Three Dimensional Study of Mandibular Movement Using an Automatic Electronic Measuring System

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INTRODUCTION

More than a hundred years have passed since the first scientific investigation of mandibular movement were began by Bonwill1 and Balkwill2. Movements of the mandible are one of the essential factors in prosthodontics and have been studied extensively and reported in the literatures. Direct visual measurement of the mandibular movement is feasible at the incisal point. It is not possible to directly attach measuring instruments on or inside the condyles and movements of the condyles have been interpreted from data measured extra orally. For this reason measurements of condylar movement have not been accurate. It is extremely important to know the exact movements of the condyles from an academic and clinical standpoint. There are many unanswered questions concerning mandibular movement due to the incapability of existing measuring systems.

In order to measure three-dimensional movement of the mandible accurately, it is necessary to measure movements at three points simultaneously: (1) right condyle, (2) left condyle and (3) the incisal point. To achieve this, sensors with a high degree of accuracy and a computer system are needed. Only a few mandibular movement measuring systems have been reported in the literature with such capabilities.3-9

The purpose of this study was to analyze mandibular movement statistically from the data obtained using the automatic electronic
measuring system developed by Hobo and Mochizuki which has a measuring accuracy of 60 µm. The investigation consisted of a three dimensional analysis of the condylar, molar and incisal paths, correlation between the condylar paths and incisal paths, the effects of teeth contact and non teeth contact upon the condylar path, and the reproducibility of mandibular movements.

METHODS

Measuring instruments
Assuming the mandible is a rigid body, its movement may be measured by the theory of solid body kinematics. The movement of a rigid body in three dimensional space has six degrees of freedom. Mandibular movement is equivalent to this movement. In order to measure mandibular movement in three dimensional space, it is essential to measure the vectors of six independent points fixed to the mandible simultaneously. With this measurement data, movement of any randomly selected point on the mandible can be computed. Six degrees of freedom of a rigid body may be measured by six one-dimensional sensors. However, one-dimensional sensors presently available are excessive in size. Another possibility would be to use three two-dimensional sensors which are not available. For these reasons, it was necessary to develop a new compact two dimensional sensor with a high degree of accuracy for this study.
Three Dimensional Study of Mandibular Movement Using an Automatic Electronic Measuring System

Fig. 2. Rectangular waveforms of electrical potential outputs to the output terminals A, B, C and D of the C.P.P. sensor.
A, B, C, D: Output terminals of the C.P.P. sensor
\( t \): Time
\( T_p \): Cycle of the rectangular waveforms
V: Electric potential
\( V_H, V_2, V_1, V_L \): Levels of the electric potentials
(\( V_H > V_2 > V_1 > V_L \))

a. Two dimensional sensor
The new sensor consists of an electronic stylus and a conductive plastic plate (C.P.P.). The C.P.P. is a plastic plate which is coated with a 15-20\( \mu \)m thickness of polyamide plastic. When an electronic stylus is in contact with the C.P.P. and an electrical current is applied the distribution of electric potential will be proportional to the distance from where the point of the stylus made contact.

Fig. 1 shows a schematic drawing of the design of the new C.P.P. sensor. Electric contacts at a,b,c, and d are connected to output terminals A,B,C and D of the C.P.P. respectively via diodes. When the electric current flows from side (b) to side (a) the electric potential (\( V_B > V_A \)) is created. Measuring the electric potential by stylus, the position S of the stylus in the X direction can be determined based on the known relationship between the electric potential and the position of the stylus. Switching off the electric current between a and b, the same procedure can be repeated between d and c (\( V_D > V_C \)) which is a 90 degree change in direction. Then the position S of the stylus in the Y direction of C.P.P. can be measured. As shown in Fig. 2 the rectangular wave-form electric potential which has the same cycle \( T_p \) were connected to points A,B,C and D. In the figure, t is time, V is electric potential, \( V_H, V_2, V_1 \) and \( V_L \) are the level of the electric potentials (\( V_H > V_2 > V_1 > V_L \)). When the electric current flows from B to A, the electric current flows from D to C is temporarily cut-off by the function of the diodes. The first half of the cycle forms the electric potential distribution which is parallel to the Y direction and the last half of the cycle forms the electric potential distribution parallel to the X direction. When the tips of stylus make contact with the surface of the C.P.P, position S is recorded in both X and Y directions in every half electric cycle. In this manner the position of the stylus is measured two-dimensionally.

Since a limited number of the electric points are connected to the C.P.P. the electric potential formed on the C.P.P. could show deformation. To minimize the effect of C.P.P. deformation, the following computations were made. According to the Laplace's equa-
A distribution of electric potential $V(X,Y)$ is expressed as follows.

$$\frac{\partial^2 V(X,Y)}{\partial X^2} + \frac{\partial^2 V(X,Y)}{\partial Y^2} = 0$$

The computations were made using computer with variations of the number and arrangement of electrodes. The examples of the computed results are shown in Fig. 3 and 4. Fig. 3 indicated the electric potential distribution of the C.P.P. when the six electrodes were used with 10 volts direct voltage. Fig. 4 shows the electric potential distribution when eight electrodes were used under the same condition. As is evident on these figures uniform distribution of electric potential was formed on the wide area of the C.P.P. surface, and the larger number of electrodes results in a better distribution of the electric potential. The results of the preliminary investigation were reflected to the design of the C.P.P. described in the following.

b. Measurement of six degrees of freedom.
With a combination of the C.P.P. and stylus it was possible to
Three Dimensional Study of Mandibular Movement Using an Automatic Electronic Measuring System

Table 1. Electric potentials in volts measured at the various points on the surface of the C.P.P. sensor, shown in relation to X, Y positions.

<table>
<thead>
<tr>
<th>X (mm)</th>
<th>30.00</th>
<th>35.00</th>
<th>40.00</th>
<th>45.00</th>
<th>50.00</th>
<th>55.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-17.00</td>
<td>2.79</td>
<td>2.79</td>
<td>2.78</td>
<td>2.78</td>
<td>2.79</td>
<td>2.79</td>
</tr>
<tr>
<td>-22.00</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
<td>3.75</td>
</tr>
<tr>
<td>-27.00</td>
<td>4.71</td>
<td>4.71</td>
<td>4.71</td>
<td>4.71</td>
<td>4.71</td>
<td>4.71</td>
</tr>
<tr>
<td>-32.00</td>
<td>5.68</td>
<td>5.68</td>
<td>5.68</td>
<td>5.68</td>
<td>5.68</td>
<td>5.68</td>
</tr>
<tr>
<td>-37.00</td>
<td>6.65</td>
<td>6.65</td>
<td>6.65</td>
<td>6.65</td>
<td>6.65</td>
<td>6.65</td>
</tr>
<tr>
<td>-42.00</td>
<td>7.61</td>
<td>7.61</td>
<td>7.61</td>
<td>7.61</td>
<td>7.61</td>
<td>7.62</td>
</tr>
</tbody>
</table>

Table 2. Difference in mm between the X positions and the measured data calculated by the expression $X = -5.177V - 2.591$ shown in relation to X, Y positions (V: volt).

<table>
<thead>
<tr>
<th>X (mm)</th>
<th>30.00</th>
<th>35.00</th>
<th>40.00</th>
<th>45.00</th>
<th>50.00</th>
<th>55.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-17.00</td>
<td>-0.03</td>
<td>-0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>-0.03</td>
</tr>
<tr>
<td>-22.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>-27.00</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>-32.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>-37.00</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td>-42.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>-0.04</td>
</tr>
</tbody>
</table>

Measuring accuracy of this system mainly depends upon the position and the electric potential of the C.P.P.. The C.P.P.'s accuracy was evaluated by the use of a special positioning instrument with accuracy of ±0.005mm. Table 1 shows one of the results of measurements which indicates the electric potential measured at the various points on one of the three C.P.P.'s in relation to X and Y positions. According to the result, the relationship between X (mm) and V (volt) is expressed by the following linear equation:

$$X = -5.177V - 2.591$$

The measured data was compared as shown in Table 2 and it was found that the maximum difference was 0.04mm. The same comparison was made in each direction of the three C.P.P.'s and it was found that the maximum measuring accuracy was ±60µm. It was determined from these comparisons the measurement accuracy of this C.P.P. sensor was ±60µm.

Principles of computation for mandibular movement.
The data obtained by these sensors were converted to mandibular movement. The principles of computation are explained as follows.

a. Coordinate system
   As shown in Figs. 5–6 the coordinate system O-XYZ is located on
the box frame. The box frame with its coordinate system was attached to the maxilla. Three styli were fixed on the mandible MA, MB, and MC. Styli MA and MB are on the straight line AB, MC is perpendicular to AB, and MC intersects with AB at point M. Points A, B, and C are the tips of the styli making contacts with the C.P.P.'s (α, β, and γ). Locations P₁, P₂, and P₃ are the constant points which are separated by the distance R₁, R₂, and R₃ from M in A, B, and C directions. The coordinates in the O-XYZ system are the following:

A (Xₐ, Yₐ, Zₐ)
B (Xₐ, Yₐ, Zₐ)
C (Xₐ, Yₐ, Zₐ)
M (Xₐ, Yₐ, Zₐ)
P₁ (X₁, Y₁, Z₁)
P₂ (X₂, Y₂, Z₂)
P₃ (X₃, Y₃, Z₃)

Among the O-XYZ coordinates A, B, and C points were measured.
Nine of the three parameters including $Y_A$, $Y_B$, $X_C$ are the known constants. The balance of the six parameters including $X_A$, $Z_A$, $X_B$, $Z_B$, $Y_C$ and $Z_C$ were measured.

b. Relationship between the measuring points and three constant points on the mandible.

In order to determine the position and the attitude of a rigid body (mandible), three definite points ($P_1$, $P_2$, and $P_3$) which are not on the straight line must be located. Coordinates of $P_1$, $P_2$, and $P_3$ were computed in accordance with points A, B, and C. The correlation formula is as follows:

Assuming that $A$, $B$, and $M$ are on a straight line, the following expression was established.

$$
\frac{X_M - X_A}{X_B - X_A} = \frac{Y_M - Y_A}{Y_B - Y_A} = \frac{Z_M - Z_A}{Z_B - Z_A}
$$

(1)

In addition, line $AB$ is perpendicular to the line $CM$, and the following expression was established.

$$(X_A - X_B)(X_M - X_C) + (Y_A - Y_B)(Y_M - Y_C) + (Z_A - Z_B)(Z_M - Z_C) = 0
$$

(2)

According to expressions (1) and (2), coordinates of $M$ ($X_M$, $Y_M$, $Z_M$) are expressed as follows.

$$
Y_M = [Y_C(Y_B - Y_A)^2 + \{X_C(Y_B - Y_A) + X_B Y_C\} (X_B - X_A) + \{Z_C(Y_B - Y_A) + Z_B Y_C - Z_A Y_B\} (Z_B - Z_A)] / (X_B - X_A) + X_B
$$

(3)

$$
X_M = \frac{(Y_M - Y_A)(X_B - X_A) + X_A Y_B - Y_A}{Y_B - Y_A}
$$

$$
Z_M = \frac{(Y_M - Y_A)(Z_B - Z_A) + Z_A Y_B - Y_A}{Y_B - Y_A}
$$

Accordingly, three coordinates of $P_1$, $P_2$, and $P_3$ located on the mandible are expressed as follows.

$$
X_1 = X_M - R_1(X_B - X_A)/L_1
$$

$$
Y_1 = Y_M - R_1(Y_B - Y_A)/L_1
$$

$$
Z_1 = Z_M - R_1(Z_B - Z_A)/L_1
$$

$$
X_2 = X_M + R_1(X_B - X_A)/L_1
$$

$$
Y_2 = Y_M + R_1(Y_B - Y_A)/L_1
$$

$$
Z_2 = Z_M + R_1(Z_B - Z_A)/L_1
$$

$$
X_3 = X_M + R_2(X_C - X_M)/L_2
$$

$$
Y_3 = Y_M + R_2(Y_C - Y_M)/L_2
$$

$$
Z_3 = Z_M + R_2(Z_C - Z_M)/L_2
$$

(4)
These expressions are true under the following conditions.

\[ L_1 = \{ (X_A - X_B)^2 + (Y_A - Y_B)^2 + (Z_A - Z_B)^2 \}^{1/2} \]
\[ L_2 = \{ (X_C - X_M)^2 + (Y_C - Y_M)^2 - (Z_C - Z_M)^2 \}^{1/2} \]

c. Coordinate transformation.

