Three-dimensional quantification of the force system involved in a palatally impacted canine using a cantilever spring design

Sumit Yadav, BDS, MDS, PhD¹
Jie Chen, PhD²
Madhur Upadhyay, BDS, MDS, MDSc³
Eugene Roberts, DDS, PhD⁴
Ravindra Nanda, BDS, MDS, PhD⁵

Aim: Although much imaging research has focused on the localization and management of the impacted canines, optimal biomechanics for successful recovery are not clear. The purpose of this research was to delineate the three-dimensional (3D) effects of a single force applied using a Kilroy spring on a palatally impacted maxillary canine positioned at different angulations (5 to 40 degrees) with respect to the line of force application. Methods: A dentoform cast was modified to simulate a palatally impacted canine. Load cells placed in the dentoform simultaneously measured the three forces (Fx, Fy, and Fz) and three moments (Mx, My, and Mz) on the canine. The activation range and force system attenuation were measured for eight different positions of a palatally impacted canine (5 to 40 degrees) as the canine moves toward the occlusal plane. The results were analyzed statistically. Results: The minimum activation range for the Kilroy spring was 11 mm, and the maximum was 14 mm. At all the different impacted canine positions, the Kilroy spring had a low load deflection rate and did not require reactivation for the successful management of a palatally impacted maxillary canine. Conclusion: A 3D force system at different bracket angulations (ie, different positions of the impacted maxillary canine) can be successfully quantified using the orthodontic force transducer. Quantification of the force system provides critical information for appropriate selection of an optimal appliance. ORTHODONTICS (CHIC) 2012;13:22-33.

Key words: force system, maxillary canine appliance

Maxillary canines are key in maintaining normal function, occlusion, and optimal esthetics. Due to their shape and size, they are regarded dimensionally as the most stable teeth. Maxillary canines play an important role in achieving a canine-protected occlusion. On laterotrusive movements of the mandible, only the canines of the maxillary and mandibular
(working side) arch make contact and therefore protect the remaining dentition from the torsional forces.\(^1\,^2\) Wheeler\(^3\) stated that maxillary canines are the cornerstone of the maxilla and necessary for normal facial expression since canine eminence has an esthetic value. At the same time, maxillary canines also happen to be the second most commonly impacted teeth after the third molar.\(^4\,^5\) An impacted canine can be defined as a tooth that has failed to erupt even after the complete formation of roots or eruption of a contralateral canine with complete root formation. The incidence of canine impaction is twice as common in females than males. They are palatally impacted in 85% of cases and labially/buccally impacted in only 15%.\(^4\,^6\) Therefore, considering their strategic importance, the time, effort, and cost invested in bringing them into alignment and optimal position has always been considered worthwhile.

An efficient orthodontic appliance should have the ability to bring about controlled three-dimensional (3D) movement of the impacted teeth within the biologic and mechanical realms of tooth movement in the direction predetermined by the treatment goal. Numerous appliances have been used for the management of palatally impacted maxillary canines. Among the prominent ones are Kilroy springs, ballista springs, simple cantilever springs, mini-implants, elastomeric chains, and extrusion springs.\(^7\,^14\) Most of these appliances or springs are designed to have a low load deflection rate, meaning that the force system delivered by these appliances tends to stay optimal and consistent in their magnitude, not causing any deleterious effects on the surrounding periodontium through the entire range of tooth movement.\(^15\) Localization and therapy used for treatment are the important determinants for the successful eruption of impacted canines in the oral cavity. Various radiographic techniques have been used to diagnose and localize the palatally impacted canine, including periapical, occlusal, and panoramic radiographs; lateral cephalograms; and cone beam computed tomography (CBCT).\(^16\,^17\) However, research and innovations on the therapeutic modalities have not been forthcoming. The design validation and product selection of any appliance for canine impaction is intricately related to the three-dimensional (3D) force delivery system, which affects the overall efficiency of the treatment. Recently, a study using an in vitro setup quantified the 3D force system involved for three different appliances for the effective management of a palatally impacted canine fixed at a predetermined position in the three planes of space (x, y, and z axes).\(^18\)
Three-dimensional quantification of the force involved in palatally impacted canines

