Original Article

Testing Force Systems and Biomechanics—Measured Tooth Movements from Differential Moment Closing Loops

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Abstract: Orthodontic tooth movement can be compared to a stimulus-response model, where the stimulus is the applied force system and the response is the resulting tooth movement. Although the principles of mechanics have been applied to orthodontic appliance design, the expression of treatment responses to the force systems is less well known. The purpose of this study was to compare measured tooth movements with the theoretical force system exerted by differential moment closing loops. Sixteen subjects requiring maximum posterior anchorage control were selected to participate in this prospective investigation. T-loop springs designed to deliver a differential moment-to-force ratio to the posterior vs the anterior teeth were used. Initial cephalometric radiographs were taken with special devices attached to the molar and canine teeth to allow precise identification. Immediately after the radiograph, the T-loop archwires were inserted and activated. After an observation period of approximately 90 days, the wires were removed, devices reinserted into the molars and canines, and a second cephalometric radiograph was obtained. Superimposition techniques were used to compare the actual tooth movements. The results showed tooth movements consistent with the prescribed force system. The anterior teeth, as represented by the canines, were retracted an average of 1.73 mm, whereas the posterior anchorage (molars) moved mesially only 0.50 mm. Furthermore, the canine teeth exhibited tipping or translation, and the molars showed mesial root movement. The variability of the treatment response as a function of the stimulus (appliance design), response (biological variation), and measurement technique was described. (*Angle Orthod* 2003;73:270–280.)

Key Words: Anchorage; Orthodontic appliances; Biomechanics; Tooth movement; Treatment outcomes

INTRODUCTION

The excellent results of well-treated patients exemplify the proficiency and potential of skilled orthodontists. The quality of their outcomes demonstrates the art of orthodontics. To make excellent treatment results routine, the science of orthodontics seeks to explain the field's objective foundations. Without this objective knowledge, the ability to deliver predictable care approaches the realm of the mystical. Therefore, studies of the efficacy and effectiveness of patient care are crucial to the specialty's continued advancement.

Clinical orthodontics provides multiple obstacles to the unbiased analysis of treatment results. Although the randomized clinical trial represents the gold standard for medicine, it presents many difficulties as applied to orthodontic therapy.[1,2] In addition, the specific needs of individual patients and talents of their orthodontists combine to further blur the explicit and direct relationship between treatment techniques and the final outcome. Rather than comparing general treatment options or techniques, Baumrind advocates a more detailed and specific approach to the analysis of orthodontic therapy, one that focuses on the midcourse adjustments made during the progress of care.[3]

It is the application of mechanical forces to teeth and their support structures that leads to tooth movement. The laws of statics and dynamics precisely define the relationships between force and movement. Forces produce acceleration, thus movement. The nature of the motion of the body can be accurately predicted by analyzing the applied force system acting on that body. Biomechanics examines the relationship of mechanical forces with biological systems. In free space, bodies move in accordance with the forces acting on them. In orthodontics, the relationship may be less direct. The applied forces are stimulus acting on a biological system. The mechanical forces must be transduced into biological activity before tooth movement. Depending on the biological response, the clinically observable tooth movement may be dependent on factors beyond the applied forces alone.

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The field of biomechanics has been mindfully applied to the principles of orthodontic appliance design. The literature contains many extensive descriptions of the static force systems produced by orthodontic spring and wire activations.[4–14] Empirical and clinical evidence support an applied biomechanical approach to developing effective orthodontic devices.[15,16] A biomechanical emphasis in orthodontic care implies a predictable stimulus-response model, ie, the teeth move in a manner consistent with the forces and moments delivered by the wires, springs, or elastics. Although this model is supported by a sincere and logical rationale, its integrity remains to be validated. Equally important, the alternative to this model (that tooth movement is independent of the force system) would suggest a nearly metaphysical capacity on the part of the clinician to select and activate appliances during orthodontic care to achieve desired results.

The relationship between the appliance-delivered stimulus and the biological response warrants objective documentation. Analogous to the dose-response model of medicine, a stimulus-response model is useful in determining the effectiveness of orthodontic springs. Because orthodontic space closure typically involves substantial tooth displacement, it invites study of the effects of force system delivery and treatment response. From a clinical perspective, the delivery of appropriate force systems during space closure aims at efficient tooth movements and maintenance of anchorage. From the perspective of a force system delivery approach, the evaluation of predetermined and preferential tooth movements during space closure will aid in testing a stimulus-response model of orthodontic treatment. Specifically, differential moment strategies for anchorage control hinge on the assumption of a force system stimulus-response model. A clinical study using qualitative force systems during extraction space closure will serve as an ideal arena for evaluating whether biomechanics works the way it is supposed to work.

The objective was to study the stimulus-response model of differential moment strategies. Because this strategy relies on the unequal application of forces and moments to the anterior and posterior teeth, one would expect unequal movements, both in the magnitude and in the nature of the movement.[17] The present study investigated the hypothesis that the static force system produced by differential moment space closure springs specifically determines the resultant tooth movement. The purpose of this experiment was to determine the response of the dentition to a qualitatively determinant force system under a single activation of a retraction spring designed to deliver differential moments to the posterior and anterior dentition. A single activation allowed the description of the horizontal, vertical, and angular responses to the stimulus while eliminating confounding treatment variables occurring from subsequent treatment.

MATERIALS AND METHODS

Sixteen subjects meeting the inclusion criteria were recruited from the patient pool available to the University of Connecticut School of Dental Medicine Orthodontic Clinic. The mean age of the subjects at the start of observation was 16.8 years with a range of 10.5 to 44 years. Thirteen of the 16 subjects were female. For inclusion in the study, each subject required bilateral extraction of upper first premolars (with or without extraction of mandibular teeth) and maximum posterior anchorage during space closure as prescribed by the orthodontic treatment plan. Additionally, all patients were required to have permanent maxillary incisors, canines, and first molars with normal periodontal support. Subjects were excluded from participation for the following reasons: (1) estimated periodontal attachment loss exceeded 25% of the root length; (2) estimated root resorption or remaining root formation exceeded three mm; (3) report of any systemic endocrine disorders; and (4) failure to provide oral and written consent for participation.