Coordinate transformation was made so that the movement of any arbitrarily selected points O(\(\eta, \xi, \epsilon\)) on the mandible could be computed from the original point O' (\(X_0, Y_0, Z_0\)). Here, it is assumed that \(\eta\) and \(\xi\) axis are parallel to MC and AB respectively, and \(\epsilon\) axis is through the point M, the distance MO being 1 mm.

According to coordinate transformation in three-dimensional Euclid space, the relationship between \((X, Y, Z)\) and \((\eta, \xi, \epsilon)\) is,

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = T \begin{pmatrix}
\eta \\
\xi
\end{pmatrix} + \begin{pmatrix}
X_0 \\
Y_0 \\
Z_0
\end{pmatrix}
\] \hspace{1cm} (5)

\(T\) is the transformation matrix and the three-dimensional square matrix. \(X_0, Y_0\) and \(Z_0\) are the coordinates of the O-XYZ system in the O'\(-\eta\xi\epsilon\) coordinate system. Assuming \(P_1, P_2\) and \(P_3\) in the O'\(-\eta\xi\epsilon\) coordinate system are:

\[
P_1 (\eta_1, \xi_1, \epsilon_1)
\]
\[
P_2 (\eta_2, \xi_2, \epsilon_2)
\]
\[
P_3 (\eta_3, \xi_3, \epsilon_3)
\]

and, those in the O-XYZ coordinate system are:

\[
P_1 (X_1, Y_1, Z_1)
\]
\[
P_2 (X_2, Y_2, Z_2)
\]
\[
P_3 (X_3, Y_3, Z_3)
\]

\(T\) is expressed as the following:

\[
T = \begin{pmatrix}
X_1 - X_0 & X_2 - X_0 & X_3 - X_0 \\
Y_1 - Y_0 & Y_2 - Y_0 & Y_3 - Y_0 \\
Z_1 - Z_0 & Z_2 - Z_0 & Z_3 - Z_0
\end{pmatrix} \begin{pmatrix}
\eta_1 & \eta_2 & \eta_3 \\
\xi_1 & \xi_2 & \xi_3
\end{pmatrix}^{-1}
\] \hspace{1cm} (6)

Thus, the expression (5) is,

\[
\begin{pmatrix}
X \\
Y \\
Z
\end{pmatrix} = \begin{pmatrix}
X_1 - X_0 & X_2 - X_0 & X_3 - X_0 \\
Y_1 - Y_0 & Y_2 - Y_0 & Y_3 - Y_0 \\
Z_1 - Z_0 & Z_2 - Z_0 & Z_3 - Z_0
\end{pmatrix} \begin{pmatrix}
\eta_1 & \eta_2 & \eta_3 \\
\xi_1 & \xi_2 & \xi_3
\end{pmatrix}^{-1} \begin{pmatrix}
\eta \\
\xi
\end{pmatrix} + \begin{pmatrix}
X_0 \\
Y_0 \\
Z_0
\end{pmatrix}
\] \hspace{1cm} (7)
In the inverse matrix, $A^{-1}$ of expression (7) the components $(i, j)$ may be expressed $\Delta ji/|A|$. $\Delta ji$ shows the $(i, j)$ algebraic complement in $A=(aji)$. As previously mentioned, $aji$ can be readily computed if $O'$-$\eta\xi\xi$ coordinate system is applied.

$$
\begin{align*}
A^{-1} = \begin{pmatrix}
\eta_1 & \eta_2 & \eta_3 \\
\xi_1 & \xi_2 & \xi_3 \\
\xi_1 & \xi_2 & \xi_3
\end{pmatrix}
= \begin{pmatrix}
0 & 0 & R_2 \\
-R_1 & R_1 & 0 \\
1 & 1 & 1
\end{pmatrix}^{-1}
= \begin{pmatrix}
1 & 0 & 0 \\
2R_2 & 2R_1 & 1 \\
1 & 1 & 2
\end{pmatrix}
= \begin{pmatrix}
1 & 0 & 0 \\
2R_2 & 2R_1 & 1 \\
1 & 1 & 2
\end{pmatrix}
\end{align*}
$$

From expressions (9) and (10), the following result were obtained.

$$
\begin{align*}
X_0 &= X_M + \frac{U}{\sqrt{U^2 + V^2 + W^2}} \\
Y_0 &= Y_M + \frac{V}{\sqrt{U^2 + V^2 + W^2}} \\
Z_0 &= Z_M + \frac{W}{\sqrt{U^2 + V^2 + W^2}}
\end{align*}
$$

From expressions (9) and (10), the following result were obtained.

$$
\begin{align*}
X_0 &= X_M + \left\{ (Y_B + Y_M)(Z_C - Z_M) \\
&\quad - (Z_B - Z_M)(Y_C - Y_M) \right\} / K \\
Y_0 &= Y_M + \left\{ (Z_B - Z_M)(X_C - X_M) \\
&\quad - (X_B - X_M)(Z_C - Z_M) \right\} / K \\
Z_0 &= Z_M + \left\{ (X_B - X_M)(Y_C - Y_M) \\
&\quad - (Y_B - Y_M)(X_C - X_M) \right\} / K
\end{align*}
$$
The following condition is necessary.

\[
K = \left[ \left( (Y_B - Y_M)(Z_C - Z_M) - (Z_B - Z_M)(Y_C - Y_M) \right)^2 + \left( (Z_B - Z_M)(X_C - X_M) - (X_B - X_M)(Z_C - Z_M) \right)^2 + \left( (X_B - X_M)(Y_C - Y_M) - (Y_B - Y_M)(X_C - X_M) \right)^2 \right]^{1/2}
\]

In summary, movement of the random points \(Q (\eta, \xi, \xi)\) on the mandible are movement in \(0-\text{XYZ}\) coordinate system and can be determined by computing the following parameters.

\[
X_1, Y_1, Z_1 \\
X_2, Y_2, Z_2 \\
X_3, Y_3, Z_3 \\
X_0, Y_0, Z_0
\]

These parameters are obtained by using the measured data \((X_A, Z_A, X_B, Z_B, Y_C, Z_C)\) with the expressions (4) and (11) previously mentioned. \(X, Y,\) and \(Z\) are calculated from the computed parameters using expression (7).

d. Inverse transformation of the coordinate

It is essential in this computation system that coordinate \((\eta, \xi, \xi)\) in the \(0'-\eta\xi_\xi\) be established before determining the position of the arbitrarily selected point \(Q\) on the mandible. It is difficult to locate \((\eta, \xi, \xi)\) in the \(0'-\eta\xi_\xi\) system because the coordinate system \(0'-\eta\xi_\xi\) is fixed on the stylus block and it is almost impossible to determine its positional relationship to the mandible.

The coordinate system \(0-\text{XYZ}\) is fixed on the box frame and its position is readily related to the maxilla by means of the face bow. It is feasible to accurately measure the coordinate of point \(Q\) on the \(0-\text{XYZ}\) system, and then convert the measured data to the coordinate's on the \(0'-\eta\xi_\xi\) system. The positional relationship between the maxillary and mandibular coordinate systems, \(0-\text{XYZ}\) and \(0'-\eta\xi_\xi\) can be computed from the data obtained by the sensor.

For example, when the movement of the condyle is determined, the position of the condyle in centric relation is measured on the face as the \(0-\text{XYZ}\) coordinate, and then the transformation is made from \(0-\text{XYZ}\) coordinate to \(0'-\eta\xi_\xi\) coordinate by applying the known data concerning the maxillary and mandibular positional relationships.

Conversion from \(0-\text{XYZ}\) system to the \(0'-\eta\xi_\xi\) system is expressed by the following equation.
This inverse transformation makes it possible to position the sensors. Once the position of the box frame in relation to the maxilla is recorded the position of the arbitrarily selected point on the mandible can be computed.

**Automatic electronic measuring system**

Using the above mentioned principle the following system was developed for measuring mandibular movement. This system consisted of sensors, rectangular wave form voltage generator, voltage detector, data recorder, computer and graphic plotter. The configuration diagram of the automatic electronic measuring system is shown in Fig. 7 and a picture of the system is shown in Fig. 8.
a. The sensor
The sensor consists of a C.P.P., stylus, and connectors. Three C.P.P.'s were located on the acrylic box frame and all plates were placed at right angles. The sensor's weight is 230gm and is attached to the maxilla. The stylus weighed 90gm and was attached to the mandible. They were fastened to the maxilla and mandible by using a para occlusal clutch in teeth contact condition and a regular clutch in non teeth contact conditions.

b. The rectangular wave form voltage generator and detector.
The rectangular wave form voltage generator provide the electric potential on the surface of C.P.P. The rectangular wave form produced by the generator is $0 - 15V$, $t=0.33 - 5.5msec$ cycle. The detector analyzes the voltage at each cycle and outputs the analogue signals in every semi-cycle. There are six analogue voltage signals outputed from the detectors. The detectors are the tips of the three styli.

c. Data recorder
A substantial number of calculations were necessary to precisely describe the movement of the mandible in three dimensions. In order to perform this task, it was necessary to store the data in a data acquisition system. Otherwise, it would not be possible for the computer used in this study to process the necessary calculations in a timely manner. A data recorder was used to store the data transferred by the detector and was retrieved as necessary for calculations. The recorder has six channels, each of which are capable of acquiring and memorizing the quantitative data. The analogue input voltage $0 - 10V$ is divided into $5 - 4005$ (analyzing capability $0.01mm$, $4000$ divisions, $1$ digit = $2.5mV$, $10V - 40mm$) which are converted to the quantitative data. Each channel has three sections and each section can memorize $1025$ units of data (address $0 - 1024$).

