A STUDY OF RATE OF TOOTH MOVEMENT AS RELATED TO FORCE

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I. Introduction

Among the unanswered questions which have persisted in orthodontics are several dealing with tooth movement. For example;

Will heavier forces move teeth faster than lighter forces?

Is there an optimum range of forces which will produce a maximum rate of tooth movement?

Is there a "differential force"?

Does human tooth movement consistently involve periods of "plateauing" where no or very little movement occurs?

The fact that definitive answers do not exist for these basic questions, precipitated the present study. This is not to say that specific answers can be obtained, but a more thorough investigation of these questions is essential.

The major objectives of this experiment were:

1. To measure and record the rate of space closure (tooth movement) between individuals using constant applied forces.

2. To observe patterns of tooth movement resulting from the application of different force loads.

3. To determine if there is an optimum range of force which will produce a maximum rate of tooth movement.

II. Material and Method

Six females and two males, aged 10 years 5 months to 16 years 11 months, were utilized for this study. The malocclusions present included three class II, division 1, and five class I, crowding cases. The criteria for selection were; a) eruption of all permanent teeth, aside from second and third molars; b) the necessity for first premolar extractions with retraction of all four cuspids, as part of routine orthodontic correction; and c) the agreement of each patient to be available for records and appliance adjustments at least twice a week for ten consecutive weeks.

Appliance Design:

A preliminary study of sectional arches demonstrated that neither Bull loops nor helical loops could overcome the rotational and tipping moments involved in cuspid retraction. (Callow 1963)[1] Therefore, it was decided to retract cuspids along a straight arch, even though this incorporates an unknown frictional component.

The cuspids, second premolars, and first molars in each quadrant were fitted with preformed stainless steel bands. The bands were marked with a notch on the occlusal portion of the buccal surface, which were to serve as reference points from which to measure space closure. Brackets (.022 in.) were placed to allow translation of these teeth in as close to their original angulation and rotation as possible. The archwires (.0215 x .025 in.) were fitted to passively engage the brackets, and contact the labial surfaces of the respective incisors.

The retraction mechanism consisted of round wire single helical open loops[2], soldered on the arch wires mesial to the second premolar brackets. These helical springs were six to eight mm. long, and varied in wire diameter from .014 to .030 inches. Once soldered to the main arch wire, each spring was separately stressed in an Instrom tensile testing instrument, which automatically records the force-deformation curve.(Callow 1968)[1] For this study, thirty springs were calibrated as shown in Table 1.

The initial seating of the arch wires involved ligating the canines with .010 in. ligature wire, twisted with Howe pliers to minimize friction. The remaining teeth were ligated and the ends of the arch wire bent over just distal to the molar tubes.

A reference mark was made on the main arch wire mesial to the spring, from which an accurate measurement to the head of the spring could be made. Each spring was activated until the desired amount of deflection was produced, which gave a known force exertion as determined from precalibration of the springs. The desired deflections were maintained with bi-weekly measurements, and adjustments. The measurements were made with an adjustable needle point caliper, and recorded on a card by piercing the needle points into it, for a later check with the load-deformation curves.(Fig. 1)

Sectional impressions of each quadrant were taken with alginate impression material; a) before the arch wires were inserted in the mouth, b) approximately 30 minutes after initial activation of each spring, c) at succeeding intervals of three to four days, over a period of seven to eight weeks, and d) approximately 30 minutes after removal of each arch wire at the end of the study. The spring and arch wire at the extraction site were obliterated with wet asbestos to reduce tearing and distortion of the impression material upon removal.

The space closure data was collected by measuring with a traveling microscope on the casts, the distance between reference marks on the canine and second premolar bands. Distances were measured to the nearest one hundredth of a mm., and at least five measurements per quadrant were duplicated to determine measurement error.

However, it was found that this dimension included distal rotation of the cuspids, and it did not account for space opening between the second premolar and first molar. Therefore, the distances from the first molar to the cuspid were measured with a fine tapered Boley gauge, to within .05 mm. This distance was measured from a chosen anatomical landmark, in or near the mesio-buccal groove of the first molar, to three different points on the cuspid; i) the mesial surface, at or near the band height, ii) the labial surface at the bracket, and iii) the lingual surface, at or near the seating lug.

The mesial surface measurements were performed on all casts, completing a full quadrant set at one sitting. At least five measurements per quadrant, and in some cases measurements of the entire quadrant were duplicated to determine measurement error. These readings gave a bi-weekly record of space closure between the cuspid and first molar.

The labial and lingual surface measurements were made on the start and finish casts, and these served to provide a measure of cuspid rotation.

III. Review of Literature

Orthodontics depends upon the application of force to move teeth. Although this premise was known to Celsus(20 B. C. - 40 A. D.)[3], very little information is available today regarding the magnitude of forces and the rate at which the teeth move.

Carl Sandstedt[4], in 1904, was probably the first investigator who systematically experimented on animals with orthodontic appliances, and reported histological evidence about tooth movement. In his three week experiment, the crowns of the central incisors were moved three mm. lingually by means of screws. The forces used were not measured, nor were they constant. However, he described the classic histologic picture of deposition of new bone on the tension side of the teeth and resorption on the pressure side. This confirmed the theory of Flourens(1841). He also coined the term "undermining resorption" for the active resorptive process which occurred on the pressure side where the alveolar bone was removed from the marrow space side of the bone.

Oppenheim[5] followed in 1911 with another contribution using baboons as experimental animals. Various tooth movements were performed on the still firmly implanted deciduous teeth over a period of thirty to forty days. No data concerning the exact magnitude of forces used or the rate of tooth movement was presented. However, a histological analysis showed apparent difference in the tissue response to light and heavy forces. With the heavy forces, the pressure side of the periodontal ligament presented a cell-free, fibrous tissue, filled with thromboses and hemorrhage. The adjacent bone was entirely unaltered with only sporadic osteoclasts. The tension side showed an entire absence of all signs of bone formation. In contrast, the teeth moved with light forces were said to show a classic lining of osteoclasts along the bony surface on the pressure side, and buds of bone formation reaching from the alveolar layer towards the tooth on the tension side.

Later publications continued to deal with histologic interpretation of tooth movement material.[6,7,8] In one, he again used monkeys to test differences between intermittent and continuous forces.[9] The evidence produced is interpreted to suggest the use of light (far below 240 grams) and intermittent forces for physiological tooth movement.

In 1932, Swartz[10] undertook two experiments relating tooth movement on dogs and described the histologic picture. He used a recurved spring to exert forces of 3.5, 17, and 67 grams on the fourth, third, and second premolars respectively, when activated a distance of one mm. Over a period of five weeks (two activations), the teeth all moved "about one mm.". The histological reactions were interpreted to mean that "biologically the most favorable treatment is that which works with forces not greater than the pressure in blood capillaries (26 grams/cm^2)".[10]

Stuteville[11,12] also reported several tooth movement studies performed on both dog and human subjects. He experimented with force values from .5 to 200 grams, active distances of .2 to 2.5 mm. The amount of tooth movement ranged from .8 to 1.1 mm. over periods of 21 to 82 days. From the histological examination of this material, it was concluded that the amount of space through which a force is active, and not the degree of force used, is the most important factor in minimizing injuries to the dental unit. He also contradicted Oppenheim by postulating that "jiggling" movement was much more harmful than rigid, guided movement since "jiggling" would not allow for repair of bone and cementum.

About this time, several investigators made an attempt to more accurately measure orthodontic forces[13-15]. Paulich[15], in 1939, referred to the fact that the phase of orthodontics relating to the intensity of the orthodontic force "seems to be sadly neglected and unsettled". Later, more studies involving measurement of the forces produced by various appliance designs were undertaken[16-23].

Weinstein[24,25] presented studies of human tooth movement generated by the oral muscular environment. He concluded that muscle forces as low as 1.68 grams above the resting force, acting over a sufficient time, are capable of moving teeth.

The literature pertaining specifically to the scientific investigation of the relationship of force to rate of tooth movement is extremely limited. Of the five known to the author, the most conclusive study was one conducted by Storey and Smith[26], involving the retraction of mandibular canines in five human subjects. Using precalibrated helical torsion springs, and weekly intraoral measurements from a fixed reference in the maxillary arch, they obtained results which showed a marked difference in tooth movement between the light (175-300 Gms.) and heavy (400-600 Gms.) springs. The cuspids moved rapidly with the application of the light forces, and the movement continued until the force had decreased to the range of 135-180 grams. However, the cuspids always moved by tipping approximately about the apical one-third of the root, as evidenced by follow-up radiographs. Forces in excess of 300 grams tended to move the second premolar and molar rather than the cuspid.

The authors expanded Oppenheim's concept and surmised that there is an optimum range of force values which should be used to produce a maximum rate of movement of the cuspid tooth, without any movement of the anchor unit. This optimum range of force extends approximately from 150 to 200 Gms. The main results from this work are summarized by the authors in a graph relating rate of cuspid movement to load applied.(Fig. 2)

For this particular experiment, the maximum rate of cuspid movement averaged about .75 mm. per week, at the so-called "optimum force range". However, the authors recognized the fact that no absolute force values can be determined since the range will vary from patient to patient because of differences in age, sex, health, etc.

Reitan[27-37] can be credited with performing the most extensive work in tooth movement research in recent years. His investigations have been most complete, attempting to illustrate the use and significance of correlating histological findings with practical observations. Initially, his experiments were carried out on dogs, but more recently he has become involved with human material.

In 1957, Reitan[32] cited a series of experiments performed with continuous forces, where measurements were made of the force applied and the distance the teeth moved. Maxillary first premolars were selected in human subjects, and each was restored with occlusal amalgam restorations, into which a tiny hole was drilled. Applying a continuous force to one (method not given), and using the opposite as a control, the exact amount of tipping tooth movement could be measured with calipers. The type of recorded for one twelve year old subject, when a force of 30 grams was applied for 29 continuous days is illustrated in figure 3.

