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The change of stress distribution on the condyle after sagittal split ramus osteotomy and mandibular setback

SUMMARY

The rigid-body spring model (RBSM) theory was incorporated into a model as a discrete method for analyzing problems of limit such as the stress distribution of condyle. The purpose of this study was to evaluate the two-dimensional (2D) RBSM for determining stress on the temporomandibular joint (TMJ) in patients after orthognathic surgery. Thirty-two patients (5 men and 27 women, mean age 21.4 ± 4.9 years) with mandibular prognathism underwent bilateral sagittal split ramus osteotomy (SSRO) and setback; 48 subjects were recruited as controls. Anatomic landmarks were traced from pre and post-operative lateral cephalograms and the information was processed using the FORTRAN analysis program. The force vector on the condyle, its degree, its direction, and the displacement coordinates (x, y) and rotation (θ) at the gonial angle were calculated. When muscular power was assumed to be 1, the post-operative degree of the force vector was higher than the pre-operative value ($p<0.05$). The X-coordinate, x, and rotation, θ , of the displacement vector in the pre-operative patients with mandibular prognathism were significantly higher than those in the control subjects ($p<0.05$). There were still significant differences between the displacement values post-operatively between the patients and the controls ($p<0.05$). The results suggest that the degree and direction of the force vector, and the resulting displacement coordinates can be used as parameters in a surgical model. The RBSM may also be useful in evaluating the pre- and post-operative skeletal morphology of jaw deformities.

Introduction

Generally, post-operative mandibular position after orthognathic surgery is determined by a standard surgical model, photographs, a lateral cephalogram, and a prediction tracing. Advanced simulation surgery uses geometric information from three-dimensional computed tomography as well as lateral cephalograms to determine the positions of the proximal and distal bone segments after sagittal split ramus osteotomy (SSRO) (Xia et al., 2000). However, it has been reported that the positioning of the segments is determined by dynamic factors that place considerable stress on the temporomandibular joint (TMJ). O'Ryan and Epker (1984) have demonstrated that different skeletal patterns represent different load characteristics on the TMJ. They found that the functional load patterns in these cases were significantly different from each other. If the function of the TMJ differs with different skeletal patterns, it is likely that the structure of the TMJ also differs. However, their study examined only the trabecular pattern of the condyle; no dynamic analysis was performed. Changes in stress on the condyle as a result of orthognathic surgery on the mandible may frequently cause condylar deformation.

Several theoretical approaches have been used in an attempt to understand various aspects of TMJ biomechanics (Koolstra et al., 1988; Korioth and Hannam, 1990; Chen and Xu, 1994; Tanaka et al., 1994; Devocht et al., 1996; Tanne et al., 1996). Some finite element models (FEM) of the TMJ have been developed to simulate condyle motion or stress change. However, the geometry of the FEM was based on only one typical image of TMJ, while in fact data on many material properties were needed. For this reason, FEM was inadequate as a technique for investigation. Instead, a stress distribution analysis method using the rigid body spring model (RBSM) was employed because many individual images had to be analyzed to provide a more comprehensive biomechanical description of the loading and the results had to be suitable for statistical analysis. Finally, the amount of data collected was potentially rather large and simple analysis was required.

The purpose of the present study was to examine stress distribution on the condyle after orthognathic surgery (SSRO and mandibular setback) using the 2D RBSM.

Subjects and Methods

Thirty two patients (5 males and 27 females, mean age 21.4 ± 4.9 years) with mandibular prognathism (ANB less than 2 degrees without asymmetry) and no radiographic apparent morphological TMJ changes who underwent SSRO and setback using a modified Obwegeser-Dal Pont procedure (Dal Pont, 1967). The mean setback was 6.7 ± 3.0 mm on the right side and 6.3 ± 2.9 mm on the left side. All patients received orthodontic treatment before and after surgery. Although, post-operative cephalogram was usually taken immediate surgery, after 1, 3 6 and 12 months, Gonion was comparatively stable from 3 months to 12 month for all subjects. Therefore, lateral cephalograms at pre- and post-operatively 3 months were used.

Forty eight subjects (28 males and 20 females, mean age 24.0 ± 1.7 years) with normal skeletal relationships and occlusions. Subjects with any maxillary skeletal anomaly were not included. No devices for repositioning the proximal segment were used and titanium miniplates were applied for fixation in the treated cases. Informed consent was obtained from the patients and the control volunteers and the study was approved by Kanazawa University Hospital.

The RBSM program of the temporomandibular joint

The geometry of the model was based on a lateral cephalogram of each subject (Fig. 1A). The gonial angle of the mandible was selected as the muscular stress generation point, and the distal portion of the first molar as the occlusal stress generation point (Fig. 1B). The stress-bearing points on the mandibular condyle were represented by approximation curves generated from the most anterior, superior, and posterior points on the condyle. Data from the lateral cephalograms were entered into a computer (model PC9821Xa13, NEC, Tokyo, Japan) and a FORTRAN program was used to analyze the mandibular 2D RBSM (Takeuchi et al., 2002).