The data was sampled periodically. Duration of the sampling was $\tau_s = 1 - 100msec$ which was continuous and changeable. At the initiation of data sampling, the information signals are sent from the sensor and were obtained as the six data in every duration, and then were stored in the address regularly. When the six sets of data were stored in the same address, channels 1 to 6 were used. The data was not stored simultaneously from channels 1 to 6, but was considered for the purposes of this study to be stored at the same time. It took approximately $0.3msec$ to acquire the 6 sets of data in the six channels of the address. It was not expected that the $0.3msec$ delay in recording data would have any significant effect upon measuring movements of the mandible. When one of the $1024$ data address was to capacity, data acquisition was stopped automatically, and the next data recording section was activated. The computer used in this study memorized the amount of data transferred and automatically stops the acquisition system.
d. Computer
The computer used for this system was a Hewlett-Packard Model HP85*. The capacity of this computer is RAM: 32KB and ROM: 80KB. The magnetic cartridge tape was capable of storing the computed results (210KB). This computer was able to perform the calculations mentioned previously. A hard copy of the calculated data was obtained by connecting an accessory printer to the computer.

e. Graphic plotter
The XY graphic plotter used for this measuring system was a Hewlett-Packard YHP-7225A*. Movements of the mandible computed from the data were displayed graphically using this plotter which magnified the actual movements 8 times. It has a maximum plotting speed of 250mm/sec, accuracy ±0.25mm, reproducibility 0.1mm, and analyzing capability 0.032mm. A4 size paper and interchangeable colored pens were used on the graphic platter.

Patient subjects
A group of eleven male adults ranging in age from 22 to 27 years, was selected as patients subjects. Their average age was 24 years. All subjects had normal orthognathic maxilla-mandibular relationships and no discernible temporomandibular joint disorder. They had definite intercuspal occlusal position, no teeth missing except the third molars, and healthy periodontal tissues. All decayed teeth were restored to completely functional anatomic form. The condylar position in centric relation was examined by means of the transcranial X-ray. It was observed that in centric relation the condyles were positioned in the anterosuperior portion of the glenoid fossa against the posterior slope of the articular eminence: This condylar position (centric relation) was used as the initial point for measurement. By means of the EMG analysis, masseter, temporalis, and digastrics muscles were examined in their rest position and under the strong biting pressure. All patient muscles were found to be functioning normally.

Measuring procedures
Three dimensional movements of the left and right condylar points, the left and right mandibular molar cusps and the incisal point during protrusive, left lateral and right lateral were measured. The box frame sensor with C.P.P. and the stylus block were attached to the maxillary and mandibular dentitions by means of two different types of clutches. In the teeth contact condition, Klett's** para-occlusal clutches were employed (Fig. 9). This clutch is made of aluminum and has an arch shape. The inside of the clutch was relined with cold-cure acrylic resin and attached to the labial surface of the maxillary and mandibular teeth. The

* Hewlett-Packard, Waltham Mass., U.S.A.
** Klett, Wurzburg, W. Germany.
clutch only makes contact with the cervical two-thirds of the labial surface of the teeth and does not interfere with teeth contact during measurement.

In the teeth contact free condition, Denar's clutch* was employed. This clutch was fabricated with a clutch former and cold-cure acrylic resin. Individual clutches were fabricated for each subject. The only contact between the maxillary clutch and the mandibular clutch is at the central bearing plate and point.

After cementing the clutches to the maxillary and mandibular dentitions, a Hoby Exacta face bow** was attached. The earpieces were inserted into the external auditory meatus and the face bow adjusted so that the length of the earpiece on both sides were equal length. The condylar position located in this manner was 13 mm anterior to the upper edge of the external auditory meatus and on the Frankfurt horizontal plane.

The anterior reference point was located 43mm above the incisal edge of the maxillary right central incisor. The verticle position of the face bow was determined by setting its reference pointer at the anterior reference point. In this way the maxillary triangle was recorded for each patient then the sensors were attached. Positional relationship of the box frame and the maxilla were recorded using a face-bow. The XY plane was set to be parallel to the horizontal reference plane and the Y axis was set to the line connecting the line connecting the left and right T.M.J.

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* Denar Corp. Anaheim C.A., U.S.A.,
** J. Morita Corp., Osaka, Japan.
The mandible was first be positioned at the starting point (centric relation) and then protrusive movement was measured. As soon as the acquisition system of the data recorder started, all data sent from the sensor was recorded continuously. When all protrusive movement were completed the data recorder was turned off. All recorded data of protrusive movement was stored in section I of the data recorder. The same procedure was followed for lateral movements. Three measurements were recorded for each movement both teeth contact and non teeth contact conditions. When the para-occlusal clutch was used the operator gave instructions verbally, and did not touch the mandible during measurement. When Denar clutches were used the operator guided the patients mandible through the movements forcefully with his fingers.

**Morphology of Denar's clutch bearing plate**

The morphology of the central bearing plate of the Denar clutch was examined. The starting point was established on the midline, 5mm anterior to the posterior border of the plate. Three straight lines 0.3mm wide were drawn on the central bearing plate to standardize the pathways for the protrusive, right and left lateral movements. One line was drawn on the midline, others at a 60° angle to the midline. A three-dimensional measuring system A221 – B3* was employed for the measurement (Fig. 10). The configurations of the central bearing plate were measured by the linear encoder arranged at 10µm intervals and the coordinates of the plate were recorded as optical signals. The measuring accuracy of this system was 6µm. The tip of the probe used in this study was a 1mm diameter ball. After the starting point was measured by the tip of the probe, the protrusive pathway was measured. Along the 9mm path a total of 25 three-dimensional measurements were recorded. Along the 5mm lateral pathway, 25 three-dimensional measurements were recorded, in respective directions. Then measurement points of equal altitude were examined. The probe was lifted every 0.2mm and the X and Y coordinates of equal altitude were obtained.

Table 3 shows the measured results of the protrusive, left and right lateral pathways of the central bearing plate. Fig. 11 is the plot of the mid-sagittal section of the bearing plate. In the protrusive pathway, the initial 0.5mm was a flat straight line. From 0.5 to 1.5mm the pathway showed a concavity with radius of 40mm. From 1.5 to 9mm, the pathway was a relatively flat straight line with a 25.5° inclination to the horizontal plane. Fig. 12 is a plot of the left frontal section of the central bearing plate and the initial 0.4mm was flat. From 0.4 to 2.5mm the pathway showed a concavity with a radius of 40mm. From 2.5 to 8mm, the pathway

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* Mitsutoyo Corp., Japan.

The Journal of Gnathology Vol. 5, No. 1, 1986 133
was a flat straight line with a 28° inclination to horizontal plane. Fig. 13 is a plot of the right frontal section. The initial 0.7mm was flat and from 0.7 to 2.4mm, the pathway showed a concavity with a radius of 40mm. From 2.4 to 8mm, the pathway was a flat straight line with a 29° inclination to the horizontal plane.

Fig. 14 shows the equal altitude lines of the central bearing plate. Thirty-four contour lines were drawn at 0.2mm intervals. On the protrusive pathway, the distance between the contour lines gradually extended as the pathway progressed. The same was true on the lateral pathway. At the intermediate portions of both the protrusive and lateral pathways, the distance between the contour lines are nearly equal and at less intervals. In summary, the
Three Dimensional Study of Mandibular Movement Using an Automatic Electronic Measuring System

Table 3. Digital data obtained by the three dimensional measurement of the configuration of the Denar's central bearing plate along the protrusive, left and right lateral pathways.

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The central bearing plate of a Denar clutch had a flat pathway at the initial 0.5mm, and showed a concave slope from 0.5 to 2.5mm. The inclination of the concave slopes was 19° on the protrusive pathway.
Table 4. Three dimensional displacements of condyles during mandibular movements under teeth contact condition.

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RESULTS

Measured data
Mandibular movements of eleven adult male subjects were measured using the automatic electronic measuring system under the teeth contact and contact free conditions. Figs. 15–25 show graphic data of the mandibular motion paths drawn by the graphic plotter. Example of the data obtained by repeating the measurements three times are also shown. Figs. 15–25 (a), (b) and (c)
Table 5. Three-dimensional displacements of first molars during mandibular movements under teeth contact condition.

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indicate the paths of the left and right condylar point, the left and right mandibular first molars and incisal point, respectively, under teeth contact conditions. (d) and (e) indicate the paths of left and right condylar point and the incisal point, respectively, under contact free condition. In Figs. 15–25, F is the protrusive movement, R is the right lateral movement, and L is the left lateral movement.

Figs. 15–25, show the three dimensional displacement of each target which was measured graphically at the terminal points of the orbits on the plots. Tables 4–8 show the results of the orbital measurements. In tables 4–8 X, Y, and Z indicate anteroposterior (anterior is +), lateral (right is + on the right lateral movement and left is + on the left lateral movement), and superoinferior (inferior...
Table 6. Three dimensional displacements of incisal points during mandibular movements under teeth contact condition.

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</table>

The exceptions were X and Z coordinates which refer to the opposite directions (posterior and superior are +) on the working orbit. The suffix consisting of three small letters differentiates the data. Those are added on the right side of the notations X, Y, and Z indicating three dimensional displacement data shown in tables 4-8. The first small letter differentiates the target and C indicates the center of the condyle, i indicates the incisal point, and m the cusp of the first molar. The second small letter differentiate the mandibular movement and p indicates the displacements during protrusive movement, l indicates the displacement of the center of the condyle (condylar point) or molar cusp on the nonworking side, and w indicates the displacement of the center of the condyle or molar cusp on the working side, respectively. The third small letter differentiates the position where the data was obtained, r indicates the right side and l indicates, the left side. Tables 4—8 show all the data of displacement obtained under the teeth contact condition, and the data of displacement of the center of condyle obtained under the contact free condition.

Tables 9—12 show the inclinations of the orbits of the condylar path, molar path and incisal path in the sagittal, frontal, and horizontal planes. These were calculated from the condylar, incisal and molar orbit data shown in the Tables 4—8. Descriptions of the data and the computation formulas (definitions) are shown in each column in the tables. On the right in Tables 9—12, the means and
Table 7. Three dimensional displacements of condyles during mandibular movements under teeth contact free condition.

X, Y, Z: Three dimensional displacements
first suffix c: the center of the condyle
second suffix p: protrusive movement
        l: lateral movement, non-working side
        w: lateral movement, working side
third suffix r: the condyle on the right side
        l: the condyle on the left side

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The standard deviations of the data in each column are shown. In the calculated data obtained from Tables 4—8, the orbits of the molar during working movement under teeth contact conditions are not shown.

**Tests of the correlation**

Twenty eight combinations of data (items 1—28) were selected from the Tables 9—12 and they are shown in Tables 13—15. Each combination was tested and the correlation coefficient was obtained and the regression line formula was computed. The results of testing and computations are as follows:
Table 8. Three dimensional displacements of incisal points during mandibular movements under teeth contact free condition.

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Table 9. Inclinations and the other data of the orbits of condylar path under teeth contact condition.