The tooth movement proceeded in a straight line acceleration for 6-8 days, and then reached a point of no further movement, which Reitan describes as indicative of the formation of an "area of hyalinization". This is defined as a cell-free area of periodontal tissue which does not permit osteoclasts to remove the adjacent bone by direct frontal resorption. Instead, he theorizes that the bone removal must occur by the undermining resorption process, which causes a delay in the tooth movement pattern. Reitan found the average time required for elimination of this compressed area by indirect resorption to vary from two to four weeks, but no mention is made of the frequency of measurement. The duration of this process is influenced by the length of the root, a short root being likely to entail a longer period of hyalinization. In fact, because of this root length differential, he feels that while for upper canines it may be necessary to apply 150-200 grams for continuous bodily movement, it may only require 100-200 grams for lower canines, and somewhat less for premolars. However, he demonstrated histologically, a tipping movement performed with continuous forces will create compressed, cell-free areas in the periodontal membrane at lower force values than for bodily movement, because of the mechanical principles involved.

Other findings included favorable histologic responses in torquing movements with 130 grams of force in the apical region. Also, he noted that only 25 grams of force were required for extrusion of individual teeth. Intermittent forces of around 70-100 grams caused hyalinized areas, but they were less extensive and of shorter duration than in continuous movement.

Burstone[18-22] recognizes the extreme difficulty of correlating forces and tooth movement due to the great number of variables that can influence the recorded rate of tooth displacement. He found that if a relatively const nt force is placed on a tooth, a typical type of graph is obtained if rate of tooth movement is plotted against time, when measurements are made on a 5 to 10 day basis.(Fig. 4)

Three phases of tooth movement can be differentiated which Burstone labels; i) initial phase- corresponding mainly to displacement of the tooth in the periodontal ligament space, ii) lag phase- period during which the tooth fails to move, or has a relatively low rate of displacement, possibly associated with hyalinization of the periodontal membrane, and iii) post-lag phase- period following during which the rate of tooth movement gradually or suddenly increases.

In comparing the application of 10 grams as opposed to 200 grams to tip a central incisor, a very similar initial rate of tooth movement was observed. However, after the lag phase, the tooth under the heavier force demonstrated a period of more rapid tooth movement. Burstone concluded that over a long time interval, the average rate of movement for heavy continuous forces may be greater than those observed for lighter continuous forces. He goes on to say, "the complexity of the tissue changes as well as the presence of a great number of variables suggests that there are inherent difficulties in postulating any simple relationship between force magnitude and the rate of tooth movement".[20]

In another study[18] conducted on 22 patients, optimal rates of tipping tooth movement for application of continuous forces to maxillary incisors were observed when 50-75 grams were applied. The force values tested ranged from 25-150 grams. Increasing the magnitude of force beyond the optimum did not increase the rate of tooth movement.

In a recent paper by Andreason and Johnson[22], the distal (bodily) movement of the first permanent molars in a selected sample of 16 individuals was reported. For each subject, during a 12 week period, a force of 400 grams was applied to the molar on one side of the maxillary arch, while a force of 200 grams was applied to the molar on the other side. The findings showed that on the average, the teeth in the 400 gram force group moved approximately 2½ times as far as did the teeth in the 200 gram force group.(Fig. 5) For this study then, a faster rate of molar movement was produced by placing an increased force upon it. These findings are not in consonance with either Storey and Smith or Reitan.

A most recent investigation[38] studied the distance and rate of tooth movement which occurred in 21 young domestic cats, in response to different force magnitudes. Thirty maxillary canine teeth were moved (tipped) in a distal direction by forces delivered from precalibrated latex elastics fastened to the third premolars. Three ranges of force intensity were used; light(40-60 grams), medium(135-165 grams), and heavy(400-560 grams). Twelve teeth on which no appliances were placed were retained as controls. The experiment lasted a minimum of 3 days for one group of animals, and a maximum of 30 days for another.

The results showed that regardless of the different magnitudes of force used, the maxillary cuspids of both the right and left sides of the same animal moved equal distances. Also, the rates of cuspid tooth movement were not related to the magnitude of the force used. Each animal exhibited its own individual rate of tooth movement, regardless of the intensity of the orthodontic force. The maximum rate of tooth movement was observed in an animal with an appliance delivering a force in the medium range, where the tip of the cuspid moved 7 mm. in 9 days, a rate of 0.8 mm. per day. The slowest rate was observed in an animal with a heavy force appliance, where the tip of the cuspid moved only 0.8 mm. in 30 days, a rate of 0.03 mm. per day. However, for this study, no correlation was found to exist between the rate of cuspid tooth movement, and the magnitude of force delivered by the appliance. This finding differs from those of all previous investigators.

IV. Findings

As described earlier, difficulties with measurement of space closure using the original reference marks became evident after comparing labial, lingual, and mesial surface measurements from the casts.(Table 3) Labial crown movement in many instances was far greater than lingual crown movement, indicating that distal rotation had occurred during cuspid retraction. Therefore, any measurements made on the labial surface of the cuspids would present an exaggerated picture of cuspid retraction due to the incorporation of the rotational component. Likewise, measurements on the lingual would not give a true picture of distal movement due to this same phenomena, only in the opposite direction. Accordingly, it was decided to use the mesial surface measurement, which falls between the two, as a description of total distal tooth movement. Undoubtedly, some error in validity is incorporated here, but this measurement is our best estimate of total distal tooth movement or in this particular study, space closure. The cuspid movement data was compiled by first determing the amount of molar movement from a comparison of before and after lateral cephalometric head-plates.(MacDonald 1968[10]) Then, by subtracting the amount of molar movement measured on the headplates from the amount of space closure measured on the casts, a value for cuspid movement was determined. An analysis of the differences between duplicated measurements on the casts gave a standard error of measurement of .082 mm., indicating a high degree of reliability.

Table 2 presents a summarization of the raw data, which is not included in this paper. Some of the findings which may be abstracted from the table are:

I. Rate of Space Closure

1. Extreme individual variation of rates of space closure in response to approximately the same applied force(300 Gms.) in both mandibular and maxillary right quadrants.(Fig. 6)

2. No direct relationship between force and rate of space closure for this sample. However, a weak tendency for higher rates of space closure with higher force values is apparent, especially when comparing the lighter(50-250 Gms.) and heavier(900-1500 Gms.) forces.(Fig.6)

3. When comparing right-left differences, there is a strong tendency for a higher rate of space closure with an increase in force within the same individual.(Figs. 8&9) In the maxilla, all eight subjects showed a definite higher rate of space closure with a higher force load.(Fig. 9) In the mandible, one subject(DH) showed a slight reversal of this pattern, and another(RA) showed no difference in rate of space closure with a higher force.(Fig. 8)

4. The intra-individual differences in rates of space closure with increased force show the greatest effect when light forces(less than 200 gms.) are replaced by moderate forces(about 300 gms.), as compared to moderate forces being replaced by heavy forces (greater than 400 gms.). This is apparent when comparing the slopes of the respective "intra-individual

difference" lines. (Figs. 8&9)

5. In general, there is a strong tendency for a higher rate of space closure in the maxilla than in the mandible for the same applied force. (Table 2) Three exceptions(MB, DS, RA) exist out of 16 comparisons.

II. Rate of Cuspid Movement

1. Again, extreme individual variation is evident in rates of cuspid movement with approximately the same applied force(300 Gms.). However, the variation is less than were the space closure dimensions.(Table 2)

2. No direct relationship exists between force and rate of cuspid movement. There is a weak tendency for higher rates of cuspid movement with higher forces, when comparing the responses to both light and heavy forces.(Fig. 7)

3. Right-left differences in rates of cuspid movement show a moderate tendency for a higher rate of cuspid movement with increased force within the same individual.(Figs. 10&11) This relationship is stronger in the mandible(Fig. 10), where only one subject(RA) shows no difference, than in the maxilla(Fig. 11), where two subjects(PC, DH) reverse direction in rates with higher forces, and one(MK) shows no difference.

4. The intra-individual differences in rates of cuspid movement with increased forces show the greatest effect when the light forces(less than 200 Gms.) are replaced by moderate forces(about 300 Gms.), when compared to the differences seen when moderate forces

are replaced by heavy forces(greater than 400 Gms.). (Figs. 10 & 11)

5. A strong tendency exists for higher rates of cuspid movement within the maxilla than in the mandible, for the same force loads.(Table 2) Two exceptions exist, both attributed to subject(NK).

III. Pattern of Cuspid Movement

Additional information was extracted from the data by plotting total cuspid movement vs. time, for those subjects whose total space closure could be attributed to cuspid movement ± .5 mm.(Figs. 12-18) It was decided to analyze the graphs for any common trends or patterns of tooth movement over a period of time, when a force above threshold is applied. This analysis entailed searching the graphs for the simplest curve (beginning with a straight line) which includes approximately 95 percent of the plotted points for that period of tooth movement.

The technique for constructing the simplest curve involved fitting a straight line, two standard errors of the measure wide, across the graph in an effort to incorporate as many points as possible. For the cast measurements, the standard error of the measure was .082 mm. Using two S.E.M. as the acceptable range would therefore produce a line(band) .326 mm. wide.

The initial and final recordings for each cuspid were rejected due to the immediate periodontal space response. Also, any points which could be attributed to appliance failures or occlusal interferences were excluded. This resulted in no subject having more than 16 measurements plotted, which would mean that a single point lying outside the constructed line would bring the percentage of points within the band to less than 95 percent of the total. Therefore, the analysis was redefined to accept a straight line relationship between total tooth movement and time, if no more than two points lie outside of a straight line two S.E.M. in width. Where a straight line could not be fitted to the points as defined above, then the next simplest curve which incorporated all points except two was accepted.

Twelve graphs were plotted(four maxillary and eight mandibular cuspid movement patterns). In all instances the applied loads were 350 grams or less, since these were the only samples whose total space closure occurred by cuspid movement ± .5 mm. The results are presented in Table 4. One record(Fig. 14) was excluded from the analysis due to numreous failures which gave a very irradic pattern of movement. Of the remaining 11 plots tested, eight were accepted as straight lines by our criteria, and three were rejected. All three of the rejected graphs could be fitted by applying a more horizontal line during approximately the first 30 days of activity, and adding a slight upward curve(acceleration in rate) from there to completion.