After surgery, the bone fragments were considered to be rigidly fixed so that the entire mandible could be considered as a single unit for analysis.

Calculations

The value of the total load, the resultant force vector of power (Pm) generated by the masticatory muscle, was defined as 1 for the calculations. This force vector was placed on the gonial angle point. Simultaneously, the values of the direction vector (Ph Angle), the degree of the resultant force vector (Ph) on the condyle, and the displacement vector (x, y) and rotation (θ) on the mandibular body were also calculated. The resultant force vector of the muscular power was different from the displacement vector, although both vectors appeared to be in the same place on the gonial angle. The displacement vector has the coordinate conversion vector in this calculation process.

The software program was modified so that the results of the simulation could be seen as an image on a personal computer (Fig. 2). Furthermore, pre- and post-operative results using this program could be compared as images (Fig. 3). The analysis was based on the definition that a condylar position is stable when the stress is distributed equally over the condylar surface. When the final calculation has been performed and contact pressure is distributed equally over the condylar surface, any slight mandibular displacement may be disregarded. The displacement from vectors on the initial mandibular position to vectors on the final mandibular position after calculations can be presented by conversion calculations from the displacement vector.

This may mean that the higher the displacement vector then, the less clinically stable are the mandible and TMJ.

As previously stated, the displacement vector is expressed in terms of three degrees of freedom at the point of the gonial angle: the coordinates that represented the displacement distance (x, y) and the rotation angle (θ). The pre- and post-operative positions of the condyle in the patients were compared with those of the control subjects with respect to the components of the direction (Ph Angle), the degree of the resultant stress vector (Ph) and the displacement vector (x, y) and rotation (θ). Because a standard cephalogram is not made parallel to the condylar long axis, the recorded image does not represent the condylar surface accurately. Therefore, the points on the condyle were replaced with approximation curves that were assumed to be the most appropriate for visualization. The outline of the condyle was traced as a circle containing the most anterior, superior, and posterior points on the condyle before the stress distribution analysis was carried out. Finally, the elliptical shape of the condylar surface was retained with the longitudinal axis aligned to the direction of the resultant force vector (Takeuchi et al., 2002).

Statistical analysis

Statistical analyses of Ph, Ph Angle, and x, y and θ between pre- and post-operative patients were performed with the Wilcoxon signed ranks test on the Stat View™ 4.5 software program (ABACUS Concepts, Inc. Berkeley, California, USA). Differences in vectors between the control subjects and the patients pre- and post-operatively were analyzed with the Mann-Whitney U test. As it was unclear whether these values were according to normally distributed, non-parametric analysis was used. The differences were considered significant at p<0.05.

Results

The degrees of the force vector (Ph Angle) on the condyle were: 21.04± 5.59 degrees in the control subjects, and for the pre- and post-operative patients 23.3 ± 7.76 degrees and 23.30 ± 7.75 degrees respectively. No significant difference was noted between the pre- and post-operative values.

The mean value of the resultant force vector (Ph)(Fig. 4) in the pre-operative patients was 0.615 ± 0.056 and in the postoperative patients, was 0.653 ± 0.062, a significant difference (p<0.05). The value in the post-operative patients was the same as that in the control subjects (0.653 ± 0.052). For these calculations, the value of the resultant force vector of muscular power was defined as 1.

The value of X-coordinate component, x, of the displacement vector was highest (0.104 ± 0.068) in the pre-operative patients, 0.069 ± 0.069 in the post-operative patients, and 0.039 ± 0.136 in the control subjects. A significant difference was noted between the groups in the value x of the displacement vector ($p<0.05$). The value of Y-coordinate component, y, of the displacement vector was 0.653 ± 0.115, 0.703 ± 0.095, and 0.666 ± 0.092 for the pre- and post-operative and controls subjects respectively. There was no significant difference among the groups in y value. The value of rotation component θ of the displacement vector was highest (9.337 ± 6.352) in the pre-operative patients, 5.495 ± 6.156 in the post-operative patients, and 1.699 ± 4.935 in the control subjects. There was a significant difference between the groups in the value of rotation component, θ, of the displacement vector. These results suggest that the value for the condyle in the control subjects was stable (Fig. 5).