However, clinical reality suggests that the position of an impacted canine varies from one patient to another. The biomechanics involved with an appliance such as the Kilroy spring (which can be likened to a cantilever spring [a one-couple system]) and its interaction with different angulations of impacted canines is an important step in delivering effective and predictable treatment. The Kilroy spring is slid onto the rectangular archwire at the site of an impacted tooth. In the passive state, the vertical loop of the spring is perpendicular to the occlusal plane. The impacted tooth is usually attached by means of a ligature wire or gold chain to the vertical loop of the Kilroy spring. Therefore, the specific aims of this in vitro study were: (1) to delineate the 3D effects of a single force applied using a Kilroy spring on a palatally impacted maxillary canine positioned at different angulations (5 to 40 degrees) with respect to the line of force application and (2) to quantify the effectiveness of the Kilroy spring in the management of a palatally impacted canine, which can help to predict its clinical applicability. Additionally, with evidence-based treatment strategies gaining popularity, a force system analysis will help the clinician to deliver efficient, accurate, and predictable treatment for the impacted canines.

**METHODS**

The quantification of the 3D force system associated with the Kilroy spring can be done analytically or experimentally. We chose to quantify it experimentally with eight separate simulated configurations of a palatally impacted maxillary canine ranging from 5 to 40 degrees in increments of 5 degrees (Fig 1).
Three-dimensional tooth movements are frequently described using a rectangular coordinate system (x, y, z) with six degrees of freedom. Thus, the load systems should be expressed in the same system. Using this representation, a coordinate system was set up with its origin coinciding with the center of the canine bracket. The x, y, and z axes were parallel to the mesiodistal, buccolingual, and occlusogingival directions, respectively. As tooth movement is 3D, teeth can translate in all three directions and rotate about these three axes. The 3D load system has six components: three force components (Fx, Fy, and Fz) and three moment components (Mx, My, and Mz) (Fig 2). The positive Fx is directed distally; the positive Fy buccally; and the positive Fz occlusally. The moment components tend to rotate the tooth about the three axes. The positive Mx tends to rotate the crown lingually; the positive My rotates the crown distally; and the positive Mz creates a crown mesial in rotation.

An orthodontic force transducer was designed to measure the force and moment along the three mutually perpendicular axes (x, y, and z) or the six components. The measuring device consisted of a Gamma load cell (ATI Industrial Automation) attached to its frame and an x, y, and z adjustment mechanism for securing a dentoform and simulating canine movement. The load cell could simultaneously measure the force (0 to 65 ± 0.2 Nm) and the moment (0 to 5 ± 0.0009 Nm) components. The clinical treatment scenario of a palatally impacted maxillary left canine was simulated on the dentoform. The preparation included the following steps. The left canine was separated from the cast and attached to the load cell through an adapter. The tooth eruption was simulated by

![Diagram of three-dimensional forces and moments on an impacted canine.](image)

Fig 2  Three-dimensional forces and moments on an impacted canine.
Three-dimensional quantification of the force involved in palatally impacted canines

adjusting the relative position of the canine with respect to the rest of the cast. The position of the maxillary canine was easily reproducible and maintained for all subsequent experiments. Tooth eruption was achieved by moving the microscopic stage vertically down each millimeter using vernier calipers (Fig 2). The resulting six force and moment components were measured. The instrument was calibrated to report moment and force values at the bracket. These readings were displayed simultaneously by a computer through an Industry Standard Architecture (ISA) bus interface.

The initial position of the canine in relation to the three axes was as follows: x, 0.000/0.000 (the distance between the upper platform and the lower platform in the x direction); y, –0.070/–1.778 (the distance from the upper and lower platform in the y direction; and z, 1.292/32.817 (the distance between the upper platform and the adapter in the z direction). The offset (inch) in the three axes was as follows: x, –0.067; y, 0.09; and z, 3.68. Thus, once these coordinates were established, the position of the maxillary canine was easily reproducible and maintained for all subsequent experiments.