All teeth were bonded with 0.022 inch by 0.028 inch preadjusted brackets (Roth prescription). Once extractions had been performed, soft tissue healing was allowed for a period of two to four weeks. After initial healing, a passive 0.032 inch Beta-titanium transpalatal arch was fitted to the maxillary first molars to limit mesiopalatal rotations. A 0.017 inch $\times$ 0.025 inch Beta-titanium (CNA, Ortho-Organizers, San Marcos, CA) continuous T-loop archwire, as described by Burstone,[6] Burstone and Koenig,[18] and Kuhlberg and Burstone,[11] was used for en masse space closure (anterior retraction).

Each closing loop was prefabricated based on the template reported by Kuhlberg and Burstone.[11] The loops were symmetrically gabled (preactivated) to 60° to provide adequate moment delivery (Figure 1). To develop the moment differential, the closing loops were asymmetrically placed (off-centered) by two mm within the interbracket dimension of the canine and molar (Figure 2). Additionally, a one-mm apical step was placed in the distal section of the wire to accommodate insertion in an auxiliary molar tube. Each spring was over bent to remove residual stresses and trial activated a minimum of four times to ensure dimensional stability. Any resulting distortions were corrected before placement. On insertion, each closing loop was activated six mm. Activation levels of the springs were confirmed with Vernier calipers. Once activated, the loops were adjusted for patient comfort but were left otherwise undisturbed during the observation period. An observation period of three months was planned to allow full expression of the force system delivered by the spring under a single activation.

T-loop force system

Several investigations of the T-loop spring force system have been reported.[6,8,11] Figure 3 schematizes the general

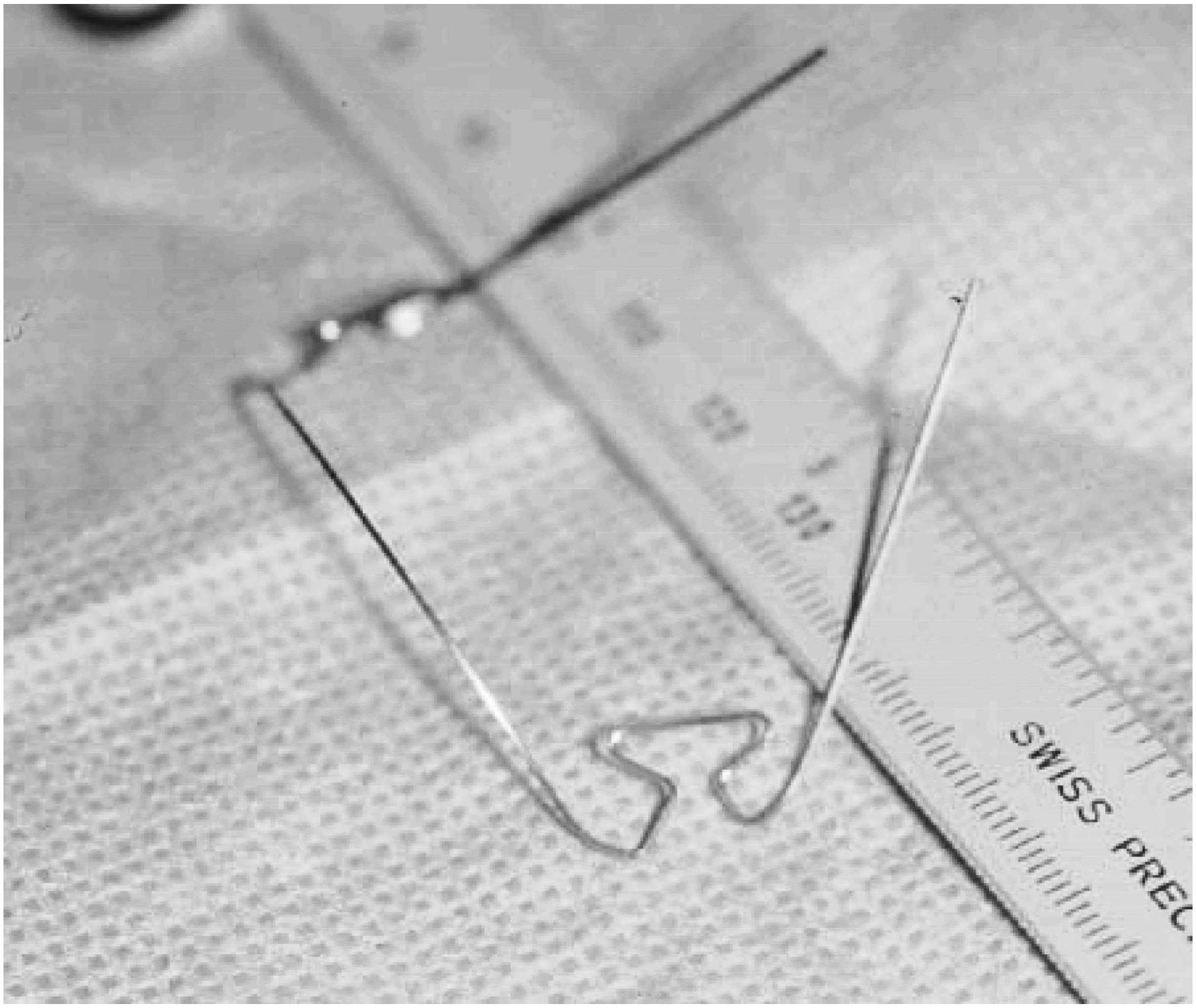

FIGURE 1. Beta-Titanium continuous T-loop archwire (0.017 inches × 0.025 inches). The anterior and posterior sections of the wire are each preactivated to 60° to provide sufficient moment magnitudes. Note that the loop has been opened-up for accurate neutral positioning (horizontal force = 0 g at 0 mm of activation) when the wire is inserted before activation.

force system of the space closure spring. For anchorage control, a larger moment is applied to the posterior teeth relative to the anterior teeth. A two-mm off-center position produces a posterior moment approximately twice the magnitude of the anterior moment. The expected tooth movements of such a force system are also shown and listed in Figure 3. Based on the applied force system, the expected movements of the teeth were (1) anterior retraction and intrusion, specifically controlled tipping and (2) posterior/molar mesial root movement and extrusion without mesial crown movement.