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<td>21.7</td>
<td>35.3</td>
<td>42.7</td>
<td>29.5</td>
<td>34.5</td>
<td>30.3</td>
<td>55.7</td>
<td>-0.7</td>
<td>40.6</td>
<td>12.1</td>
</tr>
<tr>
<td>Sagittal right lateral condylar path inclination</td>
<td>$\tan^{-1} (Z_{cIlr} / X_{cIlr})$</td>
<td>deg</td>
<td>48.2</td>
<td>48.0</td>
<td>30.6</td>
<td>45.2</td>
<td>48.0</td>
<td>43.8</td>
<td>46.6</td>
<td>48.8</td>
<td>44.3</td>
<td>49.7</td>
<td>34.3</td>
</tr>
<tr>
<td>Bennett angle during left lateral movement</td>
<td>$\tan^{-1} (Z_{cIlr} / X_{cIlr})$</td>
<td>deg</td>
<td>17.0</td>
<td>8.3</td>
<td>11.0</td>
<td>17.2</td>
<td>18.2</td>
<td>22.1</td>
<td>13.9</td>
<td>36.8</td>
<td>10.0</td>
<td>21.0</td>
<td>-3.0</td>
</tr>
<tr>
<td>Bennett angle during right lateral movement</td>
<td>$\tan^{-1} (Y_{cIlr} / X_{cIlr})$</td>
<td>deg</td>
<td>11.3</td>
<td>6.7</td>
<td>4.9</td>
<td>12.8</td>
<td>4.4</td>
<td>12.6</td>
<td>16.0</td>
<td>-3.6</td>
<td>19.3</td>
<td>12.8</td>
<td>10.6</td>
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<tr>
<td>Amount of total sidediff during left lateral movement</td>
<td>$Y_{cIlr}$</td>
<td>mm</td>
<td>1.9</td>
<td>1.3</td>
<td>1.3</td>
<td>1.9</td>
<td>1.9</td>
<td>2.2</td>
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<td>1.7</td>
<td>1.1</td>
<td>2.1</td>
<td>-0.4</td>
</tr>
<tr>
<td>Amount of total sidediff during right lateral movement</td>
<td>$Y_{cIlr}$</td>
<td>mm</td>
<td>1.3</td>
<td>0.7</td>
<td>0.6</td>
<td>1.4</td>
<td>0.4</td>
<td>1.4</td>
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<td>-0.4</td>
<td>1.9</td>
<td>1.4</td>
<td>0.7</td>
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<tr>
<td>Amount of Bennett movement during left lateral movement</td>
<td>$Y_{cwl}$</td>
<td>mm</td>
<td>1.7</td>
<td>1.1</td>
<td>1.0</td>
<td>1.7</td>
<td>1.7</td>
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<td>1.3</td>
<td>1.1</td>
<td>0.8</td>
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<td>-0.7</td>
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<tr>
<td>Amount of Bennett movement during right lateral movement</td>
<td>$Y_{cwr}$</td>
<td>mm</td>
<td>1.2</td>
<td>0.5</td>
<td>0.6</td>
<td>1.3</td>
<td>0.3</td>
<td>1.2</td>
<td>1.7</td>
<td>-0.6</td>
<td>1.8</td>
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Table 10. Inclinations and angles of the orbits of molar path under teeth contact condition.

<table>
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<th>Unit</th>
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<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal protrusive molar path inclination on the right side ( \tan^{-1} \left( \frac{Z_{mpr}}{X_{mpr}} \right) ) deg</td>
<td>32.9</td>
<td>26.9</td>
<td>45.9</td>
<td>40.5</td>
<td>28.5</td>
<td>34.5</td>
<td>22.7</td>
<td>39.4</td>
<td>6.5</td>
<td>36.5</td>
<td>27.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sagittal protrusive molar path inclination on the left side ( \tan^{-1} \left( \frac{Z_{mpl}}{X_{mpl}} \right) ) deg</td>
<td>33.8</td>
<td>21.9</td>
<td>38.7</td>
<td>41.1</td>
<td>26.6</td>
<td>31.3</td>
<td>21.1</td>
<td>40.6</td>
<td>9.4</td>
<td>36.4</td>
<td>25.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sagittal protrusive molar path inclination on the average ( \frac{1}{n} \sum \tan^{-1} \left( \frac{Z_{mpr}}{X_{mpr}} \right) ) deg</td>
<td>33.4</td>
<td>24.4</td>
<td>42.3</td>
<td>40.8</td>
<td>27.6</td>
<td>32.9</td>
<td>21.5</td>
<td>40.0</td>
<td>8.0</td>
<td>36.5</td>
<td>26.5</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sagittal left lateral molar path inclination ( \tan^{-1} \left( \frac{Z_{mll}}{X_{mll}} \right) ) deg</td>
<td>34.6</td>
<td>25.3</td>
<td>47.4</td>
<td>56.4</td>
<td>51.1</td>
<td>56.6</td>
<td>32.6</td>
<td>73.8</td>
<td>10.8</td>
<td>50.4</td>
<td>25.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sagittal right lateral molar path inclination ( \tan^{-1} \left( \frac{Z_{mlr}}{X_{mlr}} \right) ) deg</td>
<td>49.6</td>
<td>73.4</td>
<td>43.1</td>
<td>63.4</td>
<td>65.9</td>
<td>53.1</td>
<td>46.6</td>
<td>54.6</td>
<td>47.9</td>
<td>58.5</td>
<td>61.5</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sagittal left lateral incisal path inclination ( \tan^{-1} \left( \frac{Z_{ill}}{X_{ill}} \right) ) deg</td>
<td>22.5</td>
<td>33.2</td>
<td>35.2</td>
<td>42.2</td>
<td>45.0</td>
<td>47.8</td>
<td>21.8</td>
<td>44.2</td>
<td>9.6</td>
<td>38.0</td>
<td>31.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sagittal right lateral incisal path inclination ( \tan^{-1} \left( \frac{Z_{ilr}}{X_{ilr}} \right) ) deg</td>
<td>41.5</td>
<td>55.8</td>
<td>52.0</td>
<td>51.3</td>
<td>55.6</td>
<td>39.1</td>
<td>40.4</td>
<td>56.0</td>
<td>36.2</td>
<td>44.4</td>
<td>35.5</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal left lateral incisal path angle ( \tan^{-1} \left( \frac{Y_{ill}}{X_{ill}} \right) ) deg</td>
<td>59.0</td>
<td>38.8</td>
<td>57.0</td>
<td>58.9</td>
<td>51.1</td>
<td>54.0</td>
<td>58.1</td>
<td>74.2</td>
<td>48.2</td>
<td>57.1</td>
<td>37.5</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal right lateral incisal path angle ( \tan^{-1} \left( \frac{Y_{ilr}}{X_{ilr}} \right) ) deg</td>
<td>53.0</td>
<td>66.4</td>
<td>36.1</td>
<td>58.0</td>
<td>56.9</td>
<td>58.1</td>
<td>51.2</td>
<td>43.5</td>
<td>56.5</td>
<td>59.0</td>
<td>68.8</td>
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</table>

Table 11. Inclinations and angles of the orbits of incisal path under teeth contact condition.

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Description Definition</th>
<th>Unit</th>
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<th>6</th>
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<th>11</th>
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<th>SD</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Sagittal protrusive incisal path inclination ( \tan^{-1} \left( \frac{Z_{ip}}{X_{ip}} \right) ) deg</td>
<td>32.3</td>
<td>18.7</td>
<td>43.4</td>
<td>40.6</td>
<td>20.8</td>
<td>32.2</td>
<td>15.4</td>
<td>35.7</td>
<td>7.2</td>
<td>33.9</td>
<td>28.0</td>
<td>28.0</td>
<td>11.3</td>
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</tr>
<tr>
<td></td>
<td>Sagittal left lateral incisal path inclination ( \tan^{-1} \left( \frac{Z_{ill}}{X_{ill}} \right) ) deg</td>
<td>40.7</td>
<td>34.3</td>
<td>56.2</td>
<td>62.7</td>
<td>27.1</td>
<td>64.1</td>
<td>30.4</td>
<td>80.6</td>
<td>26.8</td>
<td>54.5</td>
<td>34.8</td>
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<td></td>
<td></td>
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<tr>
<td></td>
<td>Sagittal right lateral incisal path inclination ( \tan^{-1} \left( \frac{Z_{ilr}}{X_{ilr}} \right) ) deg</td>
<td>53.2</td>
<td>80.4</td>
<td>54.7</td>
<td>71.0</td>
<td>77.8</td>
<td>63.0</td>
<td>49.1</td>
<td>59.8</td>
<td>38.1</td>
<td>62.6</td>
<td>84.3</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Frontal left lateral incisal path inclination ( \tan^{-1} \left( \frac{Z_{ill}}{Y_{ill}} \right) ) deg</td>
<td>14.9</td>
<td>23.3</td>
<td>27.2</td>
<td>36.4</td>
<td>12.7</td>
<td>44.8</td>
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<td>61.9</td>
<td>13.3</td>
<td>32.4</td>
<td>22.5</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Frontal right lateral incisal path inclination ( \tan^{-1} \left( \frac{Z_{ilr}}{Y_{ilr}} \right) ) deg</td>
<td>27.4</td>
<td>50.1</td>
<td>44.8</td>
<td>45.7</td>
<td>36.0</td>
<td>28.0</td>
<td>29.0</td>
<td>43.6</td>
<td>24.5</td>
<td>35.9</td>
<td>28.1</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal left lateral incisal path angle ( \tan^{-1} \left( \frac{Y_{ill}}{X_{ill}} \right) ) deg</td>
<td>72.9</td>
<td>57.8</td>
<td>71.0</td>
<td>69.2</td>
<td>66.2</td>
<td>64.2</td>
<td>70.7</td>
<td>81.6</td>
<td>64.9</td>
<td>65.7</td>
<td>59.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Horizontal right lateral incisal path angle ( \tan^{-1} \left( \frac{Y_{ilr}}{X_{ilr}} \right) ) deg</td>
<td>68.8</td>
<td>78.6</td>
<td>54.8</td>
<td>70.6</td>
<td>81.1</td>
<td>74.9</td>
<td>64.4</td>
<td>70.6</td>
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<td>69.4</td>
<td>87.0</td>
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</tbody>
</table>

\( \text{a. Correlation of data for the condylar paths} \)
\( \text{Sagittal condylar path inclination (items 1 and 2):} \) The correlation coefficient among 22 paired groups of data between protrusive and the lateral sagittal inclinations under teeth contact condition was 0.611, and that under contact free condition was 0.624. These are statistically significant at \( p=0.01 \) level of the significance. The means of the correlation coefficient of the sagittal
### Table 12. Inclinations and the other data of the orbits of condylar path under teeth contact free condition.

