlation between the variables extracted by electromyographic data, and those extracted by cinematic data.

## 3. Results

All participants performed the masticatory task and did not report any discomfort. Descriptive statistics for each variable are reported in Table 1.

**Table 1.** Descriptive statistics.

| Variable | Mean ± SD |
|---|---|
| **Mandibular cinematic** | |
| CSL (degree) | 58.82 ± 7.82 |
| CSR (degree) | 60.09 ± 9.76 |
| BAL (degree) | 15.14 ± 11.62 |
| BAR (degree) | 17.18 ± 14.02 |
| MHR (mm) | 16.01 ± 2.74 |
| MHL (mm) | 18.21 ± 2.70 |
| MWR (mm) | 8.35 ± 2.54 |
| MWL (mm) | 9.07 ± 3.38 |
| MAL (degree) | 55 ± 16.69 |
| MAR (degree) | 54.31 ± 21.93 |
| **Electromyography** | |
| SMI (%) | 24.59 ± 24.19 |
| Frequency R (bps) | 1.77 ± 0.31 |
| Frequency L (bps) | 1.71 ± 0.25 |
| Modmed R (%) | 194.35 ± 247.95 |
| Modmed L (%) | 150.20 ± 160.61 |
| TAIR (%) | 209.82 ± 140.12 |
| TAIL (%) | 184.58 ± 100.63 |
| MMIR (%) | 132.82 ± 71.85 |
| MMIL (%) | 151.11 ± 70.79 |

The Pearson correlation coefficient was calculated and a moderate negative correlation (−0.42) was observed between the masticatory symmetry index (SMI %) during sEMG recording and the difference between the right and left masticatory angles as percentage value was calculated as $\frac{MAR}{MAL} \times 100$ (Figure 10).

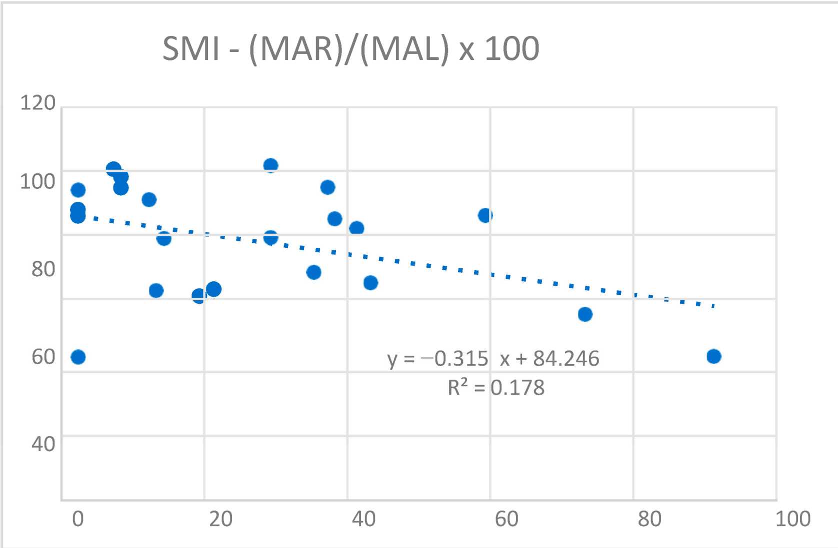



**Figure 10.** Scatterplot graph showing correlation between SMI (%) and $\frac{MAR}{MAL} \times 100$.

A weak positive correlation has been noted between the masticatory height MHR and the work produced by the masseter muscle MMIR on the right side. Furthermore, a weak positive correlation has been observed between the masticatory height MHL and the work produced by the masseter muscle MMIL on the left side (Figures 11 and 12). This section is divided by subheadings and provides a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