Recording technique

Lateral cephalograms were obtained immediately before spring insertion and activation, as well as at the end of the observation period. All radiographs were taken with the same cephalostat (B. F. Wehmer) that produces a 12% image magnification. To reduce error associated with landmark detection,[19] a tooth positional locating device (TPLD) was fabricated from sections of stainless steel wire that were attached to the maxillary first molars, canines, and a single central incisor before film exposure. These devices aided in precisely locating the before and after treatment cephalometric positions of the proximate teeth (Figure 4).

Superimposition method and measurement technique

Once the before (T1) and after (T2) radiograph records were collected at the end of the observation period, the maxillary and cranial base structures were traced on acetate using 0.5-mm drafting pencils. All bilateral landmarks were bisected to reduce the images to the midsagittal plane. Functional occlusal planes as described by Johnston[20] were traced from each film. The structures of the maxillae were then superimposed ignoring dental changes. The superimposition technique was modeled after the structural method

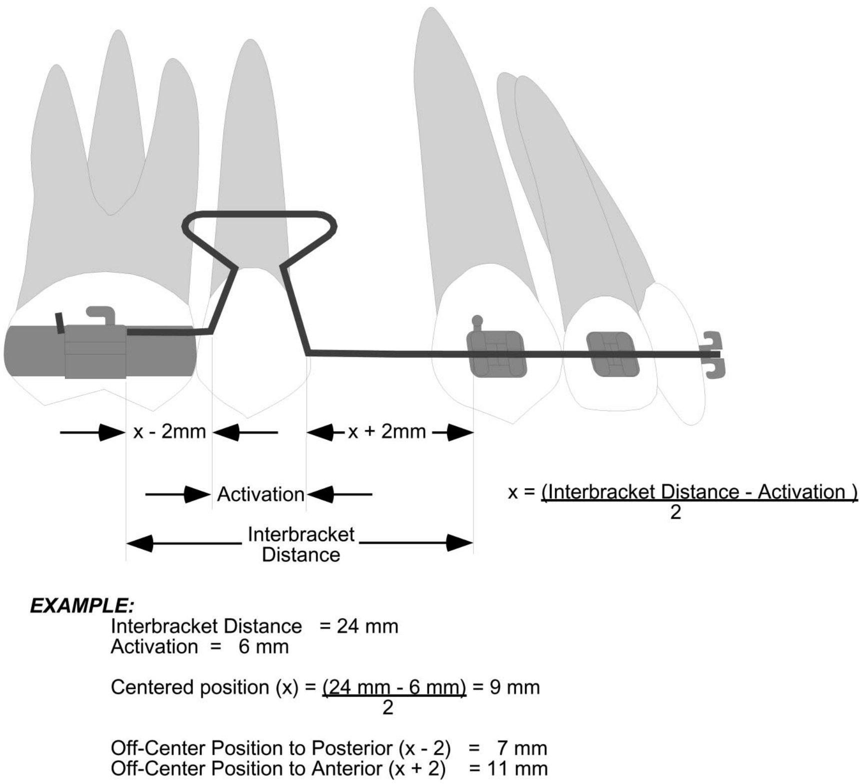

FIGURE 2. Schematic diagram of procedure for asymmetric loop positioning and activation.

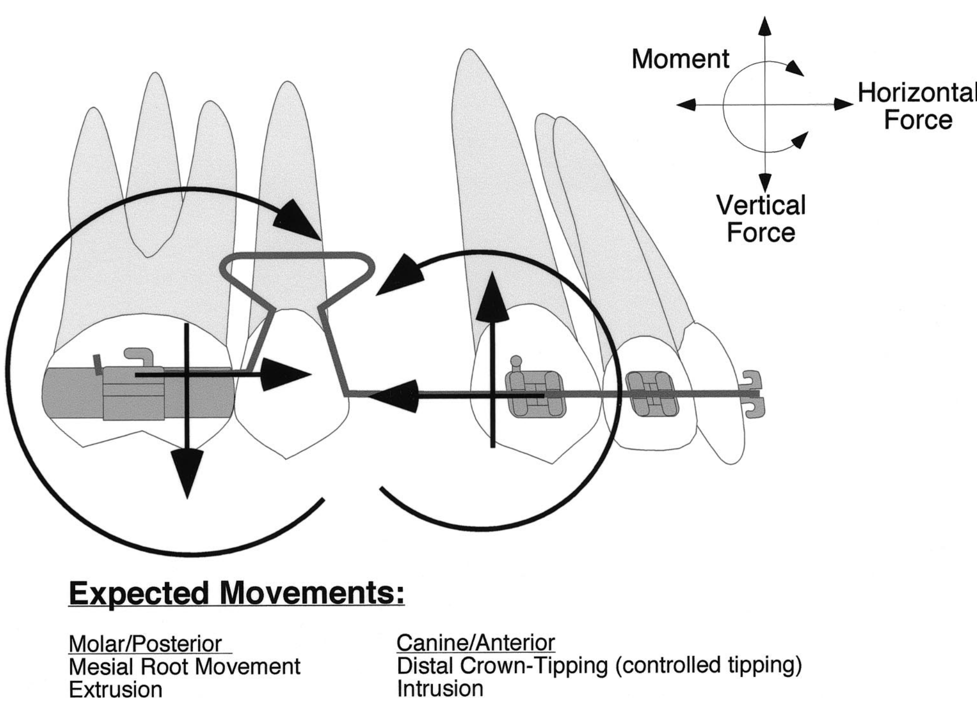

FIGURE 3. Force system and expected movements from differential moment closing loops. Arrow size reflects only direction, not magnitude.

