## *Original Article*

# Biomechanical reevaluation of orthodontic asymmetric headgear

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## ABSTRACT

**Objective:** To investigate the distribution of distal and lateral forces produced by orthodontic asymmetric headgear (AHG) using mathematical models to assess periodontal ligament (PDL) influence and to attempt to resolve apparent inconsistencies in the literature.

**Materials and Methods:** Mechanical models for AHG were constructed to calculate AHG force magnitudes and direction using the theory of elasticity. The PDL was simulated by elastic springs attached to the inner-bow terminals of the AHG. The total storage energy ($E_t$) of the AHG and the supporting springs was integrated to evaluate the distal and lateral forces produced by minimizing $E_t$ (Castigliano's theorem). All analytical solutions were derived symbolically.

**Results:** The spring-supported headgear model (SSHG) predicted the magnitude and distribution of distal forces consistent with our data and the published data of others. The SSHG model revealed that the lateral forces delivered to the inner-bow terminals were not equal, and the spring constant (stiffness of the PDL) affected the magnitude and direction of the resultant lateral forces. Changing the stiffness of the PDL produced a greater biomechanical effect than did altering the face-bow design. The PDL spring model appeared to help resolve inconsistencies in the literature between laboratory in vitro experiments and clinical in vivo studies.

**Conclusion:** Force magnitude and direction of AHG were predicted precisely using the present model and may be applied to improve the design of AHG to minimize unwanted lateral tooth movement. (*Angle Orthod.* 2012;82:682–690.)


**KEY WORDS:** Orthodontics; Headgear; Biomechanics; Elasticity; Dental

## INTRODUCTION

Unilateral Class II malocclusions are challenging to treat in orthodontics. Treatment modalities include asymmetric headgear (AHG), asymmetric extractions, differential elastic patterns, intraoral anchorage appliances, and, more recently, temporary skeletal anchorage devices (TADs).[1–4] Despite the current enthusiasm for TADs, AHG continues to be used in many orthodontic practices. Extensive clinical data over the past three decades have demonstrated the effectiveness of AHG in unilateral distalization, although these same studies reported the undesired development of cross-bites arising from lateral forces exerted by AHG.

Multiple designs for AHG have been described with the intent of increasing unilateral distal force while minimizing unwanted lateral forces.[5–7] Hershey et al.[5] evaluated five different symmetric headgear and AHG designs. Their theoretical estimation was patterned after that of Haack and Weinstein[8] and was compared to laboratory studies. They reported that the power-arm and swivel-offset designs were effective at delivering unilateral distal force, and the bilateral symmetrical, spring attachment, and soldered-offset face-bows were not effective. Their conclusion indicated that the location of the face-bow joint had no effect in unilateral distalization.

Many experimental, in vitro, and clinical studies have evaluated the side effects of AHG, but the conclusions

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Accepted: October 2011. Submitted: June 2011.
Published Online: December 8, 2011

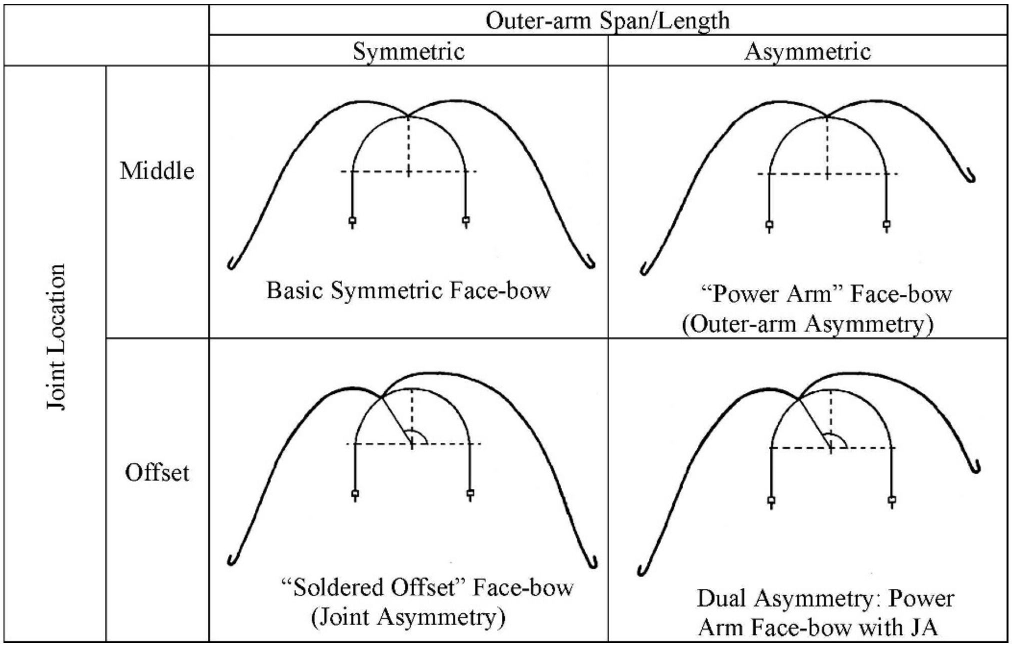


**Figure 1.** Classification of face-bow designs according to the two asymmetric factors: outer-arm span/length and joint location.