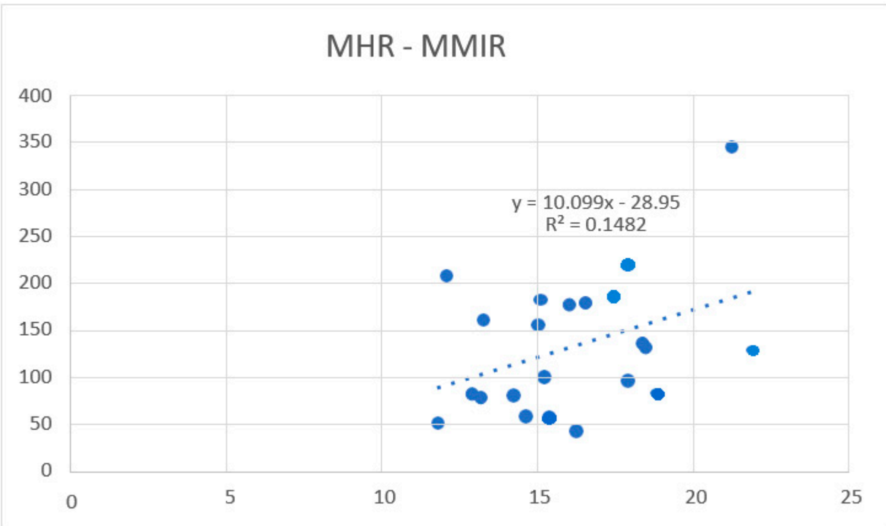



**Figure 11.** Scatterplot graph showing correlation between MHR (mm) and MMIR (%).

Finally, a weak positive association was noted between the right condylar slope (CSR) and the activity of the right anterior temporal muscle (TAIR). In addition, a weak positive correlation was detected between the left condylar slope (CSL) and the activity of the right anterior temporal muscle (TAIL) (Figures 13 and 14).