V. Discussion

Findings from this study suggest that relationships between; a.) rate of tooth movement and force, and b.) total tooth movement and time are not clear-cut issues, as some earlier studies tended to suggest.[26,32] Instead, there is a great amount of individual variation present, which even in this small sample of eight, expressed itself abundantly. This is similar to the picture portrayed by Utley,[33] in his recent tooth movement study on cats.

The differences in variation between the space closure and the cuspid movement data can probably be attributed to the fact that an analysis of space closure involves three teeth, while an analysis of cuspid movement involves only one tooth. Accordingly, we should expect more variation in the space closure data.

Certain tendencies do become apparent in varying degrees. The relationship between cuspid movement and force shows a very weak correlation for the over-all sample. If a trend had to be assigned, it probably would have to be a straight line relationship, ie. an increase in force (from 50 to 1500 Gms.) results in a higher rate of cuspid movement. This is made more apparent when the intra-individual differences in force and rates are plotted.(Figs. 10 &11) For the majority of the subjects in this study, an increase in force(within the range of 50 to 1500 Gms.) resulted in an increase(of varying degree) in the rate of cuspid movement, for that particular individual. This would tend to agree with Andresson's findings of increased maxillary molar movement with increased force, within the range of 200 to 400 grams.[22]

These findings spread some doubt on the Storey-Smith concept that "increasing the force above 150 - 200 grams causes the rate of cuspid movement to decrease".[26] This is not to say that no optimum force range exists for a maximum rate of tooth movement. Rather, that for our sample, no optimum range was apparent between the forces of 50 to 1500 grams. Optimum force ranges for maximum rates of tooth movement probably do exist, but a particular force range is optimum for the individual, not for the population. And these optimum force ranges seem to be distributed at various levels throughout the population. One individual may have a maximum rate of tooth movement from 100 to 150 grams, while another might have a maximum rate anywhere between 400 to 1500 grams. For example, in this study, subject (LC) had a higher rate of cuspid movement at 321 grams than at 156 grams, while subject (DH) had a higher rate at 153 grams than 270 grams. Likewise, subject (MB) had a higher rate of cuspid movement at 863 grams than 349 grams, and subject (PO) had a higher rate at 398grams than 1539 grams.(Fig.11) Individual variation is the most consistent pattern.

Additional contrasts to Storey and Smith's study[26] which this investigation showed includes cuspid movement at forces less than 150 grams, which they state as the force level which these teeth can support without appreciable movement. We observed cuspid movement in the range of 1.5 to 3 mm. in some individuals with active forces of 150 grams or less.

One of the strongest relationships evident in this study was the tendency for a faster rate of tooth movement in the maxilla than in the mandible, for the same applied force. However, the author chose only to report this finding. It is worthy to note that on the average, maxillary teeth have larger roots than their counterparts in the mandibular arch.[39]

The pattern of tooth movement studied in this investigation tended to disagree with Reiten's findings,[32] since over two-thirds of the subjects approximated a straight line relationship of tooth movement over time. Complete statistical evidence is lacking, but there is definitely a trend of a straight line acceleration of tooth movement over time in this study. This finding tends to question many of the theorized concepts of tooth movement, such as hyalinization,[5,31,32] undermining resorption,[4,5] and capillary compression.[10] Additional research in this area is essential, both on the histological and clinical levels, before any positive answers can be put forth. The answers will come only from a thorough and extensive examination of the problem, with accurate records taken at the shortest intervals, ie. daily if possible.

The earlier mentioned difficulties with measurements of actual cuspid movement due to the rotation effect during retraction merits a few additional comments. The cuspids used in this project were bracketed in such a way as to maintain, as close as possible, their original rotation and angulation as they were retracted along a straight arch wire. Likewise, the .0215-.025 inch arch wire was adjusted to fit the brackets as closely as possible, to effect minimal changes in cuspid position. Yet rotation, in varying degrees, occurred in over two-thirds of the cases, and tipping occurred in nearly all.(Table 3) This gives an idea of the lack of control that exists in moving teeth, even with a closely adapted edgewise appliance.

One of the unknowns in this study was the frictional resistance of the brackets, arch wires, and ligature ties. This was one of the reasons that the initial experiment design was attempted with sectional retraction arches--to eliminate the unknown frictional component. However, numerous other problems with sectional retraction[1] far out weighed the frictional component involved with retraction along an arch wire. When the frictional component can be eliminated or determined, a more accurate picture of tooth movement should be forthcoming.

VI. Conclusion

The most striking consistency of this entire study is the individual variation which prevails at all levels of tooth movement. In light of other scientific studies, this correlates highly with most biologic phenomena.

The trends described were for the most part only tendencies in that direction, and never all inclusive rules. It is unfortunate that in our search for "laws of nature", we sometimes fail to realize the individual is a creature of dynamic biologic complexities, which are not intended to fit schemes which are fundamentally static.

In conclusion, it is apparent that inherent difficulties in experimental design and measurement technique were problems which detract somewhat from the validity of the findings. Only with continued effort will these problems be eliminated, giving a deeper and more accurate insight into tooth movement.

VII. Summary

A study of tooth movement was undertaken in eight subjects who required retraction of all four cuspids for routine orthodontic correction. The retraction mechanism consisted of pre-calibrated helical open loop springs, which were soldered to an .0215x.025 inch arch wire along which the cuspids were moved. Forces within the range of 50 to 1500 grams were tested over periods of 7 to 8 weeks. Bi-weekly records of space closure were collected.

The results were reported under three headings; (1) Rate of Space Closure, (2) Rate of Cuspid Movement, and (3) Pattern of Cuspid Movement. The most consistent finding was individual variation. Certain tendencies were apparent which can be summarized as follows:

1. A weak tendency within the group for higher rates of space closure and cuspid movement with higher force values.

2. A moderate tendency for higher rates of space closure and cuspid movement with higher force values within the same individual.

3. A strong tendency for higher rates of space closure and cuspid movement in the maxilla than in the mandible for the same applied forces.

4. A strong tendency for a straight line relationship between total tooth movement and time, with very little evidence of plateauing.

It was concluded that individual variation was generally the only rule that was followed, with only a few weak tendencies applicable to the sample or population as a whole. Continued experimental refinement and scientific research are essential in the field of orthodontic tooth movement, if answers are to be found.

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Table 1 Information concerning retraction springs used in this study

Number	Wire Size (in.)	Force Range Tested (Gms.)	Deflection Tested (mm.)	Force Range Used (Gms.)	Deflection (mm.)
2	.014	0-100	0-4	75-50	2-3
4	.016	0-200	0-5	175-50	1-4
18	.020	0-400	0-6	375-200	2-6
4	.028	0-950	0-6	900-300	3-6
2	.030	0-1500	0-5	1500-1300	4-5

Fig. 1 Taking spring deflection measurement with fine point calipers from reference mark on each arch wire to head of spring

Table 2 SPACE CLOSURE AND RATE OF MOVEMENT*

Age	Mandibular Right: Force (grams)	Total Space Closure (mm.)	Av. Rate of Space Closure (mm/wk)	Total Cuspid Movement (mm.)	Av. Rate of Cuspid Movement (mm/wk)	Mandibular Left: Force (grams)	Total Space Closure (mm.)	Av. Rate of Space Closure (mm/wk)	Total Cuspid Movement (mm.)	Av. Rate of Cuspid Movement (mm/wk)
	M SD					M SD				
3-2	269±35	3.43	.462	1.68	.226	0	.05	.007	.20	.027
1-1	301±19	1.62	.202	1.42	.178	64± 3	.68	.085	.48	.060
-5	305±43	1.41	.165	1.71	.200	174±28	1.55	.181	1.65	.193
-9	339±21	2.78	.330	1.86	.221	837±62	3.70	.439	2.32	.275
-7	323±60	3.15	.401	2.15	.274	1515±124	3.82	.486	2.32	.295
-2	339±22	2.55	.302	2.65	.314	128±17†	1.72	.204	1.47	.174
-11	313±30	1.33	.160	1.33	.160	236±41††	1.33	.160	1.33	.160
-4	301±20	1.40	.158	1.20	.135	648±119†††	2.75	.310	1.83	.207

Age	Maxillary Right: Force (grams)	Total Space Closure (mm.)	Av. Rate of Space Closure (mm/wk)	Total Cuspid Movement (mm.)	Av. Rate of Cuspid Movement (mm/wk)	Maxillary Left: Force (grams)	Total Space Closure (mm.)	Av. Rate of Space Closure (mm/wk)	Total Cuspid Movement (mm.)	Av. Rate of Cuspid Movement (mm/wk)
	M SD					M SD				
-2	327±24	2.34	.315	2.34	.315	0	.55	.074	.55	.074
-1	294±18	2.25	.281	1.90	.238	65±15	.53	.066	.53	.066
-5	270±53	3.62	.422	2.37	.277	153±18	3.33	.389	3.00	.350
-9	349±31	2.60	.308	2.40	.285	863±66	4.05	.480	2.75	.326
-7	398±14	4.45	.566	3.53	.449	1539±120	4.90	.623	3.40	.433
-2	321±25	3.50	.415	3.30	.391	156±15'	1.73	.205	2.23	.265
-11	314±39	2.13	.257	1.13	.136	246±36''	1.30	.157	1.05	.127
-4	291±21	3.40	.384	2.40	.271	539±210'''	4.15	.468	2.40	.271

pace closure was measured on models. Cuspid movement is this space closure minus molar ovement as measured on radiographs.

75 decaying to 100 g.
00 decaying to 200 g.
00 decaying to 450 g.

'175 decaying to 150 g.
''300 decaying to 200 g.
'''900 decaying to 200 g.

