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Abstract: This study proposes a cephalometric analysis that can be used for biomechanical simulation by considering the important and complex relationship between craniofacial morphology and masseter muscle (MM) size and inclination and by including muscle values. The MM line of action drawn between the Gonion (Go) and Orbital (Or) point relative to dental and skeletal references (occlusal and Frankfort planes) were analyzed. A total of 510 pre-treatment lateral cephalometric tracings (217 males, 293 females, 6-50 years) and lateral Bolton standard tracings (6-18 years) were analyzed. The study examined the following: a) skeletal-cutaneous class (linear distance in mm between the projections of points A' and B' on the occlusal plane), b) the angle between the perpendicular line to the occlusal plane and the Go-Or line at the molar occlusal point, and c) the angle between the Go-Or line and the Frankfort plane. The skeletal classes of the patients ranged from -14.5 to 15.5 mm and did not differ by sex or age; the angle between the Go-Or line and the normal to the occlusal plane averaged 39° (range 15° to 53°) and decreased with age, while the angle between the Go-Or line and the Frankfort plane averaged 42° (range 30° to 54°), increased in older patients. No effect of gender was observed. The two angles were also significantly correlated with each other, but not with sagittal jaw discrepancy. Similar results were obtained with Bolton tracings; the positional relationship of the Go-Or line to the teeth and skeletal landmarks is partially consistent with the literature. The present cephalometric analysis can be usefully used to estimate the mechanical advantage of MM in biomechanical simulations of masticatory muscle performance.

Keywords: cephalometric analysis; skeletal classes; muscular lines

1. Introduction

The ultimate goal of orthodontic treatment is to achieve neuromuscular balance and a stable occlusion (1).

The performance of the masticatory muscles is one of the functional variables that can be altered by orthodontic and surgical modification of the dental arch and craniofacial skeleton (2). The assessment of the actual bite force is difficult because bite force sensors often interfere with occlusion and the relationship between electromyographic signals and bite force is nonlinear (3). Except for relatively complex imaging techniques such as computed tomography, magnetic resonance imaging, and ultrasound, which cannot be performed extensively, biomechanical models from conventional radiographs are primarily used. In these models, muscle forces and occlusal resistance are estimated from geometric variables measured against tooth and skeletal landmarks (4-7). For this purpose, the mechanical advantage of the masticatory muscles, specifically the ratio of the muscle moment arm to the occlusal force moment arm, is determined.

This ratio depends on the line of action of the muscle and the associated moment arm. The position of the occlusal force is usually defined as perpendicular to the occlusal plane at the molar or incisor midline, but there is no agreement on the direction of the lines estimating the different masticatory muscles. In particular, the superficial part of the masseter muscle (MM) is estimated by

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a line connecting the gonion (Go) and several cephalic landmarks: a) the orbit (Or), b) the intersection of the flattened process of the zygomatic bone with the frontal process, and c) the zygomatic bone (the lowest point on the outline of the zygomatic process on the zygomatic bone) (4-6,8,9). In addition, a line connecting the anterior root of the zygomatic arch with the zygomatic-temporal suture and the midpoint of Go and the anterior root, and a line drawn parallel to the anterior root-key ridge line from the midpoint of Go and the anterior root have been proposed (10,11).

This lack of congruence can be overcome by directly analyzing the muscle itself, either by actual autopsy (postmortem) or virtual autopsy (magnetic resonance or computed tomography). Unfortunately, both ex vivo and in vivo studies have mostly involved small samples of adults and have not shown correlation with x-ray analysis (11-17). Furthermore, to our knowledge, no biomechanical studies have evaluated the relationship of these hypothetical lines of action to other craniofacial structures.

In the present study, the position of the presumed MM line of action drawn between Go and Or (6) relative to dental (occlusal plane) and skeletal (Frankfort plane) standards was analyzed in a) a large sample of unselected orthodontic patients of a wide age range, and b) lateral tracings of Bolton standards (male and female average) aged 6 to 18 (16). In addition, its relationship with sex, age, and skeletal-cutaneous class (soft tissue equivalent of the Wits appraisal, 19) has also been studied.

