Original Article

Human tooth movement by continuous high and low stresses

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ABSTRACT

Objective: To compare three-dimensional tooth movements resulting from relatively higher and lower stresses in a split-mouth design.

Materials and Methods: Eight volunteers whose maxillary first premolars were removed for orthodontic treatment participated. Each subject's maxillary canines were retracted by randomly assigned constant stresses of 78 kPa and 4 kPa via segmental mechanics. Dental casts depicting 8–10 visits per subject over 84 days and a three-axis microscope were used to measure movements serially. Descriptive statistics and mixed linear modeling were applied for data analyses ($\alpha = .05$).

Results: Teeth moved by 78 kPa had significantly faster ($P = .0005$) distal movement (0.066 ± 0.020 mm/day) compared to teeth moved by 4 kPa (0.031 ± 0.012 mm/day). Lateral movement and distopalatal rotation were also significantly faster (fourfold and 10-fold, respectively) with higher than with lower stress ($P < .0001$). Average extrusion-intrusion, crown torque, and tip were small ($\leq |0.25|$ mm, $|2.29|^\circ$, and $|1.98|^\circ$, respectively), fluctuated, and not significantly different between high and low stresses. No lag phase of tooth movement was evident.

Conclusions: Maxillary canines were retracted faster by 78 kPa than by 4 kPa. Controlled translation was possible with 4 kPa, but 78 kPa outstripped appliance constraints, causing distopalatal rotation. (*Angle Orthod.* 2014;84:102–108.)

KEY WORDS: Tooth movement; Human; Mechanics; Mechanical stress

INTRODUCTION

It remains unknown if there is a "dose-response" relationship between mechanical stress and rate of orthodontic tooth movement in humans and, furthermore, if there is a threshold of stress beyond which desired movement slows or causes unwanted side effects. Stress is defined as force/area and is a "dose" variable to control and consider for comparison of orthodontic "responses" between teeth with different root areas over which force is distributed.[1] Proposed hypotheses[1,2] and a past study[3] of 66 human maxillary canines moved by stresses of 4–78 kPa suggest that increasing stress increases speed of tooth movement to a maximum. However, evidence is still lacking to test this hypothesis and quantify the optimum stress, because investigations of determinate mechanics on tooth translation rates have been exceedingly rare[4] and have demonstrated individual variation.[3,5]

Both animal and human data regarding effects of stress on rates of tooth translation are scarce. A series of four studies involving 54 beagle dogs and distal translation of 108 second mandibular premolars (estimated root area: one-third of human maxillary canines) by a range of forces demonstrated a best-fit model that explained 43% of the variance.[6] The model showed a positive nonlinear relationship between rate and force that peaked at 0.038 mm/day for 248 cN, with rates gradually decreasing up to 1200 cN.[6] Recently, similar techniques used in eight beagles applied 10 cN, 300 cN, and 600 cN, switching force

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magnitudes after 24 weeks,[7] and validated the proposed model in that increasing force from 10 cN to 600 cN significantly increased mean rate by 0.019 mm/day, whereas increasing force from 300 cN to 600 cN did not significantly change mean rate. However, unlike model predictions, mean rates for 10 cN and 300 cN were 0.029 and 0.033 mm/day, respectively, and not significantly different. Of the few human studies where different force magnitudes (50–300 cN) were used and amounts of tooth movement in a given time were compared, some have demonstrated no differences,[5,8] whereas others have shown more force was associated with more tooth movement, but not proportionally,[9] and with decreased rotational control and posterior anchorage stability.[10]

Previous research has mainly failed to quantify applied mechanics and tooth movements in ways that can be compared between studies[4]; thus, results cannot easily be translated to clinical settings. Therefore, the purpose of this split-mouth-design pilot study was to compare three-dimensional tooth movements resulting from constant stresses of relatively higher and lower magnitudes. Also, crown torque, tip, and rotation during maxillary canine retraction were measured to test the effectiveness of the orthodontic appliance in producing translation.

