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# A Study on the Measurement Accuracy and Linearity of the Mandibular Kinesiograph

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## INTRODUCTION

Jaw position and movement include more than just chewing motion, e.g., wide mouth opening such as in yawning, singing and opening wide to incise a large bite of food. Since there exist the necessity of having a jaw movement tracking system to evaluate wide range of movements, a few researchers have worked on programs for monitoring instruments analyze jaw movements.[1-12] The Mandibular Kinesiograph is the one of the measuring instruments for mandibular movements. It is noninvasive, easy to use, and applicable to many human subjects.[5] The Kinesiograph, however, has inherent nonlinear characteristics beyond a few millimeters from centric occlusion and thus quantitative analysis of data supplied by the Kinesiograph has been limited.

A linearizing formula for the Kinesiograph has been developed in the Stomatognathic Physiology Laboratory at the University of Michigan School of Dentistry.[12] Soon after the conception of the formula, it has been employed in several studies concerning jaw movements on the proximity of occlusion.[12] [13] The validity of the data from any measuring device depends on the reproducibility and accuracy of the instruments. In a preliminary study, Kim[9] tested the accuracy and reproducibility of sensor array alignment of the Kinesiograph. Also tested was the effect of head posture in relation to the earth's or other magnetic source. The results show compatible findings as described by others.[3] [6]

The purpose of this study was 1) to develop a mathematical model to obtain corrected data by means of statistical methodology; and 2) to evaluate the validity of the data from the Kinesiograph by testing the accuracy of both the raw Kinesiograph data and the corrected data.

## METHODS

The Mandibular Kinesiograph (MKG-5R, MYO-TRONICS RESEARCH INC., Seattle, Wash. 98101, U.S.A.) consists of a set of six specially constructed fluxgate magnetometers which sense the changes in the strength of the magnetic field emanating from a small permanent magnet. The magnetometers can track the displacement, in three planes, of the magnet cemented to the lower anterior teeth. These sensors are carried on a light aluminum tubing and the entire sensor array is assembled to an eyeglasses frame which can be worn by a subject and stabilized with an adjustable elastic strap behind the head.

The circuitry of the Mandibular Kinesiograph converts the outputs of the sensors to three voltages representing vertical, lateral, and anteroposterior jaw movement. The sensors are dependent on the proximity of the permanent magnet, and convert these pulse outputs into equivalent direct current signals porportional to the field strength at each sensor.

During a pilot study one problem has arisen, that is, the inherent nonlinearity of the apparatus. As the manufacturer suggest if the frame is centered in the intercuspal position, the Kinesiograph provides an accuracy of 0.1 mm for resolution of mandibular positions in the vicinity of occlusion' and distortions are greatest at the more extreme mandibular positions like maximum opening or maximum lateral excursion.

To ensure a wide linear working ranges, the validity of data supplied by the Kinesiograph was assessed under workbench conditions with a non-ferromagnetic mechanical positioning device to place the magnet in space. Three micormanipulators are arranged so that a aluminum rod can be moved in linear steps of 5 mm through three planes parallel to the frame work carrying the sensors. The magnet was carried in a acrylic slot at the end of the aluminum bar. The magnet was moved within a 3 cm wide by 4 cm deep by 5 cm high three-dimensional lattice. The magnet was moved in linear steps of 5 mm and a matrix of 693 data points was achieved. The M K G outputs were compared with those of the positioning system. Both the M K G outputs in volte and known movements in millimeters were fed into the computer. Multiple linear regression was performed through the Michigan Terminal System. Linearizing formula were then written for each of the three planes of movement.

## Statistical Methodology

The statistical analyses of the data were accomplished through the Michigan Terminal System (M T S) computing services using the Michigan Interactive Data Analysis System (MIDAS) program developed in Statistical Research Laboratory at the University of Michigan.

In order to determine whether, and to what extent, case values of actual movements (mm) may be predicted or explained by observed values of the M K G outputs, preliminary indication of such relationships was tested by viewing scatter plots and correlation between one variable and other variables. However the primary goal of this study was to find some formula or equation which relates the variable to be predicted to the one or more explanatory variables. Also questioned was to assess the strength of the relationship, i.e., to see how well the equation performs in predicting or explaining case values. Statistical regression analysis was performed to deal with these aspects of relationship between variables.

In implementing a regression analysis, case values of actual movements in millimeter was chosen to be the dependent variable, the one which is to be explained or predicted by values of three independent variables, i.e., vertical outputs (volts), horizontal outputs (volts), lateral outputs (volts).

In multiple linear regression there are two or more independent variables to be used in explaining or predicting the values of the dependent variable. Assuming that there are k independent variables indexed, say, by the integers 2 through k+1, the multiple regression model can be expressed by the equation.

$$X(i, 1)=A+B(2)*X(i, 2)+. . . . +B(k+1)*X(i, k+1)+e(i),$$

where X(i, 1) and X(i, 2) denote the values of the dependent and independent variables, respectively, and e(i) is the error term for case i. The constant, A, and the coefficients, B(i), are estimated by the method of least equares, specifically by a and b(i). The numerical values of these estimates are determined to minimize the sum of the squared residuals, $X(i, 1)-X_p(i, 1)$, where

$$X_p(i, 1)=a+b(2)*X(i, 2)+ . . . +b(k+1)*X(i, k+1)$$

and the sum is taken over the N values.