The teeth were bonded with 0.018 × 0.025-inch preadjusted edgewise twin Andrews formula brackets (Oscar). A 0.017 × 0.025-inch stainless steel wire was used as the base archwire in all experiments. To enable a passive buccolingual fit of the archwire in the bracket slots, composite offsets were built onto the buccal surface of teeth as needed. Elastomeric ties were used to hold the wire in the brackets. The canine bracket had an initial angulation of 5 degrees, and experiments were performed at 5-degree increments until a 40-degree angulation was reached. In total, eight cases were tested, which were designated as C5 through C40. The rotation of the bracket was precisely made with a protractor. The instrument was zeroed before engaging the Kilroy spring to the impacted maxillary canine. The Kilroy spring was activated maximally at the beginning of each experiment by running a stainless steel ligature through the helix of the vertical loop and tying the ligature to the bracket of the impacted maxillary canine. At each angulation, the Kilroy spring was threaded onto the archwire, with the vertical loop buccally and extending occlusally and the terminal helices of the Kilroy spring extending beyond the bracket of the teeth adjacent to the impacted maxillary canine (maxillary left lateral incisor and maxillary left first premolar). For statistical purposes, five Kilroy springs were used at each angulation. For every millimeter of activation (at the microscopic stage), five readings were recorded. Three-dimensional force measurements were taken immediately after the appliance activation and at each increment of tooth eruption.

Statistical analysis
The mean of the five measurements made on each spring at each eruption milestone was calculated. As the tooth erupts, the force will reduce. The level of tooth eruption that causes the force to vanish is the range of the spring. The ranges of different angulations were compared using log-rank tests. The degrees of angulation (5 to 40 degrees at 5-degree increments) were compared for differences in load required for Fz to be approximately 0 using log-rank tests (using the load required to get Fz approximately 0 in place of “time” in the survival-analysis framework). A repeated-measures analysis of variance (ANOVA) was used to analyze the differences in Fx, Fy, Fz, Mx, My, and Mz at each eruption milestone corresponding to different degrees of angulation. The ANOVA included terms for degrees of angulation, load, and the degree-by-load interaction in addition to a random effect to correlate measurements from the same specimen. A similar repeated-measures ANOVA was used to compare the slopes when treating load as a continuous variable. While the relationships between load and outcomes are not always linear, we expected that this analysis would provide an indication of whether the outcomes change at similar rates as the load increases.
RESULTS

Vertical eruption of impacted canines at different angulations (Fz)
Fz was the primary eruptive force in all angulations. The range, force magnitude, and rate of force attenuation were measured at different angulations (5 to 40 degrees). The range required for Fz to be 0 at C20 was significantly lower than C15 (P < .0290), C30 (P < .0301), C35 (P < .0290), and C40 (P < .0301), while C10 and C25 were significantly lower than C30 (P < .0495 and P < .0143, respectively) and C40 (P < .0495 and P < .0143, respectively) (Fig 3a). The minimum range for Fz to be 0 was 11 mm and maximum was 14 mm (Tables 1 to 3). The rate of force attenuation at each millimeter of canine eruption was nearly similar, and attenuation was linear for all the different angulations (different positions of the impacted canine).

Buccolingual and mesiodisal movement of impacted canine at different angulations (Fy and Fx)
For all angulations, Fy was positive and produced a buccally directed force on the palatally impacted canine. There was a gradual decrease in the buccal force component for all angulations as the impacted canine erupted, and the force remained buccal even when Fz was 0 (ie, the canine was fully erupted). Fy at C25 had significantly less slope than all other angulations except C5. C5 had lesser slope than C10 (P < .0017), C15 (P < .0109), C20 (P < .0006), C35 (P < .0002), and C40 (P < .0011). C30 had significantly less slope than C35 (P < .0299) (Fig 3b and Table 3). Fx was in the distal direction at the initial activation of the Kilroy spring in all degrees of bracket angulation. As the canine erupted toward the maxillary plane of occlusion, Fx gradually decreased, but the direction of force remained distal, except for C15 where the force changed to a slight mesial direction upon complete eruption of the canine. Fx in C20 had significantly less slope than C5 (P < .0005), C10 (P < .0000), C25 (P < .0001), and C35 (P < .0007). C15 and C30 had significantly less slope than C5 (P < .0291 and P < .0063, respectively), C10 (P < .0025 and P < .0004, respectively), C25 (P < .0109 and P < .0021, respectively), and C35 (P < .0417 and P < .0094) (Fig 3c and Table 3).

Moment in the buccolingual direction (Mx)
The Kilroy spring had a consistent moment both in amount (1 to 1.5 Nm) and direction, except C15 (6 Nm) and C35 (2.2 Nm), which had a higher moments in magnitude but were consistent in direction with all the other bracket angulations. C15 had a steeper negative slope than all other angulations. C10 (P < .0025), C35 (P < .0417), and C40 (P < .005) had a steeper positive slope than C20 (P < .0049) and C30 (P < .050). C25 had a steeper positive slope than C20 (P < .0001) and C30 (P < .0021) (Fig 3d and Table 3).