MATERIALS AND METHODS

Recruits demonstrated good oral hygiene, had ≥6 permanent teeth in each maxillary quadrant, and required bilateral maxillary canine retraction into maxillary first premolar extraction sites. Those who volunteered gave informed consent to participate in protocols approved by the UMKC Institutional Review Board. While enrolled, subjects were instructed to avoid nonsteroidal anti-inflammatory agents.

Previously described protocols[3] were used. During the study mandibular teeth were appliance free. Maxillary canine retraction mechanisms were activated on day 0. Ten appointments were scheduled to track progress of tooth movement, on days 0, 1, 3, 7, 14, 28, 42, 56, 70, and 84. Three weeks prior, posterior anchorage was established (Figure 1) via fixed appliances (0.018 system; 3M Unitek, Monrovia, Calif) including a Nance plus posterior teeth on each side linked via stainless-steel wires: a passive segment (0.017 × 0.025-inch diameter) and figure-8 ligation (0.010-inch diameter). Extractions and a 2-week healing time occurred before day 0.

Design and customization of the retraction mechanism, as described previously,[3,11] involved a stainless-steel auxiliary wire (0.016 × 0.022-inch diameter) with vertical loop just distal to the maxillary canine. This wire extended passively from the maxillary first molar band's auxiliary tube to the canine bracket, where it was ligated with a stainless-steel tie and elastomeric tie overlay. The loop height matched the canine's estimated center of resistance (C_R) relative to its root length (L_R, measured from a periapical radiograph of this tooth corrected for magnification) according to the relationship $C_R = 0.24L_R$.[12] The auxiliary loop was activated by a calibrated nickel-titanium closed-coil spring stretched between hooks on the molar band and auxiliary wire just distal to the loop (Figure 1). This caused both a retraction force and an apicodistal countermoment at the canine bracket that was designed for canine translation with respect to the posterior anchorage.[1,13]

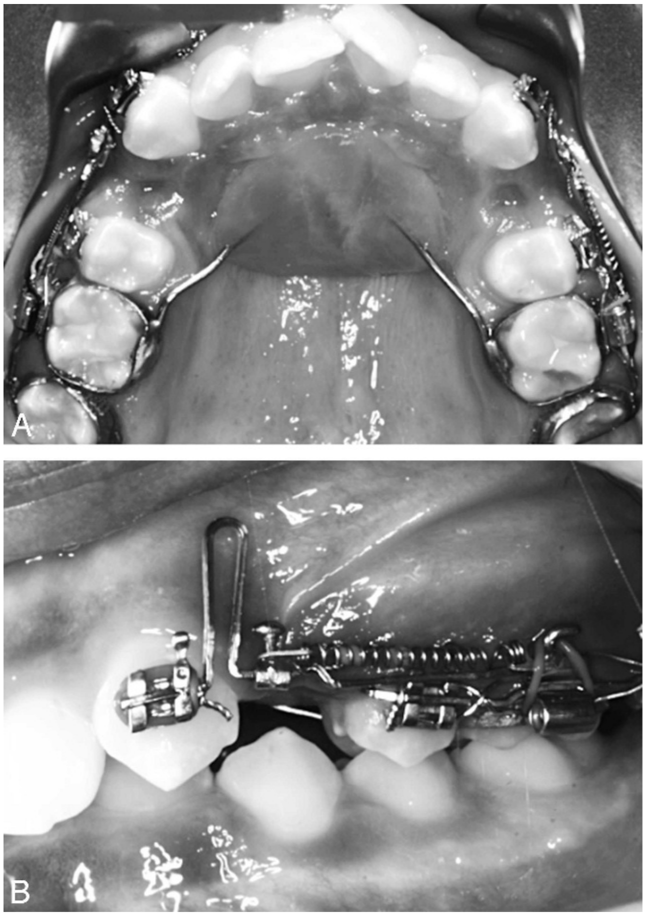

Figure 1. Maxillary occlusal and left buccal views (subject M1).