SELECTED TOOTH DIMENSIONS AND MOVEMENT OF TEETH OF MANDIBULAR LEFT QUADRANT

	1st Molar			2nd Bicuspid			Cuspid										
Force	Crown Movement	Apex Movement	Root Length	Crown Movement	Apex Movement	Root Length	Buccal Movement (cast) adj.	Lingual Movement (cast) adj.	Crown Dia (cast)	Root Length	Space Closure (cast)	Cuspid Movement Adj. S.C.-Molar Movement	Cuspid Apex	No. Days	Cuspid Movement Per Week	Bone Displacement m.m.3	Bone Displacement per week m.m.3
0	0	0	20.4	1.42	-.57	18.9	.3	.1	6.4	20.3	.1	.1	0	52	.027	18	2.43
64	.20	-.15	18.5	.80	-.20	16.0	.4	.40	5.0	18.0	.68	.48	.25	56	.060	22	2.75
174	-1.0	0.10	16.6	-.45	1.90	15.9	2.8	.8	7.0	20.3	1.55	1.65	0	60	.193	138	16.05
837	1.25	0	21.0	2.0	.75	21.0	2.3	1.2	4.0	27.3	3.70	2.45	-1.70	59	.275	109	12.98
1515	1.50	-.7	18.5	1.75	-.92	20.0	1.3	1.5	6.2	21.5	3.82	2.32	-.83	55	.295	102	12.91
175/100	.25	.20	19.0	0	.50	18.5	2.2	1.2	5.0	20.0	1.72	1.47	0	59	.174	137	16.31
300/200	0	0	21.0	0	0	22.0	1.4	1.1	6.8	23.5	1.33	1.33	.25	58	.160	117	14.10
900/450	.92	0	18.0	1.35	-1.0	23.0	1.1	1.8	5.2	23.0	2.75	1.83	-.92	62	.207	72	8.09
Mandibular Right																	
	1.75	-2.30	18.9	3.75	-.88	17.6	1.3	2.3	5.7	19.0	3.43	1.68	1.12	52	.226	153	20.68
	.20	0	15.5	.25	.50	15.0	1.0	1.2	4.6	21.0	1.62	1.42	1.35	56	.178	89	11.12
	-.30	.87	17.8	-.40	.50	16.5	3.1	.4	6.5	18.0	1.41	1.71	-2.10	60	.200	140	16.28
	.92	0	21.5	.75	-.10	22.5	1.7	1.7	5.5	24.3	2.78	1.86	-.80	59	.221	95	11.31
	1.00	.70	21.5	1.70	-.65	21.5	2.8	1.2	6.2	--	3.15	2.15	--	55	.274	--	--
	-.10	0	17.5	0	.42	19.0	3.0	2.2	5.8	21.0	2.55	2.65	-.50	59	.314	150	17.86
	0	0	21.5	0	-.20	23.5	1.7	1.0	6.8	22.5	1.33	1.33	.25	58	.160	108	13.01
	.20	.50	19.5	.50	.35	21.0	1.4	1.2	5.3	21.5	1.40	1.20	.42	62	.135	113	12.70

nus sign indicates movement in direction opposite from direction of force.

* A composite table of measurements made by investigators involved in this study.

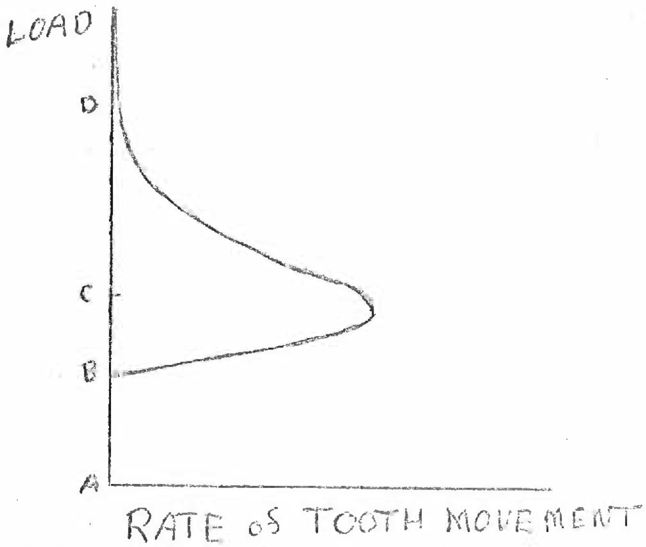
Table 4.

TESTS FOR LINEAR RATE OF TOOTH MOVEMENT

Fig.	Subject	Quadrant	Force	Tooth Movement Points Plotted	Points Within Constructed Straight Line	Points Outside Constructed Straight Line	Accept or Reject St. Line
12	D. S.	Mand. Rt.	301	16	13	3	Reject
12	D. S.	Mand. Lf.	64	16	14	1	Accept
13	L. C.	Mand. Rt.	339	14	12	2	Accept
13	L. C.	Mand. Lf.	175→100	14	13	1	Accept
14	D. H.	Mand. Rt.	305	14	11	3	Reject
14	D. H.*	Mand. Lf.	174				
15	R. A.	Mand. Rt.	313	15	13	2	Accept
15	R. A.	Mand. Lf.	300→200	15	8	7	Reject
16	D. H.	Max. Lf.	153	14	13	2	Accept
17	D. W.	Max. Rt.	327	15	13	2	Accept
18	L. C.	Max. Rt.	321	14	13	1	Accept
18	L. C.	Max. Lf.	175→150	12	10	2	Accept

*Due to numerous appliance failures which gave an erratic pattern of movement, this plot was excluded.

Fig. 2. The general relation between curve of force and rate of tooth movement for the retraction of the lower cuspids.
A, Subthreshold force.
B, Threshold force.
C, Optimum force.
D, Maximum force



(From Storey, E. and Smith, R.: Aust. J. Dent. 56:11, 1952)

Fig. 3. Graph indicating degree of movement of an upper 1st premolar with fully developed roots. As indicated by horizontal portion of the curve, a cell-free area persisted for about 16 days.

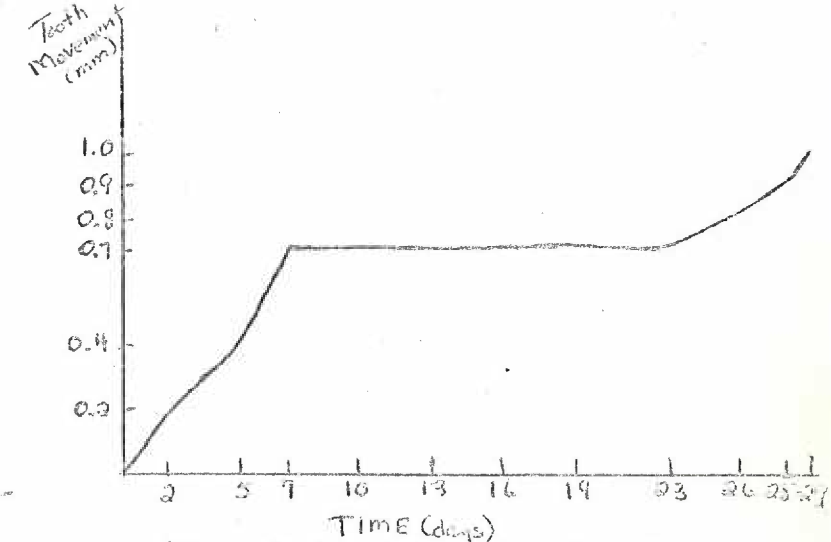


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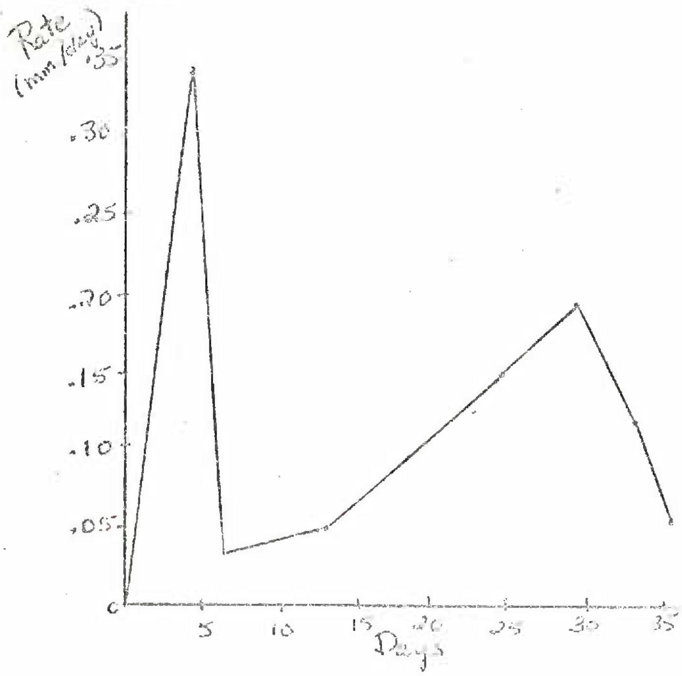
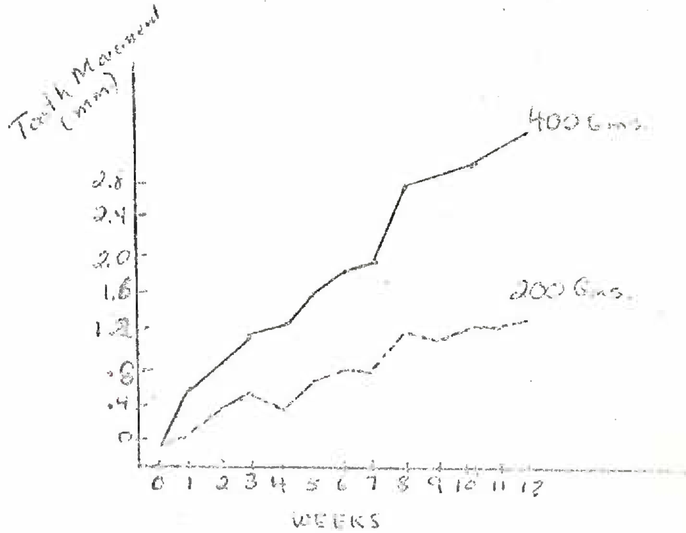
Fig. 4. Typical tooth movement graph in which rate is plotted against the number of days following the application of a continuous force (125 Gms.), to a central incisor.