Discussion

When fixing bone fragments after SSRO, displacement of the proximal bone fragment including the condyle, results in a change of the condylar location relative to the glenoid fossa. This might be a result of continuous loading on the TMJ (Leonard, 1976; Will et al., 1984; Hiatt et al., 1988; Lindquvist and Saderholm, 1988; Raveh et al., 1988; Proffit et al., 1991; Rotskoff et al., 1991). In order to prevent this continuous loading, it has been advocated that the proximal bone fragment should be restored to their pre-operative condition three-dimensionally (Paulus and Steinhauser, 1982; Epker and Wylie, 1986; Schwestka-Polly et al., 1990; Rotskoff et al., 1991). However, as dynamic factors might be more important than the geometric position of condyle, the stress distribution analysis system RBSM was developed (Takeuchi et al., 2002; Ueki et al., 2005).

This study examined all surgical cases that growth was judged to be not in progress. However, when this analysis was used for young patients during growth, this may be also useful for a prediction of condylar growth.

In Ph Angle (stress angulation on codyle), as there was no significant difference between controls and pre- and post-operation, Ph Angle could not be used as a parameter of surgical simulation. However, maxillary morphological variation of subjects might affect this result. In future study, more accurate selection should be performed.

An increase in the relative load on the condyle after SSRO and mandibular setback was seen in this study; however, this is only a relative value. In this study, the muscular force value was assumed to be 1 so that incorporating real maximum occlusal force data would make these results more apparent and meaningful. However, the direction of the resultant force vector derived from the stress distribution could still be obtained by this method so that it could be evaluated statistically.

The X-coordinate component x of the displacement vector represented the highest value in the pre-operative mandibular prognathic cases. Even though the strength of the X -coordinate component y of the displacement vector decreased after surgery, it was still significantly greater than that in the control subjects. The rotation value θ in patients also decreased after surgery, but was still greater than that in the control subjects. The displacement vector in post-operative patients still differed from that of control subjects. These results may be closely associated with the character of the surgical procedure as well as with mandibular morphology. It was assumed that the SSRO method could change only the position of the distal segment of the mandible, including the teeth, and that TMJ morphology would not change, although a slight change in condylar position might be induced. In other words, it was considered that as a result of surgery to correct prognathism, patients had acquired normal mandibular morphology with prognathic TMJ morphology, although TMJ remodelling could be induced subsequently. On the other hand, in the Y-coordinate component y of the displacement vector, there was no significant difference among the groups. This result suggests that the setback movement was mainly in the antero-posterior direction, along the X-coordinate.

The RBSM theory was incorporated into a model devised as a discrete method for analyzing R-R-type (The two bodies bonded by an interface are both rigid)-interface problems. This theory assumes that an element itself is a rigid body, and the model represents a calculation method to measure the concentration of energy by the force exerted on a bundle of springs distributed along the boundary of the element. The RBSM and the FEM calculation showed good agreement in contact pressure prediction (Li et al., 1997). Compared with the finite element method (FEM), which is commonly used in the field of dentistry (Chen and Xu, 1994; Tanaka et al., 1994; Devocht et al., 1996; Tanne et al., 1996), the RBSM theory is superior because the calculation can be carried out easily and rapidly with only a small amount of information compared with FEM. Even if a large amount of information is obtained, extrapolation to in vivo situations, so that we cannot help judge the validity from statistical accumulation of clinical finding. The FEM is suitable for calculating stress within elements, while the RBSM theory is used for calculating the surface force between elements. This theory has been used to analyze stress on the knee, hip, and wrist in the field of orthopaedic surgery (Genda et al., 1995; Schuind et al., 1995). These studies prove that RBSM can provide reliable results. On the other hand, the structure of the TMJ is significantly different from that of the knee or hip joint and its characteristic anatomy and movement make it difficult to manage the data.

In this study, the distal portion of the first molars was used as reference points. Pruim et al. (1980), others have observed the maximum bite force that can be produced on the last molar is less than that on the first molar. However, in this model, as the centre position of total bite force, the point between the first and second molar was calculated and determined. Furthermore, antero-posterior movement of the first molar by orthodontic treatment was so small that the point could present the movement of distal segment by SSRO.

Regarding to gonion point as reference point, it was unclear whether the gonion point remained stable after operation. It is generally accepted that morphology of the gonial angle change after setback surgery. This may be due to mandibular angle remodeling and osteotomy line. However, muscular attachment also change accompanied with morphological change at the mandibular angle (Hong et al., 1997). In fact, the tension in the pterygomasseteric sling by posterior part of distal segment following setback surgery could induce the relapse (Rodrigez and Gonzalea, 1996). Therefore, it was considered that the use of gonion point was reasonable as generated point of muscle power. Even if the gonion point changes after operation, the analysis is possible by using gonion point on the post-operative cephalogram.