Moment in the mesiodistal direction (My)
The Kilroy spring had a distal moment to begin with in all bracket angulations, except at C30, in which there was no moment to begin with. As the impacted canine erupted, though, the moment became distal. At the end of canine eruption, the moment was slightly mesial. Similarly, the moment became slightly mesial at C5, C20, C30, and C35, whereas the distal moment at C10, C15, C25, and C40 gradually decreased but the direction remained unchanged. C30 had significantly less slope than all other angulations. C25 and C40 had significantly less slope than C5 (P < .0027 and P < .0006, respectively), C10 (P < .0000 and P < .0000, respectively), C15 (P < .0004 and P < .0001, respectively), C20 (P < .0485 and P < .0413, respectively), and C35 (P < .0020 and P < .0001, respectively) angulations. C20 had significantly less slope than C10 (P < .0162) (Fig 3e and Table 3).
Three-dimensional quantification of the force involved in palatally impacted canines

Fig 3a  Representation of the force (Fz) at each load for the different bracket angulations (5 to 40 degrees).

Fig 3b  Representation of the force (Fy) at each load for the different bracket angulations (5 to 40 degrees).

Fig 3c  Representation of the force (Fx) at each load for the different bracket angulations (5 to 40 degrees).
**Fig 3d** Representation of the moment (Mx) at each load for the different bracket angulations (5 to 40 degrees).

**Fig 3e** Representation of the moment (My) at each load for the different bracket angulations (5 to 40 degrees).

**Fig 3f** Representation of the moment (Mz) at each load for the different bracket angulations (5 to 40 degrees).
Table 1  Load required for Fz (force in the occlusogingival direction) to be zero

<table>
<thead>
<tr>
<th>Degrees</th>
<th>No. of tests conducted</th>
<th>Mean (SD)</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>13.4 (1.3)</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>13.4 (0.5)</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>15</td>
<td>5</td>
<td>13.6 (0.5)</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>12.6 (0.5)</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>25</td>
<td>5</td>
<td>13.2 (0.4)</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>14.0 (0.0)</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>35</td>
<td>5</td>
<td>13.6 (0.5)</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>40</td>
<td>5</td>
<td>14.0 (0.0)</td>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

SD, standard deviation.

Table 2  P values for the load required for Fz to be about 0: Comparisons between each degree of angulation pair

<table>
<thead>
<tr>
<th>Degrees</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>.3532</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>.6377</td>
<td>.5485</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>.0520</td>
<td>.0571</td>
<td>.0290*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>.1700</td>
<td>.5127</td>
<td>.2207</td>
<td>.0951</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>.3173</td>
<td>.0495*</td>
<td>.1336</td>
<td>.0031*</td>
<td>.0143*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>.6377</td>
<td>.5485</td>
<td>.9999</td>
<td>.0290*</td>
<td>.2207</td>
<td>.1336</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>.3173</td>
<td>.0495*</td>
<td>.1336</td>
<td>.0031*</td>
<td>.0143*</td>
<td>&gt; .9999</td>
<td>.1336</td>
</tr>
</tbody>
</table>

*P < .05 (statistically significant).

Moment in transverse plane (Mz)

Mz was minimal for all the bracket angulations (~1.5 to 0.5 Nm). There was a distal rotation at C10 and C15 that remained distal until the complete eruption of the canine, whereas C5, C20, C25, C30, C35, and C40 had mesial rotation to start with, which either remained mesial or showed a slight distal tendency at the complete eruption of the canine. Mz for C20 had a steeper positive slope than all other angulations. C40 had a steeper negative slope than C15 (P < .0417), C20 (P < .0001), and C25 (P < .0274) angulations (Fig 3f and Table 3).

DISCUSSION

Our primary objective was to provide a description of the complex biomechanical force system involved in the extrusion of a canine impacted palatally at different angulations using a one-couple force system in the form of a Kilroy spring (cantilever design). The goal was to come up with an efficient force system that can achieve this task in the most convenient method. Here, an efficient force system can be defined as a system that can work accurately and effectively in a predictable manner to shorten treatment time.12 It also becomes important to state that it was not our intention to accurately simulate the oral conditions and/or control other variables, including bone morphology, length and shape of the root, saliva, and tongue and lip pressure, that might have an effect on tooth movement.
The argumentative topic of 3D force system on palatally impacted maxillary canines was unresolved until Yadav et al.\textsuperscript{18} accurately quantified the force system of three different appliances on a single position of palatally impacted canines. The generation of appropriate forces and moments on the impacted canine can be accomplished by using a combination of various techniques and appliances. The force system quantified in this experimental research is on an impacted canine, and the force system determines the 3D movement of the canine toward the maxillary occlusal plane. Clinicians need to know the 3D
forces applied on palatally impacted canines when the specific combination of bracket and a particular cantilever spring (Kilroy spring) is used for an effective and predictable treatment strategy. It is speculated that the canine angulation has an impact on the force system. This study showed that there are no significant differences among the force systems of different cases. Therefore, the effects of canine angulation have a negligible effect on the force systems.