This statistic is used to test the null hypothesis that all of the regression coefficients, except the constant A, are simultaneously zero against the alternative hypothesis that at least one differs from zero. When this hypothesis,

$$H_0: B(2)=B(3)= . . . =B(k+1)=0,$$

is true the statistic F has an F-distribution on k and N-k-1 degrees of freedom. The hypothesis $H_0$ is rejected if the F-statistic is too large or, equivalently, if the attained significance level (the area under this F-distribution to the right of the computed F-statistic) is smaller than the desired significance level. Output is also given for obtaining a T-test of the hypothesis that any particular regression coefficient is zero. Thus to test

$$H_0: B(j)=0$$

against

$$H_1: B(j)\neq,$$

appropriate output is provided giving the T-statistic and an attained significance level.

## RESULTS

Each of 693 data points of the M K G outputs was compared with those of positioning system. Statistical analysis was performed using Michigan Interactive Data Analysis System (MIDAS). The outputs for each regression analysis include the analysis of variance for the regression, the regression coefficients, and their associated test statistics. Linearizing formula were then made from the outputs.

Fig. 1 to Fig. 3 show scatter plots of data. Fig. 1 is for depicting X valus (actual) versus vertical outputs from MKG, Fig. 2 for Y value (actual) versus A/P output, Fig. 3 for Z value (actual) versus lateral output. The plot characters are an "*" for one data point, the number of data points for 2 through data points, and an "X" for more than 9 data points. However, the use of the plot character "2", for example, does not imply identity of the data points-only that they are so close together that the use of two separate "*" characters was not feasible.

Table 1 is the correlation matrix which show correlation between X (actual value) and VV (observed value), Y (actual value) and AP (observed value), Z (actual value) and LL (observed value). Correlation between X and VV is 9686, 9893 for Y and AP, .0963 for Z and LL.

Table 3 shows minimum and maximum deviation from linear models that are formulated from least squares regression. Minimum deviations of X, Y, Z are.00372, .00357, .00785, respectively.

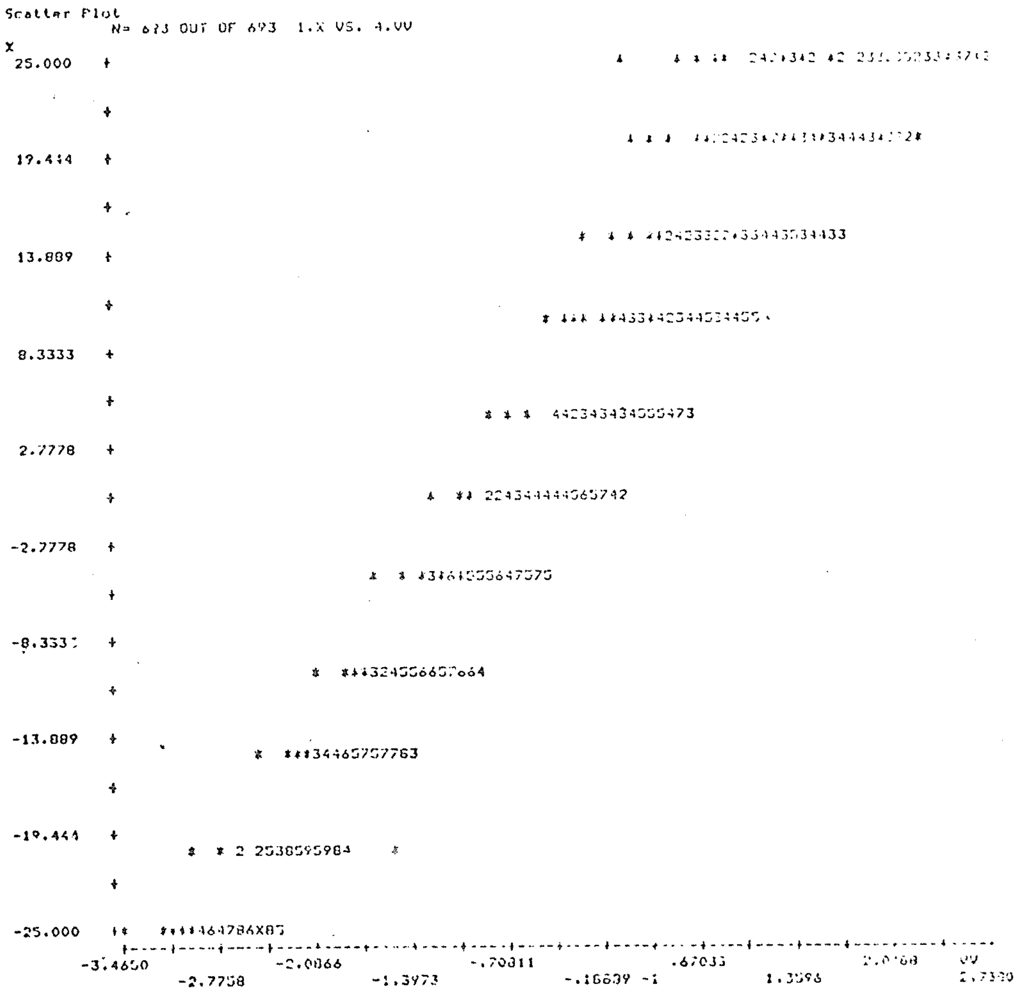


Fig. 1. Scatter plot of X vx. VV.

Maximum deviations from the regression line are 19.187 for X, 13.866 for Y, and 13.866 for Z.

Table 4a, b, c describe ten data points which have the least deviations from the regression line in order (first to tenth) and also ten data points which deviate most from the line (684th to 693th). Table 4 a is for X values, Table 4b for Y values, and Table 4c for Z values, respectively.