2. Materials and Methods

Sample

Pre-treatment lateral cephalometric tracings of 510 orthodontic patients (217 males and 293 females, aged 6-50 years) were used. The patient records used in this cross-sectional study were obtained from the dental department of the Fondazione IRCCS Ca' Granda Ospedale Maggiore Policlinico, Milan, Italy. Cephalograms were obtained by cone beam computed tomography (CBCT), as currently used in dentistry (20).

The study population included patients with the following dentoskeletal characteristics at the time of pretreatment lateral cephalometric imaging:

1. be of European (Caucasian) descent;
2. malocclusion that could be corrected by orthodontic treatment alone, as determined by a specialized orthodontist;
3. complete primary or permanent dentition (excluding third molars);
4. a maximum difference of 3 mm in the distance between each crest and maxillary point from the mid-sagittal plane in the posterior-anterior projection according to Hwang et al. (39);
5. no crossbite as reported in the patient's records and confirmed by CBCT scan.

Exclusion criteria were as follows:

1. missing molars or bicuspids;
2. a history of orthodontic treatment;
3. altered bone metabolism;
4. skeletal asymmetry greater than 2 mm on the left and right cephalograms;
5. syndromic disorders (acquired or congenital);
6. patients requiring surgery were not evaluated.

The objective of selecting orthodontic subjects was to design a simplified model that minimizes measurement error compared to interindividual variability (21).

Patients were divided into three non-overlapping age groups: 6-10 years (children), 11-15 years (adolescents), and 16-50 years (adults), all rounded to the nearest 6 months.

Details of the technique are described by Ferrario et al. (19,22); Bolton standard lateral tracings were digitized as previously described by Ferrario et al. (18,19).

Measurements

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CBCT raw data was stored in Digital Imaging and Communications in Medicine file format (DICOM3). Lateral radiographic projections of the entire volume were reconstructed for each raw data set using iCAT Vision (Imaging Sciences International Inc., https://ct-dent.co.uk/i-cat-vision/), according to Baldini et al. (21). All 2D cephalograms were then traced by two expert orthodontists (NC, CM) using dedicated software (Dolphin Imaging Cephalometric and Tracing Software, V 11.9, Chatsworth CA, USA, https://www.dolphinimaging.com/product/Imaging?Subcategory_OS_Safe_Name=Ceph_Tracing). Cephalometric points on CBCT scans were firstly identified in one plane (axial, coronal or sagittal) and then checked in the other two and in the 3D volumetric rendering (Figure 1). Linear and angular measurements, were obtained by means of computer software currently in use at our laboratory, according to Farronato et al. (20).