(From Burstone, C.: Vistas in Orthodontics, 1962)

Fig. 5. Two unsmoothed curves of mean weekly posterior maxillary 1 molar movements for 400 and 200 gram values during the twelve weekly intervals.



(From Andreasson, G. and Johnson, P.: Angle O.:37:9, 1967.)

Fig. 6 The Relation Between Force and Rate of Space Closure

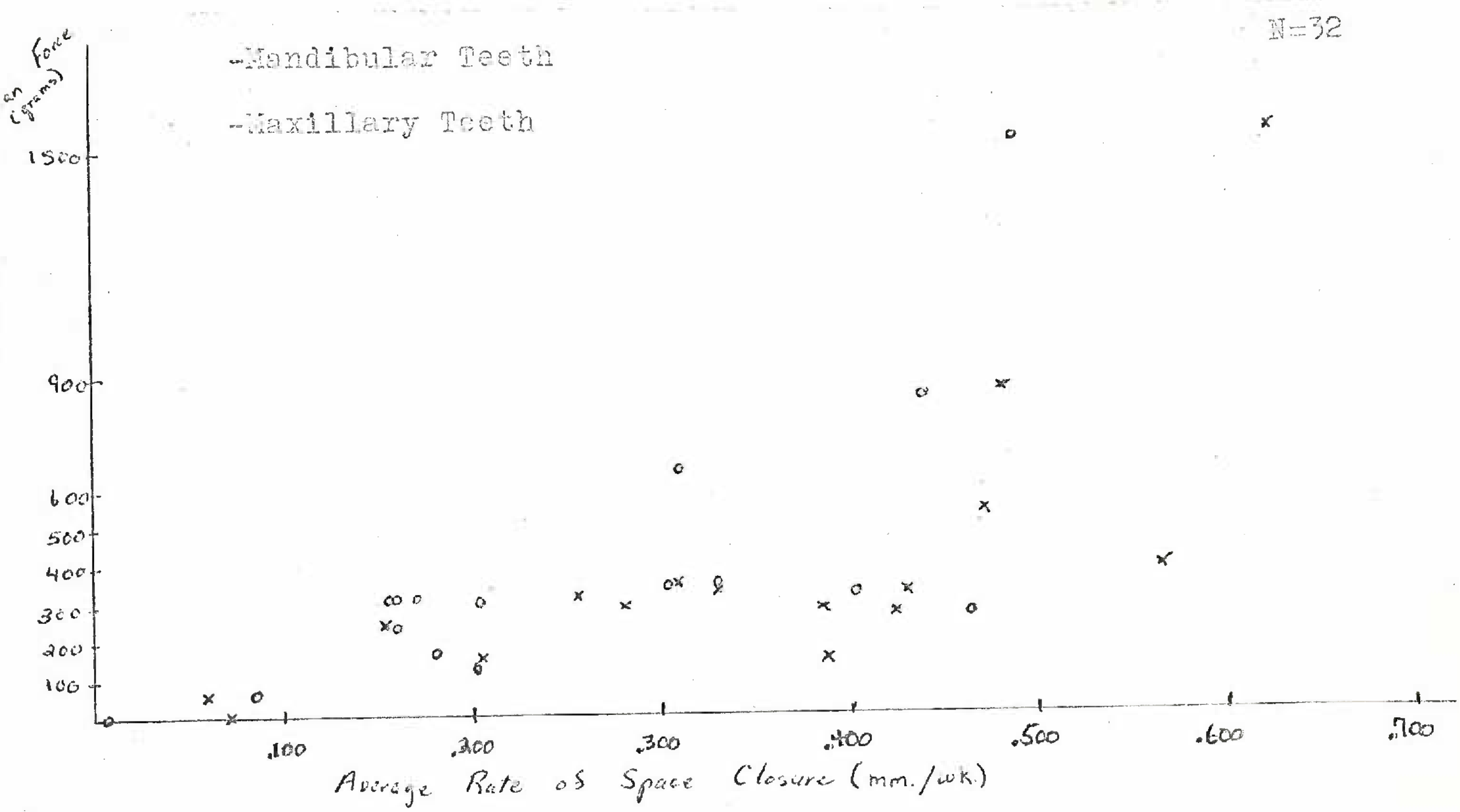
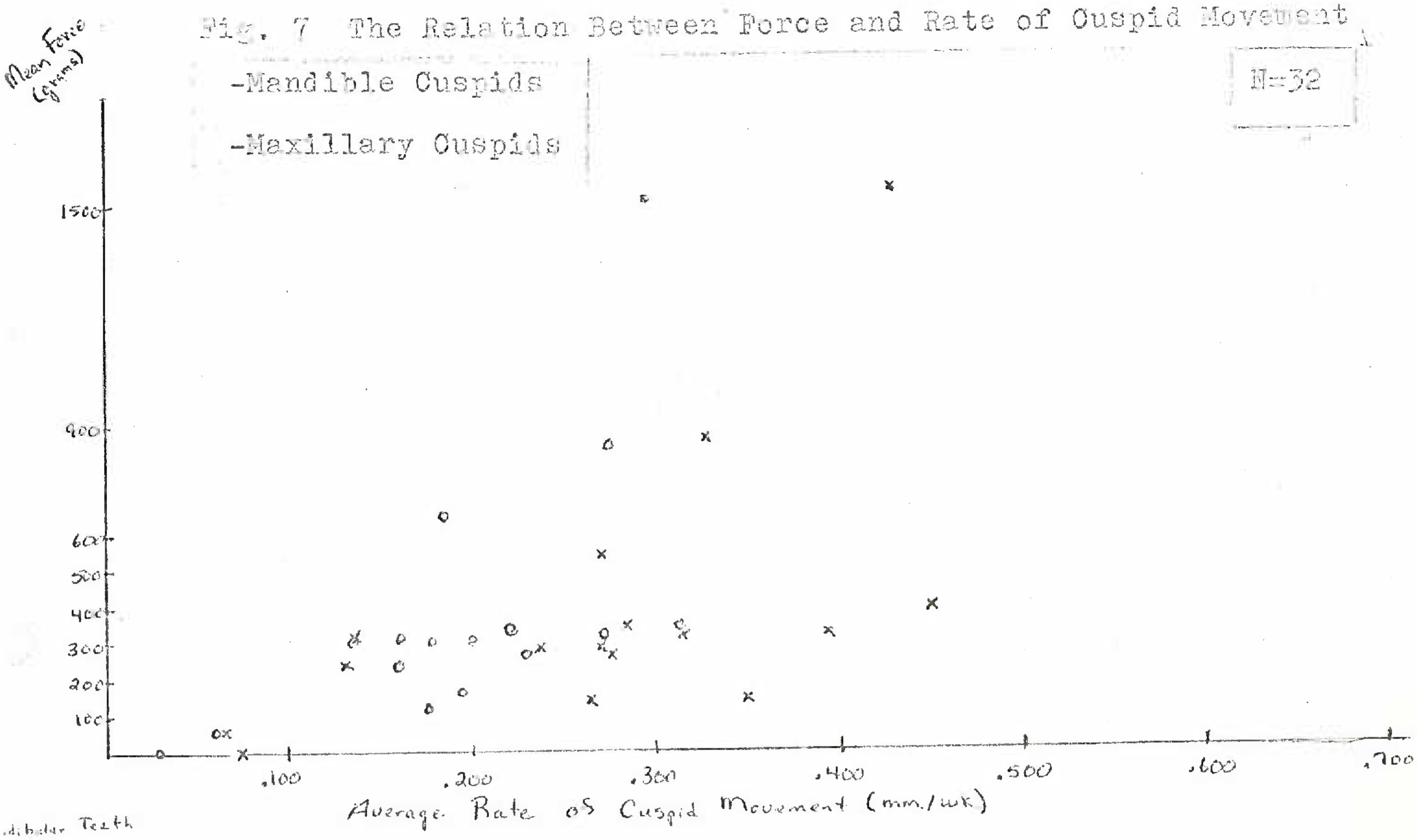


Fig. 7 The Relation Between Force and Rate of Cuspid Movement



...dibular Teeth

Fig. 8 Mandibular Right-Left Intra-Individual Differences in Rate of Space Closure with Change in Force

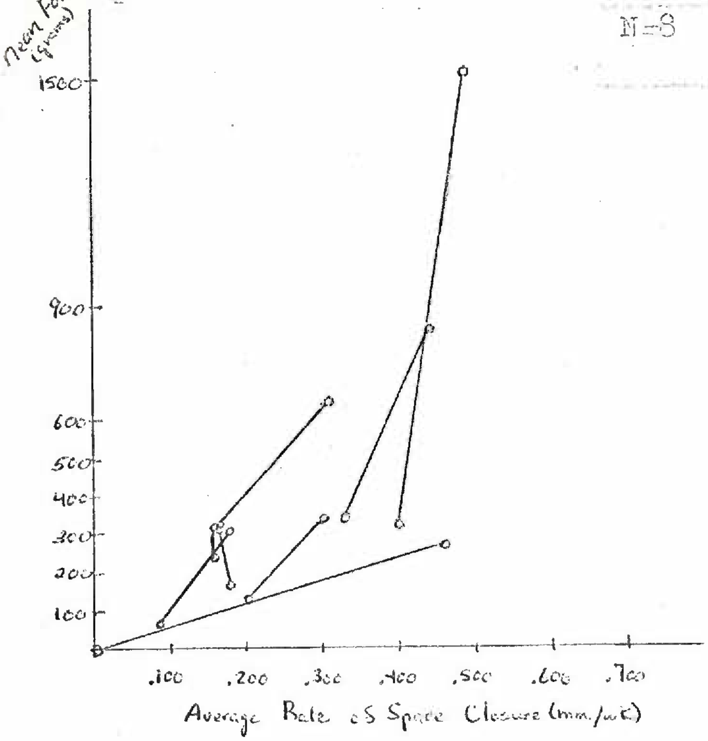


Fig. 9 Maxillary Right-Left Intra-Individual Differences in Rate of Space Closure with Change in Force