Fig. 4 to Fig. 6 show scatter plots of residual versus predicted values. Here, residual means difference between predicted values which were calculated from least squares regression and independent variables. The case values for residuals were $X(i, 1)\text{-}X_p(i, 1)$, for 693 cases where predicted values $X_p(i, 1)$ were computed for each case via the fitted least squares regression equation.s

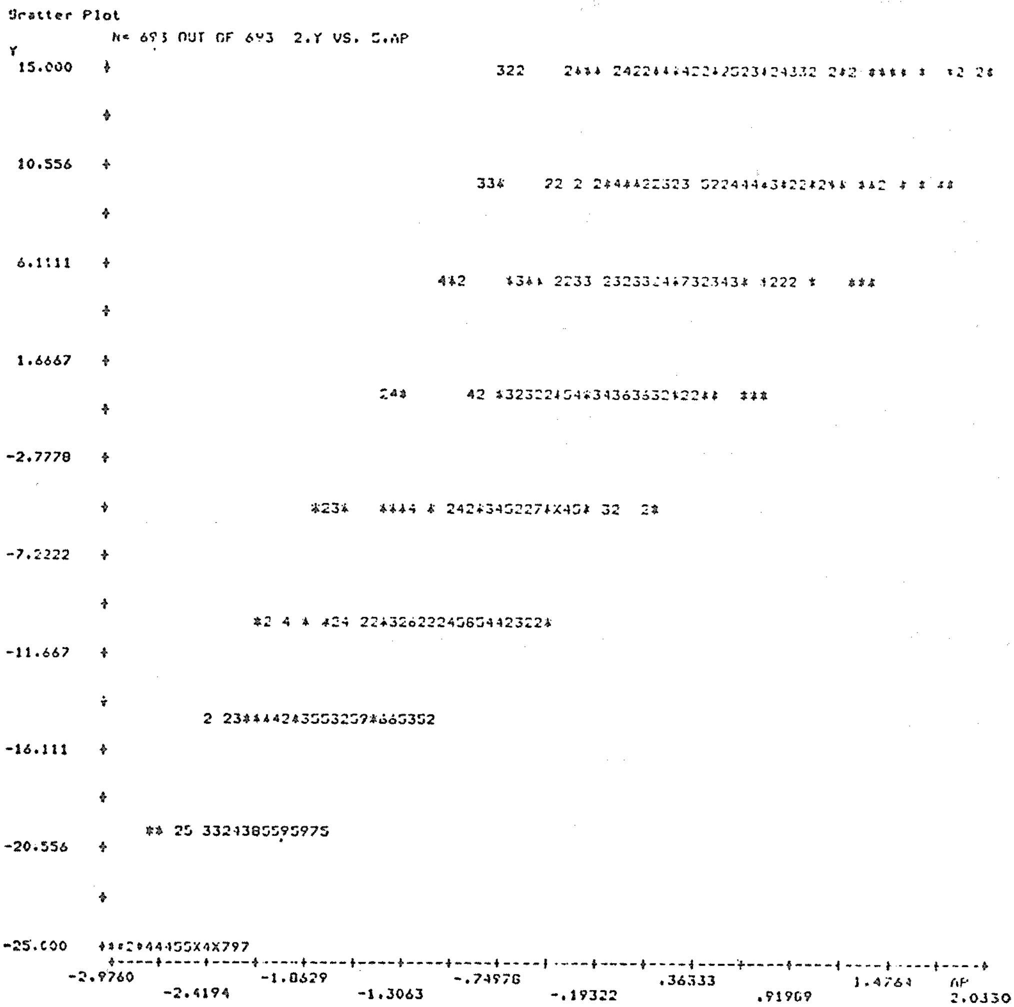


Fig. 2. Scatter plot of Y vx. AP.

Table 1. Correlation between actual and observed values.

Correlation Matrix

N= 693 DF= 691 RG .0500= .0745 RG .0100= .0978

CORRELATION BETWEEN 1. X AND 4.VV = .9686

Correlation Matrix

N= 693 DF= 691 RG .0500= .0745 RG .0100= .0978

CORRELATION BETWEEN 2.Y AND 5.AP = .8993

Correlation Matrix

N= 693 DF= 691 RG .0500= .0745 RG .0100=,.978

CORRELATION BETWEEN 3.2 AND 6.LL = .9063

Table 2. Descriptive results of least squares regression.

Least Squares Regression

ANALYSIS OF VARIANCE OF 1.X N= 693 OUT OF 693

| SOURCE | FG | SUM SQRS | MEAN SQR | F-STAT | SIGNIF |
|---|---|---|---|---|---|
| REGRESSION | 3 | .16358 +6 | 54526. | 3863.7 | 0. |
| ERROR | 689 | 9673.3 | 14,040 | | |
| TOTAL | 692 | .17328 +6 | | | |

MULT R= .97168 R-SOR= .94417 SE= 3.7469

| VARIABLE | PARTIAL | COEFF | ST. ERROR | T-STAT | SIGNIF |
|---|---|---|---|---|---|
| CONSTANT | | 4.2844 | .18465 | 23,203 | 0. |
| 4.VV | .97050 | 10,359 | .96036 †1 | 105.67 | 0. |
| 5.AP | .22629 | .78387 | .12854 | 6.0982 | .0000 |
| 6.LL | .22749 | 1.8856 | .50750 | 6.1321 | .0000 |

Least cuares Regression

ANALYSIS OF VARIANCE OF 2.Y N= 693 OUT OF 693

| SOURCE | DF | SUM SQRS | MEAN SQR | F-STAT | SIGNIF |
|---|---|---|---|---|---|
| REGRESSION | 3 | 97113. | 32371. | 1213.0 | 0. |
| ERROR | 689 | 18387. | 26.687 | | |
| TOTAL | 692 | .11556 +6 | | | |