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Description</th>
<th>Definition</th>
<th>Unit</th>
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<th>2</th>
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<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sagittal protrusive condylar path inclination on the right side</td>
<td>$\tan (Z_{cpr} / X_{cpr})$</td>
<td>deg</td>
<td>27.1</td>
<td>23.3</td>
<td>44.0</td>
<td>28.3</td>
<td>26.2</td>
<td>36.4</td>
<td>29.2</td>
<td>43.8</td>
<td>-3.4</td>
<td>60.3</td>
<td>10.1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Sagittal protrusive condylar path inclination on the left side</td>
<td>$\tan (Z_{cpl} / X_{cpl})$</td>
<td>deg</td>
<td>32.5</td>
<td>32.9</td>
<td>25.0</td>
<td>31.0</td>
<td>28.0</td>
<td>31.4</td>
<td>25.1</td>
<td>43.3</td>
<td>17.2</td>
<td>50.6</td>
<td>17.1</td>
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</tr>
<tr>
<td>3</td>
<td>Sagittal protrusive condylar path inclination on the average</td>
<td>Average on the above</td>
<td>deg</td>
<td>29.8</td>
<td>28.1</td>
<td>34.5</td>
<td>29.7</td>
<td>27.1</td>
<td>33.9</td>
<td>27.2</td>
<td>43.6</td>
<td>6.9</td>
<td>55.5</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Sagittal left lateral condylar path inclination</td>
<td>$\tan (Z_{clr} / X_{clr})$</td>
<td>deg</td>
<td>23.5</td>
<td>17.3</td>
<td>22.7</td>
<td>30.1</td>
<td>17.5</td>
<td>49.4</td>
<td>16.8</td>
<td>39.1</td>
<td>10.7</td>
<td>36.2</td>
<td>19.5</td>
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</tr>
<tr>
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<td>Sagittal right lateral condylar path inclination</td>
<td>$\tan (Z_{cll} / X_{cll})$</td>
<td>deg</td>
<td>49.3</td>
<td>46.5</td>
<td>31.0</td>
<td>28.9</td>
<td>31.3</td>
<td>53.0</td>
<td>35.4</td>
<td>43.4</td>
<td>24.1</td>
<td>52.8</td>
<td>17.3</td>
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</tr>
<tr>
<td>6</td>
<td>Bennett angle during left lateral movement</td>
<td>$\tan (Y_{clr} / X_{clr})$</td>
<td>deg</td>
<td>12.9</td>
<td>5.9</td>
<td>11.4</td>
<td>15.1</td>
<td>17.0</td>
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<td>14.6</td>
<td>12.5</td>
<td>23.6</td>
<td>5.9</td>
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</tr>
<tr>
<td>7</td>
<td>Bennett angle during right lateral movement</td>
<td>$\tan (Y_{cll} / X_{cll})$</td>
<td>deg</td>
<td>15.7</td>
<td>9.0</td>
<td>5.2</td>
<td>15.9</td>
<td>4.9</td>
<td>15.7</td>
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<td>5.6</td>
<td>14.5</td>
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</tr>
<tr>
<td>8</td>
<td>Amount of total sideshift during left lateral movement</td>
<td>$Y_{clr}$</td>
<td>mm</td>
<td>1.4</td>
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<td>1.2</td>
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<td>0.7</td>
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<td>1.3</td>
<td>3.0</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Amount of total sideshift during right lateral movement</td>
<td>$Y_{cll}$</td>
<td>mm</td>
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<td>0.9</td>
<td>0.8</td>
<td>2.0</td>
<td>0.5</td>
<td>1.4</td>
<td>1.6</td>
<td>0.7</td>
<td>0.9</td>
<td>1.6</td>
<td>1.1</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Amount of Bennett movement during left lateral movement</td>
<td>$Y_{cwl}$</td>
<td>mm</td>
<td>1.2</td>
<td>0.5</td>
<td>0.9</td>
<td>1.7</td>
<td>2.4</td>
<td>1.6</td>
<td>0.6</td>
<td>0.8</td>
<td>1.1</td>
<td>2.9</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Amount of Bennett movement during right lateral movement</td>
<td>$Y_{cwr}$</td>
<td>mm</td>
<td>1.3</td>
<td>0.7</td>
<td>0.6</td>
<td>1.8</td>
<td>0.4</td>
<td>1.1</td>
<td>1.3</td>
<td>0.6</td>
<td>0.7</td>
<td>1.3</td>
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### Table 13. Correlation coefficients and formulas for regression lines among the data for condylar path.

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<th>Item No.</th>
<th>Data designated as X</th>
<th>Teeth condition</th>
<th>Data designated as Y</th>
<th>Teeth condition</th>
<th>N_value</th>
<th>P_value</th>
<th>Correlation coefficient</th>
<th>Formula for regression line</th>
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<tbody>
<tr>
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<td>Sagittal protrusive condylar path inclination</td>
<td>Contact</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact</td>
<td>22</td>
<td>&lt; 0.01</td>
<td>0.611</td>
<td>Y = 0.697X + 13.8</td>
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<td>Sagittal protrusive condylar path inclination</td>
<td>Contact free</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact free</td>
<td>22</td>
<td>&lt; 0.01</td>
<td>0.624</td>
<td>Y = 0.597X + 13.8</td>
</tr>
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<td>Sagittal protrusive condylar path inclination</td>
<td>Contact</td>
<td>Sagittal protrusive condylar path inclination</td>
<td>Contact free</td>
<td>11</td>
<td>&lt; 0.001</td>
<td>0.911</td>
<td>Y = 1.040X - 4.9</td>
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<td>Contact</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact free</td>
<td>22</td>
<td>&lt; 0.001</td>
<td>0.705</td>
<td>Y = 0.682X - 6.4</td>
</tr>
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<td>5</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact</td>
<td>Bennett angle</td>
<td>Contact</td>
<td>22</td>
<td>&gt; 0.05</td>
<td>0.295</td>
<td>Y = 0.189X + 5.7</td>
</tr>
<tr>
<td>6</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact free</td>
<td>Bennett angle</td>
<td>Contact free</td>
<td>22</td>
<td>&gt; 0.05</td>
<td>0.393</td>
<td>Y = 0.176X + 6.6</td>
</tr>
<tr>
<td>7</td>
<td>Bennett angle</td>
<td>Contact</td>
<td>Bennett angle</td>
<td>Contact</td>
<td>22</td>
<td>&lt; 0.01</td>
<td>0.586</td>
<td>Y = 0.397X + 7.1</td>
</tr>
<tr>
<td>8</td>
<td>Amount of total sideshift</td>
<td>Contact</td>
<td>Amount of Bennett movement</td>
<td>Contact</td>
<td>22</td>
<td>&lt; 0.001</td>
<td>0.986</td>
<td>Y = 0.996X - 0.20</td>
</tr>
<tr>
<td>9</td>
<td>Amount of total sideshift</td>
<td>Contact free</td>
<td>Amount of Bennett movement</td>
<td>Contact free</td>
<td>22</td>
<td>&lt; 0.001</td>
<td>0.988</td>
<td>Y = 1.007X - 0.23</td>
</tr>
<tr>
<td>10</td>
<td>Amount of total sideshift</td>
<td>Contact</td>
<td>Amount of total sideshift</td>
<td>Contact free</td>
<td>22</td>
<td>&gt; 0.001</td>
<td>0.632</td>
<td>Y = 0.541X + 0.68</td>
</tr>
<tr>
<td>11</td>
<td>Amount of Bennett movement</td>
<td>Contact</td>
<td>Amount of Bennett movement</td>
<td>Contact free</td>
<td>22</td>
<td>&gt; 0.001</td>
<td>0.633</td>
<td>Y = 0.547X + 0.56</td>
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## Table 14. Correlation coefficients and formulas for regression lines for the combinations of data between condylar path and incisal path.

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Data designated as X</th>
<th>Teeth condition</th>
<th>Data designated as Y</th>
<th>Teeth condition</th>
<th>N</th>
<th>value</th>
<th>Correlation coefficient</th>
<th>Formula for regression line</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Sagittal protrusive condylar path inclination</td>
<td>Contact</td>
<td>Sagittal protrusive incisal path inclination</td>
<td>Contact</td>
<td>11</td>
<td>( &lt; 0.05 )</td>
<td>0.687</td>
<td>( Y = 0.679X + 5.2 )</td>
</tr>
<tr>
<td>13</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact</td>
<td>Sagittal lateral incisal path inclination</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.001 )</td>
<td>0.682</td>
<td>( Y = 0.905X + 21.2 )</td>
</tr>
<tr>
<td>14</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact</td>
<td>Frontal lateral incisal path inclination</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.01 )</td>
<td>0.613</td>
<td>( Y = 0.526X + 11.2 )</td>
</tr>
<tr>
<td>15</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact</td>
<td>Horizontal lateral incisal path angle</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.05 )</td>
<td>0.495</td>
<td>( Y = 0.286X + 59.1 )</td>
</tr>
<tr>
<td>16</td>
<td>Bennett angle</td>
<td>Contact</td>
<td>Horizontal lateral incisal path angle</td>
<td>Contact</td>
<td>22</td>
<td>( &gt; 0.05 )</td>
<td>0.232</td>
<td>( Y = 0.209X + 67.1 )</td>
</tr>
<tr>
<td>17</td>
<td>Sagittal protrusive condylar path inclination</td>
<td>Contact free</td>
<td>Sagittal protrusive incisal path inclination</td>
<td>Contact</td>
<td>11</td>
<td>( &lt; 0.05 )</td>
<td>0.609</td>
<td>( Y = 0.529X + 12.1 )</td>
</tr>
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<td>18</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact free</td>
<td>Sagittal lateral incisal path inclination</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.01 )</td>
<td>0.549</td>
<td>( Y = 0.753X + 31.0 )</td>
</tr>
<tr>
<td>19</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact free</td>
<td>Frontal lateral incisal path inclination</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.01 )</td>
<td>0.646</td>
<td>( Y = 0.572X + 12.5 )</td>
</tr>
<tr>
<td>20</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact free</td>
<td>Horizontal lateral incisal path angle</td>
<td>Contact</td>
<td>22</td>
<td>( &gt; 0.05 )</td>
<td>0.155</td>
<td>( Y = 0.093X + 66.8 )</td>
</tr>
</tbody>
</table>

## Table 15. Correlation coefficients and formulas for regression lines for the combinations of data between condylar path and molar path or between incisal path and molar path.

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Data designated as X</th>
<th>Teeth condition</th>
<th>Data designated as Y</th>
<th>Teeth condition</th>
<th>N</th>
<th>value ( P ) value</th>
<th>Correlation coefficient</th>
<th>Formula for regression line</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>Sagittal protrusive condylar path inclination</td>
<td>Contact</td>
<td>Sagittal protrusive molar path inclination</td>
<td>Contact</td>
<td>11</td>
<td>( &lt; 0.001 )</td>
<td>0.845</td>
<td>( Y = 0.751X + 5.2 )</td>
</tr>
<tr>
<td>22</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact</td>
<td>Sagittal lateral molar path inclination</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.001 )</td>
<td>0.867</td>
<td>( Y = 1.011X + 11.7 )</td>
</tr>
<tr>
<td>23</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact</td>
<td>Frontal lateral molar path inclination</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.001 )</td>
<td>0.717</td>
<td>( Y = 0.622X + 16.9 )</td>
</tr>
<tr>
<td>24</td>
<td>Sagittal lateral condylar path inclination</td>
<td>Contact</td>
<td>Horizontal lateral molar path angle</td>
<td>Contact</td>
<td>22</td>
<td>( &gt; 0.01 )</td>
<td>0.532</td>
<td>( Y = 0.375X + 40.7 )</td>
</tr>
<tr>
<td>25</td>
<td>Sagittal protrusive incisal path inclination</td>
<td>Contact</td>
<td>Sagittal protrusive molar path inclination</td>
<td>Contact</td>
<td>11</td>
<td>( &lt; 0.001 )</td>
<td>0.963</td>
<td>( Y = 0.867X + 6.2 )</td>
</tr>
<tr>
<td>26</td>
<td>Sagittal lateral incisal path inclination</td>
<td>Contact</td>
<td>Sagittal lateral molar path inclination</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.001 )</td>
<td>0.862</td>
<td>( Y = 0.758X + 7.6 )</td>
</tr>
<tr>
<td>27</td>
<td>Frontal lateral incisal path inclination</td>
<td>Contact</td>
<td>Frontal lateral molar path inclination</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.001 )</td>
<td>0.824</td>
<td>( Y = 0.834X + 14.4 )</td>
</tr>
<tr>
<td>28</td>
<td>Horizontal lateral incisal path angle</td>
<td>Contact</td>
<td>Horizontal lateral molar path angle</td>
<td>Contact</td>
<td>22</td>
<td>( &lt; 0.001 )</td>
<td>0.857</td>
<td>( Y = 1.048X - 18.5 )</td>
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</table>
Fig. 15. Graphic data of the mandibular motion orbits for patient No. 1:
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition
F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
Fig. 16. Graphic data of the mandibular motion orbits for patient No. 2
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition
F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
Fig. 17. Graphic data of the mandibular motion orbits for patient No. 3
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition
F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
Fig. 18. Graphic data of the mandibular motion orbits for patient No. 4
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition
F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
Fig. 19. Graphic data of the mandibular motion orbits for patient No. 5
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition
F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
Fig. 20. Graphic data of the mandibular motion orbits for patient No. 6.
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition