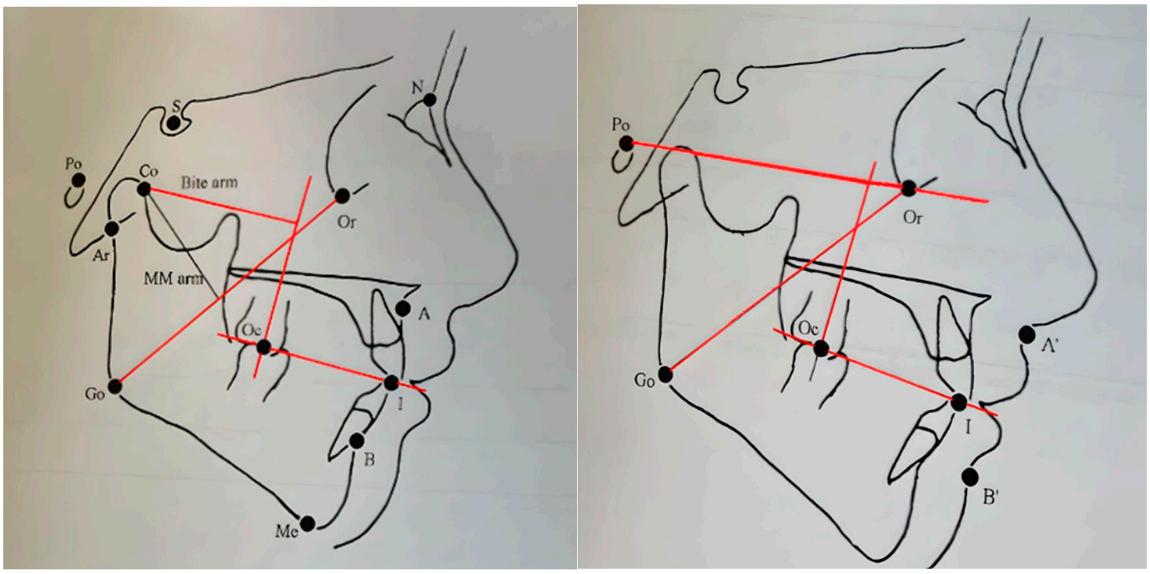

Figure 1. Digitized cephalometric landmarks. Po = Porion; Or = Orbital; Go = Gonion; I = inter-incisal point; Oc = occlusal point of first permanent molar; A′ = soft-tissue sub-spinal point; B′ = soft tissue supramental point; OP = occlusal plane; FP = Frankfort plane; XX = perpendicular line to the bisecting occlusal plane through Oc. The estimated MM line of action connects Go and Or.

Among others, the following measurements were selected and analyzed:

1. skeletal-cutaneous class (soft tissue equivalent of the Wits appraisal, i.e., the linear distance (mm) between the projections of the points A' and B' on the bisecting occlusal plane (OP), i.e., the plane bisecting the overbite of the molar and incisor teeth (19);
2. the angle between the Go-Or line (estimated MM action line) and the perpendicular line to the bisecting occlusal plane through the molar occlusal point (Oc);
3. the angle between the Go-Or line and the Frankfort plane (Po-Or).

Error evaluation method

Intra- and inter-operator reliability of the analyzed cephalometric measurements (ANB and AFBF) has been investigated in a previous study (20). Briefly, three independent observers with the same professional background and five years of orthodontic experience performed three cephalometric analyses at 15-day intervals. Intraclass correlation coefficient (ICC) estimates and their 95% confidence intervals for intra- and inter-rater reliability were calculated using SPSS® 25.00 for Windows™ (single-measure, absolute agreement, 2-way mixed effects model for each variable). Based on this, for the present calculations, two expert operators were calibrated in a training session, where the inter-examiner agreement on the tested characteristics was set to 95%.

In addition, a random sample of 30 images was retraced and redigitized by the same investigators one month later. Each set of cephalometric landmark coordinates was normalized with respect to rotation and translation by placing the origin of the axis at the center of gravity of the coordinates and aligning the X axis with the Frankfort plane (Po-Or). Each pair of repetitions was then compared between landmarks. Repeated digitization of the same traces produced differences of less than 2 mm (average 1.2 mm), and repeated tracing of the same radiographs produced differences of less than 2.5 mm (average 1.8 mm).

A linear correlation analysis between the measured variables was performed. Significance was set at α level of 5% (i.e., $p \leq 0.05$). Univariate (for linear variables) and bivariate (for angles) statistics were used to calculate means within sex and age groups (9).

Estimation of sample size

To estimate the line of action of MM from the lines of the simplified cephalogram, the results considered were Wits appraisals (see above). The skeletal-cutaneous class values for all patients before treatment, as measured by the lateral cephalogram, ranged from -14.5 to 15.5 mm, with no differences by sex or age. Therefore, with a significant difference @=0.05, @=0.8, mean difference in Wits values of 2.5 mm, and SD of 5.0 mm, the minimum sample size required for the study was N=140 (N=70 for each group).