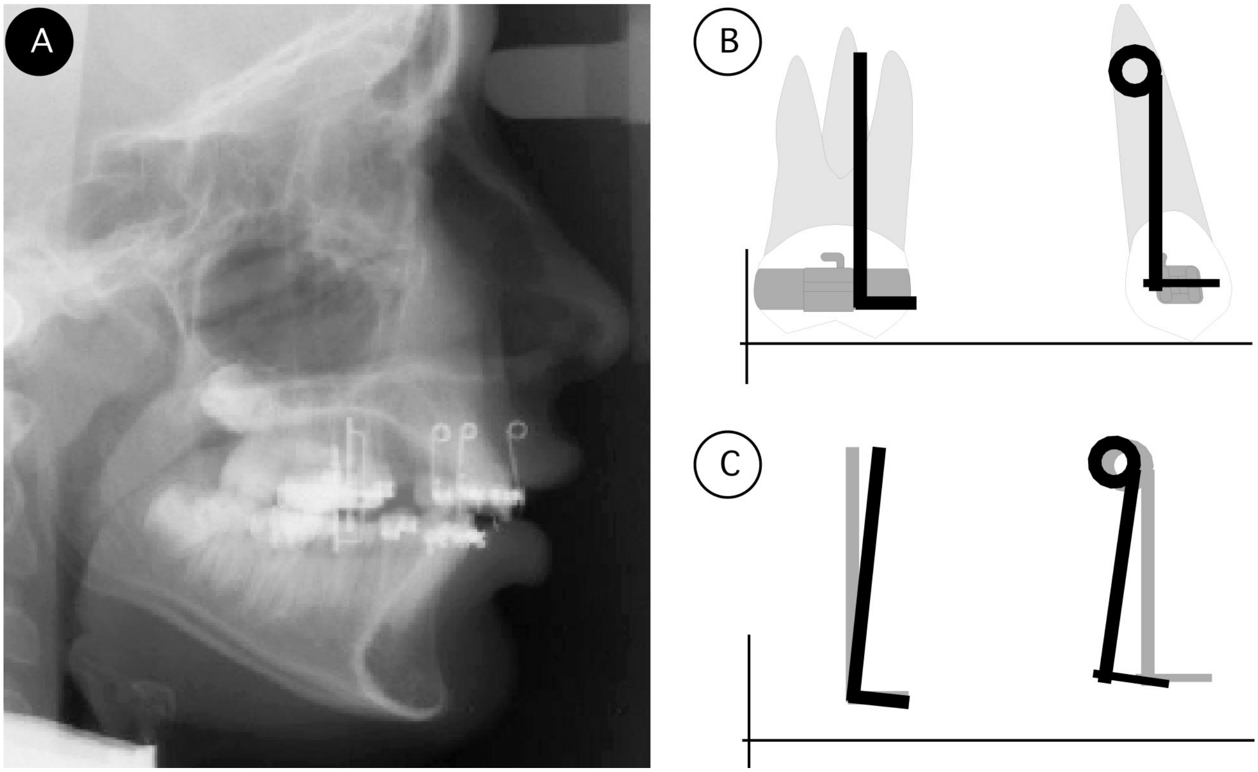

FIGURE 4. Example of tooth position locating devices. (A) Example of lateral cephalometric radiograph with devices in place. (B) Illustration of devices inserted into molar and canine. (C) Illustration of superimposed devices reflecting changes in tooth position.

proposed by Bjork and Skieller.[21] After superimposition, a mean functional occlusal plane (MFOP), as described by Johnston,[20] was chosen as a horizontal reference plane. At 90° to the MFOP, a vertical reference plane that intersected common posterior borders of the tracings of the two maxillae was drawn. From this coordinate system, dental changes were assessed.

All tooth positions were represented by the traced image of the TPLDs. Figure 5 illustrates the technique for the horizontal, vertical, and angular measurements of tooth position change for each subject.

Data and error analysis

Data for bilateral molar and canine movements were combined so that a total of 32 observations of each variable was assessed among the sample of 16 subjects. Descriptive statistics of means, standard deviations, and ranges were computed for horizontal, vertical, and angular dental changes. Paired one-tail *t*-tests were used to test mean differences between intrasubject molar and canine horizontal, vertical, and angular displacements. Alpha levels were set at 0.05; mean differences were considered significant at $P < .05$.

The error standard deviation between original and repeat measures of five randomly selected film series was determined using Dahlberg's formula.

$$\mathrm{SD}_{\mathrm{error}} = \sqrt{\sum \frac{D^2}{2n}}$$

RESULTS

Observation period

On average, the subjects underwent observed space closure for 99 days (SD = 36 days). A number of subjects, however, were observed for greater or lesser time periods with a range of 55 to 198 days. In general, reduction of the observation period occurred when anchorage requirements changed during space closure or the treatment outcome deviated from the original treatment objectives, including the failure to maintain acceptable oral health and hygiene.

Measurement error

The error standard deviations for six repeated measurements from five randomly selected two-film series are given in Table 1. Each of series was retraced and resuperimposed by a single operator. These values approximate the precision of the measuring instruments in which linear and angular measurements were interpolated to the nearest 0.25 mm and 1.0°, respectively.

FIGURE 5. Schematic illustration of superimposition method. The black lines represent structures as recorded at the start of the observation period and the gray lines represent those at the end of the observation period. All bilateral landmarks (eg, zygomatic buttresses) were reduced to the midsagittal plane. Maxillae were superimposed using Bjork and Skieller's structural technique[21] in which the anterior borders of the zygomatic processes of the maxilla were aligned. When the shadows of the processes were difficult to discern on the radiograph, internal trabecular details of the maxillae were aligned to aid superimposition.[20] Additionally, the cranial bases were traced to help eliminate gross rotational errors when aligning the tracings. The tracings of the TPLDs were calibrated to maintain equal dimensions before and after observation. The horizontal reference plane represents the MFOP. The vertical reference plane was drawn 90° to the MFOP and intersects common posterior borders of the superimposed maxillae. All linear and angular dental changes, as represented by the TPLD images, were assessed relative to the reference planes.