MULT R= .91695 R-SOR= .84080 SE= 5.1659

| VARIABLE | PARTIAL | COEFF | STD ERROR | T-STAT | SIGNIF |
|---|---|---|---|---|---|
| CONSTANT | | 4.0946 | .25457 | 16.084 | .0000 |
| 4.VV | .36888 | 1.4080 | .13516 | 10.417 | .0000 |
| 5.AP | .91609 | 10,623 | .17722 | 59,971 | 0. |
| 6.LL | .21295 | 2.4254 | .42395 | 5.7210 | .0000 |

Least Squares Reqression

ANALYSIS OF VARIANCE OF 3.Z N- 693 OUT OF 693

| SOURCE | DF | SUM SQRS | MEAN SQR | T-STAT | SIGNIF |
|---|---|---|---|---|---|
| REGRESSION | 3 | 57296. | 19099. | 1096.2 | 0. |
| FRROR | 689 | 12004. | 17,422 | | |
| TOTAL | 692 | 69300. | | | |

MULT R= .90928 R-SOR= .82678 SE= 4.1740

| VARIABLE | PARTIAL | COEFF | STD ERROR | T-STAT | SIGNIF |
|---|---|---|---|---|---|
| CONSTANT | | -.53667 | .20569 | -2.6091 | .0093 |
| 4.VV | -.14294 | -.41401 | .10921 | -3.7910 | .0002 |
| 5.AP | -.13401 | -.50829 | .14319 | -3.5497 | .0004 |
| 6.LL | .90829 | 18,522 | .34255 | 56.992 | 0. |

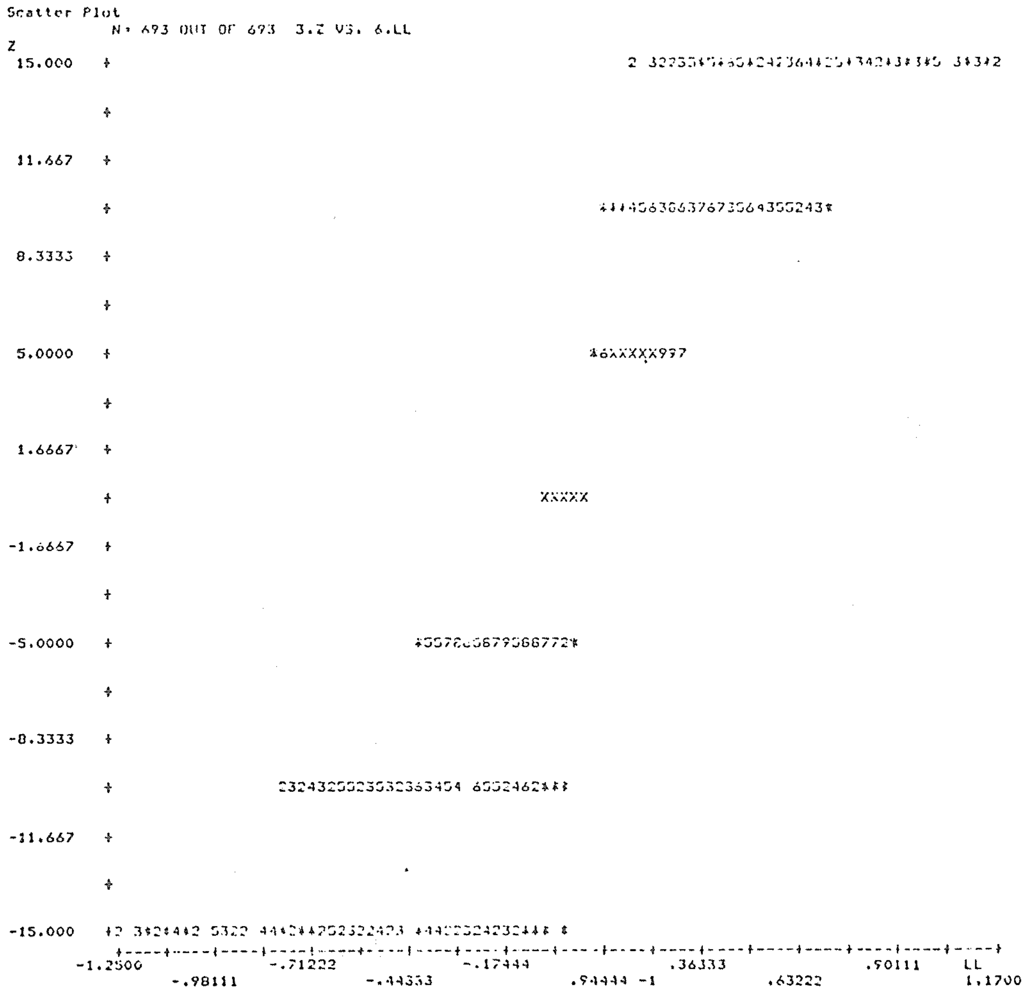


Fig. 3. Scatter plot of Z vx. LL.

Table 3. Descriptive measures of min. and max. deviation.

Descriptive Measures

| VARIABLE | N | MINIMUM | MAXIMUM | MEAN | STD DEV |
|---|---|---|---|---|---|
| 7.XE | 693 | -8.5707 | 19.187 | .13485-13 | 3.7388 |
| 8.YE | 693 | -10.561 | 16.648 | .32256-13 | 5.1547 |
| 9.ZE | 693 | -13.806 | 12.033 | -.18724-13 | 4.1649 |
| 10.V10 | 693 | .37263 -2 | 19.187 | 2.8585 | 2.4075 |
| 11.V11 | 693 | .35742 -2 | 16.646 | 4.0937 | 3.1287 |
| 12.V12 | 693 | .78580 -2 | 13.866 | 3.0396 | 2.8450 |

Table 4. The least and the most deviated data points.