The condylar surface outline was approximated as a circle that passed through the most anterior, superior, and posterior points on the condyle. Then, the condylar surface was approximated as an ellipse with the longitudinal axis aligned with the direction of the resultant force vector after the stress distribution analysis. A higher degree of stress was noted on the anterior aspect of the condyle. The narrowest part, between the centre of the articular disc and the centre of the posterior slope of the articular eminence, was suggested to be the path of the resultant force vector. This hypothesis is validated by reports that the articular cartilage is thickest at the anterior slope of the condyle and the posterior slope of the articular eminence. Furthermore, load-enhancing glycosaminoglycan has been identified at the centre of the articular disc (Kopp, 1976; Blaystein and Scapino, 1986). This finding supports results previously obtained using FEM (Tanaka et al., 1994; Tanne et al., 1996) and RBSM (Ueki et al., 2005).

There is no consistent value for the optimal load on the TMJ. Smith et al. (1986) found that TMJ loads in a numerical model varied from 5 to 60 per cent of the bite force. However, because it is impossible to measure the actual load on the human TMJ, this value can only be estimated by analysis of a model based on mathematical calculations. The load on the condyle was also estimated in the present study. However, multiple stress-releasing structures, such as the interpositional disc, the articular cartilage, and the periodontal ligament, were not taken into account. Therefore, if the occlusal load and the stress-releasing capacity of the TMJ could be accurately measured, estimation of the stress on the TMJ would be more realistic with this system. The results of the displacement suggest that the condyles of subjects with normal skeletal relationships and occlusions were dynamically more stable than those of subjects with mandibular prognathism. The finding also suggest that the displacement vector (x, y) and rotation θ can be used as a parameter in the surgical model. The application of the RBSM is useful and the calculations may be quickly performed. Furthermore, this method enables an oral and maxillofacial surgeon to make a direct assessment of a patient in the clinic, which is not possible with the FEM. However, this analysis could be used for just symmetric patients as the limitation of this study, because lateral cephalogram was used.

Conclusion

The results of this study suggest that the degree and direction of the force vector, and the resulting displacement coordinates can be used as parameters in a surgical model. The RBSM may also be useful in evaluating the pre- and post-operative skeletal morphology of jaw deformities. Although the RBSM appears promising, further studies are needed to determine the strengths and weaknesses of this analytical method.

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Figure Legends

Figure 1. Data from lateral cephalograms.

(A) The distal portion of the first molar, the gonial angle, and the condylar surface in the articular fossa were traced and the data were entered into the computer program.

(B) The gonial angle was selected as the reference point for the variables of the three degrees of freedom: parallel displacement (x,y) and rotation (θ). The reaction force on the teeth is assumed to act on the molars, especially on the first molar, so the distal portion of the first molar was selected as the occlusal stress generation point. The integral points for calculating the contact stress were determined along the condylar contour.

Figure 2. Visualization of the results of analysis with the rigid-body spring model. Ah: direction of resultant force vector, Ph: degree of resultant force vector, Pm: muscular power. Arrows on the condylar surface indicate relative stress on the integral points. U, V and Angle represent the displacement vector (x, y) and (θ).

Figure 3. The pre- and post-operative results on cephalogram.

The mandibular body involving teeth was shortened by sagittal split ramus osteotomy and fixed by miniplate.

Figure 4. Statistical analysis of the resultant force vector. The value of the resultant force vector in the pre-operative patients is significantly smaller than

that in the control subjects. There is no significant difference between the value of the resultant force vector in the post-operative patients and that in the control subjects. * : $P<0.05$. Column presents average and the error bar shows standard deviation.

Figure5. Statistical analysis of the displacement vector. Significant differences are recognized between groups. * : $P<0.05$. Column presents average and the error bar shows standard deviation.