TABLE 1. Measurement Error: Error Standard Deviations

Molar AP	Canine AP	Molar Vert	Canine Vert	Molar Ang	Canine Ang
0.40 mm	0.42 mm	0.41 mm	0.75 mm	1.2°	1.5°

Total space closure

Figure 6 shows the distribution of total space closure among the samples. On average, 2.1 mm (SD = 1.06 mm) of space closure was observed over the range of observation periods. Two-thirds of the premolar extraction spaces were closed in excess of 1.5 mm, and nearly half of them experienced greater than two mm of space closure. The distribution of the sample, however, was skewed because of two data points (highlighted as gray in Figure 6): one premolar extraction space closed by only 0.5 mm and another actually *opened* 0.5 mm. These outlining data points derived from a single subject were suggestive of some error in appliance delivery or distortion of the appliance after delivery. Nevertheless, the possibly erroneous data were included for analysis because they presumably represent normal clinical conditions.

Anchorage maintenance and anterior retraction

Because of the disparity in observation periods, the data were normalized to 90 days allowing like comparisons of tooth displacements over time.

$$\text{normalized value (mm)} = \frac{\text{measured movement (mm)} \times 90 \text{ (days)}}{\text{observation period (days)}}$$

The mean mesial displacement of the maxillary first molars was 0.50 ± 0.90 mm SD (Table 2). Thirteen of the 32 observed molars (41% of sample) maintained their position or actually tipped as much as two mm *away* from the extraction site. Twelve molars (38% of sample), however, moved mesially by 0.5 mm, and 1.7 mm to 2.5 mm of anteroposterior anchorage loss was observed for the remaining seven molars (20% of sample).

Conversely, the canines (representing all six anterior teeth) showed a mean retraction of 1.73 ± 1.36 mm SD (Table 2). Figure 7 illustrates the distribution of anterior retraction and posterior anchorage loss in millimeters per month of space closure. Two distinct distributions for the movement of the respective teeth are apparent. The mean tooth movements were significantly different at $P < .0001$ (paired t-test, $t = 4.33$).

Vertical response

The mean vertical change of the molars was 0.08 mm in an *intrusive* direction (SD = one mm). The mean vertical change of the canines was similar, with a mean intrusion of 0.11 ± 0.81 mm SD. Although the *mean* vertical changes were effectively zero, a substantial range variation was seen in the vertical displacements of the canine and the molar teeth (Table 2). Seventy-five percent of the canines showed zero to two mm of intrusion. Conversely, 66% of the molars demonstrated zero to two mm of extrusion. Additionally, the distributions shown in Figure 8 follow a nearly normal curve, suggestive of random variation or the possibility of measurement error.

Angular response

Figure 9 shows the distribution of the measurements of the angular changes in position for the canine and molar teeth. The angular changes for the canines are centered about a mean of −0.4°, indicating average translation for the sample. The mean molar angular change was 5.3° of mesial root movement. Both the canine and molars exhib-

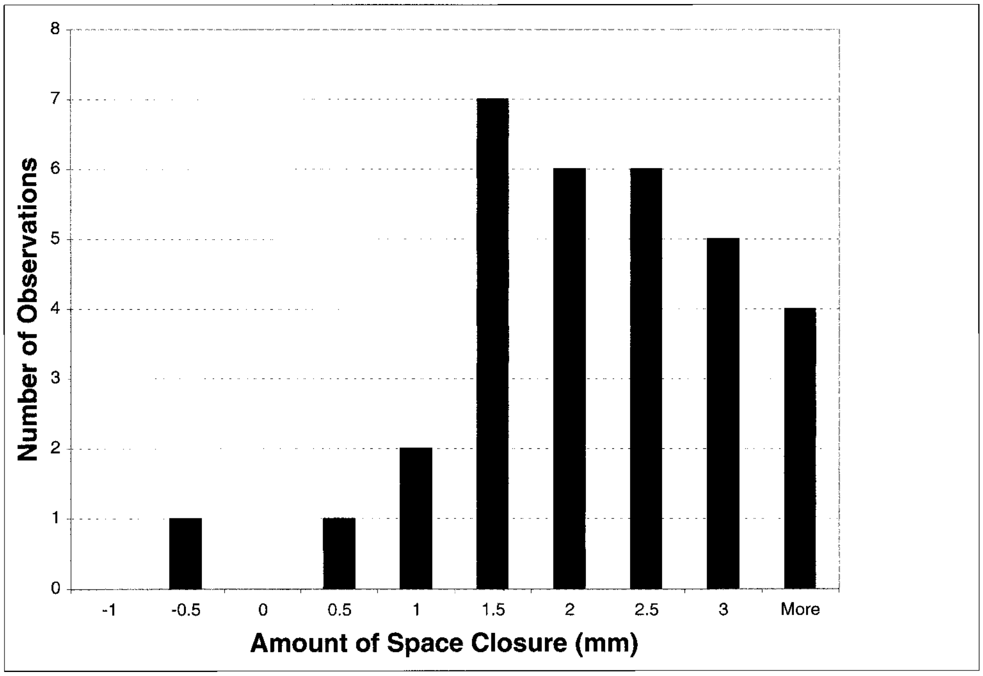

FIGURE 6. Distribution of total space closure. Mean space closure = 2.1 mm (SD = 1.06 mm). An excess of one mm of space closure was observed in 88% of extraction spaces. Sixty-six percent of the observed spaces closed in excess of 1.5 mm and 47% closed in excess of two mm.

TABLE 2. Descriptive Statistics of Measured Movements

Variable	Min	Mean (SD)	Max
Molar AP (mm)	2.02[a]	0.50 (0.90)	−1.73
Canine AP (mm)	−0.8	1.73 (1.36)	3.7
Molar vertical (mm)	−3.21[b]	−0.08 (1.0)	2.41
Canine vertical (mm)	−2.50[b]	0.11 (0.81)	4.02
Molar angular (mm)	−6.43[c]	5.25 (4.31)	12.86
Canine angular (degrees)	−9.6[c]	0.4 (5.2)	8.8

[a] Negative values = anchorage loss, positive values = anchorage gain, i.e. 2.02 mm of tip back.