Table 4a

Write Observations START–V13:1–10.684–693

VARIABLES BY CASE

| 1. | 2. | 3. |
|---|---|---|
| X | Y | Z |
| 20.000 | 5.0000 | −10.000 |
| 10.000 | 15.000 | −5.0000 |
| 20.000 | 10.000 | 5.0000 |
| 20.000 | −20.000 | 10.000 |
| −20.000 | −20.000 | −10.000 |
| −5.0000 | 15.000 | 5.0000 |
| 5.0000 | 10.000 | −10.000 |
| −25.000 | 15.000 | 0. |
| 5.0000 | 5.0000 | 10.000 |
| −25.000 | −5.0000 | 15.000 |
| 25.000 | −25.000 | 15.000 |
| 15.000 | 15.000 | 15.000 |
| 25.000 | −20.000 | −15.000 |
| 20.000 | 10.000 | 15.000 |
| 25.000 | −5.0000 | 15.000 |
| 25.000 | 0. | 15.000 |
| 20.000 | 15.000 | 15.000 |
| 25.000 | 5.0000 | 15.000 |
| 25.000 | 10.000 | 15.000 |
| 25.000 | 15.000 | 15.000 |

20 CASES WRITTEN FOR 3 VARIABLES

Table 4b.

Write Observations START–V14:1–10.684–693

VARIABLEES BY CASE

| 1. | 2. | 3. |
|---|---|---|
| Z | Y | Z |
| 15.000 | −10.000 | 15.000 |
| 10.000 | 15.000 | 15.000 |
| 15.000 | 0. | 5.0000 |
| 15.000 | 0. | 0. |
| −20.000 | 0. | −15.000 |
| 10.000 | 5.0000 | 0. |
| 15.000 | −25.000 | −15.000 |
| 10.000 | 10.000 | −10.000 |
| 15.000 | 0. | −5.0000 |
| 5.0000 | 10.000 | 5.000 |
| −25.000 | 15.000 | −5.000 |
| −25.000 | 15.000 | 5.0000 |
| −25.000 | 15.000 | 0. |
| 25.000 | 15.000 | −10.000 |
| 25.000 | 15.000 | −5.0000 |
| 25.000 | 15.000 | 0. |
| 25.000 | 15.000 | −15.000 |
| 25.000 | 15.000 | 5.0000 |
| 25.000 | 15.000 | 10.000 |
| 25.000 | 15.000 | 15.000 |

20 CASES WRITTEN FOR 3 VARIABLES

Table 4c.

Write Observations START–V15:1–10.684–693

VARIABLES BY CASE

| 1. | 2. | 3. |
|---|---|---|
| X | Y | Z |
| −23.000 | −10.000 | 5.0000 |
| 0. | 5.000 | −15.000 |
| 0. | 5.0000 | 5.0000 |
| 5.0000 | −25.000 | −15.000 |
| 10.000 | −10.000 | 10.000 |
| 20.000 | −10.000 | 0. |
| −5.0000 | −25.000 | 10.000 |
| −15.000 | −20.000 | 0. |
| 15.000 | −25.000 | 0. |
| 20.000 | −15.000 | 0. |
| 25.000 | 0. | −15.000 |
| 25.000 | −20.000 | −15.000 |
| 25.000 | 5.0000 | −15.000 |
| 25.000 | 10.000 | 15.000 |
| 20.000 | 15.000 | 15.000 |
| −25.000 | 15.000 | −15.000 |
| 20.000 | 15.000 | −15.000 |
| 25.000 | −25.000 | −15.000 |
| 25.000 | 10.000 | −15.000 |
| 25.000 | 15.000 | −15.000 |