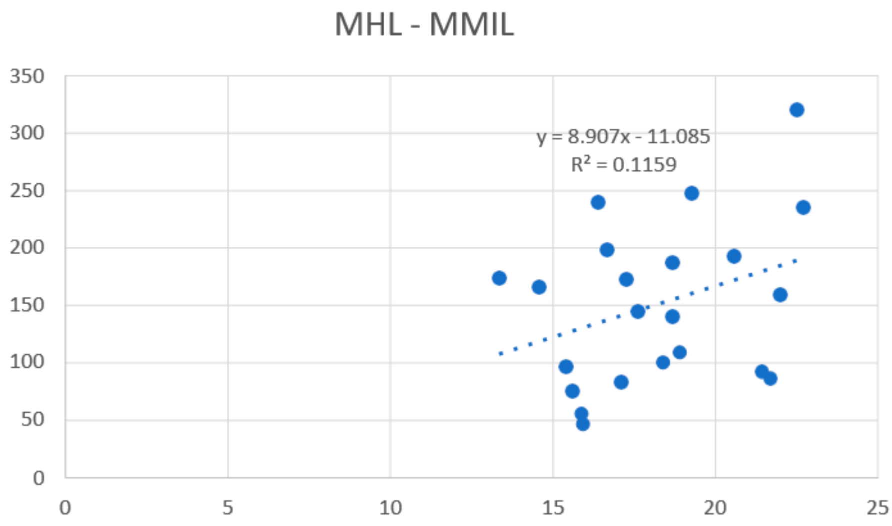



**Figure 12.** Scatterplot graph showing correlation between MHL (mm) and MMIL (%).

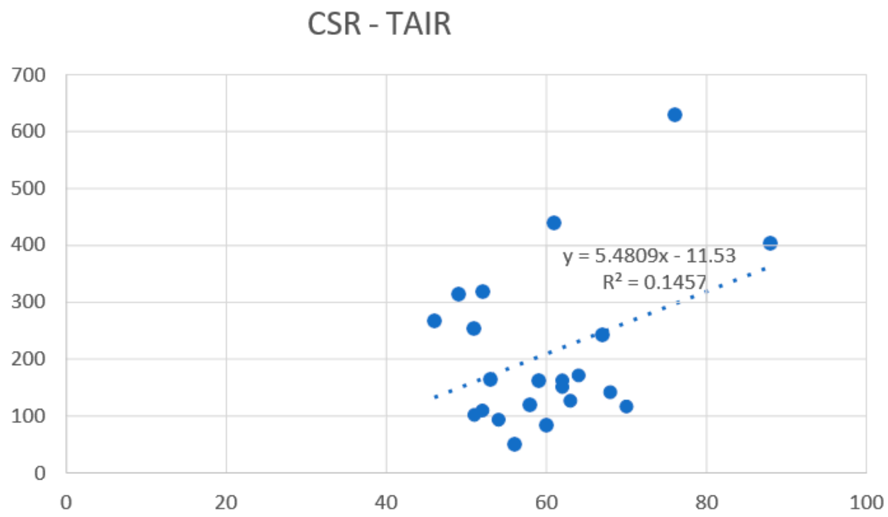



**Figure 13.** Scatterplot graph showing correlation between CSR (°) and TAIR (%).

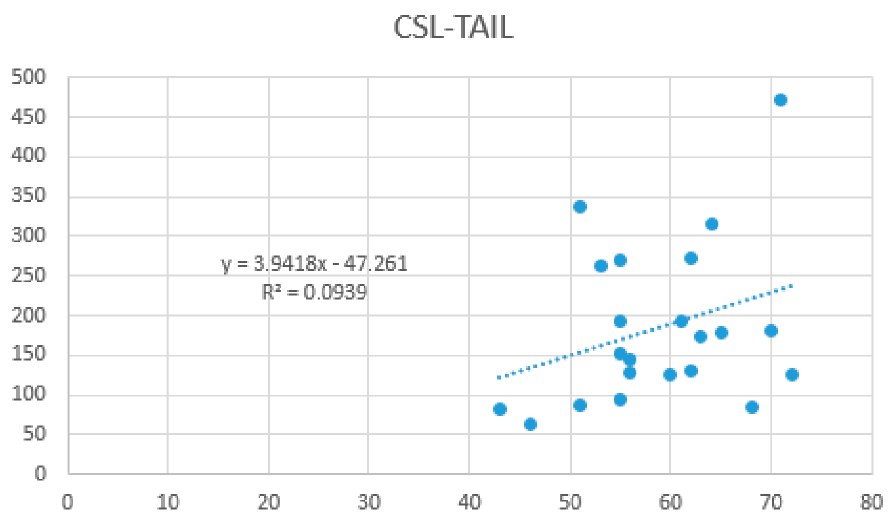



**Figure 14.** Scatterplot graph showing correlation between CSL (°) and TAIL (%).

## 4. Discussion

This study investigated the correlations between sEMG activity of the major masticatory muscles and mandibular kinematics in 22 healthy volunteer subjects during the unilateral chewing cycle both on the left and right side.

Focusing on outcomes, consistency was found in data collected through Modjaw® with previous studies conducted in 2023 regarding the mean condylar slope angle during protrusion movement.

Lassman et al., who analyzed 30 healthy subjects with the age range of 21–23 without a history of trauma, orthodontic treatment, or temporomandibular disorders, found the sagittal condylar guidance to be 56.6° ± 6.62° [21].

In our study, the right condylar slope angles (60.09° ± 9.76°) were slightly higher on average compared to the left ones (58.82° ± 7.82°). A study on 22 non-TMD volunteers (15 F/7 M; mean age: 22.2 years) reported sagittal condylar guidance of 51.07° ± 9.43° using Modjaw®, and the results of the present study were higher by 2° [4].

According to Dragust et al., differences of up to 26.1° between the right and left condylar slope angles were not uncommon; furthermore, they found no statistically significant association with skeletal class, age, gender, dentate status, TMJ pathology, or parafunctional habits [22].