F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
Fig. 21. Graphic data of the mandibular motion orbits for patient No. 7
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition

F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
Fig. 22. Graphic data of the mandibular motion orbits for patient No. 8
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition
F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
Fig. 23. Graphic data of the mandibular motion orbits for patient No. 9
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molar on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition
F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
Three Dimensional Study of Mandibular Movement Using an Automatic Electronic Measuring System

Fig. 24. Graphic data of the mandibular motion orbits for patient No. 10
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition

F: The orbit of the protrusive movement
R: The orbit of the right lateral movement
L: The orbit of the left lateral movement
Fig. 25. Graphic data of the mandibular motion orbits for patient No. 11
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars on both sides under teeth contact condition
(c) The orbits of the mandibular incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
(e) The orbits of the mandibular incisal point under teeth contact free condition
F : The orbit of the protrusive movement
R : The orbit of the right lateral movement
L : The orbit of the left lateral movement
condylar inclination and lateral inclinations was 3.6° and they were larger than the protrusive inclination under the teeth contact condition. The lateral inclination was 1.7° and was larger than the protrusive inclination under contact free conditions. As the Fischer's angle was compared individually, the standard deviation under teeth contact condition was 11.0° and that under teeth contact free condition was 11.6°.

**Sagittal condylar path inclinations under teeth contact and contact free conditions (items 3 and 4):** The means of the sagittal condylar path inclinations under teeth contact condition showed greater values than those under contact free condition. The differences were 3.5° in the protrusive condylar path and 5.4° in the lateral condylar path. The correlation coefficients were 0.911 and 0.705 for the protrusive and lateral sagittal condylar path inclinations, significant at p=0.001 level of the significance. Figs. 26–27 show the correlation plots for teeth contact and contact free conditions. In the figures, X indicates the data and the straight line was the regression line.
Bennett angle and sagittal condylar path inclination (items 5 and 6): The correlation coefficients between Bennett angle and the lateral sagittal condylar path inclination were 0.295 for teeth contact and 0.393 for the contact free condition. These were not significant at p=0.05 level of significance, Figs. 28–29 are the correlation plots. X indicates the data and the solid line is the regression line. The broken line indicated Hanau’s formula. \( L = \frac{H}{8} + 12 \) (L: Bennett angle, H: sagittal condylar path inclination).

Bennett angles under teeth contact and contact free conditions (item 7): The correlation coefficient of Bennett angles between teeth contact and contact free conditions was 0.586. This was significant at p=0.01 level of the significance. Fig. 30 shows the correlation plot.
**Total sideshift and Bennett movement (items 8–11):** The amount of the total sideshift, consisting of immediate and progressive sideshifts, and the amount of Bennett movement was correlated. The correlation coefficients under teeth contact and contact free conditions were 0.986 and 0.988, and were significant at $p=0.001$ level of the significance. Figs. 31–32 show the correlation plot.

**b. Correlation between condylar path and incisal path**

*Condylar path and incisal path during protrusive movement (item*
12): Sagittal protrusive condylar path inclination and incisal inclination path showed a correlation coefficient of 0.687 which was significant at $p=0.05$ level of significance. Fig. 33 shows the correlation plot.

Condylar path and incisal path during lateral movements (items 13–15): The correlations were evaluated between the sagittal lateral condylar path inclination, the sagittal lateral path, the frontal lateral incisal path and the horizontal lateral incisal path inclinations. Their correlation coefficients were 0.682, 0.613 and 0.495, respectively. Each of these correlation coefficients showed significant correlation at $p=0.001$, 0.01, and 0.05 level of significance. Figs. 34–36 are the correlation plots. Although it was found that the data (X signs) were distributed in a rather wide range around the regression line (straight line), there was significant correlation between the data of each combination.
Bennett angle and horizontal lateral incisal path (item 16): The correlation coefficient between Bennett angle and the horizontal lateral incisal path inclination was 0.232, which was not significant at \( p = 0.05 \) level of the significance. Fig. 37 shows the correlation plot.

Sagittal condylar path under the contact free condition and incisal path (items 17–20): The correlation coefficients between the sagittal condylar path inclination under contact free condition and the incisal path during protrusive and lateral movements were less than those measured under the teeth contact condition. The correlation coefficient between the sagittal lateral condylar path inclination under contact free condition and the frontal lateral incisal path inclination (item 19), increased to 0.646 when compared to that under teeth contact condition 0.613.

c. Correlation between the condylar path and molar path or between the incisal path and molar path.

Correlation between condylar path and molar path (items 21–24):
Correlation between the incisal path and molar path (items 25–28): Correlation coefficients of the four pairs of combinations were sagittal protrusive incisal path inclination and molar path inclination 0.963, sagittal lateral incisal path inclination and molar inclination 0.862, frontal lateral incisal path inclination and molar path inclination 0.824, and horizontal lateral incisal path inclination and molar path inclination were 0.963, 0.862, 0.824, and 0.857. Every coefficient was significant at p=0.001 level of significance.

Reproducibility of mandibular movement
Seven sample subjects who showed typical and normal mandibular movements during measurement were selected from the eleven subjects. Their lateral pathways were superimposed so that starting points (centric relation) coincided and the coordinate system
X, Y, and Z were arranged to be parallel.

Figs. 38–44 show the superimposed diagrams of three pathways including movement of the condylar point under the teeth contact condition (a), contact free conditions (d), movement of the incisal point under teeth contact conditions (c), and movement of molar cusps under teeth contact condition (d). Figs. 45–51 show the superimposed diagrams of three pathways of the condylar point under teeth contact condition and another three pathways of the condylar point under contact free condition. The black line indicates the pathway under teeth contact condition and the red line indicates the pathways under contact free condition. These diagrams showed the pathways did not overlap, but exhibited deviation to each other. The average amount of the deviation perpendicular to the pathways were measured on the diagrams. The results are shown on Table 16. The measurements were made on sagittal, horizontal and frontal surfaces under teeth contact and contact free conditions. The means and the standard deviations of the results are shown on the right in Table 16.

Results of this study indicate the following:
1. Under the teeth contact condition, the mean deviation (reproducibility) of the condylar path was 0.35mm, 0.23mm, and 0.20mm on the sagittal, horizontal and frontal planes respectively. Deviation of the condylar path was greatest on the sagittal plane and least on the frontal plane.
2. Under the teeth contact condition, the mean deviation of the incisal path on the sagittal plane was 0.20mm, 0.20mm, on the horizontal plane and 0.21mm on the frontal plane.
3. Under the teeth contact condition, the mean deviation of the molar path on the sagittal plane was 0.14mm on the horizontal plane, 0.18mm, and on the frontal plane 0.11mm.
4. Under the teeth contact condition, the least amount of deviation was found on the molar pathways lesser degree on the incisal pathways. The greatest amount of deviation was on the condylar pathways.
5. Under the contact free condition, the mean deviation of the condylar path on the sagittal plane was 0.48mm, on the horizontal plane 0.28mm and on the frontal plane 0.22mm. Deviation of the condylar paths was greatest on the sagittal plane and least on the frontal plane.
6. Combined deviation of the condylar path under teeth contact and contact free conditions was 1.00mm on the sagittal, 0.35mm on the horizontal, and 0.48mm on the frontal planes. The greatest amount of deviation was found on the sagittal plane.
7. Deviations of the condylar path on the sagittal plane measured under teeth contact and contact free conditions were compared. It was found that when the condylar path was measured under the contact free condition showed 40% more deviation...
Table 16. The average amounts of the deviation among and along the three times repeated pathways of the condylar center, incisal point and first molar on the sagittal, horizontal and frontal planes during lateral movement.

<table>
<thead>
<tr>
<th>Teeth condition</th>
<th>Path</th>
<th>Plane</th>
<th>Direction of lateral movement</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact</td>
<td>Condylar</td>
<td>Sagittal</td>
<td>Right Left</td>
<td>0.10 0.29 0.78 0.40 0.31 0.14 0.36</td>
<td>0.35</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>Right Left</td>
<td>0.34 0.13 0.06 0.12 0.25 0.20 0.27</td>
<td>0.23</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>Right Left</td>
<td>0.43 0.08 0.15 0.08 0.10 0.08 0.25</td>
<td>0.20</td>
<td>0.13</td>
</tr>
<tr>
<td>Contact</td>
<td>Incisal</td>
<td>Sagittal</td>
<td>Right Left</td>
<td>0.13 0.14 0.16 0.33 0.20 0.13 0.15</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>Right Left</td>
<td>0.15 0.08 0.17 0.11 0.35 0.38 0.19</td>
<td>0.20</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>Right Left</td>
<td>0.27 0.18 0.10 0.19 0.30 0.11 0.13</td>
<td>0.21</td>
<td>0.12</td>
</tr>
<tr>
<td>Contact free</td>
<td>Condylar</td>
<td>Sagittal</td>
<td>Right Left</td>
<td>0.05 0.05 0.25 0.23 0.13 0.05 0.07</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>Right Left</td>
<td>0.17 0.08 0.19 0.48 0.04 0.08 0.08</td>
<td>0.18</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>Right Left</td>
<td>0.21 0.05 0.08 0.35 0.15 0.25 0.08</td>
<td>0.21</td>
<td>0.09</td>
</tr>
<tr>
<td>Contact free</td>
<td>Incisal</td>
<td>Sagittal</td>
<td>Right Left</td>
<td>0.36 0.11 0.22 0.50 0.33 0.50 0.65</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>Right Left</td>
<td>0.38 0.37 0.09 0.34 0.38 0.10 0.19</td>
<td>0.28</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>Right Left</td>
<td>0.27 0.27 0.10 0.15 0.25 0.03 0.27</td>
<td>0.22</td>
<td>0.12</td>
</tr>
<tr>
<td>Contact and contact free (combined)</td>
<td>Condylar</td>
<td>Sagittal</td>
<td>Right Left</td>
<td>0.54 1.91 0.75 0.70 0.95 0.58 1.00</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Horizontal</td>
<td>Right Left</td>
<td>0.44 0.79 0.12 0.27 0.59 0.25 0.12</td>
<td>0.35</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>Frontal</td>
<td>Right Left</td>
<td>0.66 0.11 0.33 0.41 0.95 0.15 0.66</td>
<td>0.48</td>
<td>0.27</td>
</tr>
</tbody>
</table>

than when measured under teeth contact condition. The combined deviation recorded under both conditions was twice as great.