Stresses of 78 kPa and 4 kPa (average forces of 306 ± 83 cN and 16 ± 5 cN, respectively) were randomly assigned to left and right maxillary canines of each subject. Using previously described methods,[11] the force required was determined by dividing the assigned stress by the maxillary canine's distal root surface area (A), estimated by $A = L_R a(1 - b^2/a^2)^{1/2}$, where a and b were half the labiopalatal and mesiodistal widths of the canine at the cementoenamel junction, respectively, and $a > b$, assuming an elliptical

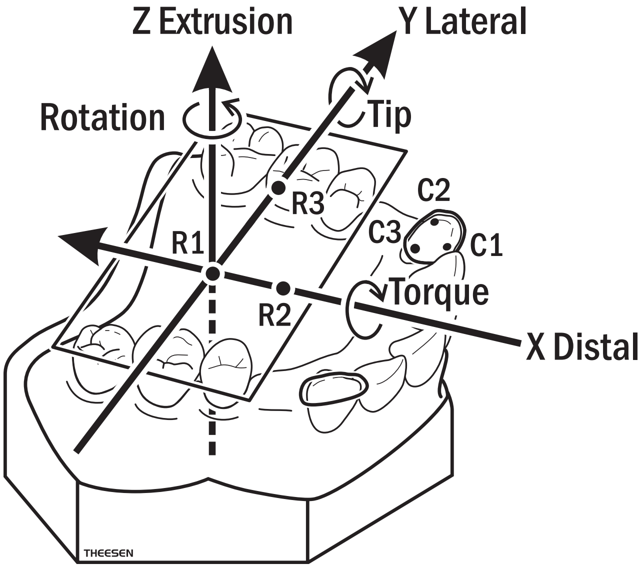

Figure 2. Modified schematic diagram[3] of maxillary dental model with three custom acrylic templates. Each template has three markers, shown as R1, R2, and R3 on the posterior template and C1, C2, and C3 on the right canine template (markers B1, B2, B3 on left canine template not shown).

root cross section. Load-displacement characteristics of closed-coil springs (G&H Wire, Franklin, Ind) were measured ex vivo during unloading at 37°C. For a given maxillary canine, assigned stress, and displacement, a spring was selected that would deliver the target force. The spring displacement was checked at each appointment to ensure delivery of this force, and if needed, the spring was changed.

Methods for measuring maxillary canine positions in six degrees of freedom over time were adapted from previous work.[11] Vinyl polysiloxane impressions (Extrude; Kerr Corp, Romulus, Mich) made at each visit were used to produce a set of maxillary dental casts for each subject. Posterior, right canine, and left canine custom templates (Figure 2) were constructed for each set of casts using acrylic (Triad; DENTSPLY International Inc, York, Pa). Each template was checked to ensure it fit the same on all casts in a set. Three markers were secured to each template (Figure 2). On the posterior template, these defined the orthogonal axis system for a given set of casts (Figure 2).

The x-axis, y-axis, and z-axis coordinates of each template marker in the local orthogonal axis system of a three-axis microscope (Measurescope MM-22; Nikon Inc, Melville, NY) were recorded using a digital crosshair generator (DCG-100A; TechniQuip Inc, Pleasanton, Calif), a video screen (LMD-1410; Sony Corp, New York, NY) and customized software (MatLab R2009b; The MathWorks Inc, Natick, Mass). These data were formulated to express the markers' linear and angular positions relative to the global orthogonal axis system defined by the posterior template markers (Figure 2).