Bennett angles measured during lateral movements were on average 15.14° ± 11.62° on the left side and 17.18° ± 14.02° on the right side. Conversely, Bapelle et al. found a mean value of 7.1° ± 5.1° in mediotrusion. As supported by Zwijnenburg et al., the choice of condylar reference point significantly influences the three-dimensional excursions of the condylar points. Furthermore, the Bennett angle and Bennett shift exhibit significant variations depending on the position of the reference point during lateral movements. These findings underscore the importance of using a consistent condylar reference point for meaningful comparisons of condylar movements among different studies and highlight the need for a standardized consensus on the choice of condylar reference point [23].

Continuing the analysis from a kinematic perspective, in a study by Pasinato et al., which tested masticatory cycle parameters using a jaw-tracking device in eight male patients aged 19–24 years with a diagnosis of Angle Class I malocclusion, the masticatory cycle height on the habitual side was found to be 12.43 ± 3.11 mm. The mean value for unilateral chewing was 12.21 ± 2.34 mm. These data were slightly lower than those observed in the present study. In the left trial, chewing resulted in a 2 mm increase compared to the mean of the right trial. In the same study, the parameters of masticatory cycle amplitude were also analyzed, resulting in a value of 9.49 ± 0.87 on the habitual side and 9.61 ± 1.77 for unilateral chewing. These results are consistent with the present study. However, similar to this work's findings, there was a slight increase in the parameters on the left side [24].

It must be said that the slight discrepancies with the previous studies could be related to the different samples, the test food used, and other protocol differences involved.

No studies were found to compare the angle relative to the right or left chewing cycle graph from the incisal viewpoint. This angle was directly drawn and measured on the Modjaw® chewing cycle graph from the incisal viewpoint using the angle tool to evaluate chewing asymmetry between the left and right trials.

Focalizing on electromyographic data, findings of the present study from assessments of unilateral chewing cycles on the right and left sides have revealed challenges in interpretation and comparison with other literature data.

To evaluate whether the left and right chewing tests were conducted with symmetrical muscular patterns, the symmetrical mastication index (SMI, %) was assessed. The Symmetrical Masticatory index is computed using the center of the two confidence ellipses to assess whether the left and right masticatory trials were performed with symmetrical muscular patterns.

The SMI, according to Ferrario et al., ranges from 0% (asymmetric muscular pattern) to 100% (symmetric muscular pattern). Several studies confirm the data introduced by Ferrario et al. in 2000 [24,25]. Additionally, Ferreira et al. noticed that TMD patients showed significantly greater difficulty in chewing, reduced symmetrical mastication index (SMI), and increased standardized activity during EMG tests than healthy subjects. In the study by Ferreira, the mean SMI% value was evaluated during unilateral gum chewing: 30 healthy subjects measured 66.50 ± 18.33 and 46 subjects suffering from TMD scored 44.76 ± 29.20 [24].

The SMI mean value measured in this study was significantly lower than expected (24.59 ± 24.19) and was calculated as follows by the BTS Dental Contact Analyzer software version 4.0.43.2:

$$\text{SMI} = 100.0 - ((\text{DistDxSx}/(2 \times \text{Math.Max}(\text{ModMedDx}, \text{ModMedSx}))) \times 100.0)$$

$$\text{DistDxSx} = \text{distance from the centroid of the left side flipped with respect to the centroid of the right side}$$

$$\text{Math.Max}(\text{ModMedDx}, \text{ModMedSx}) = \text{Maximum distance between the two centroids}$$

The SMI values calculated in this study appear to fall below the TMD cut-off values described by Ferreira et al. and Mapelli et al., but this study's subjects did not exhibit any signs or symptoms of TMD or chewing impairments. This value seems to be less accurate of the actual health condition of the subjects belonging to the study, as it is worth noting that Ferreira et al. also observed that 56% of the control subjects scored an SMI lower than 55% [24].

The frequency of the unilateral chewing cycle, intended as masticatory rhythm (bps), is not a common value found in dentistry literature. To convert "bps" (bites per second) to "Hz" (Hertz), we assumed the average duration of a single bite or chewing cycle was 1 s 1 Hz = 1 bps/average duration of a bite.