have been inconsistent. Nobel and Waters[9] reported solely buccal displacement of both molars with AHG. Houghton[10] found some buccal-buccal displacement and some lingual-buccal displacement of the molars; the buccal-buccal displacement was attributed to the arch expansion effect of the inner bow. Nobel and Waters[9] ascribed the divergent lateral forces to the asymmetry of the outer arms. Yoshida et al.[6] and Martina et al.[11] showed that AHG often produced buccal displacement on the light-force side molar and a lingual displacement on the heavy-force side. They also showed that the resulting buccal and lingual cross-bites did not have the same amount of overjet. These in vitro experiments indicated that the two lateral forces may not be equivalent, in contrast to the assumption of equal lateral forces theorized by Haack and Weinstein.[8] We hypothesized that a biomechanical model incorporating the periodontal ligament (PDL) with various stiffness constants could influence the magnitude and direction of lateral forces and that it may explain the divided outcomes. The PDL was modeled as elastic springs without adopting time-dependent behaviors. This allowed us to investigate initial loading on the molars, which accounts for the first minute of tooth movement according to Slomka et al.[12]

We also hypothesized that factors related to AHG designs, including joint location, outer-arm asymmetry, and inner-bow terminal length asymmetry, should be reevaluated and optimized for improved clinical outcomes. The importance of joint location in adjusting distal/lateral forces has not been reported. Asymmetric inner-bow shape with long and short terminals has also attracted interest.[7] Previous studies focusing on outer-arm and inner-bow asymmetry have not provided theoretical predictions of how to improve AHG designs.

To test our hypotheses, two types of AHG were investigated using the theory of elasticity[13] with the PDL as a linear spring. The analytical solutions of vertical and lateral forces were calculated in relation to (1) PDL stiffness, (2) face-bow joint location, (3) outer-arm asymmetry, and (4) length of the inner-bow terminals.

## MATERIALS AND METHODS

An AHG consists of an outer bow, an inner bow, and a joint connecting them, and its configuration has been generalized in this study for mechanical analysis. The inner bow was depicted as a half-circle with two straight bars distally extended to the molar tube. This inner-bow configuration approximates the dental arch form. This shape was adopted for computational simplicity and feasibility for exact solutions. The actual dental arch forms will greatly exacerbate the computational complexity, yet the result may not significantly deviate from the model proposed.

Two design parameters of AHG—outer-arm length and joint location—were analyzed to solve force distributions on molar teeth (Figure 1). The power-arm face-bow was characterized by differential lengths of outer arms, and the soldered-offset face-bow was represented by an asymmetric joint location. The dual asymmetric face-bow combined the joint asymmetry with the power-arm design. Varying the lengths of the

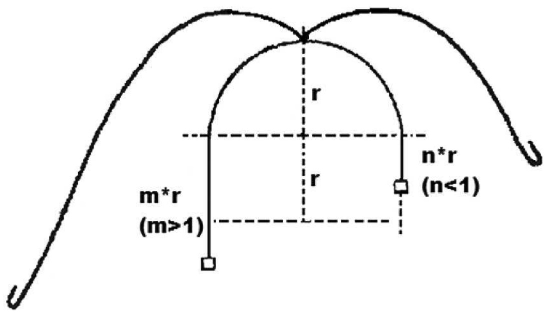


**Figure 2.** Power-arm face-bow with variations of inner-bow terminal length; r indicates radius of inner-bow half-circle; m and n, factors to lengthen and shorten terminals, respectively.

two inner-bow terminals was also calculated for both power-arm and soldered-offset headgears (Figure 2).

Two sets of sagittal and horizontal springs (Figure 3) were added to each of the two terminal molars in the analysis to simulate PDL support for the molars. This spring approximation assumed a quasi-static loading on the periodontal tissue without considering the complexity of time-dependent behaviors. This allows the first step toward testing our hypotheses. Using Castigliano's theorem (appendix), elastic storage energy of PDL was calculated when the headgear was in activation. As such, the mechanical system of the present AHG is illustrated in Figure 3A, with the distal and lateral forces on molars labeled with $T_A$, $T_B$, $N_A$, and $N_B$, respectively. The acting (external) forces are labeled as F, and the force directions are indicated by angles $\beta$ and $\delta$. The soldered-offset face-bow model is shown in Figure 3B, in which the additional variable is the joint location denoted by angle $\alpha$. The detailed equations are derived in the supporting appendix to enable future investigators to examine our results.

In our model, the maxillary molars are treated as mass points, as all forces under study are coplanar. Clinically, external forces exerted on face-bows are not parallel with the face-bow plane. However these non-coplanar forces can be viewed as the result of two component forces that are parallel and vertical to the face-bow plane, indicating that the parallel component force can still be solved using the current model.