20 CASES WRITTEN FOR 3 VARIABLES

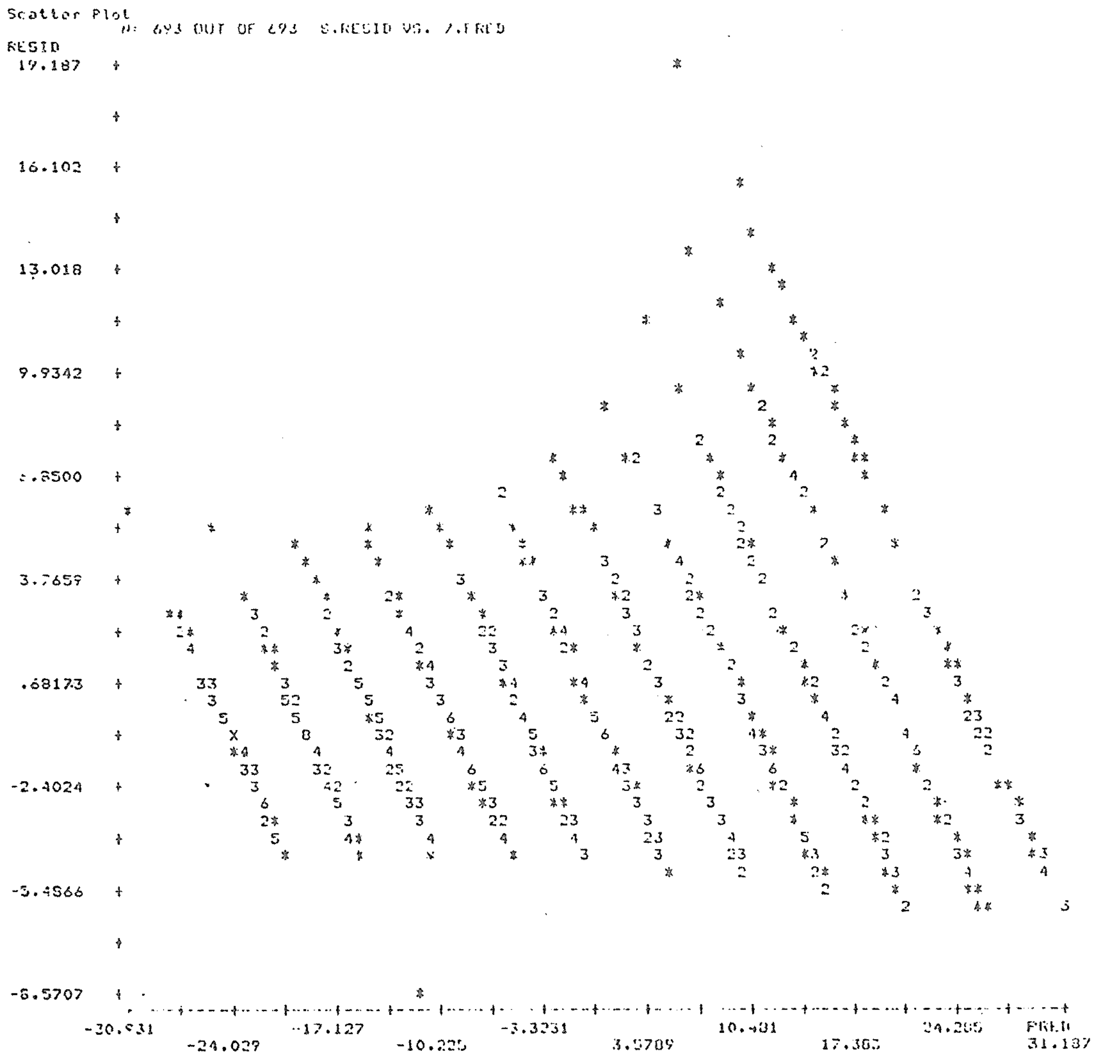

Fig. 4. Scatter plot of residual vs. predicted values (X).

*LEAST SQUARES REGRESSION*

Table 2 shows the results of least squares regression. The regression was carried out using N=693 cases. Under the column headed SUM of SQRS are given SSR, SSE, and SST, respectively. The column headed DF gives the degrees of freedom associated with these respective sums of squares. The MEAN SQR column gives the ratios of the regression and error sum of squares to their corresponding degrees of freedom. The F-test statistic is given as the ratio of the regression mean square to the error mean square, and the final column displays the attained significance level.

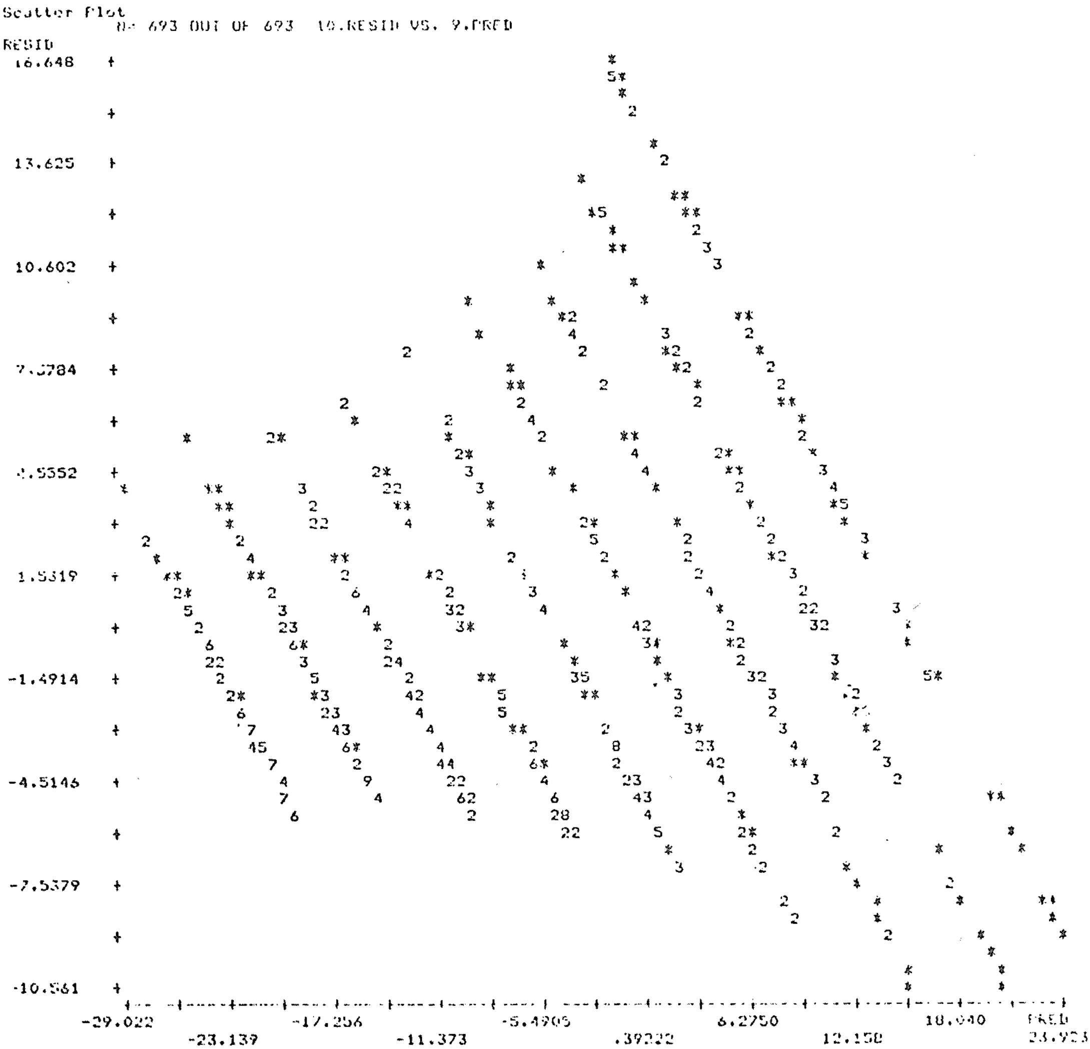


Fig. 5. Scatter plot of residual vs. predicted values (Y).