The measurements of this work converted parameters in Hz showed a slight increase compared to the values reported by Ferrario in elderly subjects, with 1.77 ± 0.3 Hz on the right and 1.71 ± 0.25 Hz on the left [26].

Healthy individuals typically exhibit a notable level of masticatory frequency stability, whereas those wearing complete dentures or diagnosed with temporomandibular disorders (TMD) often demonstrate decreased mastication frequency compared to their healthy counterparts.

Furthermore, chewing frequency has been reported to range from 1.00–1.6 Hz [24].

The distance from the center of the graph and the center of the ellipse, also called ModMed, was evaluated and was similar among healthy subjects [24].

In 2021, researchers conducted an analysis of new functional measures for evaluating the activity of masticatory muscles. They compared these measures to the existing and widely used indices in both healthy and individuals suffering from TMDs [27].

However, consensus on the appropriate indices for assessing masticatory muscle activity using surface electromyography (sEMG) during chewing has not been reached yet.

Regarding the kinematics of movements, a variable representing the degree of symmetry between chewing on the right side and chewing on the left side was introduced. This was done by considering the angle between the true vertical and a line passing through the highest point of the opening path and the point farthest from the vertical line.

The symmetry (ratio) between the right angle (MAR) and the left angle (MAL) was then expressed as a percentage $\frac{MAR}{MAL} \times 100$.

This variable was created to facilitate the comparison of kinematic data with electromyographic data, which are expressed in the literature using the SMI index (%), describing the symmetry through the overlap of the electromyographic trace on the right side with that on the left side [28,29].

In general, this study found only weak correlations between variables related to mandibular kinematics and variables related to electromyographic activity of the masseter and anterior temporal muscles. This may be attributed to the fact that the process of mastication involves multiple intra-oral structures, such as the lips, tongue, and hard and soft palates, which play a role in food intake and size reduction. However, these structures were not assessed in this research protocol as human studies typically focus on surface masseter and anterior temporalis EMG activity due to their non-invasive nature and ease of measurement.

Based on the negative correlation (−0.42) obtained between the SMI (%) muscular symmetry index and the symmetry variable between the masticatory angles $\frac{MAR}{MAL} \times 100$, it can be deduced that as the complexity of the masticatory path increases, functional symmetry between the right and left sides tends to decrease (Figure 10).

However, it's important to note that the magnitude of the correlation indicates a moderate strength, which means that while there is an association between the variables, it is not particularly strong.

Based on the literature review, the SMI % parameter for healthy participants in the study was found to significantly deviate from the indicated values. Thus, we conclude that this parameter is not reliable or reproducible in this analysis.

Furthermore, a positive weak correlation has been noted between the masticatory height MHR and the work produced by the masseter muscle MMIR on the right side. A corresponding positive weak correlation has been observed between the masticatory height MHL and the work produced by the masseter muscle MMIL on the left side (Figures 11 and 12).

The jaw-closer muscles, especially the masseter, perform most of the mastication work during the jaw-closing power stroke. Therefore, the observed results suggest that greater work is produced by the masseter muscles when the amplitude of mouth opening during the chewing cycle is larger.

In people with particularly large movements, the increased work of the masseter muscles may cause overexertion and noticeable movements during chewing.

Moreover, a weak positive association was noted between the right condylar slope (CSR) and the activity of the right anterior temporal muscle (TAIR). Also, a weak positive correlation was detected between the left condylar slope (CSL) and the activity of the right anterior temporal muscle (TAIL). It follows from this positive correlation that as the work produced by the temporalis muscle increases, so does the CS. In other words, as the temporalis is a postural muscle that also comes into action in retrusive movements, the greater the CS, the greater the activation and work expressed by the temporalis muscle (Figures 13 and 14).

In a study published in 2022, the possible correlations between mandibular kinematics and electromyography during the chewing cycle were evaluated using a Motion Capture System and landmarks on the two mandibular angles, specifically at the Nasion and Frankfurt planes. The study found a correlation between the vertical amplitude of the opening path and the electromyographic activity of the suprahyoid muscles [30].