## RESULTS

### Power-arm Face-bow

Figure 4A displays the surface plot of the two predicted distal forces ($T_A$ and $T_B$) due to variation of angles $\beta$ and $\delta$, ranging from 0 to 90°. It revealed that $T_A$ differs from $T_B$ at any given pair of $\beta$ and $\delta$, except for the line $\beta = \delta$, where the two surfaces intersect. The $T_A$ and $T_B$ appeared symmetric relative to the plane $\beta = \delta$. A selected plane at $\delta = 10°$ was drawn to illustrate the variation of $T_A$ and $T_B$ in terms of angle $\beta$ (Figure 4B), which resembled a power-arm headgear. $T_A$ was always greater than $T_B$ as long as $\beta > \delta$. The $T_A$ increased as $\beta$ increased, and the value was greatest at $\beta \sim 65°$. The distal force $T_B$ on the light side became negative when $\beta$ approached 90°. The spring constant at the molars also affected the distal forces: the stiffer the spring (PDL), the greater the difference between $T_A$ and $T_B$, as was shown by three values of spring stiffness labeled by a dimensionless $\kappa$: E * r/k = 1, $10^6$, and 9 *$10^6$, where E is the Young's modulus of stainless steel and k represents the spring constant of PDL, corresponding to rigid PDL, moderate PDL, and soft PDL, respectively. Interestingly, when the stiffness of PDL decreased one million times, that is, when E * r/k increased from 1 to $10^6$, the distal force curves showed minimal change. If the stiffness of PDL further decreased nine times, that is, when E * r/k increased from $10^6$ to 9 *$10^6$, the force curves were dampened greatly.

Figure 4C portrays the unequal-length inner-bow terminals, with the long bar = 1.3 * r (heavy-force side A) and the short bar = 0.7 * r (light-force side B). Figure 4D shows the influence of joint location on distal force, with face-bow joint deviated from midline ($\alpha = 90°$) to the location of $\alpha = 60°$. Figures 4C and 4D

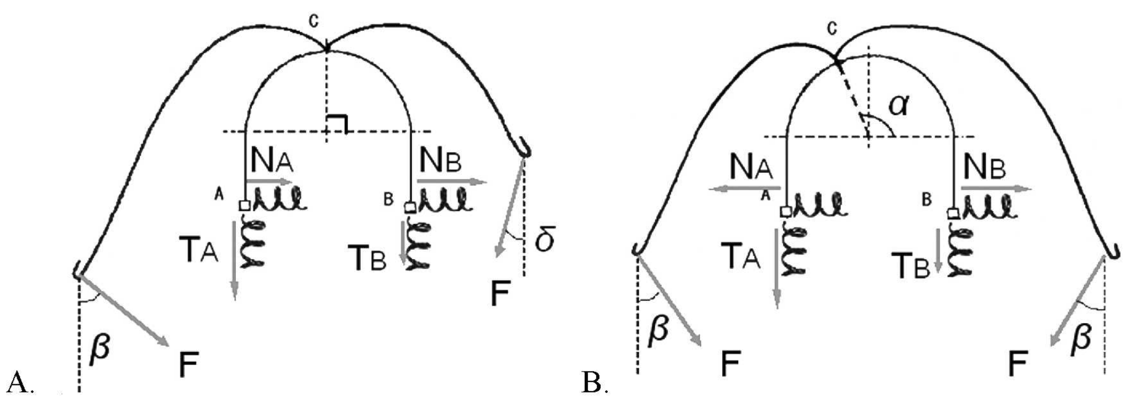


**Figure 3.** Schematics of distal and lateral forces exerted on molars by asymmetric headgears. (A) Power-arm headgear. (B) Soldered-offset headgear.