Measurements were repeated until the agreement between two trials was <0.5 mm for all linear measurements. Ten casts from one subject, M2, were measured on nine occasions separated by at least 1 day, and measurement reliability was evaluated using the Cronbach α (where $\alpha > .8$ indicated good internal consistency) and standard errors about mean measurements. Progressive movements over time were quantified using slopes of linear regression relations and coefficients of determination (R^2), whereas fluctuating movements over time were assessed by calculating means and standard deviations. A mixed linear model was applied to the tooth movement data, with subjects as random factors, side (right or left) and stress (78 kPa or 4 kPa) as fixed factors, and time (day 0–84) as a covariate. Least-significant differences identified if fixed factors had significant effects on tooth movements. Statistical analyses were performed (Statistical Analysis System, version 9.1.3; SAS Inc, Cary, NC) with significance set at $\alpha = .05$.

RESULTS

Five males and three females with mean age 14.9 ± 4.0 years participated (Table 1). All subjects presented for at least eight and three subjects presented for all 10 of the scheduled appointments. Timing of the final scheduled visit was the most variable, but on average was at 84 ± 5 days. One subject (F3) reported using one dose of over-the-counter analgesic medication between days 0 and 1.

When one set of casts was measured nine times, the standard error for measurements along and about the x-, y-, and z-axes were 0.05 mm, 0.07 mm, and 0.09 mm, and 0.94°, 0.65°, and 0.30°, respectively. Tests of reliability showed measurements of distal, lateral, and distopalatal movements were highly consistent, with Cronbach $\alpha = .935–1.000$, whereas for extrusion, labial crown torque, and distal crown tip $\alpha < .700$.

Within subjects, 78 kPa moved maxillary canines distally faster than did 4 kPa by factors of 1.53–3.88 times (Table 1). Among subjects, the largest distal tooth movement was 7.36 mm measured at day 85 in subject M2, and the fastest distal tooth movement was 0.094 mm/day in subject F3 (Table 1). Distal tooth movements for both stresses were fastest and slowest in subjects F3 and M5, respectively (Table 1), where the largest individual rate differences were 2.4:1.0 for teeth moved by 78 kPa and 4.0:1.0 for teeth moved by 4 kPa.

Four subjects (F2, M2, M4, M5) experienced broken or loose springs or ligatures, which were corrected

Table 1. Subject Identifier, Age, Side of, and Stress Applied to Maxillary Canines and Resulting Maximum Distal Movement (at End of Study Unless Otherwise Indicated), Velocity, and Coefficient of Determination

Subject	Age, y	Maxillary Canine	Stress, kPa	Maximum Distal Movement, mm	Velocity of Distal Movement, mm/day	Coefficient of Determination (R^2)
F1	14.2	Right	4	2.73	0.032	.96
		Left	78	3.37	0.049	.95
F2	17.5	Right	78	5.83	0.066	.98
		Left	4	1.95	0.024	.96
F3	10.1	Right	4	4.09	0.052	.93
		Left	78	6.89 (at day 56)	0.094	.74
M1	12.6	Right	78	5.80	0.060	.96
		Left	4	2.41	0.031	.88
M2	11.7	Right	4	1.91	0.024	.80
		Left	78	7.36	0.093	.98
M3	13.6	Right	4	3.32	0.046	.18
		Left	78	6.77	0.076	.82
M4	22.4	Right	78	4.49 (at day 71)	0.052	.79
		Left	4	1.99	0.029	.44
M5	17.0	Right	4	0.76 (at day 41)	0.013	.52
		Left	78	2.93	0.039	.95

when noted. Although these incidents affected tooth movement at these particular time points, the overall patterns of tooth movements appeared to resume once the appliance was corrected. For example, subject M4 had a broken wire associated with the tooth moved by 78 kPa on days 43 and 84, nevertheless, R^2 for distal movement vs all nine time points for this subject was .79.

Distal movement plotted vs time was linear, as indicated by coefficients of determination (Table 1) that averaged .80 ± .23. Combined data for teeth moved by the same stress showed relatively large amounts of initial distal tooth movement at day 1 (means: 0.70 ± 0.55 mm for 78 kPa and 0.23 ± 0.72 mm for 4 kPa) followed by generally steady rates for both stresses, where R^2 values for mean distal movement vs time were .95 and .91 for teeth moved by 78 and 4 kPa, respectively (Figure 3A). Average speeds for teeth moved by 78 kPa were 0.066 ± 0.020 mm/day, and those for teeth moved by 4 kPa were 0.031 ± 0.012 mm/day; these were significantly different ($P = .0005$).