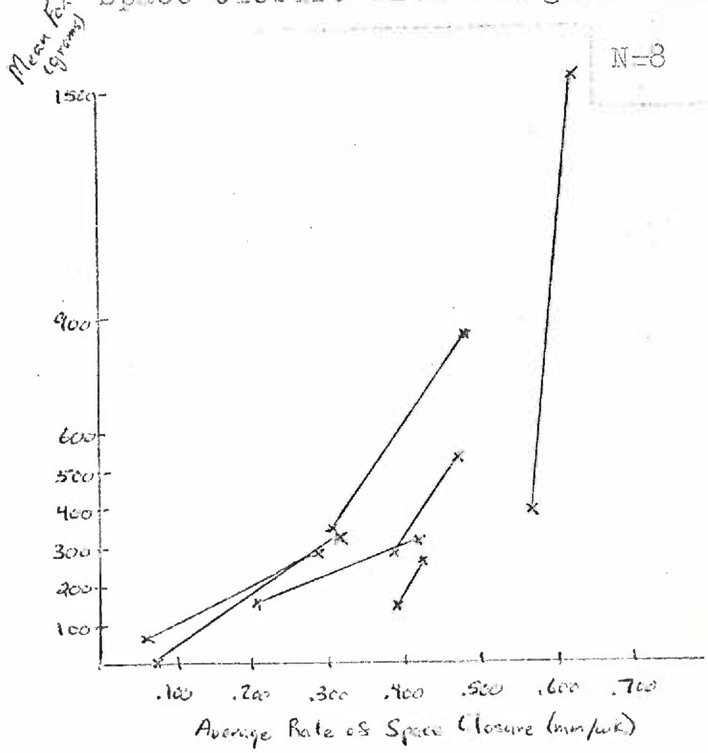


Fig. 10 Mandibular Right-Left Intra-Individual Differences in Rate of Cuspid Movement with Change in Force

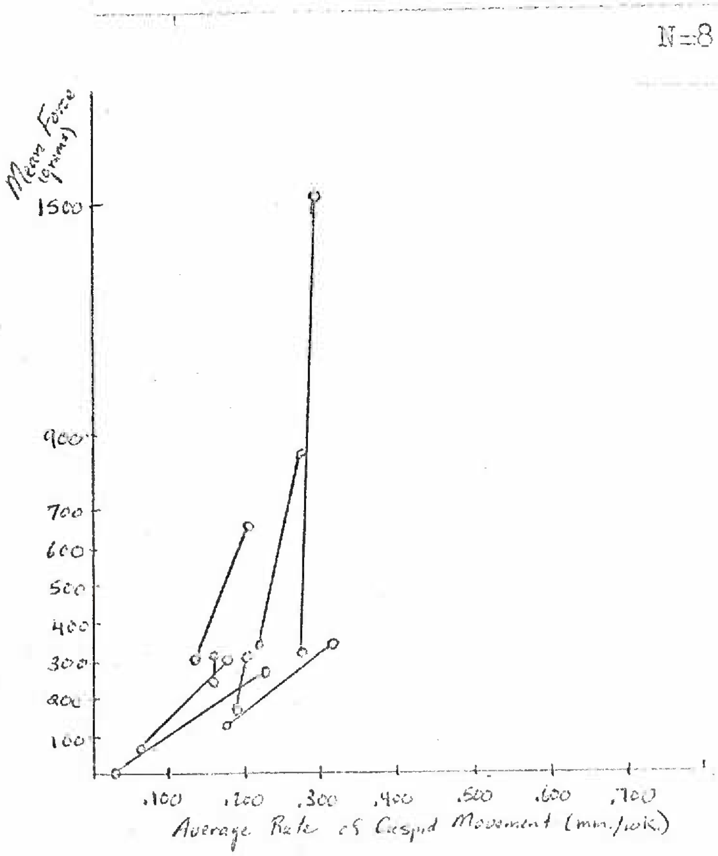


Fig. 11 Maxillary Right-Left Intra-Individual Differences in Rate of Cuspid Movement with Change in Force