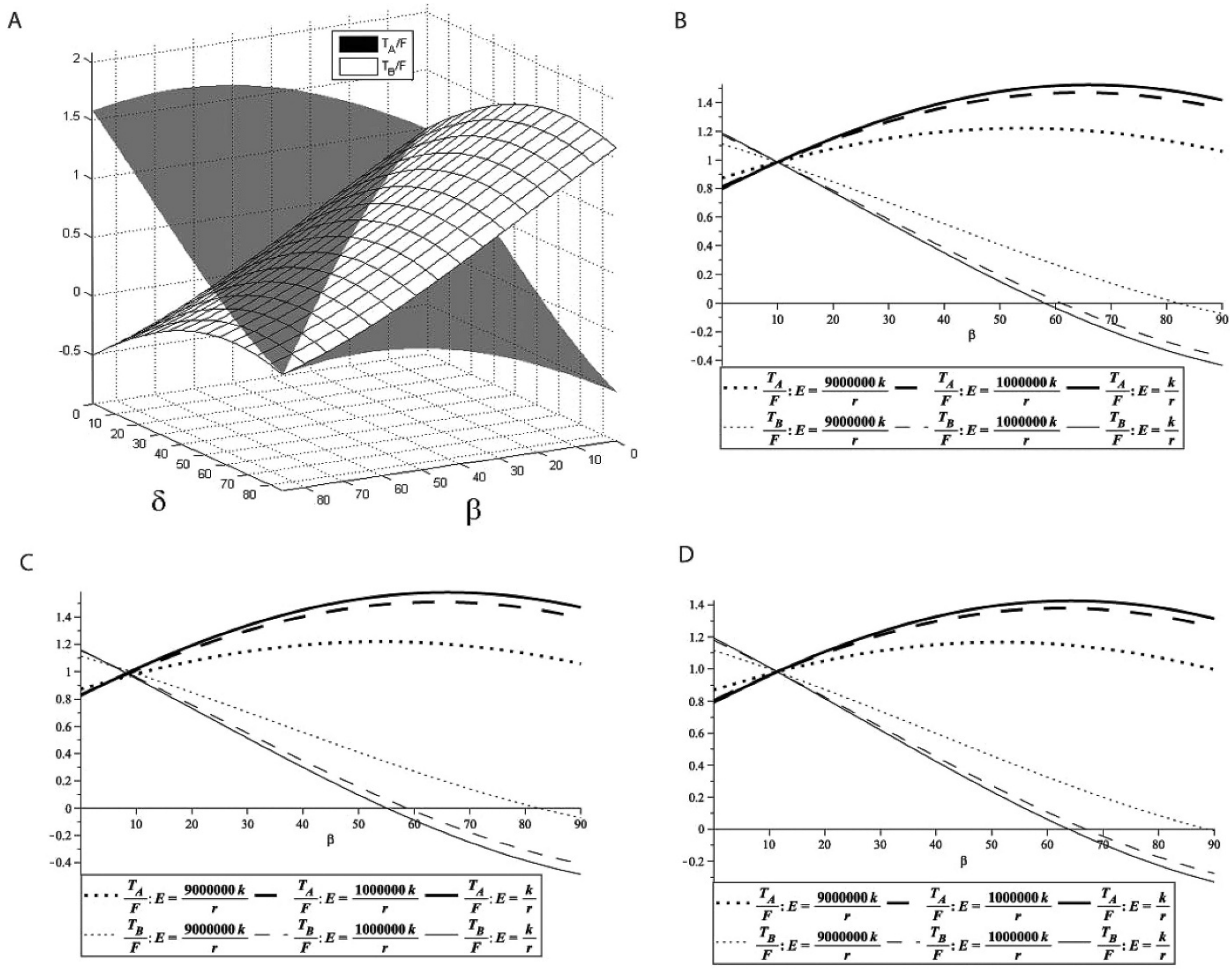


**Figure 4.** Power-arm face-bow. (A) Three-dimensional plot of distal forces on molars, $T_A/F$ and $T_B/F$. E * r/k = $10^6$. (B) Distal forces in terms of β when fixing δ = 10°. (C) Distal forces with unequal-length inner-bow terminals. (D) Distal forces when adding joint asymmetry (α = 60°).

represent modifications to the power-arm face-bow in Figure 4B, where all other parameters are unchanged. Changes in inner-bow terminal lengths and joint location did not influence the distal force distribution to a noticeable degree.

Figure 5 compares the lateral molar forces exerted by power-arm headgear with different designs. In these models the PDL not only damps the magnitude of lateral forces but also determines the direction change of lateral force on the heavy-force side ($N_A$). In Figure 5B, when β increases from 0° to 90°, $N_A$ intersects with the x axis, indicating that the lateral force on the heavy side actually reversed from buccal to lingual direction at this point (a negative value represents buccal; a positive value indicates lingual direction). The existence of soft PDL significantly shifts the intersection point to the smaller value of β; that is, the lingual force is more likely to exist on the heavy side with softer PDL than without PDL. This effect is very sensitive to the PDL stiffness in the magnitude of E * r/$10^6$. As the outer-arm asymmetry increases, the lingual forces increase correspondingly.

Varying the inner-bow terminal lengths and joint location significantly influenced the lateral force distribution as shown in Figure 5C and 5D. This was evident in the joint offset; when the joint was deviated by 30° from the midline, the heavy side lateral forces ($N_A$) were primarily buccal, which will not cause an undesired cross-bite. When the face-bow joint was offset to the light-force side (α < 90°), the heavy side lateral force $N_A$ changed buccally, even with the softest PDL supporting the molars (Figure 6).

## Soldered-offset Face-bow

For the soldered-offset AHG, the distal forces were plotted in terms of joint location (α = [0, 180°]) in