Progressive changes occurred with distal and lateral movements and distopalatal rotation (Figures 3A–C), whereas fluctuating changes occurred with extrusion, labial crown torque, and distal crown tip (Figures 3D–F). Average maximum tooth movements over 84 days were significantly higher ($P < .0001$) for 78 kPa vs 4 kPa for distal movements (5.43 ± 1.66 vs 2.40 ± 1.01 mm, respectively), lateral movements (3.21 ± 1.63 vs 1.21 ± 0.60 mm, respectively), and distopalatal rotation (25.03 ± 6.57° vs 1.73 ± 5.79°, respectively; Table 2). Small, fluctuating changes of $\leq|0.25|$ mm, $|2.29|^\circ$, and $|1.98|^\circ$ occurred on average for extrusion, labial crown torque, and distal crown tip, respectively. Results between stresses for these movements were not significantly different ($P > .05$).

DISCUSSION

Retraction of 16 maxillary canines in eight individuals by continuous stresses of 78 kPa and 4 kPa was measured at 8–10 time points over approximately 84 days. Distal and lateral movements as well as distopalatal rotation changed progressively, and these displacements were significantly higher for teeth moved by 78 kPa than for those moved by 4 kPa. Relatively small, fluctuating changes were seen for extrusion, labial crown torque, and distal crown tip, without significant differences in results from 78 kPa vs 4 kPa.

A previous study[3] of 66 human maxillary canines retracted by five stresses ranging from 4 kPa to 78 kPa showed increased translation rate with increased stress, but effects of stress were not statistically significant. Although both this previous and the current studies used similar protocols, the previous study was underpowered for five stress levels, and no subject had teeth moved by the highest and lowest stresses in the range. The current study addressed these matters and found similar speeds of distal tooth movement for 78 kPa and 4 kPa (0.066 ± 0.020 and 0.031 ± 0.012 mm/day, respectively) as did the previous study (067 ± 0.024 and 0.028 ± 0.012 mm/day, respectively). Proposed models relating stress magnitude and tooth movement suggest that an increase in stress increases rate of tooth movement to a maximum.[1,6] Mathematical modeling based on combined data from nine human studies where 205 maxillary and mandibular canines were retracted predicted a mean maximum speed of 0.041 mm/day using a force of 272 cN.[6] The current study showed that higher speeds can be achieved with 78 kPa, using an average force of 306 cN, but stresses above and below 78 kPa must be tested to determine if an optimal stress magnitude