[b] Negative values = intrusion, positive values = extrusion.

[c] Negative values = crown tipping, positive values = root movement.

ited a fair degree of variability of treatment response (Table 2). The angular change of the canines had a standard deviation of 5.25° with a range of 10° of clockwise rotation (ie, distal tipping) to 9° of counterclockwise rotation (ie, root correction). Like the canine angular data, the molars exhibited variation (SD = 4.3°), with a range of 6° of counterclockwise rotation (tipping) to 13° of clockwise rotation (root movement).

The variation in the amount of angular change in tooth movement may be associated with the duration of the observation period. Because the anterior moment-to-force ratio (M/F), like the posterior M/F, progressively increases during deactivation of the spring it serves to reason that a changing center of rotation would be a function of time.[22] Therefore, the canine and molar angular changes were correlated with the observation times. The correlation coefficients for both the canine and the molar were low (canine, $R = 0.15$; molar, $R = 0.03$).

DISCUSSION

This investigation aimed to quantify the actual tooth movements that resulted from the single activation of a closing loop designed to preserve posterior anchorage by a differential moment strategy. This approach focuses the analysis of orthodontic treatment on the clinical response of a specific treatment action. By limiting the study this way, the clinical effects of the prescribed force system can be more carefully evaluated. The question was not, do T-loops work for anchorage control? Rather, this study was directed at the question—Do the teeth respond in a manner consistent with the force system stimulus?

The results of this study generally indicate that the clinical responses are consistent with the applied force system. Figure 10 depicts the mean anteroposterior tooth movements, as measured at the occlusal plane, for the canine and molar teeth during the observation period. Canine retraction exceeded mesial molar movement. More important, the axial inclination changes, ie, controlled tipping-translation for the canine and anterior teeth and root movement for the molar teeth, follow the applied force system.

Interestingly, the narrow tolerances and high repeatability common to experiments in physics or mechanics were not found in the present investigation. Rather, these results reveal a broader distribution of the measured observations. This clinical study bridges the gap between the laboratory

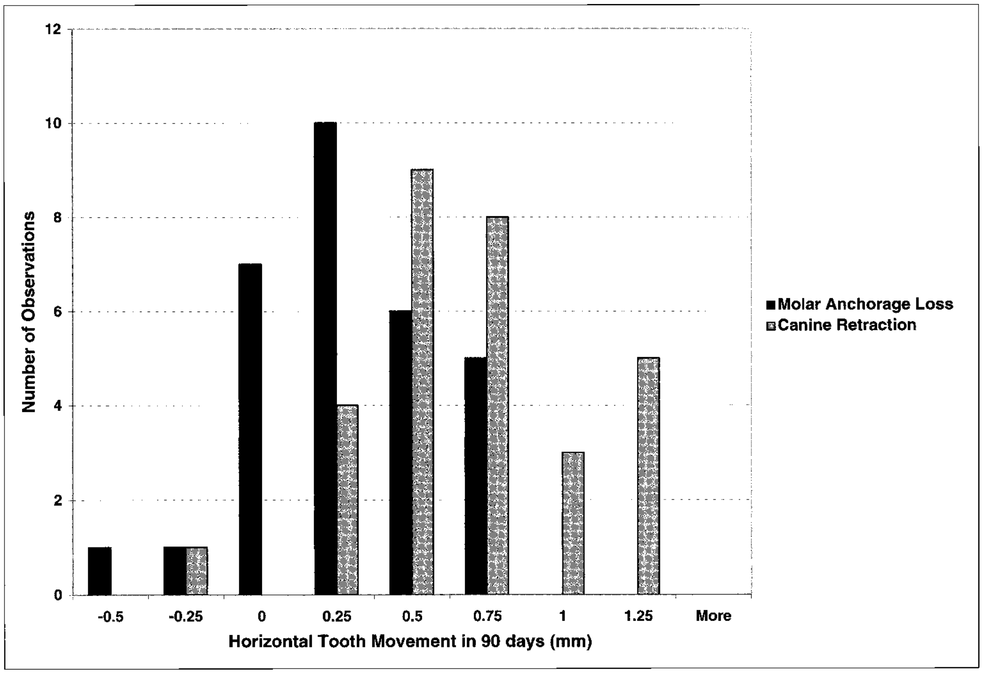

FIGURE 7. Distribution of horizontal tooth movement as molar anchorage loss and canine retraction, normalized to 90 days. The mean normalized canine retraction was 1.73 mm, whereas molar anchorage loss was 0.50 mm.

bench-top, where the investigator can maintain exceptional levels of control, and the clinical-biological realm, where variability is frequently the rule rather than the exception. Although the data suggest that the response was consistent with the stimulus, there was a degree of variation that warrants discussion. The observed variation may be partly caused by one or all of the following factors: (1) a stimulus that differed from that which was intended (clinical error); (2) a variability in biologic response; or (3) variability of the measurement techniques.

Variation as a function of the stimulus

Although all the springs were bent by hand using specially designed pliers (Modified Nance loop pliers, Dentronix, Penn) to replicate the dimensions of the template, previous data of the spring shows that even with careful bending, a different force system may result. Burstone[6] reported that the spring is unforgiving of fabrication error and that the force system may suffer as a result. Additionally, if any of the springs reflected outlying standard deviations of their constituent force components, as reported by Kuhlberg and Burstone,[11] a force system distinctly different from the objective may have been applied. More likely, however, if altered force systems were present, they were probably due to two factors. First, several patients required intraoral adjustment of the spring to relieve impingement on the buccal gingiva. This was achieved by applying a third-order bend just mesial to the auxiliary buccal tube of the molar. Although care was taken to not alter the second-order preactivation (gabling) of the spring, distortion was quite possible. Second, the springs were subject to the demands of the oral environment, which may have caused spring distortion and a change in the force system.