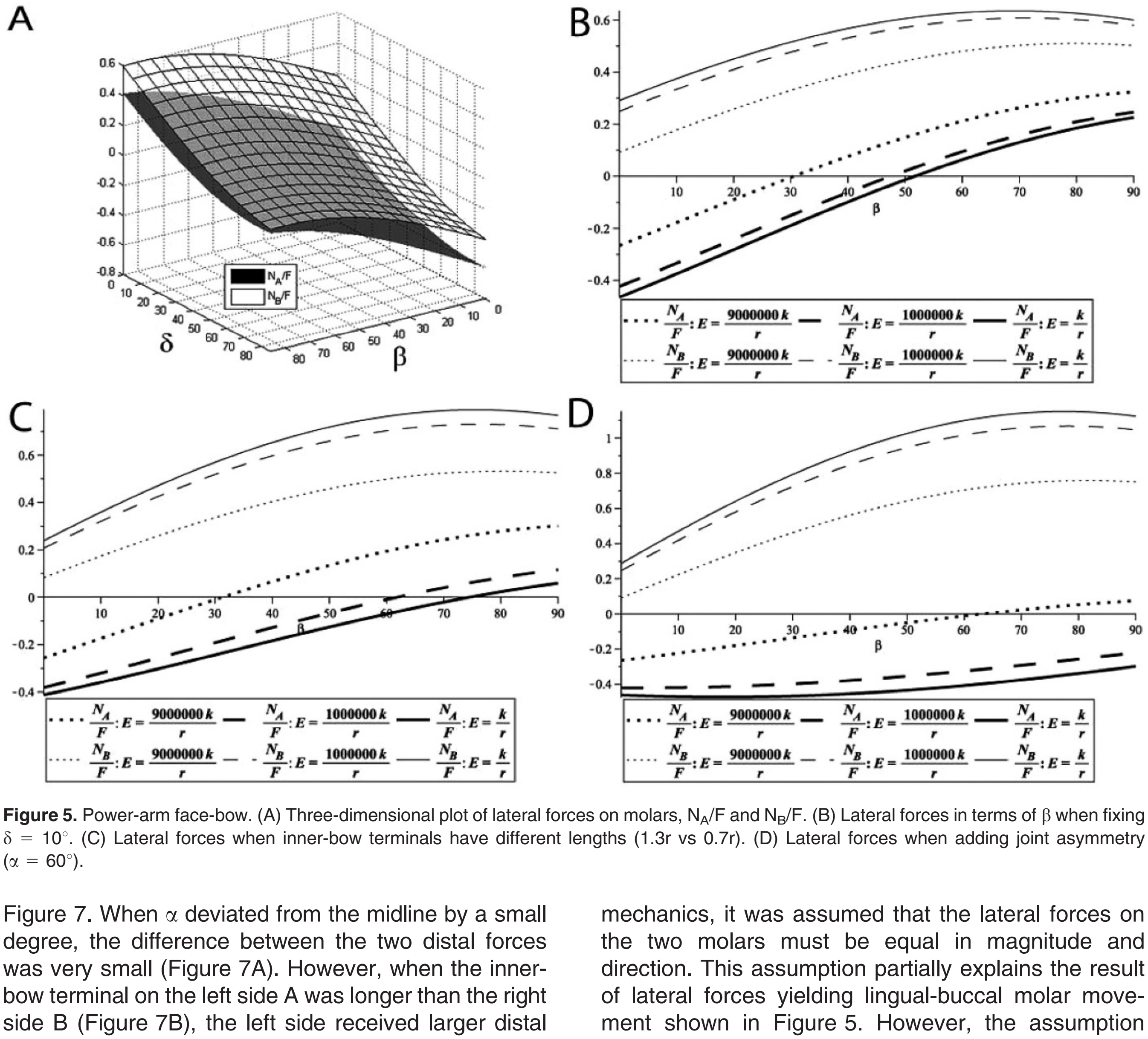


**Figure 5.** Power-arm face-bow. (A) Three-dimensional plot of lateral forces on molars, $N_A/F$ and $N_B/F$. (B) Lateral forces in terms of $\beta$ when fixing $\delta = 10^\circ$. (C) Lateral forces when inner-bow terminals have different lengths (1.3r vs 0.7r). (D) Lateral forces when adding joint asymmetry ($\alpha = 60^\circ$).

Figure 7. When $\alpha$ deviated from the midline by a small degree, the difference between the two distal forces was very small (Figure 7A). However, when the inner-bow terminal on the left side A was longer than the right side B (Figure 7B), the left side received larger distal forces. This effect was more pronounced for cases with stiffer PDL (dash curves) or no PDL (solid curves).

Figure 8 shows that the lateral forces exerted by soldered-offset headgear were of equal magnitude and always in the opposite directions (both pointing to the buccal side). Again, when PDL became soft, the force magnitude was reduced by almost half. In Figure 8B, the inner-bow terminal on the left side was longer than that of the right side, which showed that deviating the joint to the right side ($\alpha < 90^\circ$) would decrease lateral forces.

## DISCUSSION

### Power-arm Face-bow

For 50 years after Haack and Weinstein[8] proposed a mathematical derivation for orthodontic headgear mechanics, it was assumed that the lateral forces on the two molars must be equal in magnitude and direction. This assumption partially explains the result of lateral forces yielding lingual-buccal molar movement shown in Figure 5. However, the assumption cannot be generalized and cannot provide a theoretical explanation for the buccal-buccal movement observed in the current investigation, in vitro tests,[10] and some clinical studies.[6]

Incorporating a simulated PDL into the model offers a broader solution that represents an improved explanation of two scenarios: the high E/k ratio ($\kappa$) to represent the human PDL and the low E/k to simulate the laboratory model without PDL. For the power-arm AHG, we found that, in addition to outer-arm asymmetry, the $\kappa$ would influence the direction of lateral force on the heavy side; that is, the larger $\kappa$ would be more likely to produce lingual-buccal displacement than the buccal-buccal movement. This finding offers a plausible explanation for the broad, inconsistent data previously reported in the literature. Previous laboratory experiments with fixed terminals (no PDL) showed