3. Results

Orthodontic sample

The assessment of anterior-posterior jaw discrepancy, measured as the linear distance between the soft tissue A' and soft tissue B' projections on the occlusal plane (skeletal-cutaneous class or "soft tissue" Wits, 19), ranged from -14.5 to 15.5 mm. Abnormal values were found in two adolescents, the smallest being a 15-year-old girl and the largest being a 14-year-old boy. No specific gender- or age-related behavior was observed for this distance (Table 1), and the linear correlation coefficient with age was only 0.025 (Table 2).

The average angle between the estimated line of action (Go-Or) of the MM and the normal of the occlusal plane was 39.3°. On the other hand, the angle between the lines of Go-Or and Po-Or (Frankfort plane) averaged 41,99°, ranging from 30.4° to 53.8° (Table 1). No effect of gender was observed. The angle value decreased with increasing age, and on average was about 3° smaller in adults than in children. Conversely, the angle between the Go-Or line and the Frankfort plane increased an average of about 4° between ages 6 and 50. In fact, the correlation analysis between age and this variable showed a correlation coefficient of r = 0.449 (Table 2), which was the largest age effect found in the present orthodontic sample. The two angles were also significantly correlated.

Although the relationship between the sagittal jaw discrepancy and the angle between the estimated MM action line and the Frankfort plane was poor, about 20% of the variance in the angle between the Go-Or line and the normal of the occlusal plane was explained by the anteroposterior relationship between the maxilla and mandible (Table 2).

Table 1. Number of analyzed cephalograms, and descriptive statistics (mean and standard deviation in brackets) of the measured variables. Age was rounded at the nearest 6 months.

	Males	Females	All subjects	6-10 years	11-15 years	16-50 years
Orthodontic patients	217	293	510	257	134	119
Skeletal-cutaneous class (mm)	4.7 (4.1)	3.4 (3.7)	4.2 (4.0)	3.8 (3.4)	4.8 (4.2)	3.4 (5.8)
Go-Or to normal to OP (°)	39.59 (0.27)	39.12 (0.27)	39.33 (0.19)	39.92 (0.23)	39.41 (0.37)	36.87 (0.59)

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Go-Or to Po-Or (°)	41.99 (0.28)	41.98 (0.22)	41.99 (0.18)	40.95 (0.19)	42.34 (0.26)	45.39 (0.50)

Skeletal-cutaneous class = linear distance between the projections of A′ and B′ points on the occlusal plane.

Table 2. Linear correlation coefficients between the analyzed variables in the orthodontic sample.

	Age	Skeletal-cutaneous class	Go-Or to Po-Or
Skeletal-cutaneous class	0.025	-----	-----
Go-Or to normal to OP	0.255	0.444	0.322
Go-Or to Po-Or	0.449	0.057	-----

All analyses are significant at the 0.001 level.

Skeletal-cutaneous class = linear distance between the projections of A′ and B′ points on the occlusal plane.

Bolton tracings

Overall, the mean values of the three variables measured in Bolton tracings were similar to those found in orthodontic patients of similar age (Table 3), but the differences were less than 1 mm (skeletal-cutaneous class) and 2.5° (angles). The correlation between age and the angle between the Go-Or line and the Frankfort plane was particularly strong (Table 4).

Table 3. Descriptive statistics (mean and standard deviation in brackets) of the measured variables in the Bolton tracings between 6 and 18 years of age.

	All tracings	6-10 years	11-15 years	16-18 years
Skeletal-cutaneous class (mm)	3.5 (1.2)	2.8 (1.5)	4.2 (0.5)	3.8 (0.7)
Go-Or to normal to OP (°)	38.77 (0.47)	39.04 (1.11)	39.29 (0.20)	37.39 (0.45)
Go-Or to Po-Or (°)	40.72 (0.55)	38.89 (0.49)	41.16 (0.51)	41.09 (0.56)

Skeletal-cutaneous class = linear distance between the projections of A′ and B′ points on the occlusal plane.

Table 4. Linear correlation coefficients between the analyzed variables in the Bolton tracings.