Several limitations of this study should be considered when interpreting the findings. First, we recruited only healthy young male and female participants, so these findings could not be generalized to other/older populations. Considering the effects of age, particularly regarding the effects of dental status or oral dryness, recruiting other populations would help clarify how these conditions affect masticatory behaviors. Moreover, volunteer subjects were not asked which was their preferred or habitual chewing side.

In future studies, it will be interesting to focus on the effect of age and gender on masticatory kinematics as well as EMG activity.

In addition, only one type of food (biscuits) was used, so we could not determine specifically which factors, including the shape, size, or taste of the foods, were critical for determining the masticatory movements. Finally, the focus was on only the mandibular range of motion, while other kinematic parameters, such as the duration and speed of mandibular movements, should also be evaluated.

## 5. Conclusions

With the above considered limitations, the present findings demonstrate that analyzing both EMG activity and mandibular kinematics provides a useful modality for evaluating the masticatory physiology of a range of solid foods.

It can be inferred from the results that the chewing cycle with a greater vertical movement results in increased masseter muscular activity, and condylar slopes are positively related to an increase in temporalis muscle activation.

Lastly, by combining the findings from sEMG and Modjaw® in further studies, clinicians could enhance their diagnostic capabilities, improve treatment planning, and develop more personalized therapeutic interventions for patients with temporomandibular dysfunctions.

**Author Contributions:** Conceptualization, A.N. and S.T.; Data curation, A.N., L.P., A.C.L. and S.T.; Formal analysis, A.N., L.P. and S.T.; Investigation, A.N., L.P., F.M.M., A.C.L. and S.T.; Methodology, A.N. and S.T.; Project administration, S.T.; Supervision, A.N. and S.T.; Validation, A.N., L.P. and S.T.; Visualization, A.N., L.P. and S.T.; Writing—original draft, A.N., L.P., A.C.L. and S.T.; Writing—review & editing, A.N., L.P., F.M.M., A.C.L. and S.T. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** This study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of I.R.C.C.S. San Raffaele Hospital, Milan, Italy ("parere09/int/2023" 25 January 2023).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Individual patients' data are not shown for privacy reasons but are available upon reasonable request at Vita-Salute San Raffaele University in Milan, Italy.