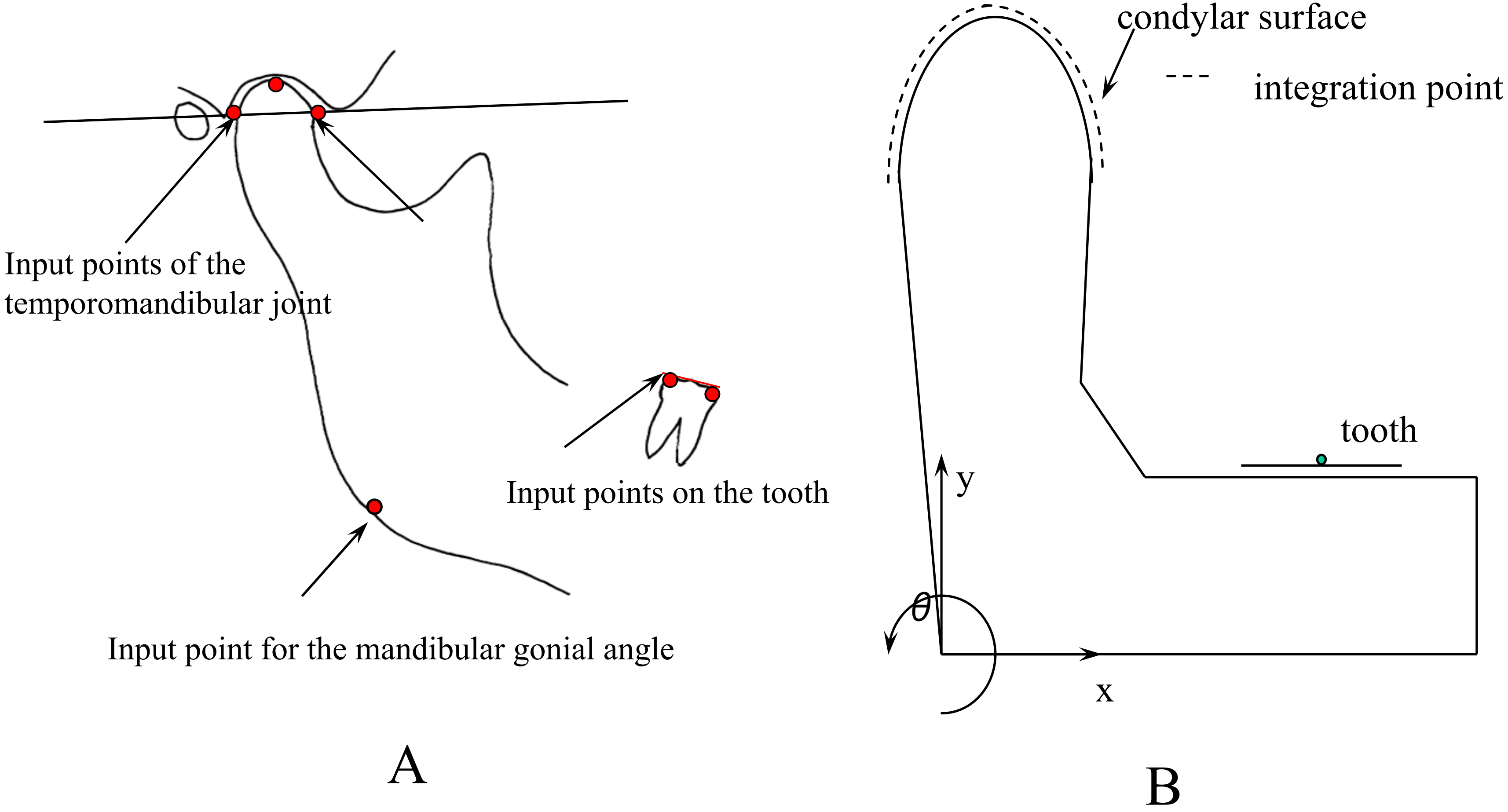