	Age	Skeleto-cutaneous class	Go-Or to Po-Or
Skeleto-cutaneous class	0.410	-----	-----
Go-Or to normal to OP	0.397	0.530	0.481
Go-Or to Po-Or	0.965	0.367	-----

All analyses are significant at the 0.001 level.

Skeletal-cutaneous class = linear distance between the projections of A′ and B′ points on the occlusal plane.

Other correlation analyses showed slightly larger correlation coefficients for Bolton tracings than for patients ones.

4. Discussion

The study by Bakke et al. asserts that a defect or excess on one side of the skull can lead to an imbalance of muscular activity, which may worsen with growth. Thus, one of the influencing factors is occlusion. If the occlusion is correct, an increased neuromuscular response during muscle activity has been observed (23).

Patients with crossbite are asymmetrical in both static and dynamic phases of the activity of masticatory muscles. Some authors have stated that asymmetry at rest, during maximal clenching, and during mastication is not statistically significant (20,24-28). Farronato et al. proposed to investigate changes in temporalis and masseter muscle activity before and after SARPE (Surgically Assisted Rapid Palatal Expansion) in adult patients by measuring electromyographic and electrokinetic activity (29).

The biomechanical model should use cephalometric estimates of the muscle's line of action, which connects the midpoints of two skeletal attachments, i.e., close to the muscle's central axis. Unfortunately, muscle is a complex three-dimensional structure, and 2-dimensional representation by X-ray landmarks is only an approximation (30). In fact, all reported analyses use Go as the posterior end of the MM surface (4,5,8,9). This landmark is considered to be the midpoint of the mandibular attachment zone of the MM. Conversely, the midpoint of the Go and antegonion used by Osborn and Gionhaku and Lowe seemed too anterior for a human muscle (10). The superior end of the muscle should be between the zygomatic-temporal suture and the anterior end of the maxillary process of the zygomatic bone or, if well developed, the lateral corner of the zygomatic process of the maxilla (31). Unfortunately, identification of the corresponding cephalometric profile is often difficult, and alternative approaches have been devised.

The MM line of action used in this study was assumed to follow the line drawn between landmarks Go and Or, and was derived from a study by Throckmorton and Dean (6). This proposal appeared to be the simplest of several biomechanical models that define cephalometric landmarks that are difficult to identify on standard radiographs and thus may be of limited value in orthodontics, where X-ray exposure in pediatric patients should be limited. The angle between the line of action of the masseter muscle and the normal of the occlusal plane averaged about 40° for the patient sample and about 39° for the Bolton tracings, and the hypothesized line of action was far from perpendicular to the occlusal plane in both the orthodontic sample and in the "reference" group. In fact, it should be mentioned that the minimum joint load during symmetrical molar occlusion is predicted when the MM is 70° to 75° to the occlusal plane, i.e., 15° to 20° inclined to the normal of the occlusal plane (31). The variation within groups is small, and the present calculations are considered to be an approximation of reality, since the lines of action of the muscles are estimated with systematic errors.

A slight decrease with aging was observed in the mean values, which can be explained by changes in both the occlusal plane (second and third molar eruption, incisor movement) and gingival angle. Considering only the adult group (patients and Bolton's occlusion), the mean value of 37° compares well with the 33° for the long head type and 38° for the short head type found by Iwasaki in the dry cranium (12).

The values reported by Throckmorton ranged from 0° to 31° (4,6-8). Osborn found an almost 1:1 relationship between the MM angle and the occlusal angle of the molars in dry skulls, which means that the muscle line is approximately parallel to the normal of the occlusal plane.(10) Gionhaku and Lowe found an average radiographic inclination angle of 21° with respect to the occlusal plane in MM, and an average angle of 28° in their own study of 14 adult male subjects (14). In both cases, the subjects were between 4 and 6 years of age. The mean values of 12° and 20° are taken from the relevant autoptic (8) and cephalometric (9) literature, respectively (see references here). In a group of young adults (22-48 years), magnetic resonance studies showed a mean inclination angle of 16°, but with large individual differences, with a maximum value of 27° (12). However, in no case the muscle lines were defined in the same way. Furthermore, it has already been suggested that there may not be a constant relationship between the MM angle and the occlusal plane (12).