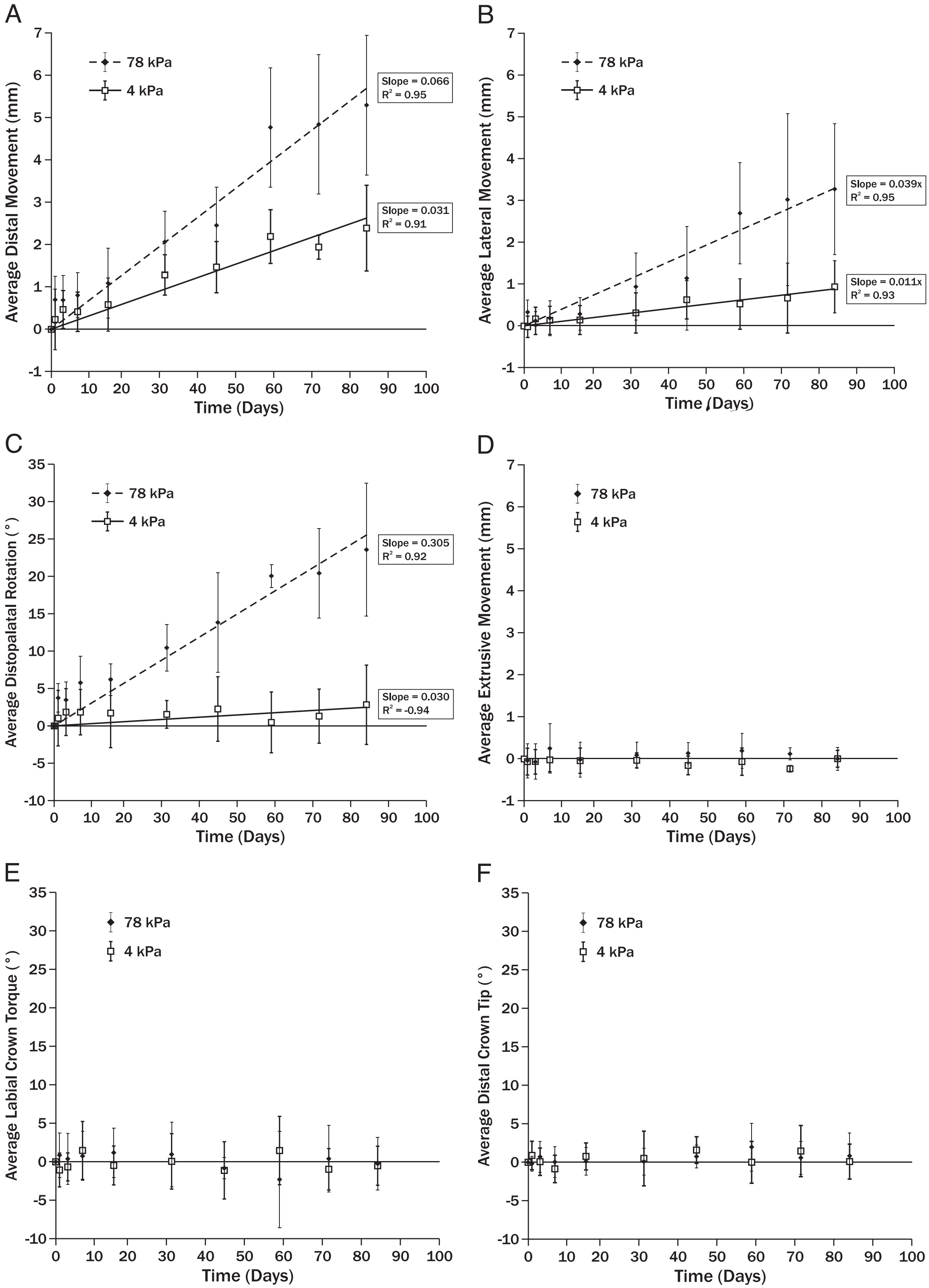

Figure 3. Average movement over time (days) for all maxillary canines retracted at 78 kPa and 4 kPa. (A) Distal movement (mm), (B) lateral movement (mm), (C) distopalatal rotation (°), (D) extrusive movement (mm), (E) labial crown torque (°), and (F) distal crown tip (°), where vertical bars indicate ±1 SD.

Table 2. Average Maximum Movements (±Standard Deviation) of Maxillary Canines Retracted at High (78 kPa) and Low (4 kPa) Stresses for All Subjects

	Average Maximum Movement of Maxillary Canines					
Stress, kPa	Distal, mm	Lateral, mm	Extrusion, mm	Labial Crown Torque, °	Distal Crown Tip, °	Distopalatal Rotation, °
78	5.43 ± 1.66	3.21 ± 1.63	−0.03 ± 0.55	−1.00 ± 7.44	0.83 ± 4.07	25.03 ± 6.57
4	2.40 ± 1.01	1.21 ± 0.60	0.02 ± 0.65	0.94 ± 5.68	1.49 ± 4.07	1.73 ± 5.79

exists for fastest tooth movement without undesirable effects.