DISCUSSION

Pantographs and checkbites are routinely used in daily practice to register the mandibular movements of patients. Although these methods are effective, they do not provide the data necessary to analyze a patient's mandibular movement statistically. In this study, the movement of the mandible were measured using an

Three Dimensional Study of Mandibular Movement Using an Automatic Electronic Measuring System

Fig. 38. Superimposed diagrams of three pathways of patient No. 1.
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars under teeth contact condition
(c) The orbits of the incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition

Fig. 39. Superimposed diagrams of three pathways of patient No. 4.
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars under teeth contact condition
(c) The orbits of the incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
Fig. 40. Superimposed diagrams of three pathways of patient No. 5.
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars under teeth contact condition
(c) The orbits of the incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
Fig. 41. Superimposed diagrams of three pathways of patient No. 7.
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars under teeth contact condition
(c) The orbits of the incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
Three Dimensional Study of Mandibular Movement Using an Automatic Electronic Measuring System

Fig. 42. Superimposed diagrams of three pathways of patient No. 8.
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars under teeth contact condition
(c) The orbits of the incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
Fig. 43. Superimposed diagrams of three pathways of patient No. 10.
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars under teeth contact condition
(c) The orbits of the incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
Fig. 44. Superimposed diagrams of three pathways of patient No. 11.
(a) The orbits of the centers of the condyles on both sides under teeth contact condition
(b) The orbits of the mandibular first molars under teeth contact condition
(c) The orbits of the incisal point under teeth contact condition
(d) The orbits of the centers of the condyles on both sides under teeth contact free condition
Fig. 45. Superimposed diagrams of pathways of the centers of the condyles on both sides of patient No. 1.
black line: under teeth contact condition (three lines)
red line: under non teeth contact condition (three lines)

Fig. 46. Superimposed diagrams of pathways of the centers of the condyles on both sides of patient No. 4.
black line: under teeth contact condition (three lines)
red line: under non teeth contact condition (three lines)

Fig. 47. Superimposed diagrams of pathways of the centers of the condyles on both sides of patient No. 5.
black line: under teeth contact condition (three lines)
red line: under non teeth contact condition (three lines)
Fig. 48. Superimposed diagrams of pathways of the centers of the condyles on both sides of patient No. 7.
black line: under teeth contact condition (three lines)
red line: under non teeth contact condition (three lines)

Fig. 49. Superimposed diagrams of pathways of the centers of the condyles on both sides of patient No. 8.
black line: under teeth contact condition (three lines)
red line: under non teeth contact condition (three lines)

Fig. 50. Superimposed diagrams of pathways of the centers of the condyles on both sides of patient No. 10.
black line: under teeth contact condition (three lines)
red line: under non teeth contact condition (three lines)
Fig. 51. Superimposed diagrams of pathways of the centers of the condyles on both sides of patient No. 11. 
black line : under teeth contact condition (three lines) 
red line : under non teeth contact condition (three lines) 

automatic electronic measuring system and the data was statistically analyzed.

**Visual comparison of the graphic data obtained under teeth contact and contact free conditions.**
Since the pantograph is used under the teeth contact free condition, it is questionable whether the data obtained using this method is accurate under teeth contact condition. Figs. 15—25 (a) show the condylar path under teeth contact condition and Figs. 15—25 (d) show the condylar path under teeth contact free condition. The former figures indicate that the pathways under teeth contact show zig-zag configurations with steeper inclinations, while the latter figures indicate under teeth contact free conditions the pathways show a relatively smooth and more slanted line. Incisal paths measured under teeth contact and contact free conditions were also different. When the lateral incisal paths under contact free condition (Figs. 15—25 (c)) were examined on the frontal plane they show a relatively flat configuration, with a rounded top. The lateral incisal paths under tooth contact condition (Figs. 15—25 (e)) on the frontal plane showed a relatively acute angle with the top edged. The incisal path differences might be due to the morphology of the central bearing plate of the clutch employed in this study. As shown in Figs. 11—14 using Denar’s central bearing plate the plots were flat on the initial 0.5mm from centric relation and gradually inclined from 19°—26° for the protrusive pathway and 15°—28° for the lateral pathway. In either case the contour of the bearing plate did not have as much inclination as the anterior guidance of the natural teeth. On the contrary the incisal path under teeth contact condition is similar to the superior surface of the Posselt’s envelope of motion and the tip of the pathway formed an edge. It was
concluded from visual comparison of the results of this study that the configuration of the condylar path is altered depending upon teeth contact or contact free conditions.

**Correlation of mandibular movement**

The special relationship that exists between the condylar and incisal path has been a topic of discussion for a substantial length of time. Gysi\(^1\) stated that the sagittal condylar path and the incisal path had an equal effect upon the cusp inclination of the molars. He concluded that the sum of half of the condylar and incisal inclinations would give ideal cusp inclination for the molars. He also examined the effect of Bennett angle on the molar path and found that its effect was minimal. He suggested fixing the condylar setting for Bennett angle on articulators at a constant mean value. Hanau\(^12,13\) introduced the famous expression for calculating the Bennett angles

\[
L = \frac{H}{8} + 12
\]

in which the special correlation between sagittal lateral condylar path inclination and Bennett angle is used. This expression is employed to set the Bennett angle mechanism on the Hanau Model H articulator. Lundeen and Wirth\(^14\) measured the horizontal lateral condylar paths of 50 adults and found that the progressive sideshift did not differ significantly, but the immediate sideshift differed between individuals. Hobo\(^15,16\) measured horizontal lateral condylar pathways, and found correlations among immediate sideshift, progressive sideshift and Bennett angle. This correlation was designated as the I.P.B. value and its formula was used to set the immediate and progressive sideshift on Pana Hobby semiadjustable articulator from the Bennett angles obtained using lateral checkbites.

In order to study the correlation of mandibular movement 28 pairs of condylar paths, molar paths and incisal paths were selected and correlated. Twentyone of twentyeight pairs correlated at or under \(p=0.01\) level of significance. Four pairs including (1) sagittal lateral condylar path inclination and Bennett angle under teeth contact condition, (2) Bennett angle under teeth contact free condition (3) Bennett angle and horizontal lateral incisal inclination under teeth contact condition, (4) sagittal lateral condylar path inclination under teeth contact free condition and (5) horizontal lateral incisal path inclination under tooth contact condition, did not correlate even at \(p=0.05\) level of significance. Three pairs, including (1) sagittal protrusive condylar path inclination and sagittal protrusive incisal path inclination under tooth contact condition, (2) sagittal lateral condylar path inclination and horizontal lateral incisal path inclination under teeth contact condition, and (3) sagittal lateral condylar path inclination and horizontal lateral incisal path inclination under teeth contact condition, failed to correlate.
condition and (3) sagittal protrusive condylar path inclination under contact free condition and sagittal protrusive incisal path inclination under teeth contact condition, showed weak correlation at p=0.05 level of significance.

a. Correlation between the sagittal protrusive condylar path inclination and the sagittal lateral condylar path inclination:
Between the protrusive and lateral sagittal condylar path inclinations, there was correlation under p=0.01 level of significance. The difference between the lateral and protrusive condylar path inclinations is known as the Fischer’s angle. It has been reported that Fischer’s angle is usually a positive value of 5°. The mean of the Fischer’s angle in this study was 3.6° under teeth contact conditions and 1.7° under teeth contact free conditions. The standard deviation was 11° in both situations. Individual Fischer’s angles ranged from +20° to -20°, and negative value found. The Fischer’s angle seemed to relate to the superoinferior deviation of the working condylar path. The correlation coefficient between Fischer’s angle and the working condylar path were computed and were 0.742 under teeth contact and 0.526 under contact free conditions. It was not determined if these results were significant.

b. Sagittal condylar path inclinations under teeth contact free conditions:
The existing consensus of opinion that mandibular movement recorded under teeth contact free conditions is equal to the value of that recorded under teeth contact conditions is a controversial subject. Pantograph recording of mandibular movements are measured with clutch which provides teeth contact free condition, while in the checkbite procedure, they are measured under teeth contact condition. McCollum and Stuart believed that the condylar paths obtained under teeth contact conditions coincided with the condylar paths obtained under teeth contact free conditions. Gnathologically the use of a teeth contact free clutch’s was considered more advantageous because they prevent possibility of harmful teeth contact.

In this study, the effect of using a teeth contact free clutch and a teeth contact clutch were compared. It was found that correlations in both protrusive movement (correlation coefficient 0.911) and lateral movement (correlation coefficient 0.705) were under p=0.001 level of significance. It was concluded that the sagittal condylar path inclinations measured under teeth contact and contact free conditions had close correlation. However as shown in Figs. 26–27, the individual measurements (X signs) deviated from the broken line (line of agreement). Specifically the X signs for lateral movement deviated to the right and inferior to the line of agreement and regression line. This means that the sagittal lateral condylar path inclination measured under the teeth contact free conditions (with clutches) was smaller than that measured under
teeth contact conditions. The means of the differences between two conditions were $3.5^\circ$ for protrusive movement and $5.4^\circ$ for lateral movement. It was noted that these results also correlated with the configuration of the anterior guidance and the effect of the clutch morphology on the condylar path inclination. The results of this study indicated that the inclination of the central bearing plate was not steep enough when compared to the anterior guidance of the natural dentition.

c. Correlation between Bennett angle and sagittal lateral condylar path inclination:
Hanau$^{12,13}$ stated that the Bennett angle ($L$) and the sagittal lateral condylar path inclination ($H$) correlated as $L = \frac{H}{3} + 12$. There has not been reported an explanation of the origin of Hanau’s expression. Since Hanau’s expression has been universally accepted and used for setting the Bennett angle on articulators the correlation between Bennett angle and the sagittal lateral condylar path inclination were examined. In this study it was found that the Bennett angle did not correlate to the sagittal lateral condylar path inclination even at $p=0.05$ level of significance. Figs. 28–29 show that the measured data (X signs) were positioned away from the broken line which indicated the results of calculations using Hanau’s expression. Therefore Hanau’s expression did not represent accurate mandibular movement. As mentioned before, Gysi$^{11}$ stated that Bennett angles did not vary much between individuals and can be set at a constant angle. This statement connotated that Bennett angle did not correlate to the sagittal lateral condylar path inclination and this agrees with the results of this study.

d. Bennett angles under teeth contact and contact free conditions:
Bennett angle measured under teeth contact condition’s did not correlate well with these under contact free conditions (correlation coefficient 0.586). This indicated that when the teeth are in contact they have a substantial influence on the Bennett angle.

e. Correlation between total sideshift and Bennett movement:
A sum of the lateral component of progressive side shift and immediate side shift may be defined as total sideshift of the non-working condylar path. Hobo$^{19}$ examined mean mandibular movements of 50 adults and reported that the total sideshift of the non-working condylar path precisely coincided with the sideshift of the working condylar path. In this study, individual data was analyzed and it was found that there exists a correlation coefficient of 0.986 and 0.988 between total sideshift and sideshift of the working condyle under the teeth contact and contact free conditions, respectively. The results of this study indicate the total sideshifts of the nonworking side and Bennett movement of the working side are the same phenomenon and are the result of the bodily lateral movement of the mandible. These bodily lateral shifts of
mandibular movement were reproducible on the articulator.