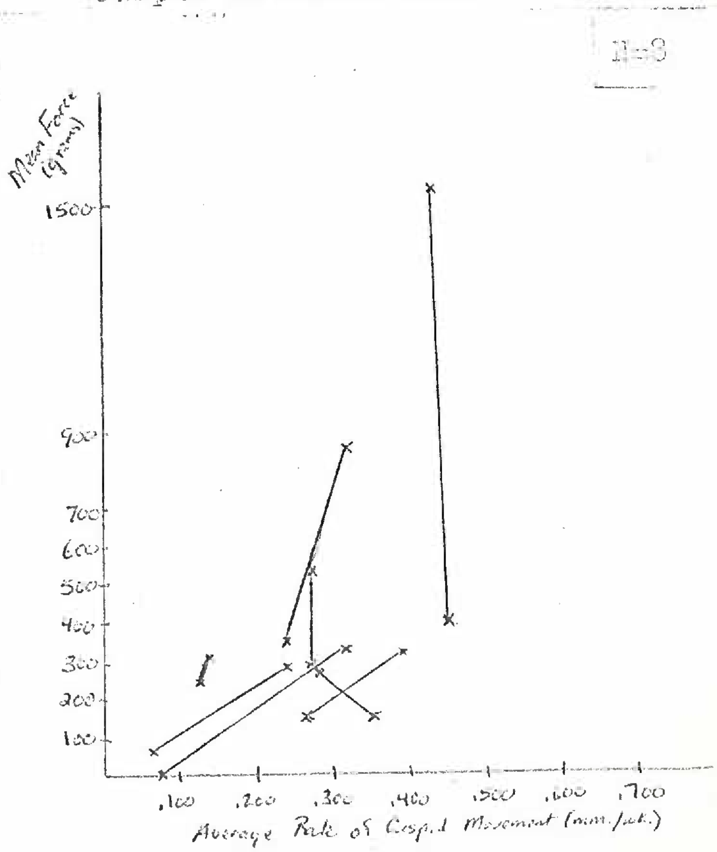


FIG. 12. RELATION OF TOTAL TOOTH MOVEMENT TO TIME

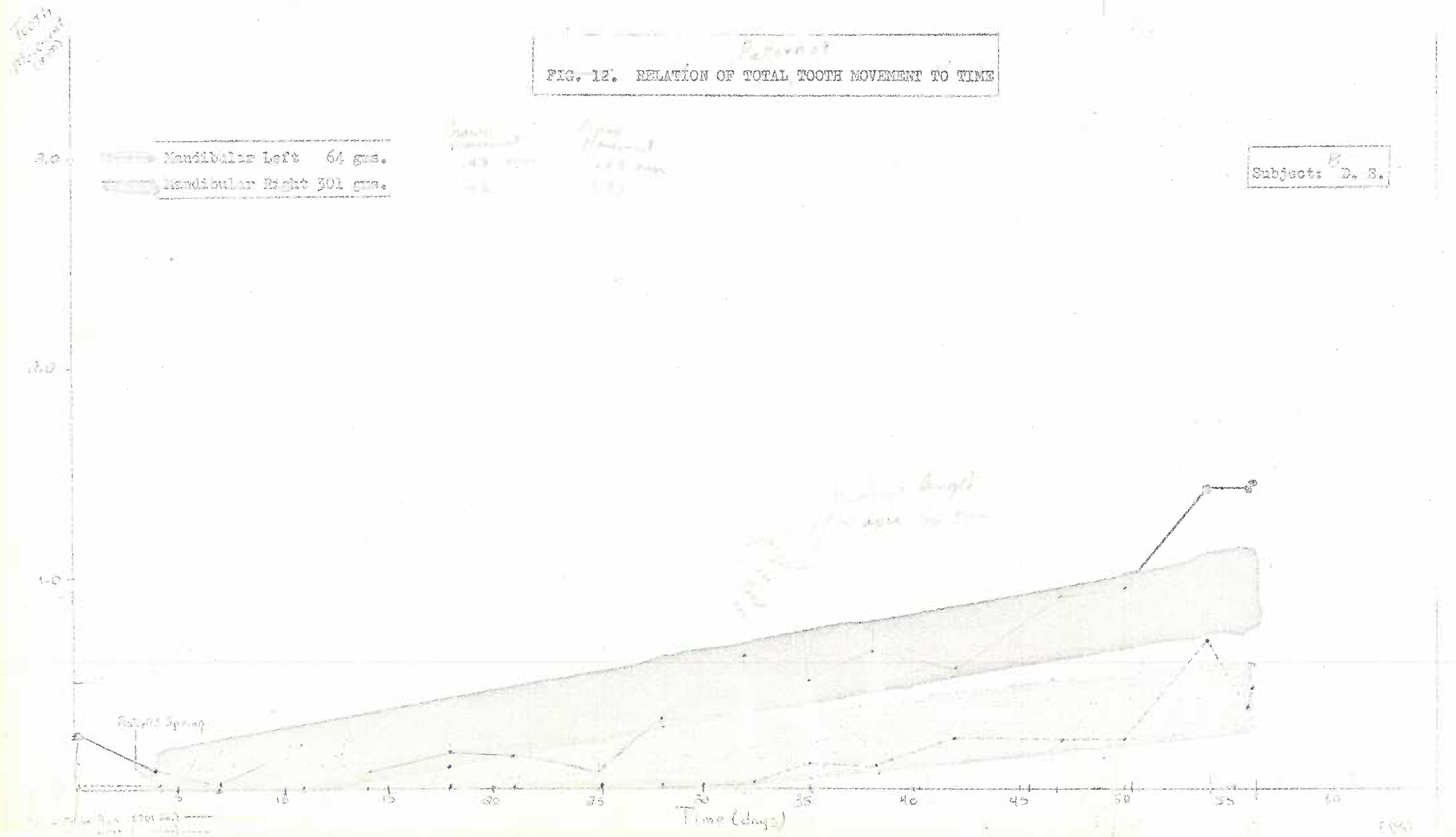
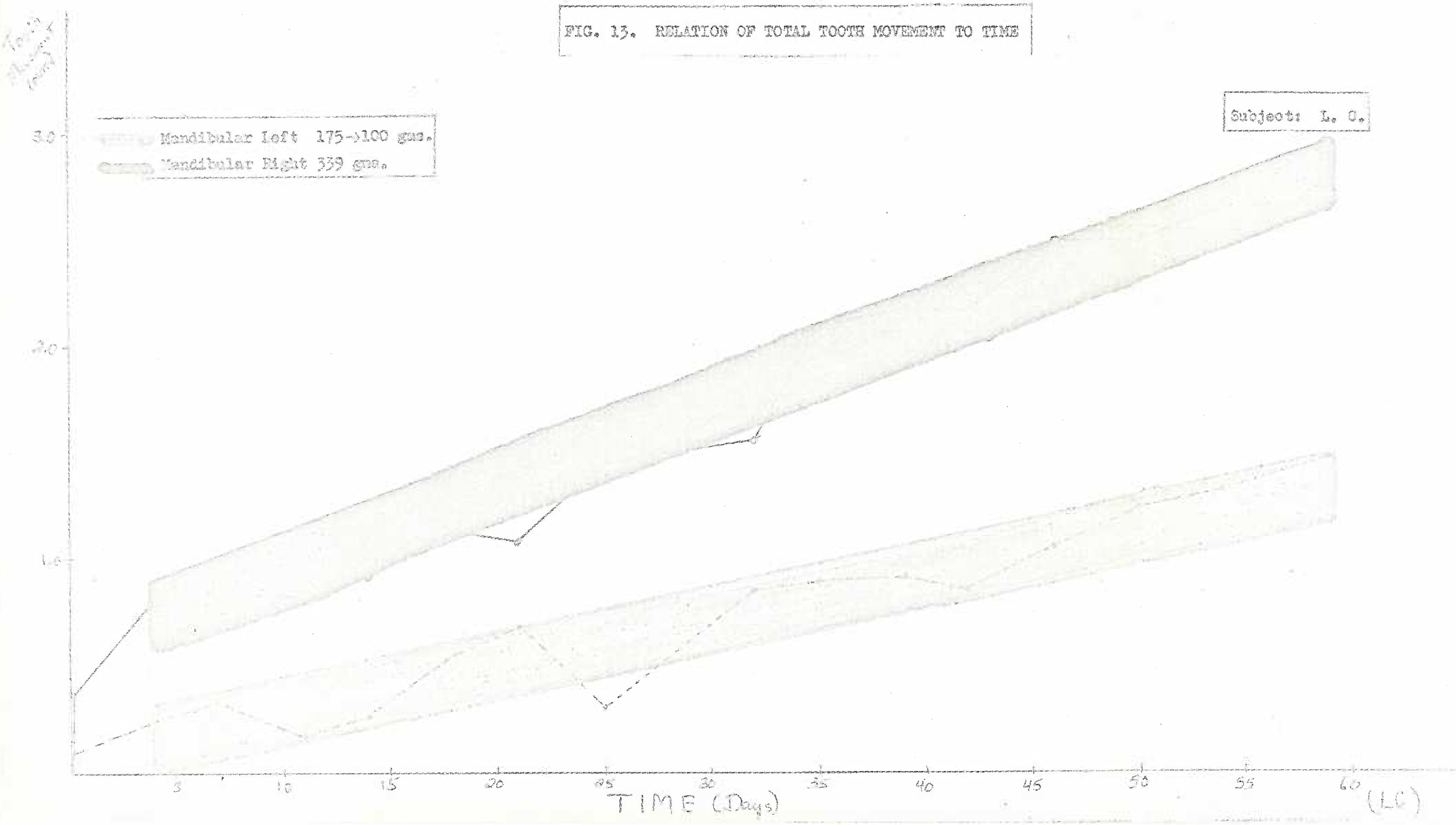


FIG. 13. RELATION OF TOTAL TOOTH MOVEMENT TO TIME



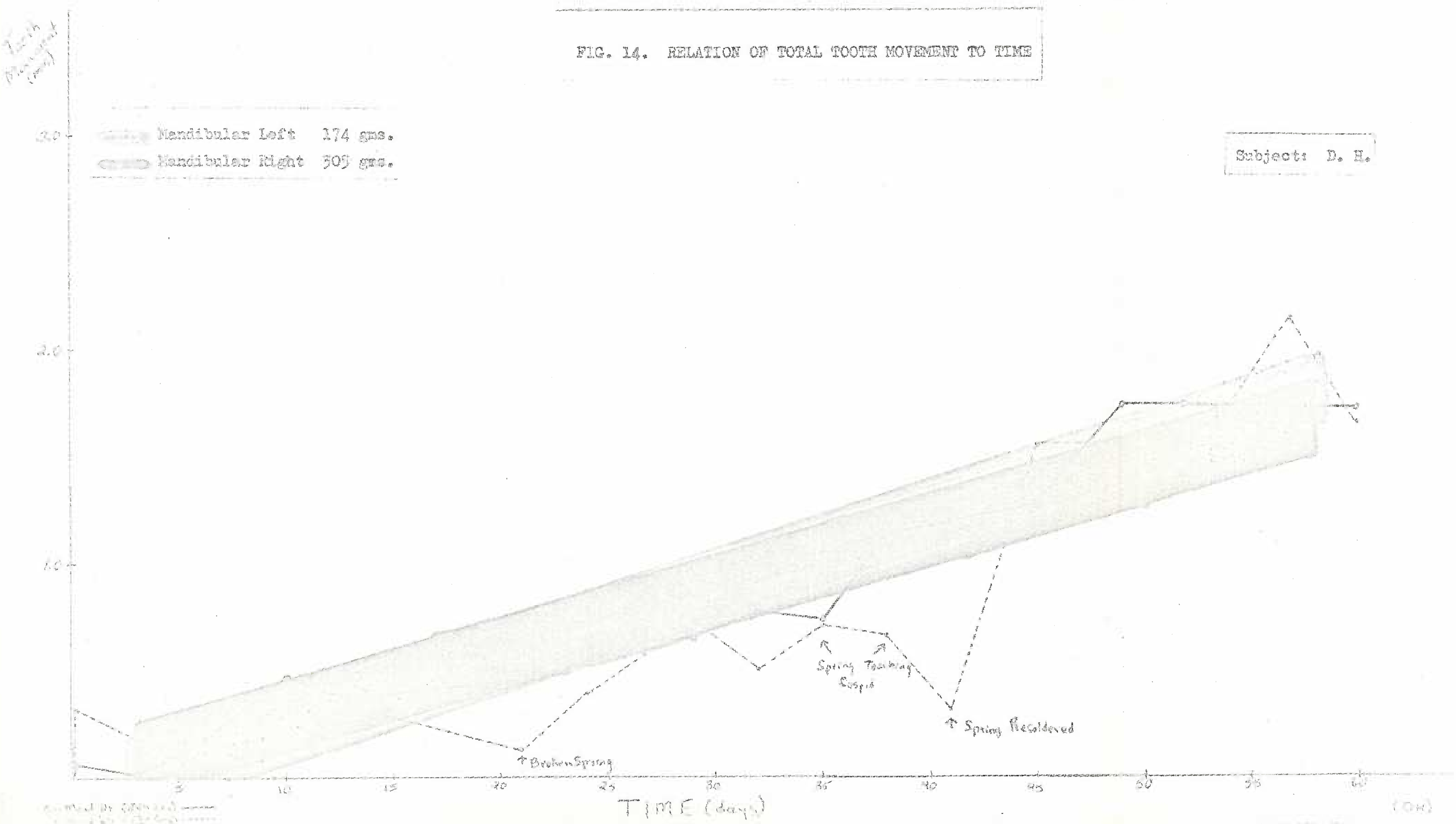
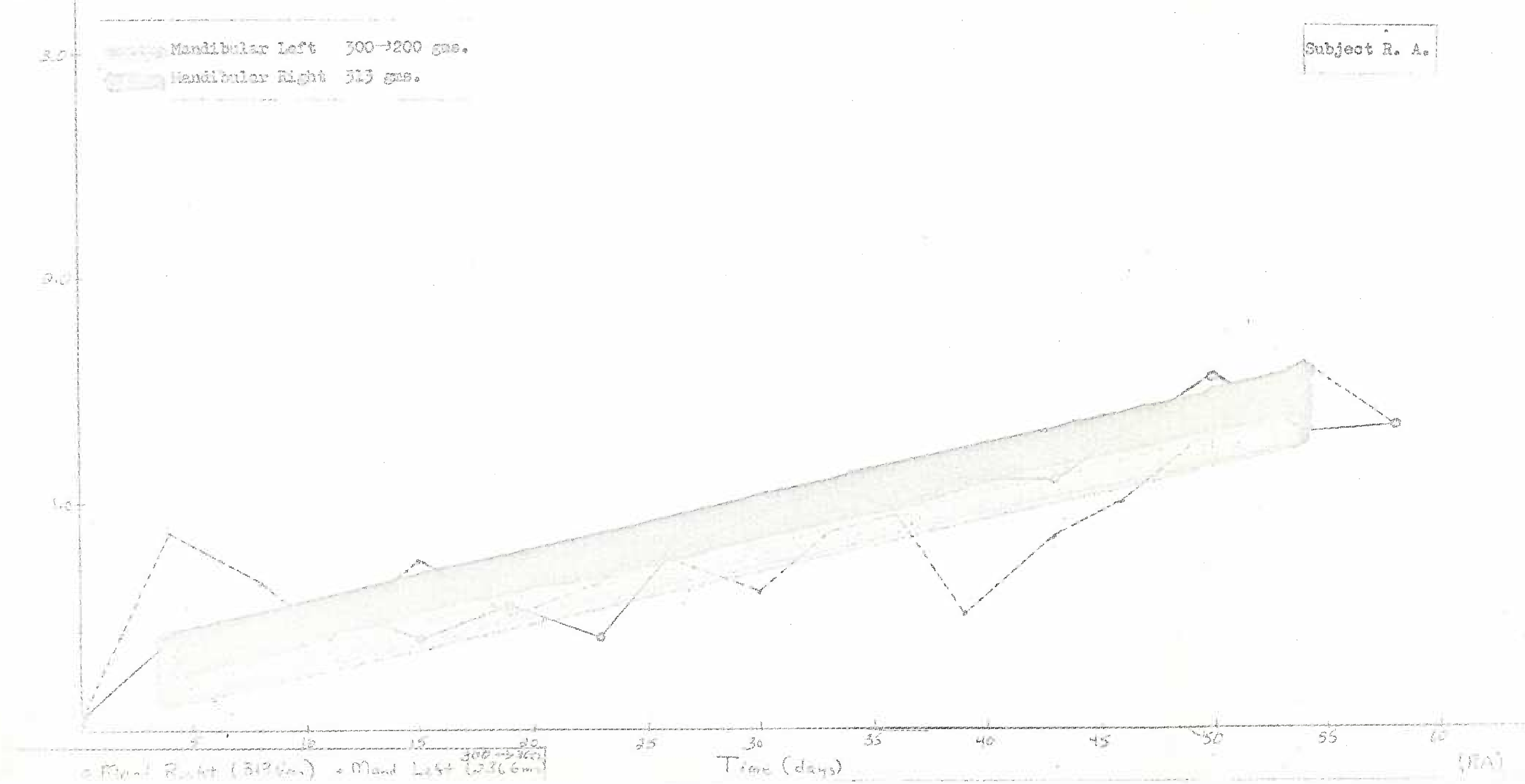