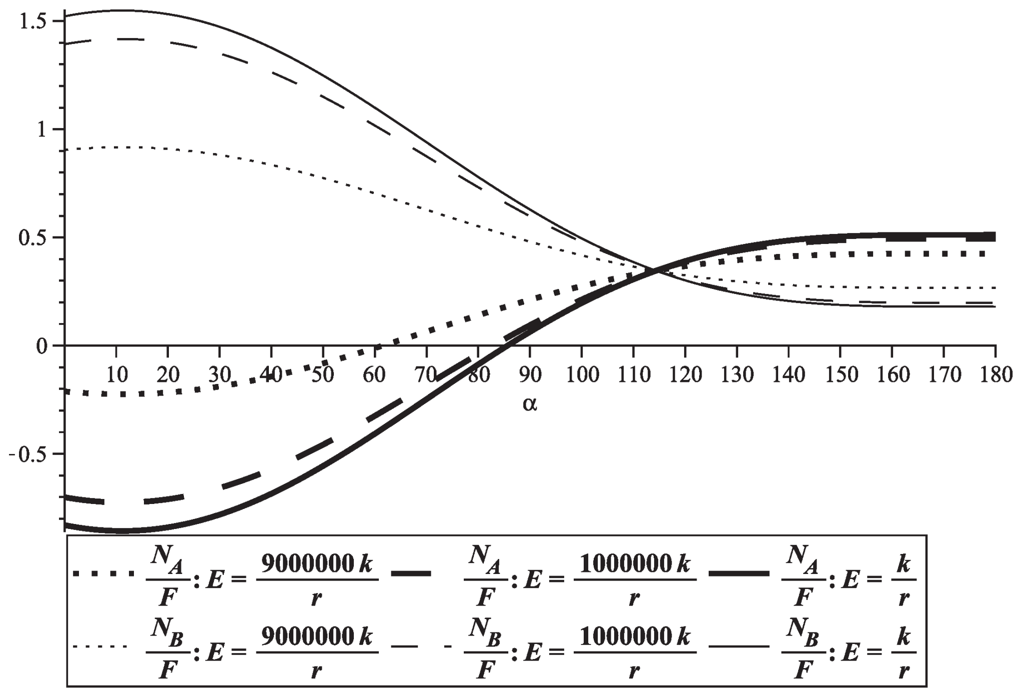


**Figure 6.** Influence of joint location on lateral forces of power-arm asymmetric headgear: setting $\beta = 60^\circ$ and $\delta = 10^\circ$ for power-arm asymmetric headgear.

the two lateral forces acting in opposite directions (buccal-buccal movement).[9,10] Yet, clinical studies measuring lateral forces on human teeth reported that lingual force predominantly occurred on the heavy-force side and buccal force accompanied the light-force side.[6,11] This could be explained by the fact that in vitro experiments did not include PDL simulators in the models, and that a clinical study applying the headgear device to human molars would inherently incorporate PDL effects in the system.

Two previous studies reporting buccal-buccal forces from in vitro experiments showed that the deviation between the magnitudes of the two lateral forces could reach 30%.[9,10] Along with this finding, we predicted 30% and 50% differences for the case of $\delta = 45^\circ$ and $\delta = 10^\circ$, respectively. Our low $\kappa$ model (a large PDL spring constant) could be considered the theoretical predictor for this type of in vitro model, providing reasonable estimates for the laboratory findings.

In addition, Nobel and Waters[9] reported that the magnitude of the lateral force ($N_A$) on the heavy-force side was smaller than that on the light-force side, which is in agreement with Hershey et al.[5] Furthermore, they found that $N_A$ gradually decreased, but remained buccally directed, as the asymmetry increased. Based on the finding, they guessed that $N_A$ might finally become lingually directed under a high degree of asymmetry. Yoshida et al.[6] confirmed this concept using human data, and we verified it with our computer models using the theory of elasticity.

These lateral forces could produce undesired cross-bites. Carefully adding joint asymmetry or inner-bow terminal asymmetry to the power-arm AHG design may avoid such complications. Figure 6 shows that by moving the joint from the midline on the power-arm AHG, the lateral force distribution could be changed and optimized for various treatment plans. Figure 5D illustrates this concept by the fact that the undesired lingual displacement ($N_A$) can be actually reduced or eliminated while the distal forces are only slightly changed (Figure 4D), thereby preserving the unilateral distalization effect of AHG.

In addition, altering the inner-bow terminal lengths may reduce undesired cross-bites. Varying terminal lengths had little effect on distal forces (Figure 4C), but it produced moderate changes to lateral forces (Figure 5C). This could be an effective strategy to reduce the side effects of lateral displacement of the power-arm AHG.