Next the simple correlation coefficient is given (r), as well as the coefficient of determination, the square of r. There are labeled MULTIPLE R and R-SQR, respectively. The value of correlation coefficient (r) for X, Y, Z is .97168, .91695, .90928 and the coefficient of determination ($r^2$) for X, Y, Z is .94417, .84080, and .82678. The standard error, labeled SE, is simply the square root of the error mean square.

The last section of output yields the estimates of the regression coefficients, their estimated standard errors, and output for individual T-tests. The column headed PARTIAL gives the simple correlation coefficient, R. The next column headed COEFFICIENTS gives the estimates of the regression coefficients. The standard errors of these estimated coefficients are shown in the column headed STD ERROR. The T-statistics are given in the next column followed by the attained significance levels.

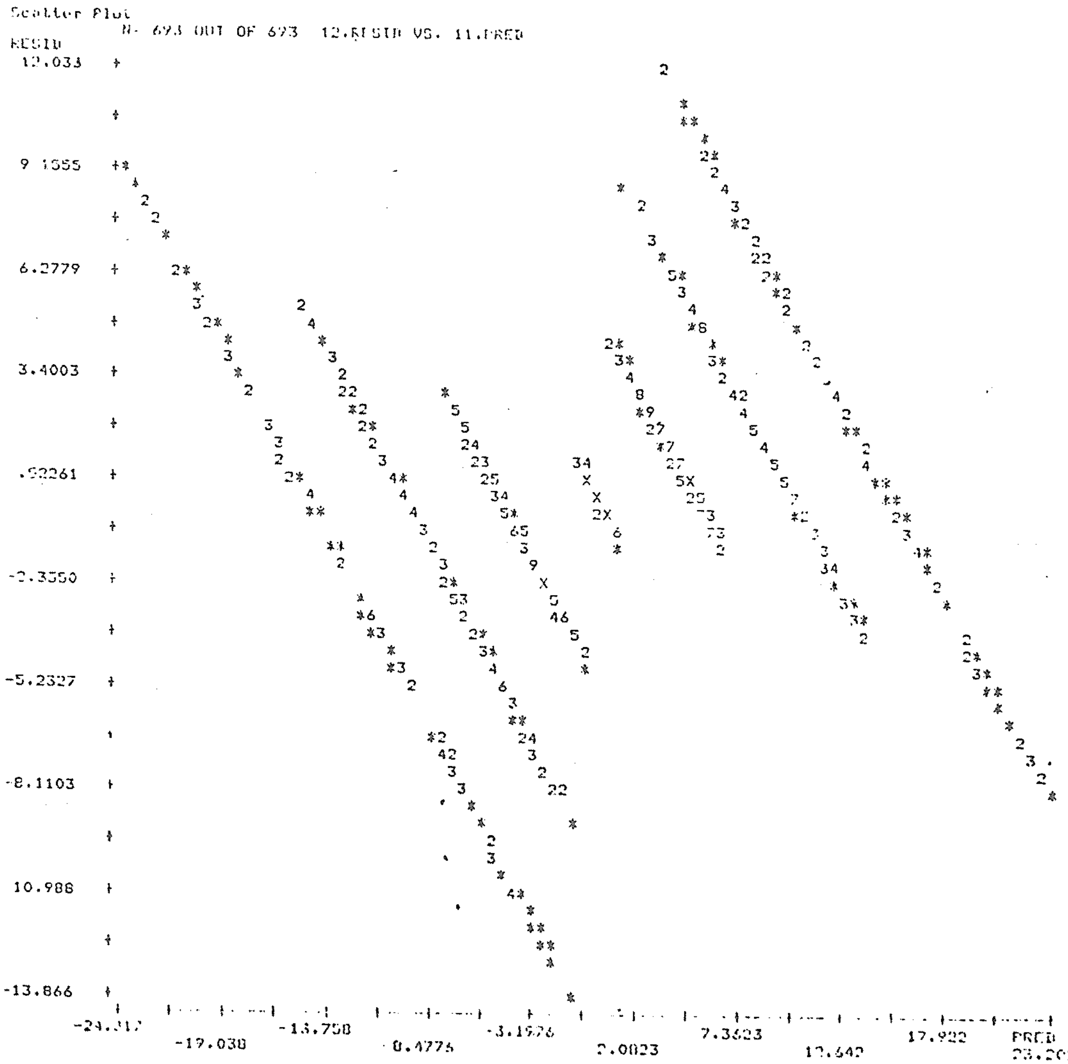


Fig. 6. Scatter plot of residual vs. predicted values (Z).

## *CONVERSION ROUTINES*

Conversion routines were made from the results of least squares regression.

$$X=C_{x1}+C_{x2}*VV+C_{x3}*AP+C_{x4}*LL$$

$$Y=C_{y1}+C_{y2}*VV+C_{y3}8AP+C_{y4}*LL$$

$$Z=C_{z1}+C_{z2}*VV+C_{z3}*AP+C_{z4}*LL$$

where,

Z=actual vertical excursion from zero

Y=actual antero-posterior excursion from zero

Z=actual lateral excursion from zero

VV=observed vertical output from MKG
AP=observed antero-posterior output from MKG
LL=observed lateral output from MKG

| | | |
|---|---|---|
| $C_{x1}$= 4.2844 | $C_{y1}$= 4.0946 | $C_{z1}$=− .53667 |
| $C_{x2}$=10.359 | $C_{y2}$= 1.4080 | $C_{z2}$=− .41401 |
| $C_{x3}$= .78387 | $C_{y3}$=10.628 | $C_{z3}$=− .50829 |
| $C_{x4}$= 1.8856 | $C_{y4}$= 2.4254 | $C_{z4}$=19.522 |

## DISCUSSION

For a sample size of 693, the absolute value of should exceed R@.05= .0745 in order to reject the hypothesis at the 5 % level of significance. Thus the hypothesis that population correlation between values of "X" and these of "VV" is zero can just be rejected at the 5 % level of significance (since r= .9686 > .0745). The value of correlation coefficient (r) is .9686 which indicates that "X" and "VV" are linearly related. Coefficient of determination, $r^2$= .94417. It implies that 94% of the variability in "X" values can be accounted for by a linear relationship with "VV".