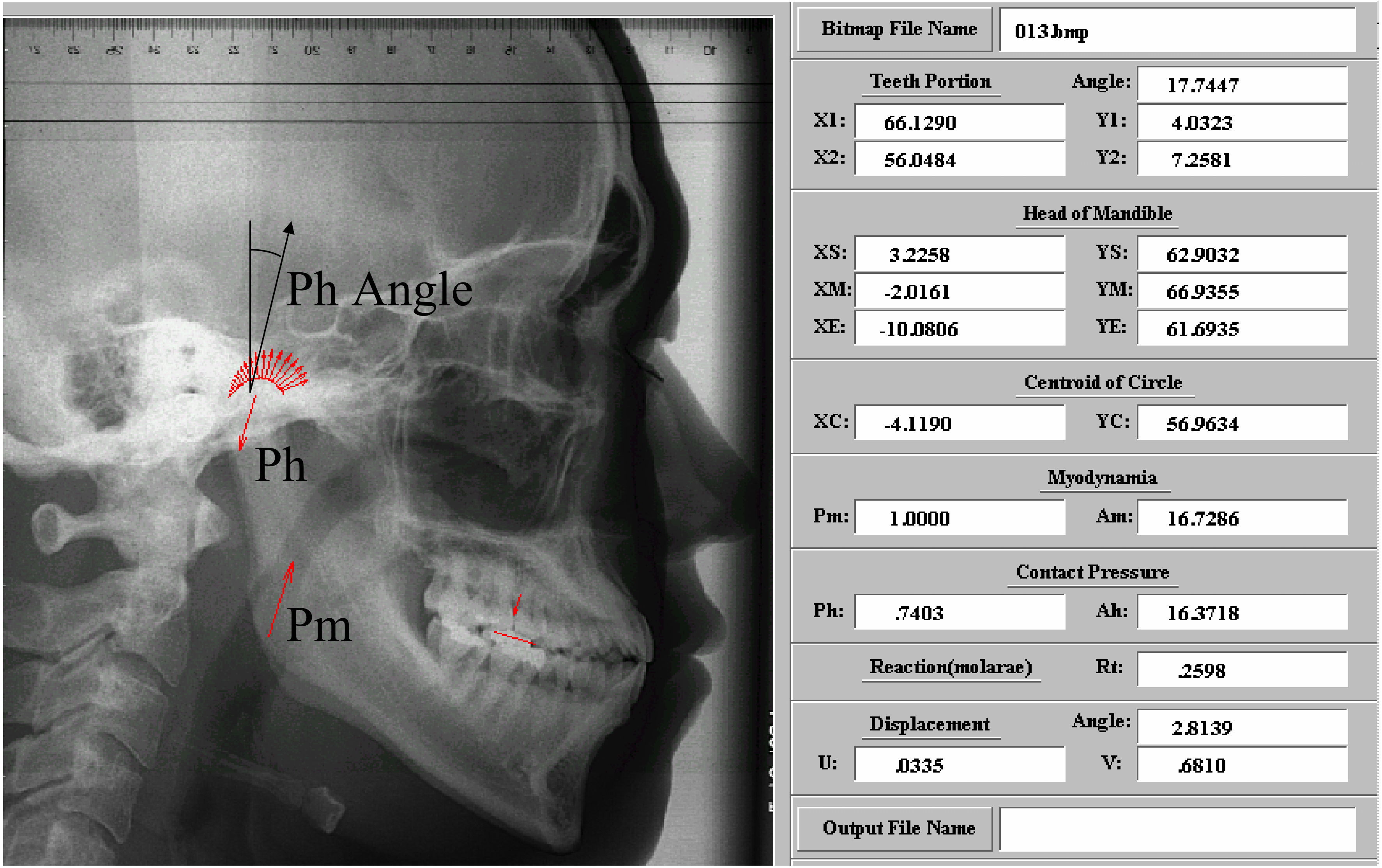