In this study a continuous spring rather than the segmental spring was used. The rationale for using a continuous spring was threefold. First, the continuous spring allowed the use of this technique among a sample of patients who were being seen by several providers. These patients may or may not have had bonding of the special attachments necessary for a segmental spring. Second, the original design of the T-loop spring was based on the segmental technique in which heavy, passive individual wire sections are bound to the anterior and posterior teeth before space closure.[6] The alternative use of the continuous arch beta-titanium spring provided sufficient flexibility to allow its use before complete alignment of the anterior teeth. Finally, the continuous-wire spring is more typical of conventional clinical practice and is consistent with the force system–driven mechanics of the segmental arch technique.

Nevertheless, there are some inherent problems with the use of a continuous arch, the most notable being the ‘‘play’’ that occurs between a 0.017 inch $\times$ 0.025 inch cross-section archwire and a 0.022 inch $\times$ 0.028 inch bracket. This slop allows for some deactivation of the spring before any moment delivery expression at the incisors. It will fail to deliver moments to the incisors until second-order movement of the canines has occurred (simple trigonometry suggests that the anterior limits of the archwire must rotate approximately 13° before a couple is applied at the incisor bracket). Additionally, as Burstone[6] has suggested, the low-

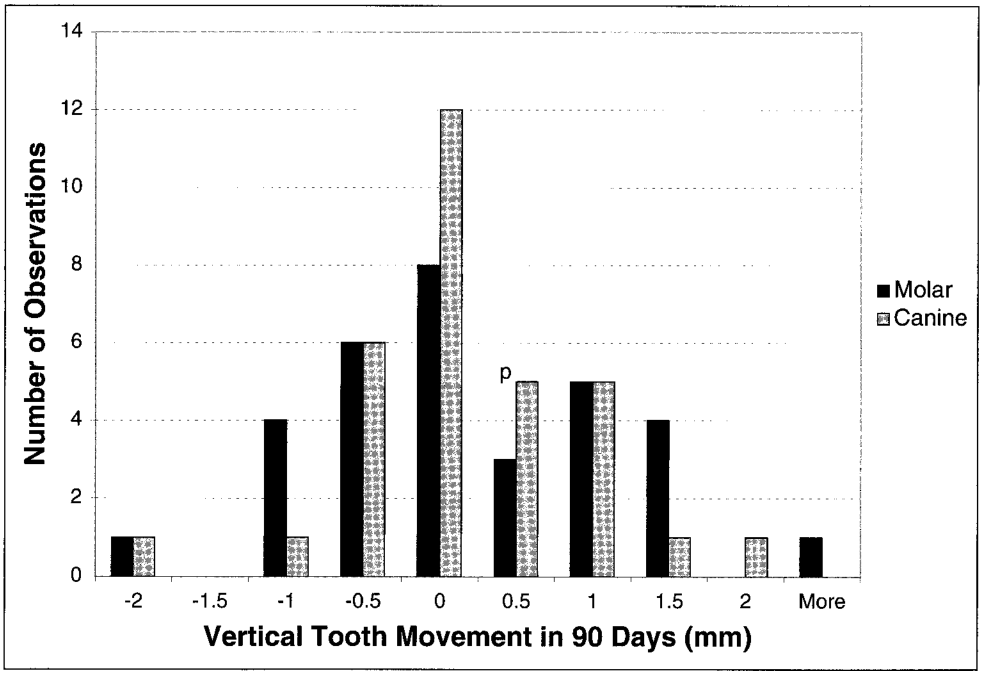

FIGURE 8. Distributions of vertical tooth movement for molar and canine teeth (90 days normalized). Negative values indicate intrusion, positive values indicate extrusion.

er modulus of beta titanium relative to steel, in combination with wire-bracket interplay, may allow individual centers of rotation of the incisors and thus obscure the quantitative evaluation of the force ''stimulus.'' For this reason, the incisor movement was excluded from the data analysis. Alternatively, the canines served the purpose of representing the anterior teeth for data collection because the moment delivery to the canines was instantaneous upon deactivation of the spring.

Variation as a function of biologic factors

Biologic variation may also be considered. Studies of tooth displacement and space closure using human[23–25] and animal[26] models report substantial variability that could not be explained by the force system and thus implicate individual biologic factors, for example—cellular turnover rates, vascularity, or bone density. Moreover, the variation may represent the time points of observations relative to the phasic patterns or kinetics of tooth displacement.

As classically described, the kinetics of tooth movement follows three phases: initial, lag, and postlag. Data derived from clinical or animal studies may reflect temporal differences based on the time points of observations. The inter- or intrasubject differences may reflect kinetics rather than differences in stimuli. Additionally, in a study using a rat model, Keeling et al[27] have documented tandem patterns of bone remodeling over time, represented by activation, resorption, reversal, and formation. These cyclic waves of remodeling events may be occurring at different time points during clinical observation and thus may reflect the variability documented in the present and other studies.

Additionally, Isaacson et al[28] argue that the interpretation of data relating tooth displacement to orthodontic force systems is clouded by the fact that stress distributions are in flux because of constantly changing centers of rotation of the tooth or teeth. Constantly changing centers of rotation may not be observed during studies, such as this, that use extended observation intervals. For example, tooth movements that may be ultimately perceived as translation have more than likely gone through courses of tipping and root correction. In this way, description of tooth movement based on a static force system represents an average of movements occurring over time.

Variation as a function of the measurement technique

Clearly, cephalometric measurement is fraught with potential error because of problems with magnification, projection, landmark identification,[19] and superimposition.[29] Because of this potential error, devices (TPLDs) were used to enhance the precision and the accuracy of identifying tooth positions related to treatment. Any changes, however, in head orientation during radiograph exposure at the two time points may have adversely affected the comparability of the two head films and acted as confounding error. Given alterations of the subjects' head positions in the frontal plane, the varying vertical projections of the TPLDs may account for the normal distributions of the vertical data.