Lateral movement was progressive for both high and low stresses, which was expected because the retraction mechanism was dependent on the shape of the individual's maxillary dental arch. That is, increased lateral canine movement occurred in more tapered arch forms in order to achieve proper contact with the second premolar. Progressive distopalatal rotations were also seen, with a significantly larger amount for teeth moved by 78 kPa compared to those moved by 4 kPa. This was not expected since both stainless-steel and elastic ties ligated each canine bracket and auxiliary wire to prevent this type of movement. These results confirm previous findings in which rotational constraints were overcome when higher stress magnitudes were used.[10] This further suggests that if higher stresses are applied for faster tooth movement, constraint conditions must be optimized to prevent excessive distopalatal rotation. Amounts of extrusion, labial crown torque, distal crown tip, and distopalatal rotation were minimal with 4 kPa and demonstrated "jiggling" movements during retraction, in agreement with past research.[3,14]

As previously shown,[3] relatively large distal movement occurred between days 0 and 1, possibly due to initial periodontal ligament compression in response to force application. After day 1, steady canine retraction was seen, in contrast to literature suggesting that a 21-day lag phase is present with forces >100 cN.[15] Overall, linear distal tooth movement vs time was demonstrated (average $R^2 = .80 \pm .23$). Exceptions were three teeth moved by 4 kPa (Table 1; $R^2 = .18–.52$; subjects M3, M4, and M5), which showed relatively large initial then steady smaller movements with time; hence, these data did not conform as well to linear models.

Individual differences in distal movement rates for the same stress were ≤4.0:1.0. This is comparable to previous studies that showed individual differences for canine retraction ≤4.8:1.0 by the same stress[3] and ≤3.8:1.0 by the same 100 cN force.[5]

Standard error data from reliability trials were lower for linear measurements than for rotational because the template markers were identified more consistently for coplanar linear measurements. Among linear data, z-axis measurements depended on focusing magnified images of the markers, which was difficult to perform consistently. Therefore, among rotational data, distopalatal measurements showed the lowest standard error because these did not contain a z-axis component. Cronbach α values were high for movements that progressed over time, indicating high internal consistency in these measurements, but were below the .700 cut point, demonstrating poor reliability, for relatively small fluctuating movements (extrusion, labial crown torque, and distal crown tip).

Limitations of this study need to be considered. First, although the results demonstrate that this sample of eight subjects was sufficient to show clinically important and statistically significant differences in the rate of canine retraction by 4 kPa vs 78 kPa, the sample was not balanced for gender or stages of growth; hence, the effects of these variables could not be studied. Design and analysis of applied mechanics included assumptions that auxiliary wires within molar tubes slid freely (Figure 1) and that static theory applied because tooth movement is relatively slow. Also, measuring only distal (along x-axis) rather than resultant rates underestimated overall speeds of desired tooth movement by a given stress because, depending on the individual dental arch form, some displacement along the y- and z-axes may have been needed for ideal tooth alignment. Posterior anchorage was indirectly checked and confirmed through consistent three-dimensional fit of the posterior template on all casts in a set for all subjects, and in some cases via lateral cephalometric superimpositions, which showed anchorage preservation ≤1 mm. Ideally, cephalometric superimpositions should confirm anchorage preservation for all subjects. Finally, although no adverse effects on the periodontium or root structure were observed radiographically, these effects were not measured quantitatively. Future studies should address these limitations. In addition, testing for markers of genetic and biological importance, for example via saliva and gingival crevicular fluids, should be completed to further investigate the causes of individual variability in speed of tooth movement.

CONCLUSIONS

- Maxillary canines were retracted significantly faster by 78 kPa compared to 4 kPa.

- Controlled translational retraction of maxillary canines is possible with 4 kPa, but 78 kPa outstripped constraints and resulted in distopalatal rotation.
- Individual variation for teeth moved by the same stress was ≤4.0:1.0.
- No lag phase was associated with either 78 kPa or 4 kPa.

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