Input points of the temporomandibular joint
Input points on the tooth
Input point for the mandibular gonial angle
A
condylar surface
integration point
tooth
y
x
θ
B

FIGURE 1.



Bitmap File Name: 013.bmp

Teeth Portion
Angle: 17.7447
X1: 66.1290
Y1: 4.0323
X2: 56.0484
Y2: 7.2581

Head of Mandible
XS: 3.2258
YS: 62.9032
XM: -2.0161
YM: 66.9355
XE: -10.0806
YE: 61.6935

Centroid of Circle
XC: -4.1190
YC: 56.9634

Myodynamia
Pm: 1.0000
Am: 16.7286

Contact Pressure
Ph: .7403
Ah: 16.3718

Reaction(molarae)
Rt: .2598

Displacement
Angle: 2.8139
U: .0335
V: .6810

Output File Name

FIGURE 2.

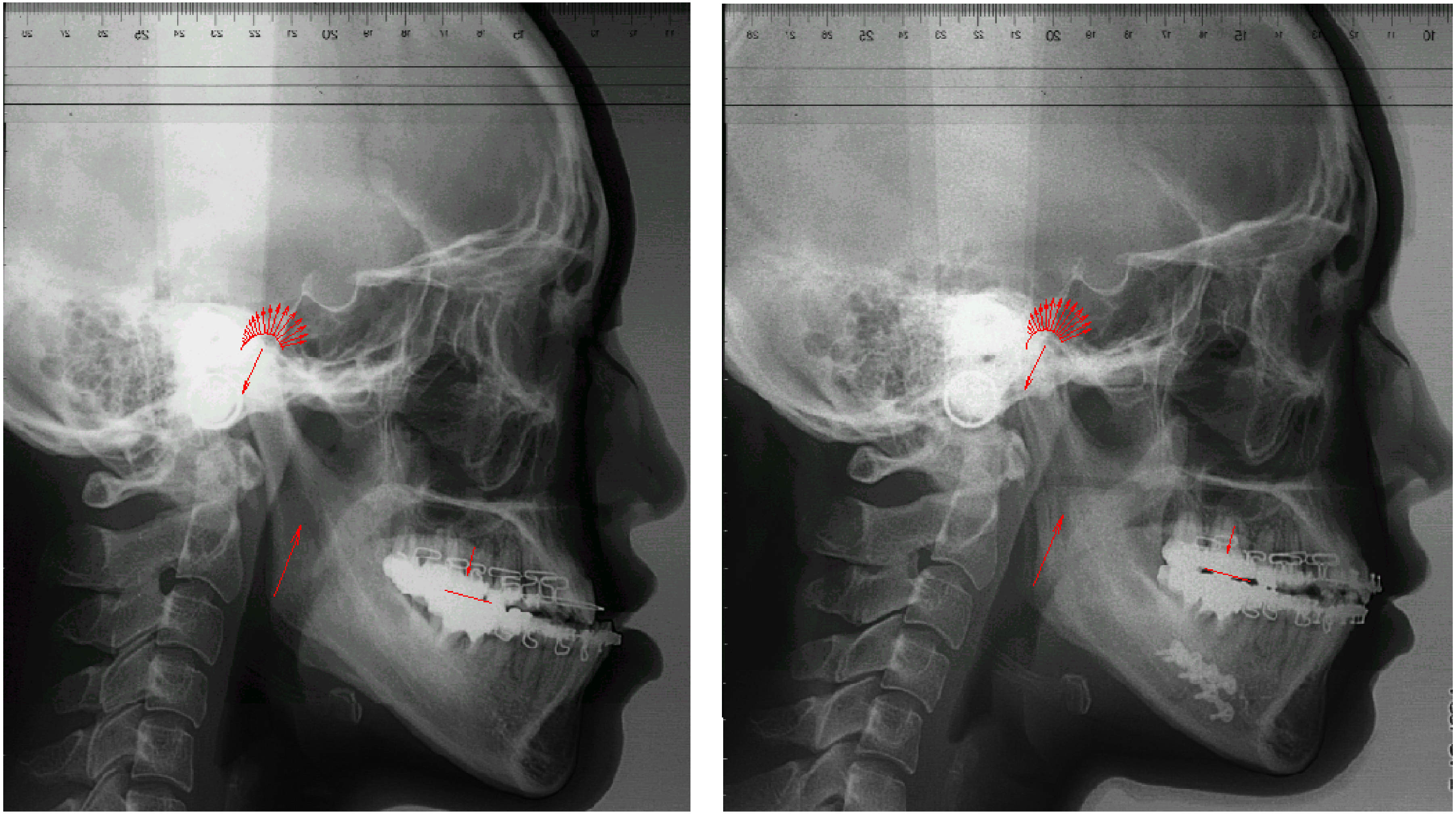


FIGURE 3.