**Acknowledgments:** The authors acknowledge the Companies Teethan (Garbagnate Milanese, Milan, Italy) and ModJaw (Villeurbanne, France) for the technical support and the loan for the use of the device.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Bedrossian, E.A.; Bedrossian, E.; Kois, J.C.; Revilla-León, M. Use of an optical jaw-tracking system to record mandibular motion for treatment planning and designing interim and definitive prostheses: A dental technique. *J. Prosthet. Dent.* **2022**, *132*, 659–674. [CrossRef] [PubMed]
2. Nota, A.; Ryakhovsky, A.N.; Bosco, F.; Tecco, S. A full digitalworkflow to design and mill a splint for a patient with temporomandibular joint disorder. *Appl. Sci.* **2021**, *11*, 372. [CrossRef]
3. Baldini, A.; Beraldi, A.; Nota, A.; Danelon, F.; Ballanti, F.; Longoni, S. Gnathological postural treatment in a professional basketball player: A case report and an overview of the role of dental occlusion on performance. *Ann. Stomatol.* **2012**, *3*, 51–58.
4. Bapelle, M.; Dubromez, J.; Savoldelli, C.; Tillier, Y.; Ehrmann, E. Modjaw® device: Analysis of mandibular kinematics recorded for a group of asymptomatic subjects. *CRANIO-J. Craniomandib. Pract.* **2021**, *42*, 483–489. [CrossRef]
5. Tecco, S.; Nota, A.; Pittari, L.; Clerici, C.; Mangano, F.; Gherlone, E.F. Full-Digital Workflow for TMDs Management: A Case Series. *Healthcare* **2023**, *11*, 790. [CrossRef]
6. Karasan, D.; Sailer, I.; Lee, H.; Demir, F.; Zarauz, C.; Akca, K. Occlusal adjustment of 3-unit tooth-supported fixed dental prostheses fabricated with complete-digital and -analog workflows: A crossover clinical trial. *J. Dent.* **2023**, *128*, 104365. [CrossRef]
7. Al Hamad, K.Q.; Al Rashdan, B.A.; Al-Kaff, F.T. Virtual patient representation with silicone guide and a 3D scanner accessory for a user-friendly facial scanning workflow: A clinical report of smile design and ceramic veneers. *J. Prosthet. Dent.* 2023, in press. [CrossRef]
8. Møller, E. The chewing apparatus. An electromyographic study of the action of the muscles of mastication and its correlation to facial morphology. *Acta Physiol. Scand. Suppl.* **1966**, *280*, 1–229.
9. Colonna, A.; Bracci, A.; Ahlberg, J.; Câmara-Souza, M.B.; Bucci, R.; Conti, P.C.R.; Dias, R.; Emodi-Perlmam, A.; Favero, R.; Häggmän-Henrikson, B.; et al. Ecological Momentary Assessment of Awake Bruxism Behaviors: A Scoping Review of Findings from Smartphone-Based Studies in Healthy Young Adults. *J. Clin. Med.* **2023**, *12*, 1904. [CrossRef]
10. Nota, A.; Pittari, L.; Gamba, L.; Monticciolo, F.M.; Lannes, A.; Carta, C.; Beraldi, A.; Baldini, A.; Marzo, G.; Tecco, S. Cervical Range of Motion Analysis Performed with an Accelerometer: A Study of Intersession Reliability for Dental Practice. *Healthcare* **2023**, *11*, 1428. [CrossRef]
11. Nowak, M.; Golec, J.; Wieczorek, A.; Golec, P. Is There a Correlation between Dental Occlusion, Postural Stability and Selected Gait Parameters in Adults? *Int. J. Environ. Res. Public Health* **2023**, *20*, 1652. [CrossRef] [PubMed]