FIG. 14. RELATION OF TOTAL TOOTH MOVEMENT TO TIME

FIG. 15. RELATION OF TOTAL TOOTH MOVEMENT TO TIME



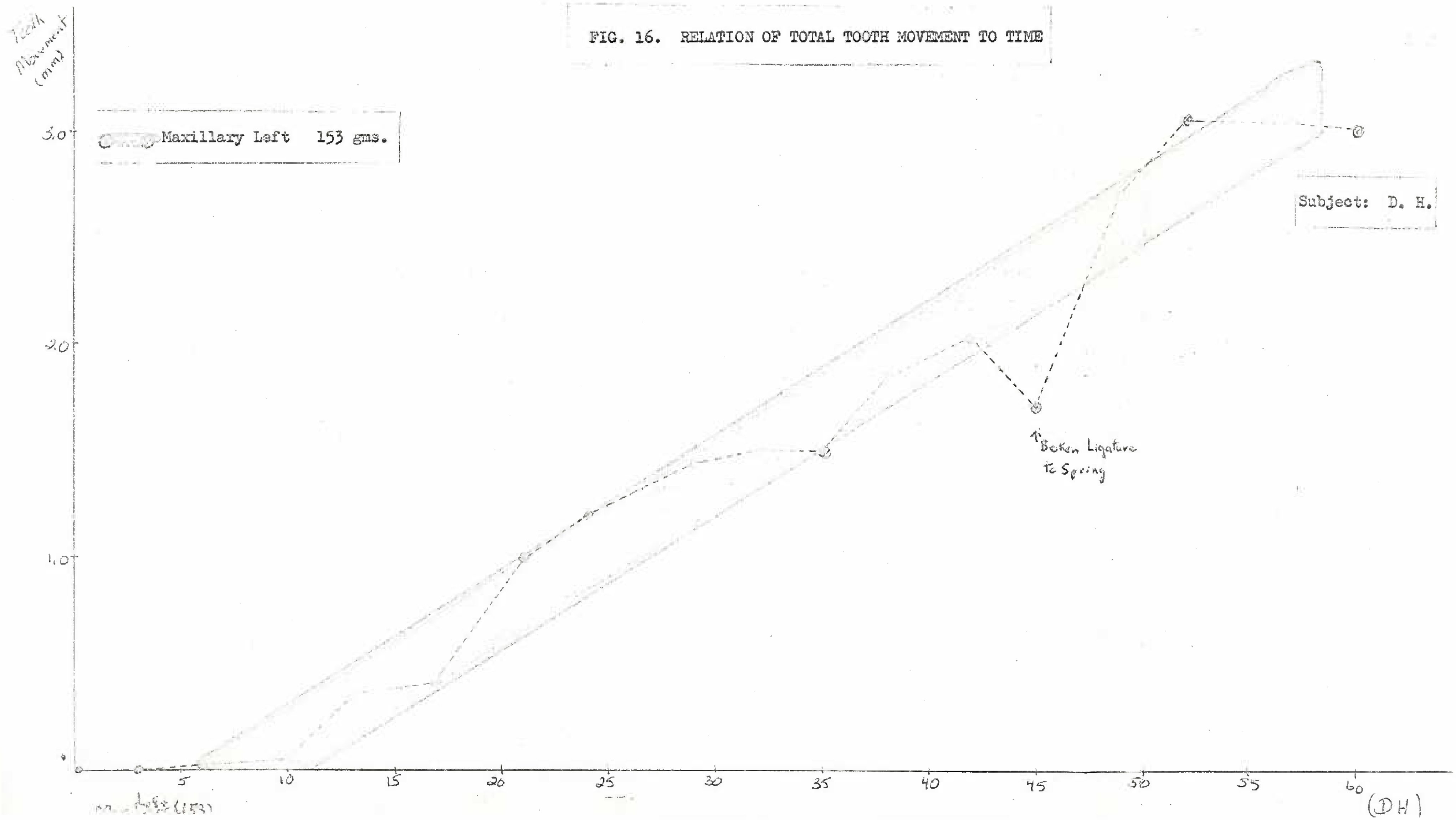


FIG. 16. RELATION OF TOTAL TOOTH MOVEMENT TO TIME

FIG. 17. RELATION OF TOTAL TOOTH MOVEMENT TO TIME

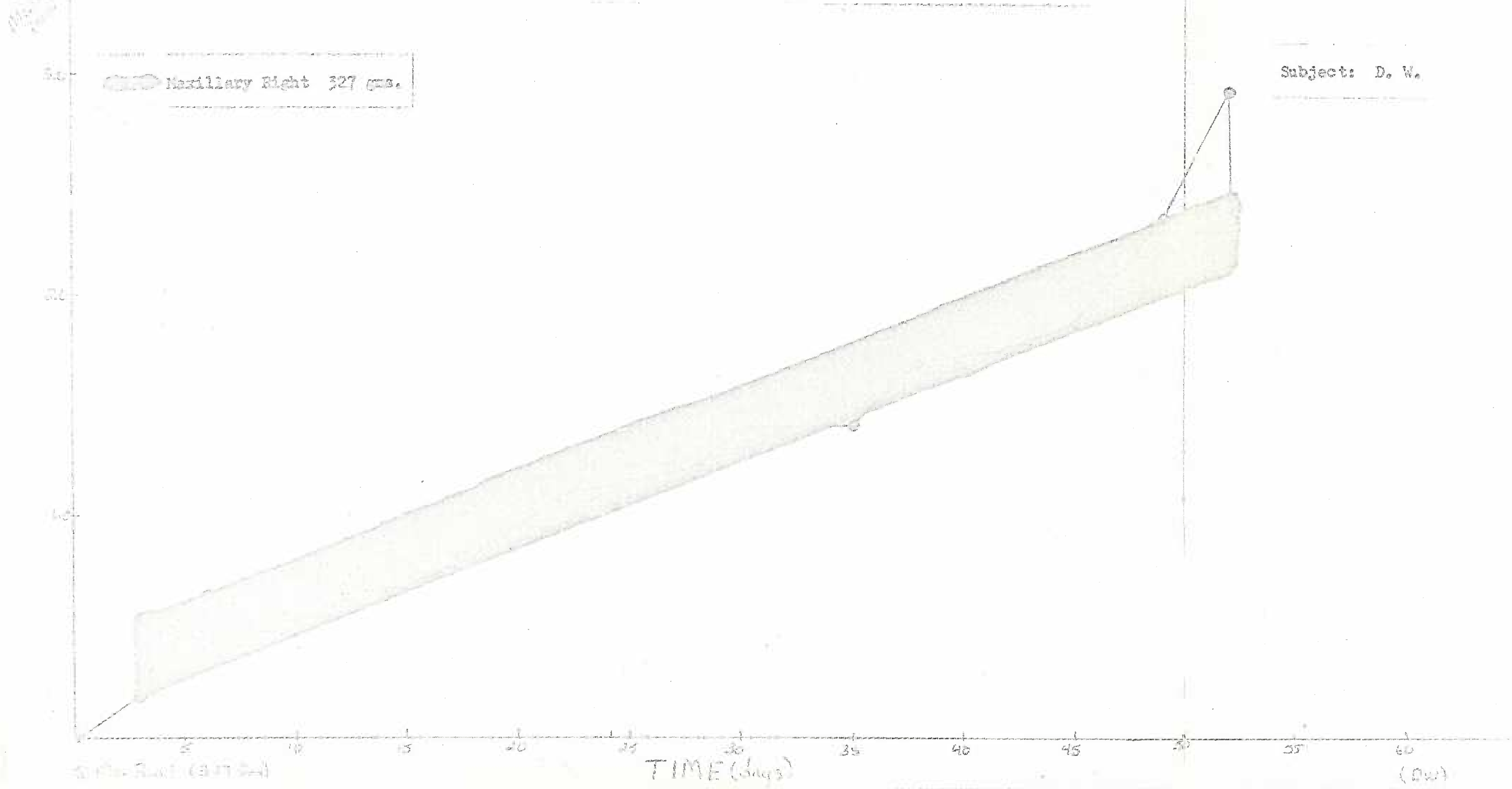


FIG. 18. RELATION OF TOTAL TOOTH MOVEMENT TO TIME