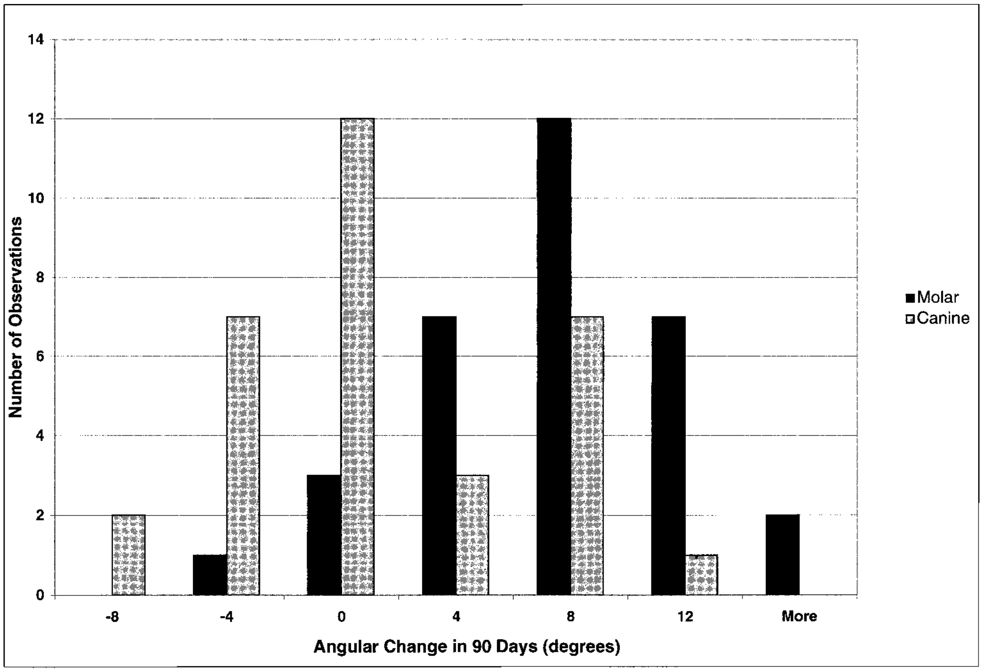

FIGURE 9. Distributions of angular change or axial inclination change for molar and canine teeth. Positive values indicate clockwise rotation (mesial root movement for the molar, distal crown tipping for the canine), negative values indicate counterclockwise rotation.

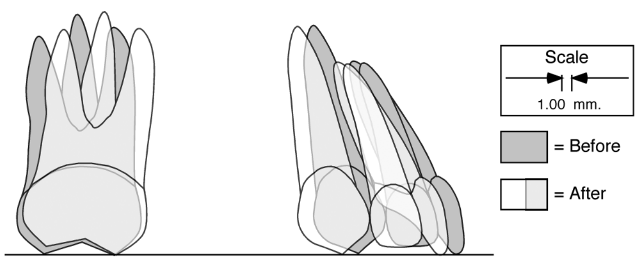

FIGURE 10. Graphic depiction of the mean tooth movements for the canine and molar teeth during the observation period. Note the preferential and controlled retraction of the six anterior teeth with little concomitant anchorage loss, as assessed at the occlusal plane. The ultimate angular changes are representative of the expression of the force system.

Additionally, rotations in the coronal plane may reflect the range of recorded horizontal changes. Kantor et al[30] reported that patient positioning is an insignificant factor contributing to measurement error in cephalometric techniques. However, using subtraction radiography techniques they found a mean absolute variability of 0.74 mm to 0.91 mm for four maxillary landmarks due to patient positioning. This range of method error could be a contributor to the variation found in the present study.

Nevertheless, as indicated by Table 1, the standard deviation of the error between repeated measures was well within clinical limits. With the exception of the canine vertical response data, the error values are less than 0.50 mm. This magnitude of error is certainly difficult to detect at a clinical level. Moreover, the error suggests that careful superimposition techniques, using positional locating devices, may be a reliable method in determining treatment effects.

The use of a small sample size tends to require large differences between means to demonstrate clinical significance and reduce Type II errors (failure to reject a false null hypothesis or false negative errors). Therefore, the fact that a small sample (ie, low power) detected differences great enough to reject the null hypothesis, notwithstanding the clinical significance of the data makes for a compelling argument in support of differential moment strategies. Additionally, as suggested by Baumrind,[3] the use of a small sample may offer increased inferential value to the clinician because it relates to the predictive power of a given response. The low values obtained from the error analysis, moreover, validate the recording and superimposition methods.

Previous studies have reported that differential moment strategies effectively maintain posterior anchorage. These previous efforts analyzed the clinical outcomes in total. These investigators used alternative techniques but clearly demonstrated the utility of differential moment approaches to anchorage control. The limitation of these clinical studies is the confounding effects of the overall treatment. The necessary and individually specified adjustments during treatment for each patient promoted successful treatment results but clouded a focused analysis on the effects of the differential force system. Newton's laws of motion define the limits of mechanics. The third law, the law of action and reaction, states that for every action there is an equal and opposite reaction. This rule succinctly describes the problem of anchorage control; the distal retraction force necessarily is opposed by a mesial protraction force acting on the anchor unit. The clinician must determine a means of overcoming this natural state. The differential moment strategy attempts to reduce or eliminate compliance-dependent options, such as intermaxillary elastics or headgear. But this study illuminates what should be a key expectation of a differential moment technique—the anchor teeth do move, but the nature (high moment-to-force ratio) of the applied force system minimizes the mesial anchorage loss.

SUMMARY AND CONCLUSIONS

A nonrandomized prospective clinical trial was conducted to investigate a force system stimulus–tooth movement response model. Sixteen patients undergoing en masse space closure requiring posterior anchorage served as subjects. T-loop retraction springs delivering qualitative differential moment force systems were used as the stimulus. A carefully designed cephalometric approach was used to assess the response. The findings suggest that the force system does predict the tooth movement response. The physics of the force system are predictive of the resultant dental displacements despite a biologic environment. Proposed sources of the variability are presumed to be a product of both clinical and measurement errors. The significance of this investigation is the documentation of a short-term response to a qualitative stimulus without confounding effects of continued treatment. As Baumrind[3] suggests, this method may be preferable to studies conducted during a comprehensive course of treatment. The documentation of responses occurring as a result of relatively discrete stimuli enhance orthodontists' ability to make reasonably predictable in-course corrections and carefully refine their appliance adjustments to achieve specific treatment objectives.

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