The angulation of the MM action line relative to the Frankfort plane was also calculated. In this case, the relationship with age was stronger, with correlation coefficients of 0.449 for patients (Table 2) and 0.965 for bolt tracings (Table 4). In the adult group of the orthodontic patient sample, the mean angle of 45° was 4° to 5° greater than in the pediatric group (mean 41°) and about 3° greater than in the adolescent group (mean 42°). Similar differences were found in the Bolton traces (Table 3). Thus, the present mean angle is in good agreement with the self-viewing findings of 45° by van Eijden et al. and about 54° by Kasai et al. Conversely, it differs from the 60°-90° range (mean 70°-78°) reported in recent magnetic resonance studies (13-15,17,32,33,34,35). In magnetic resonance testing, muscles are virtually sectioned along several spatial planes and their lines of action are mathematically reconstructed in three spatial dimensions. Furthermore, individual differences in muscle position and angle have been reported (14).

The inclination of the Go-Or line relative to the Frankfort plane was not related to the anteroposterior relationship of the jaw as assessed by the skeletal-cutaneous classes (A' and B') projected to the occlusal plane, nor was it poorly related to the inclination of the same Go-Or line relative to the normal to the occlusal plane (19). Conversely, there was a higher correlation between the estimated inclination of the muscle relative to the normal to the occlusal plane and the same skeletal-cutaneous class (Tables 2 and 4). Because Kasai et al. did not analyze the jaw-jaw relationship, we could not find any literature data on this point. Kasai et al. found a significant correlation of r=0.63 between the inclination of the masseter muscle to the occlusal plane and the saddle-nose line (13).

In this study, we studied both a standard group of well-known cephalometric patients (Bolton tracings14) and a large, heterogeneous group of orthodontic patients of both sexes in a wide age range. No selection criteria were used for orthodontic patients, and several types of malocclusions were sampled, as indicated by skeletal-cutaneous class values. Even if the mean value of 4 mm is representative of skeletal-skin Class I, the wide range indicates that the present results are not limited to a specific subject but can be extended to the general orthodontic population (19,36,37,38).

Furthermore, the similarity between the results obtained in patients and the Bolton standard, which should represent average normal craniofacial growth, suggests that the present results may be extrapolated beyond the orthodontic population. A more accurate analysis would require studying a new group of normal individuals. This is because the Bolton traces are from a population with a different ethnic origin (North American Caucasians with Northern European ancestry), a population that predates the current orthodontic population (data collection began in the 1930s). Unfortunately, there is no longer a general population outside of patients for whom invasive radiographic analysis is available, and both magnetic resonance imaging and autoptic studies are limited to small samples. Thus, biomechanical analysis must rely on either selected healthy subjects (usually adults), a small number of potentially unhealthy cadavers, or data collected from many patients of almost any age.

In conclusion, the current lines used to approximate MM inclination in cephalometric radiographs were readily identifiable in all cases. Its position with respect to the dental and skeletal reference (occlusal and Frankfort planes) partially agreed with the literature findings, even if different approximations of the MM line of action were made. With respect to the inclination to the Po-Or line, a significant effect of age was observed, which may explain some of the literature differences. Overall, given the important and complex relationship between craniofacial morphology and MM dimensions and inclination, the present cephalometric analysis can be usefully used to estimate the mechanical advantage of MM in biomechanical simulations of masticatory muscle performance.

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

Data Availability Statement: Data supporting reported results can be found on the database of the Dolphin software: https://www.dolphinimaging.com/product/Imaging?Subcategory_OS_Safe_Name=Ceph_Tracing).

Conflicts of Interest: The authors declare no conflict of interest".

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