## Soldered-offset Face-bow

Haack and Weinstein[8] predicted that the soldered-offset AHG is noneffective in delivering asymmetric distal forces. Hershey et al.[5] showed that a soldered-offset face-bow only produced a differential distal force of 5%, which they attributed to experimental error. Our analysis reveals that soldered-offset AHG could actually deliver unilateral distal forces with only an insignificant difference when the offset angle was

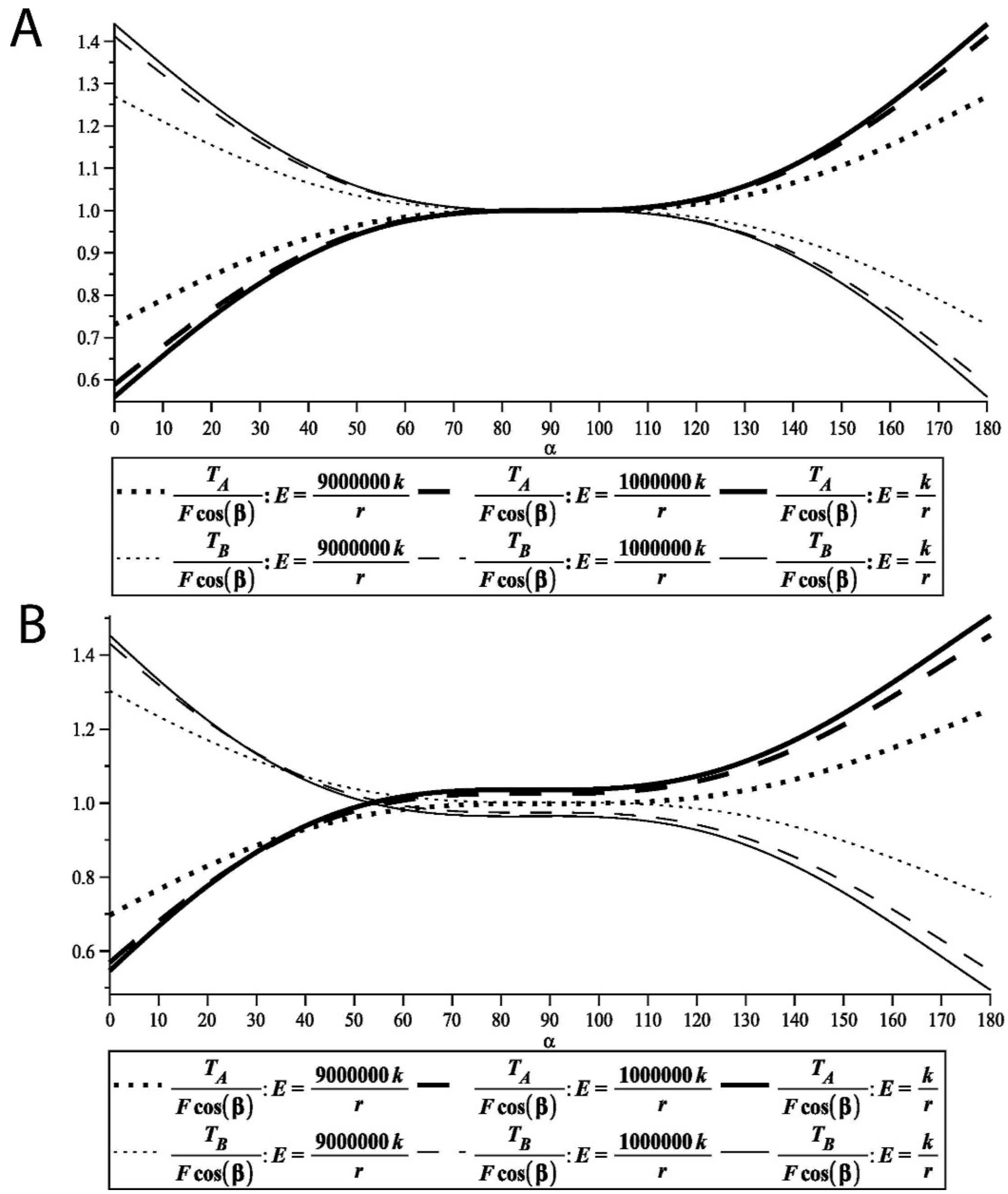


**Figure 7.** Soldered-offset face-bow. (A) Distal molar forces vary as α changes from 0° to 180°. (B) Distal molar forces when inner-bow terminals have unequal length (1.3r vs 0.7r).

small, which suggests that the experimental data (5% differences) of Hershey et al.[5] might be real rather than an error. For the large offset angle, we showed theoretically that face-bow joint offset could produce a 30% difference in distalization forces.

The present study extended analyses of the soldered-offset AHG by incorporating influence of the joint location, PDL stiffness, and inner-bow terminal lengths. It showed that PDL stiffness, particularly in the magnitude of E * r/$10^6$, profoundly altered the magnitude of forces exerted on molars. Variation of the inner-bow terminal lengths also altered the distal force curves (Figure 7B), showing that the longer terminal received more distal forces when the joint offset angle was small. Therefore, elongating the one-side inner-bow terminal could be considered as an approach to exaggerate the distalization effect of small-angle soldered-offset AHG, especially for the case with rigid PDL. This is in agreement with the in vitro study by Brosh et al.,[7] who showed that the longer terminal receives more distal forces.