The fully activated Kilroy spring applies a mean of 2.5 Nm of force. When the canine was at an angle to the direction of the force application (F), which was perpendicular to the occlusal plane, the activation range of the Kilroy spring varied between 11 and 14 mm, similar to what we had obtained previously. The Kilroy spring applied a diminishing continuous force, Fz, for its entire range of deactivation. The rate of tooth eruption is usually about 1 to 1.5 mm/month depending on the quality and quantity of the bone present.

If an acceptable force level is between 1.0 and 2.5 Nm, the spring will not need to be adjusted for 6 to 9 months. This information can help clinicians to set the interval for office visits. It is always desirable that acceptable magnitude of force is maintained in the appliance during treatment to avoid frequent reactivations. Therefore, clinicians must know the behavior of impacted teeth when using a Kilroy spring with different bracket combinations for palatally impacted canines. In a clinical scenario, a canine is backward in the maxilla and near to the palatal surface of the root of incisors, especially the lateral incisor. A buccally directed traction will bring the canine into contact with the roots of these teeth, which may damage them. Furthermore, the position of the canine may not improve due to the physical impediment. To overcome this, the Kilroy spring at different bracket angulations applies a distal crown torque (My) along with a buccally directed force (Fy) when activated. The combination changes to mesial crown torque, thus avoiding the chances of canine crown and lateral incisor root contact, which also might prevent root resorption of the teeth involved.

Fy is directed buccally for all cases. Although Fy is small in magnitude, it persistently pulls the crown buccally while the root remains palatally placed. A root correction will be needed, which can be accomplished by increasing the buccal root torque (Mx). Mx, in the buccolingual direction, is important in obtaining optimal eminence of the canine root when it is brought into the arch. Relatively less attention is paid to the torque control (Mx) of the palatally impacted canine while applying an extrusive force. It is important to remember that torque control is not difficult during the initial stages of canine eruption, but it is an arduous task once the torque control on the impacted canine is lost. The Kilroy spring applies a relatively constant low buccal root torque throughout the process of canine eruption, except at 15 degrees when the torque value almost becomes three times that at other angulations, only diminishing when the canine eruption was almost complete.

This research shows that to deliver a predictable force-moment system using a one-couple spring design on an impacted maxillary canine, the cantilever springs (Kilroy spring) must be set according to the initial position of the impacted canine. However, to provide evidence-based orthodontic mechanics, the position of the impacted canine used for laboratory measurement should be obtained from patients, which may allow clinicians to apply laboratory results in day-to-day practice.

Our future research will focus on the delineation of a 3D force system on the labial or lingual positioning of the brackets on palatally impacted canines and how the bracket angulation on the lingually placed brackets affects the 3D force system on palatally impacted canines. In addition, we will delineate 3D force systems on palatally impacted canines with different types of brackets and their orientations along the long axis of the clinical crown.
CONCLUSION

The following conclusions were drawn from this study:

- Three-dimensional force systems at different bracket angulations can be successfully quantified.
- The force and moment components at different bracket angulations follow a definitive pattern, except for Mz.
- Minimum activation range for a Kilroy spring is 11 mm; maximum is 14 mm. At all different bracket angulations, the Kilroy spring has a low-load deflection rate and does not require reactivation for the successful management of palatally impacted maxillary canines.
- This in vitro study manifests the effectiveness of the Kilroy springs at different positions of palatally impacted maxillary canines. Nevertheless, minor modifications may be required, initially or during the treatment, as dictated by the individual case and due to the heterogeneity of individual responses to the spring.
- This was a bench-top study, and we did not simulate oral conditions and/or control for other variables, including bone morphology, length and shape of the root, saliva, or tongue and lip pressure, which might affect tooth movement.

REFERENCES