The scatter plot and correlation matrix of variable Y VS. AP shows that the hypothesis that population correlation between values of "Y" and those of "AP" is zero can be rejected at the 5 % level of significance since r= .8993> .0745. The value of correlation coefficient (r) is .8993 which indicates that "Y" and "AP" are linerly related. Coefficient of determination, $R^2$, equals .84080. That means 84% of the variability in "Y" values can be accounted for by a linear relationship with "AP".

In the scatter plot Fig. 3 for a same sample size of 693, the absolute value of r should exceed R@.05= .745 in order to reject the hypothesis that population correlation between values of "Z" and those of "LL" is zero at the 5 % level of significance. The hypothesis is rejected. The value of r (.9063) indicates that "Z" and "LL" are linearly related. In this case $r^2$ is .82678. Thus, 83 % of the variability in "Z" values can be accounted for by a linear relationship with "LL".

Table 3 shows minimum and maximum deviations from linear models. Data points appear to be as close as .00372 for X value and as far as 19.187 for X value from the regression line. The reason of this difference between minimum and maximum deviation is due to the nature of divergent observed values (independent variables) and its discreteness. The regression line is merely the one which minimizes the sum of variability between the observed values and the values predicted from the linear models.

Fig. 4 to Fig. 6 indicate that as predicted values increase, so do the case values of residuals. One reason for looking at the residuals is to check on the normality assumption of the given model. Another reason is to check on the assumption that the error variance does not depend on values of the independent variables. Here in this case residual values do not show normal distribution, the values are not random and independent. It is not clear why the patterns of scatter plots of Gig. 6 is different from the rest of them. However, it is certain that the normality assumption is not applicable to the given linear model. It is in part due to the fact that dependent variables are not continuous. They are discrete.

The outputs from the MKG were linearized in the vicinity of centric occlusion using a statistical methodology.12) As indicated in this study, it was unable to demonstrate linear models using the same mathematical approach since a high correlation does not necessarily mean perfect predictability of a formulated linear model although the analysis of data showed that observed values and actual values were strongly correlated. Another restriction of the Kinesiograph is in that eventhough the advantages of choosing an incisal point as the basis for assessing functional movement s of the jaw like the system used in this study are fairly obvious,[4)] measurements of a single point on the mandibular body cannot record the rotation and tipping of the mandible which usually occur during mandibular opening and lateral movement. Also the inherent nonlinearity of the system output limits its application to the measurement of a limited range of jaw movements, i.e., a few millimeters from the centric occlusion.

## SUMMARY


The validity of the Kinesiegraph (MHG-5R) output was studied using a non-ferromagnetic positioning device within working range of a 3 cm wide by 4 cm deep by 5 cm high three dimensional lattice. To determine how well observed values of the M K G outputs may predict case values of actual measurements, relationships between those values were tested by viewing scatter plots and correlation between observed values and actual values. In order to devise some form of equation which can be used to predict or explain case values of actual movements (mm) by observed values of the M K G outputs (volts), statistical regression analysis was performed.

The statistical analysis showed that observed values and actual values were strongly correlated. However, high correlation does not necessarily mean perfect predictability of given linear models. The formulated models were not able to predict all of acutal values. This is partly due to the discreteness of dependent variables (actual values) and also is because of independent nature o of observed values.

In conclusion, unless the Kinesiograph is suitably modified, the inherent nonlinearity characteristic of the system output limits its application to the measurement of a limited range of jaw movements.


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=국 문 초 록=

## Mandibular Kinesiograph의 선형충실도 및 계측정확도에 관한 연구

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Mandibular Kinesiograph(MKG-5R)으로부터 얻어지는 자료의 유효성에 관한 연구를 위하여 비철, 비자석성의 기구를 이용해서 3 cm× 4 cm× 5 cm의 3 차원적 입체공간내에서 수행하였다. Kinesiograph로 부터의 직접 얻어지는 자료(관찰치)와 실제 움직인 거리(실제치)간의 관계를 먼저 보기위해 Scatter plot과 Correlation이 연구됐다. 그러나 최종의 목표는 어떤 형태의 공식을 만들어 이것으로 Kinesiograph관찰치를 이용, 실제치를 알도록 하는 것이었으므로 관찰치의 통계학적 회귀분석이 수행되었다. 통계분석의 결과는 Kinesiograph 관찰치와 실제치 간의 강한 상관관계를 보였다. 그러나 높은 상관계수가 반드시 얻어진 선형모형의 완벽한 예측성을 의미하는 것은 아니다. 이 연구로 부터 얻어진 선형모형이 실제치를 모두 완벽하게 예측할수는 없었다. 그 이유로서는 종속변수(실제치)의 불연속성과 관찰치(비종속변수) 상호간의 독립성 때문이다. 결론적으로 Kinesiograph가 어떤 형태로든 적절한 방법에 의해 수정이 있지 않으면 그 계통자체내에 내재하는 비선형적 특성때문에 그 이용이 하악운동의 제한된 범위내에만 적용될 수 있다.