Correlation between condylar path and incisal path
It has been widely accepted that the condylar path and incisal path do not correlate and that they were independent. Dawson reported that because the mandible could rotate around the hinge axis, the incisal point could move freely without being restricted by the condylar path. For these reasons, he suggested that the incisal path could be determined by the operator rather subjectively. In this study, correlation between condylar and incisal paths were examined in three dimensions.

a. Correlation between sagittal protrusive condylar path and incisal path:
There was correlation between the sagittal protrusive condylar path inclination and the sagittal protrusive incisal path inclination under $p=0.05$ level of significance. This result indicated that sagittal protrusive condylar path inclinations would be the determinants for sagittal protrusive incisal path inclination. However as seen on Fig. 33, there were deviations of data and this connoted that the sagittal protrusive condylar path inclination was not the only determinant, but other parameters also had an affect upon the sagittal protrusive incisal path inclination. The authors determined that the rotational movement of the mandible around the terminal hinge axis during protrusive movement might have an affect on this correlation. This suggested that the hinge rotation described by Dawson might be another parameter of correlation between condylar and incisal paths.

b. Correlation between the sagittal lateral condylar path inclination and the lateral incisal path:
Correlations between the sagittal condylar path inclination and the lateral incisal path, consisting of sagittal, frontal, and horizontal lateral incisal path inclinations were examined. Each of three combinations of condylar and incisal path inclinations during lateral movement correlated under $p=0.001$, $0.01$, and $0.05$ level of significance, respectively. According to these result it was determined that the sagittal lateral condylar and incisal path inclinations correlated. It was concluded that the sagittal lateral condylar path inclination was one of the determinants of the lateral incisal path. Since there were deviations of data, the sagittal lateral condylar path inclination was not the only determinant of the lateral incisal path. The authors suggest that rotational movement of the mandible around the hinge axis may be another parameter.

c. Correlation between Bennett angle and the horizontal lateral incisal path:
Statistically significant correlations between the Bennett angle and the horizontal lateral incisal path were not found in this study.
This result gives support to Gysi's statement that the Bennett angle of the articulator can be set at a constant value. Bennett angle is the angle formed between the midsagittal plane and horizontal lateral straight line, and it is composed by immediate side-shift and progressive side shift. In this study Bennett angle was measured at the terminal point of the orbit and thus the effect of immediate sideshift and progressive side shift was not introduced into the measurements.

d. Correlation between the sagittal condylar path inclination and the incisal path under teeth contact free condition:
Correlations between sagittal condylar path inclinations and incisal path under teeth contact and contact free conditions were compared and no statistically significant difference were found. This indicated that it was feasible to determine the incisal path by applying the sagittal condylar path data measured under contact free condition.

**Correlation between condylar and molar paths and between incisal and molar paths**

a. Comparison of the correlation coefficients between the condylar path and molar path, and between the condylar path and incisal path: The correlation coefficient between the sagittal protractive condylar path inclination and the sagittal protractive incisal path inclination was 0.687. The correlation coefficient between the sagittal lateral condylar path inclination and the sagittal lateral incisal path inclination was 0.682. While the correlation coefficient between the sagittal protractive condylar path inclination and the molar path inclination was 0.845. The correlation coefficient between the sagittal lateral condylar path inclination and molar path inclination was 0.867. Correlation coefficients between the sagittal lateral condylar path inclination was 0.717 where, the frontal and horizontal lateral molar path inclinations was 0.532. Correlation coefficient between the condylar path and molar path was always greater than that between of the condylar path and the incisal path. The reason for this was the distance between the condyles and molars was shorter than that between condyles and incisal point. Thus the effect of condylar rotation as another parameter as previously mentioned, was greater on the incisal path than it was on the molar path.

b. Comparison of correlation coefficients between incisal path and molar path, and between the condylar path and molar path: Correlation coefficients between the sagittal protractive condylar path inclination and the sagittal protractive molar path was 0.845, between the sagittal lateral condylar path inclination and frontal lateral molar path was 0.717 and between the sagittal lateral condylar path inclination and the
horizontal lateral molar path was 0.532. Correlation coefficients between the sagittal protrusive incisal path inclination and the sagittal protrusive molar path was 0.963, between the sagittal lateral incisal path inclination and the sagittal lateral molar path inclination was 0.862, between the sagittal lateral incisal path inclination and the frontal lateral molar path inclination was 0.824 and between the sagittal lateral incisal path inclination and the horizontal lateral molar path inclination was 0.857.

As mentioned previously, Gysi\textsuperscript{11} stated that the cusp inclination of the molars was determined by dividing the sum of the sagittal condylar path inclination and the sagittal incisal path inclinations. This proposed that the molar was located on a line extending from the incisal point bisecting and the distance between the bisected condyles anteroposteriorly. The position of the molar used as the target of this study was closer to the incisal point, 1:2 proportion anteroposteriorly to the incisor and the condyle. Therefore when the sagittal protrusive condylar path inclination was X and the sagittal protrusive incisal path inclination was Y, the sagittal protrusive molar path inclination was expressed $\frac{X + Y}{2}$ while in this study it was $\frac{X + 2Y}{3}$. According to Gysi, the effects of the incisal path and the condylar path upon the molar path were equivalent. In this study the effect of the incisal path upon the molar path was greater than that of the condylar path. This was proven by the fact that the correlation coefficients between the incisal path and the molar path were greater than those between the condylar path and the molar path.

Reproducibility of mandibular movement
Reproducibility of mandibular movement has been a controversial subject in conjunction with temporomandibular joint disorders. McCollum and Stuart\textsuperscript{18} stated that the condylar path obtained during the border movement did not alter in the adult period. Clayton\textsuperscript{21} conducted pantograph studies and stated that there were statistically significant differences between the reproducibility of pantographic tracings of normal and TMJ patients and he advocated a Pantograph Reproducibility Index (PRI). Clark and Lynn\textsuperscript{22} compared tracings of mandibular movement of patients with normal and abnormal TMJ function at the incisal point and concluded that TMJ disfunction patients showed greater deviation than normal patients.

The condylar path obtained in this study was not absolutely reproducible as a single line. The sample patients selected in this investigation had normal TMJ function, however, there were recorded deviations of their pathways, as were seen of Figs. 38-51. The maximum amount of deviation was observed on the sagittal
condylar path and it's mean value was 0.35mm, with a standard deviation of 0.21mm. This data indicated that even normal TMJ subjects had a maximum of 0.8mm deviation of condylar path. The deviation became greater (2.0mm) when the teeth contact and contact free conditions were combined. The reason a single line condylar path of border movements is obtained using a mechanical pantograph may be due to the measuring accuracy of these instruments.

Under the teeth contact condition, the deviation of the molar path was the least. The condylar path was the greatest. The deviation of the condylar path was twice as great as those of the molar and incisal paths. This was due to the position of the condyle which was seated against eminentia by the articular disc which has elastic soft tissue, while the teeth are rigidly anchored in maxillary and mandibular bone. When comparing deviation of the molar and incisor paths, the molar path showed less mobility then the incisor path. The molar path did not significantly deviate.

Deviation of the condylar path under teeth contact free conditions was greater than that under teeth contact conditions. This indicated that anterior guidance restricts the deviation of condylar path. When the teeth did not make contact, deviation of the condylar path increased. When Denar’s clutches were employed, the mandible tended to move more horizontally, due to the flat guiding plane of the central bearing plate. This phenomena is similar to the cases of Angle Class II malocclusion or open bite. In such cases, it was expected that deviation of the condylar path would become more severe, and thus create a greater possibility of TMJ disorders. This result corresponds to clinical finding that TMJ disorders are found more often with Class II malocclusion patients. In order to clarify the etiology of TMJ disorder, reproducibility of the condylar path needs further investigation.

Gnathological principles suggested that the condylar path should be reproducible without any deviation. This principle could be altered if accurate measuring instruments were employed. In this study, it was demonstrated that there existed three-dimensional deviation of the condylar path. These deviations should be taken into consideration for future gnathologic rehabilitation procedures.

CONCLUSIONS

Protrusive and lateral movements of the mandible were measured in three dimensions by means of a newly developed automatic electronic measuring system. Eleven males, average age of 24 years, without any TMJ symptoms were selected as subjects. All measurements were repeated three times under teeth contact and contact free conditions. Digital data of the condylar, molar and incisal
paths were computed and statistically compared. The conclusions from the results of this study are:

1. The pathways of the various targets placed on the mandible were different under teeth contact and contact free conditions. Under contact free condition, the pathways were relatively flat. This was possibly due to the configuration of the central bearing plate of the clutch used during measurement. The configuration of the incisal path had an effect upon the condylar path.

2. Twenty eight pairs of combinations of condylar, molar and incisal paths were analyzed. Twenty one of the pairs correlated at or under p=0.01 level of significance.

3. Bennett angle did not correlate to the sagittal lateral condylar path inclination, even at p=0.05 level of significance. Hanau’s expression $L = \frac{H}{8} + 12$ is not acceptable for accurately reproduce mandibular movement.

4. A correlation coefficient of 0.985 was found between the total sideshift consisting of the lateral component of progressive sideshift, immediate sideshift, and the lateral component of Bennett movement. The lateral shift of Bennett movement and medial shift of the nonworking condyle are the same phenomenon.

5. There was correlation between the sagittal protrusive condylar and the sagittal protrusive incisal path inclinations and between the sagittal lateral condylar and the sagittal lateral incisal path inclinations at p=0.05 and p=0.001 level of significance, respectively. The condylar path is one of the determinants of the incisal path. Since the data showed deviation, the condylar path was not the only determinant, but other parameters exist.

6. The condylar path and molar path showed higher correlation than the condylar path and incisal path. This was due to anatomical positional relationship among the three paths.

7. Although Gysi stated that condylar path and incisal path had equal effect upon the molar path, the incisal path according to this study, had greater effect upon the molar path than did the condylar path.

8. The condylar, incisal and molar paths were measured repeatedly, were superimposed and the deviations of these paths were analyzed. The amount of deviation observed was less than 0.8mm under the teeth contact condition. The greatest amount of deviation was found in the sagittal plane. There was more deviation of the pathways under the teeth contact free condition. Such deviation of pathways is considered to have an effect upon the etiology of TMJ disorders.

9. Under the teeth contact condition, the deviation of the molar path was the least and that of incisal path was between the molar and condylar paths. The greatest amount of deviation was found under the teeth contact conditions and was
twice that of the other deviations. This might be caused by anatomical differences of the subjects. The condyle is seated against the eminnetia by the articular disc and surrounding soft tissue, while the teeth are rigidly anchored in the hard bone of the maxilla and mandible.

10. Deviation of the condylar paths were greater the under teeth contact free condition than they were under the teeth contact condition. This result indicated that the anterior guidance restricted the amount of deviation of the condylar path. When Denar clutches were employed under the teeth contact free condition the mandible tended to slide horizontally. This situation is similar to the case of Angle's Class II or open bite malocclusion in which anterior guidance control does not function. This result corresponds to the clinical finding that TMJ disorders are found more often for Class II malocclusion patients.

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