12. Lanteri, V.; Cagetti, M.G.; Ugolini, A.; Gaffur, F.; Maspero, C.; Abate, A. Skeletal and dento-alveolar changes obtained with customised and preformed eruption guidance appliances after 1-year treatment in early mixed dentition. *Eur. J. Paediatr. Dent.* **2023**, *24*, 1–9. [CrossRef]
13. Lepidi, L.; Galli, M.; Mastrangelo, F.; Venezia, P.; Joda, T.; Wang, H.L.; Li, J. Virtual Articulators and Virtual Mounting Procedures: Where Do We Stand? *J. Prosthodont.* **2021**, *30*, 24–35. [CrossRef] [PubMed]
14. Bates, J.F.; Stafford, G.D.; Harrison, A. Masticatory function-a review of the literature III. Masticatory performance and efficiency. *J. Oral Rehabil.* **1976**, *3*, 57–67. [CrossRef]
15. Piancino, M.G.; Falla, D.; Merlo, A.; Vallelonga, T.; De Biase, C.; Dalessandri, D.; Debernardi, C. Effects of therapy on masseter activity and chewing kinematics in patients with unilateral posterior crossbite. *Arch. Oral Biol.* **2016**, *67*, 61–67. [CrossRef]
16. Piancino, M.G.; Tortarolo, A.; Di Benedetto, L.; Crincoli, V.; Falla, D. Chewing Patterns and Muscular Activation in Deep Bite Malocclusion. *J. Clin. Med.* **2022**, *11*, 1702. [CrossRef] [PubMed]
17. Piancino, M.G.; Isola, G.; Merlo, A.; Dalessandri, D.; Debernardi, C.; Bracco, P. Chewing pattern and muscular activation in open bite patients. *J. Electromyogr. Kinesiol.* **2012**, *22*, 273–279. [CrossRef] [PubMed]
18. Schiffman, E.; Ohrbach, R.; Truelove, E.; Look, J.; Anderson, G.; Goulet, J.P.; List, T.; Svensson, P.; Gonzalez, Y.; Lobbezoo, F.; et al. Diagnostic Criteria for Temporomandibular Disorders (DC/TMD) for Clinical and Research Applications: Recommendations of the International RDC/TMD Consortium Network* and Orofacial Pain Special Interest Group†. *J. Oral Facial Pain Headache* **2014**, *28*, 6. [CrossRef]
19. Machin, D.; Campbell, M.J.; Tan, S.B.; Tan, S.H. *Sample Size Tables for Clinical Studies*, 3rd ed.; John Wiley & Sons Ltd.: West Sussex, UK, 2009.
20. Moinester, M.; Gottfried, R. Sample size estimation for correlations with pre-specified confidence interval. *Quant. Methods Psychol.* **2014**, *10*, 124–130. [CrossRef]
21. Lassmann, Ł.; Nowak, Z.; Orthlieb, J.D.; Żółtowska, A. Complicated Relationships between Anterior and Condylar Guidance and Their Clinical Implications—Comparison by Cone Beam Computed Tomography and Electronic Axiography—An Observational Cohort Cross-Sectional Study. *Life* **2023**, *13*, 335. [CrossRef]
22. Dragus, A.C.; Mihai, A.; Tanase, G.; Burlibasa, M.; Cristache, C.M. Intraindividual Left–Right Side Differences of Sagittal Condylar Inclination (SCI) in Different Skeletal Classes. *Healthcare* **2023**, *11*, 1341. [CrossRef] [PubMed]
23. Zwijnenburg, A.; Megens, C.C.E.J.; Naeije, M. Influence of choice of reference point on the condylar movement paths during mandibular movements. *J. Oral Rehabil.* **1996**, *23*, 832–837. [CrossRef] [PubMed]
24. Pasinato, F.; Oliveira, A.G.D.; Santos-Couto-Paz, C.C.; Zeredo, J.L.L.; Bolzan, G.D.P.; Macedo, S.B.; Corrêa, E.C. Study of the kinematic variables of unilateral and habitual mastication of healthy individuals. In *CoDAS*; Sociedade Brasileira de Fonoaudiologia: São Paulo, Brazil, 2017; Volume 29. [CrossRef]
25. Ferreira, C.L.P.; Machado, B.C.Z.; Borges, C.G.P.; Da Silva, M.A.M.R.; Sforza, C.; De Felício, C.M. Impaired orofacial motor functions on chronic temporomandibular disorders. *J. Electromyogr. Kinesiol.* **2014**, *24*, 565–571. [CrossRef] [PubMed]
26. Mapelli, A.; Machado, B.C.Z.; Giglio, L.D.; Sforza, C.; De Felício, C.M. Reorganization of muscle activity in patients with chronic temporomandibular disorders. *Arch. Oral Biol.* **2016**, *72*, 164–171. [CrossRef]
27. Ginszt, M.; Zieliński, G. Novel functional indices of masticatory muscle activity. *J. Clin. Med.* **2021**, *10*, 1440. [CrossRef]
28. Ferrario, V.F.; Sforza, C.; Serrao, G.; Colombo, A.; Schmitz, J.H. The Effects of a Single Intercuspal Interference on Electromyographic Characteristics of Human Masticatory Muscles during Maximal Voluntary Teeth Clenching. *CRANIO-J. Craniomandib. Sleep Pract.* **1999**, *17*, 184–188. [CrossRef]
29. Ferrario, V.F.; Sforza, C.; Colombo, A.; Ciusa, V. An electromyographic investigation of masticatory muscles symmetry in normo-occlusion subjects. *J. Oral Rehabil.* **2000**, *27*, 33–40. [CrossRef]
30. Sasa, A.; Kulvanich, S.; Hao, N.; Ita, R.; Watanabe, M.; Suzuki, T.; Magara, J.; Tsujimura, T.; Inoue, M. Functional Role of Suprahyoid Muscles in Bolus Formation During Mastication. *Front. Physiol.* **2022**, *13*, 881891. [CrossRef]