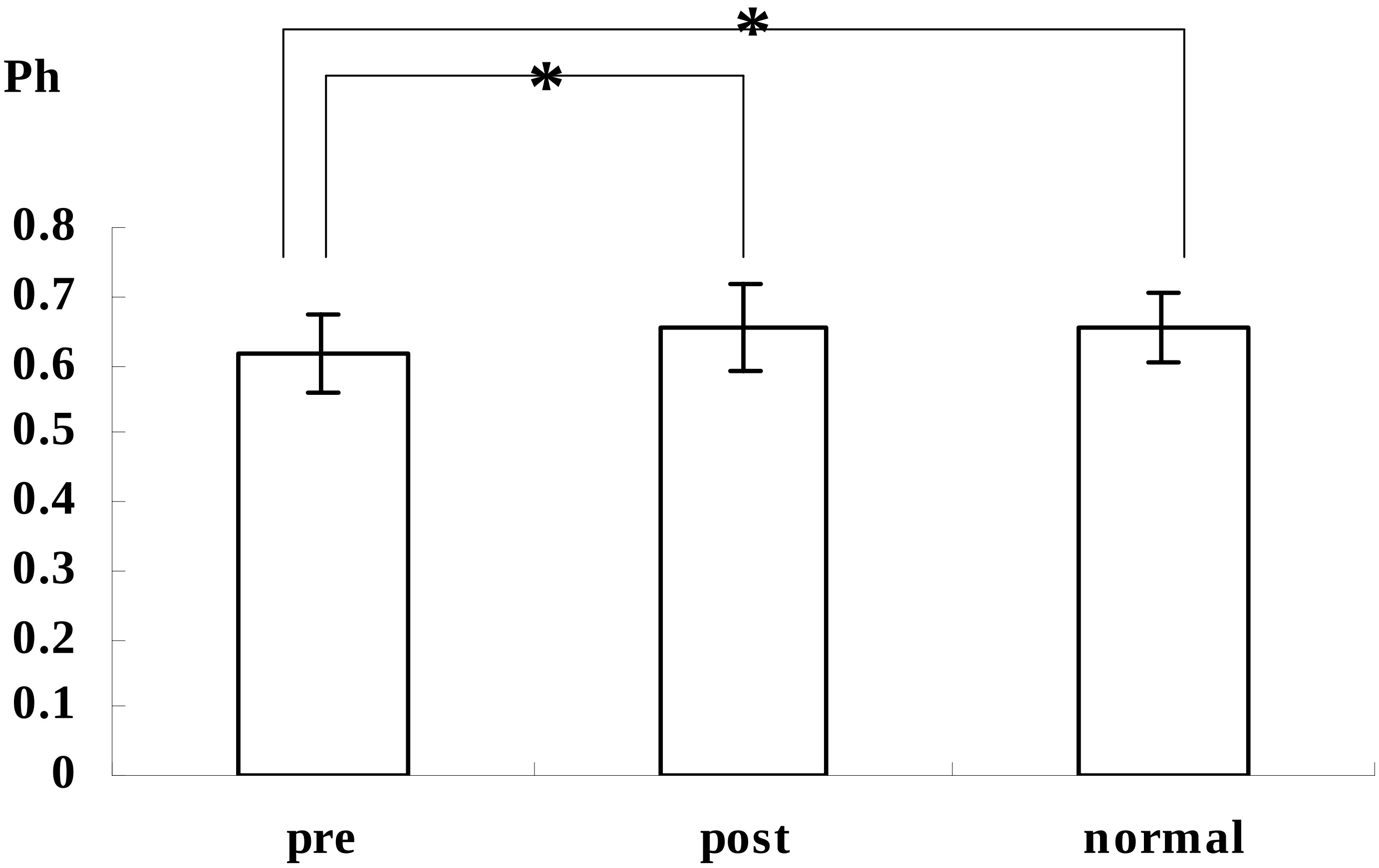


FIGURE 4.

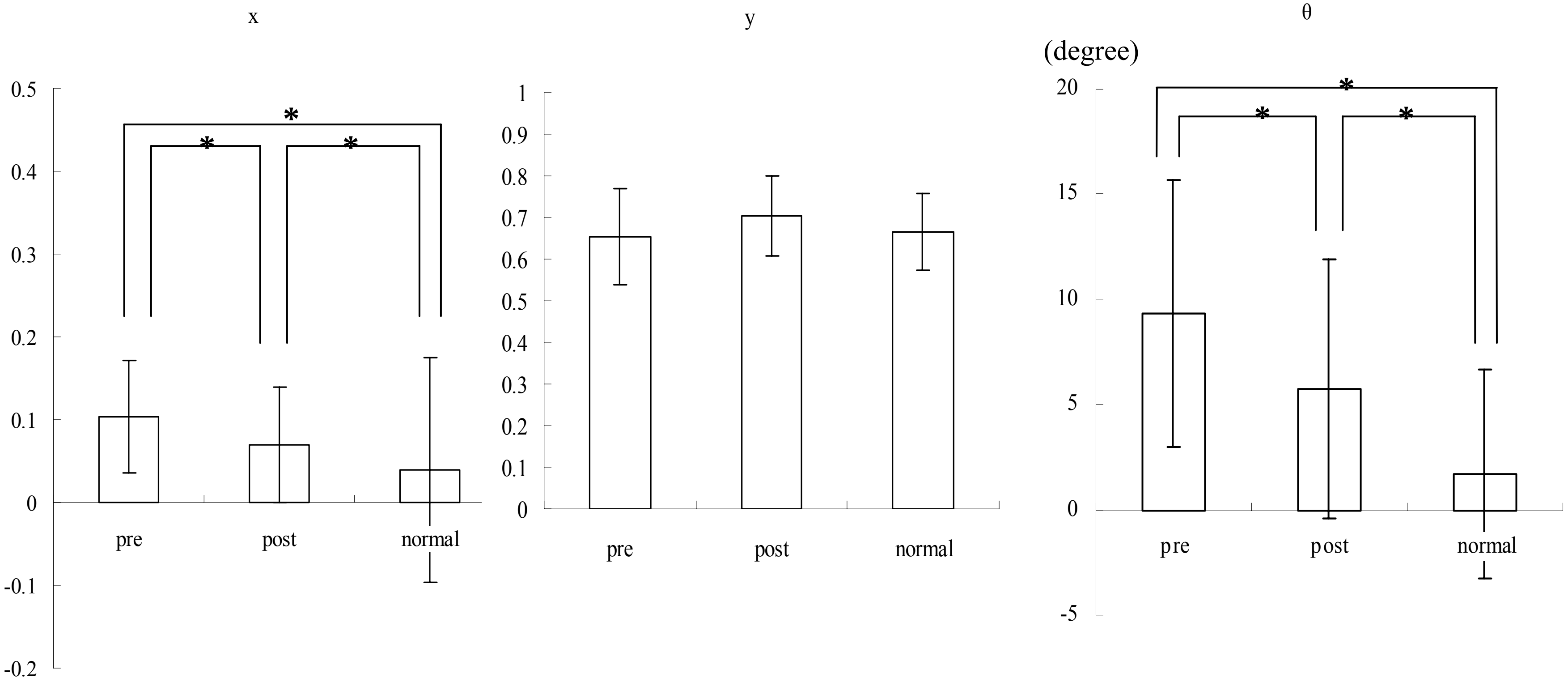

x
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
*
*
*
pre
post
normal
y
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
pre
post
normal
θ
(degree)
20
15
10
5
0
-5
*
*
*
pre
post
normal

FIGURE 5.