By measuring deformation/recovery cycles of periodontal ligament, Brosh et al.[14] concluded that 82% of the pre-deformation level was regained in 1 minute (elastic response), and 6% was regained 30 minutes later because of the viscous response. Slomka et al.[12] suggested that interproximal contacts among the posterior teeth portend the importance of the elastic

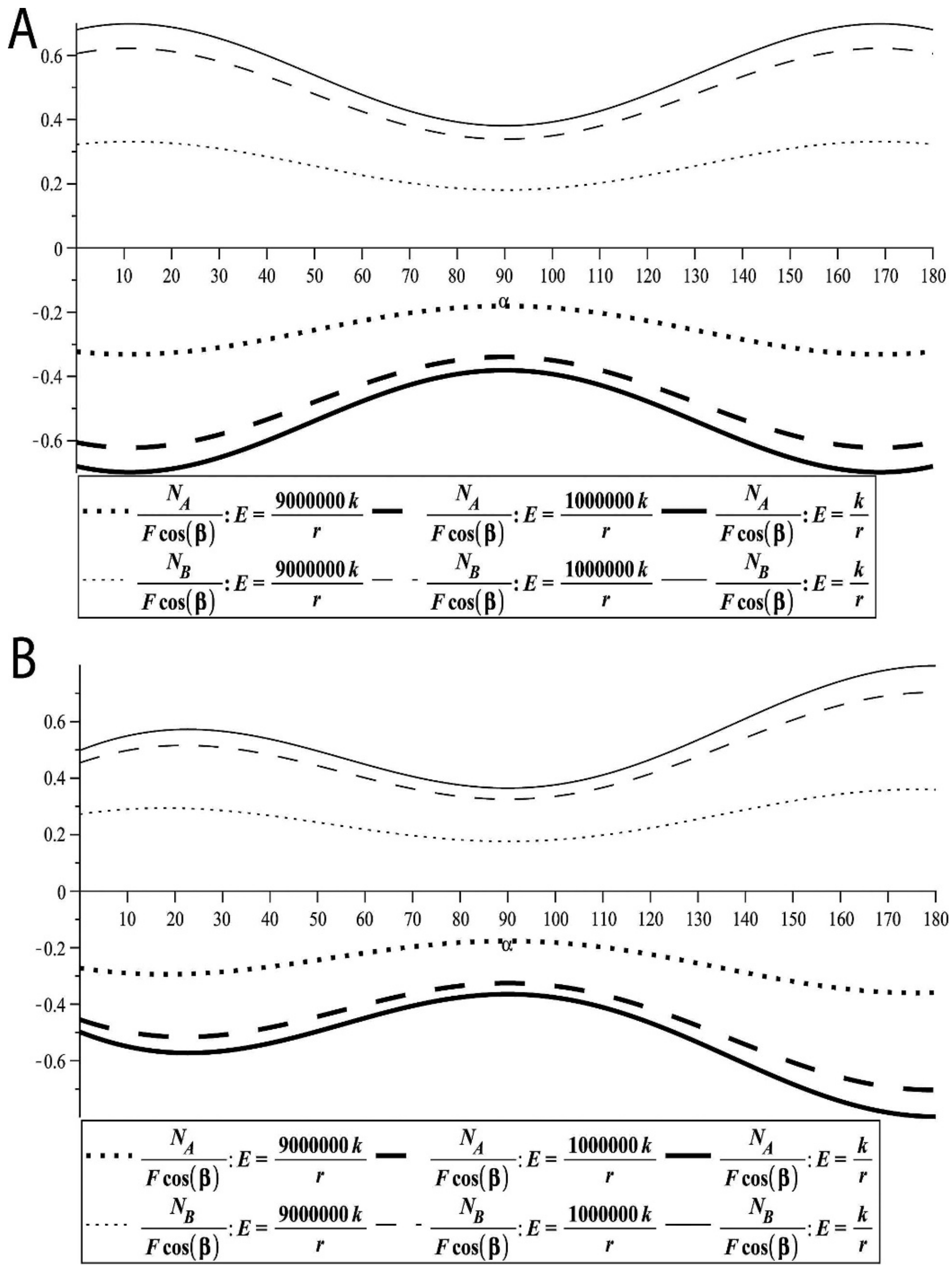


**Figure 8.** Soldered-offset face-bow. (A) Lateral forces on molars in terms of α. (B) Lateral forces when inner-bow terminals have different lengths (1.3r vs 0.7r).

response of PDL in headgear force. Although our model ignored the viscous compartment of PDL, it should provide meaningful prediction of initial loading. However, the model was limited to the two-dimensional configuration of the headgear, including sagittal and transverse dimensions; no vertical components were considered. Other limitations included ignoring rotational spring in the PDL simulation and using parallel rather than divergent bars in the inner bow. Including these factors would make the calculations and analytic solutions too complicated to derive meaningful conclusions.

## CONCLUSIONS

The following conclusions can be drawn from the present study:

- The difference in force magnitude (both distal and lateral) between the two molars was smaller with PDL presence than without.

- The PDL stiffness and the outer-arm asymmetry were the most important variables in determining distal forces exerted by the power-arm AHG, and the effects of joint location and inner-bow terminal length were negligible.
- The soft PDL model showed more prevalent lingual-buccal movement. Adding joint asymmetry to the power-arm AHG could minimize undesired transverse cross-bites.
- The force distribution of the soldered-offset AHG was influenced primarily by PDL stiffness, followed by inner-bow terminal lengths and joint location.

## ACKNOWLEDGMENT

This study was supported by the American Association of Orthodontists Foundation, National Institutes of Health #K08DE018695, and University of North Carolina Research Council.

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