An analytical evaluation of a new spring design for segmented space closure

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The segmented arch technique was designed to deliver light continuous forces to teeth in order to optimize their movement during space closure.[1] Since the pure form of this technique does not use a continuous archwire, it may be particularly desirable because it is also frictionless. It has been suggested, however, that the segmented-arch space-closure technique has not gained universal acceptance within the orthodontic specialty because of numerous biomechanical components that may be difficult to manipulate.[2]

The primary objective in developing a space closure mechanism that does not use a continuous archwire is one of precisely controlling tooth movement. These movements are difficult to achieve because a mesiodistal force applied directly to the facial or lingual surface of a bracket produces a combination of tipping, rotation, and translation as this force acts about the center of resistance of the tooth. The center of resistance is defined as the point at which a force can be applied so that the result is one of pure translation rather than rotation or tipping.[3] The clini-

Abstract

Contemporary segmented-arch space-closure springs require activation techniques that have the side effect of producing a significant amount of geometric nonlinearity. This nonlinearity makes these springs difficult to manipulate because it allows tipping during space closure which may be considered adverse. A new spring mechanism has been designed in response to these difficulties so that the advantages of the segmented-arch technique can be extended to those clinicians presently using simple sliding mechanics as a means of space closure. This spring mechanism has eliminated a significant portion of the geometric nonlinearity by using force-application devices (activators) such as elastics or coil springs as the means of activation. By selecting the right activator it may be possible to close an entire extraction site (approx. 7 mm) with one activation. The proposed mechanism essentially consists of two units: an anchorage unit (M/F = 18 mm), and a translational unit (M/F = 11 mm). These units are combined in order to achieve anterior retraction, posterior protraction, or a combination of the two, which is termed reciprocal attraction. The finite-element method was used in place of bench studies to test the new spring design. The commonly used reciprocal-attraction spring tested with a nearly constant M/F ratio equal to 11 ± 1 mm over an effective force range of 50 gm to 450 gm. The results from the other two tests also showed that precisely controlled couple-to-force (M/F) ratios can be maintained over a wide range of effective forces.

Key Words

Geometric nonlinearities • Segmental spring • Translational unit • Anchorage unit • Applied force • Effective force • Limit of activation • Activator

Submitted: August 1993 **Revised and accepted:** August 1994 Angle Orthod 1995;65(3):187-198

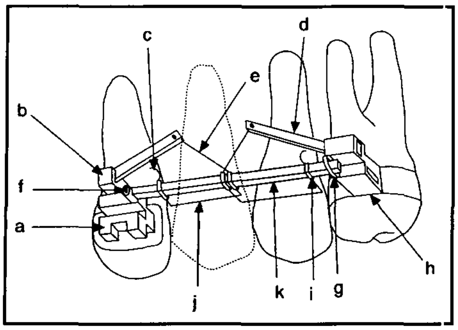


Figure 1

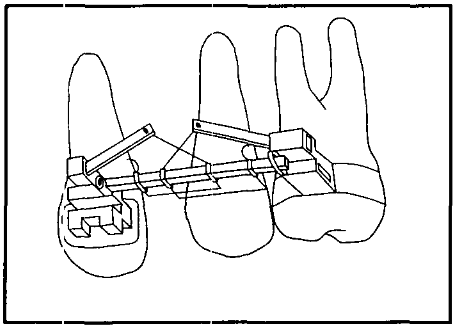


Figure 2

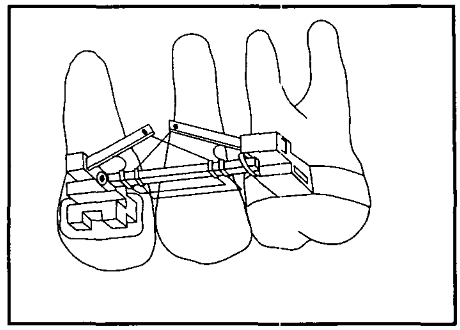


Figure 3

Figure 1
Segmental spring/bracket system
(a) canine bracket
(b) auxiliary tubes vertically oriented
(c) hooks for attachment of activator
(d) auxiliary wires
(e) link
(f) hinge
(g) guide ring
(h) first molar bracket
(i) slide sleeve
(j) sleeve link
(k) stabilizing wire

Figure 2
Segmental spring after controlled tooth movement has taken place

Figure 3
Segmental spring after the space is closed. Note: The canine represents the anterior segment, which consists of multiple teeth.

cian can achieve translational movement by simultaneously applying a couple and a force to the bracket so that the couple-to-force ratio (M/F) is equal to the distance from the center of the applied force to the center of resistance. For the purpose of this paper, "M" will be used to denote a force couple.

It is important to realize, however, that the distance from the applied force to the center of resistance increases as the alveolar support becomes increasingly compromised,[4] and in general, it has been assumed that translation starts to occur at an M/F ratio equal to 10 in a healthy dentition.[5,2] An M/F ratio lower than this suggests tipping, implying that the crown displaces faster than the root. Conversely, a higher M/F ratio suggests root movement, implying that the root displaces faster than the crown.

Large deflections within a structure are classified as geometric nonlinearities.[6] In other words, when a structure undergoes large deflections, its structural stiffness (K), as used in Hooks Law (F=KX), changes because the geometry changes. Take a coil spring, for example, and assume the material is linear elastic: If it starts off at a length of 7 mm, and you stretch the spring to 8 mm, K can be assumed to be constant because the deflections are small. It changes, but not significantly. If, however, you start off at 7 mm and stretch it to 20 mm, K at 20 mm is not the same as it was at 7 mm. The change in K is no longer insignificant. If a structure undergoes a large deflection, and this changing structural stiffness is ignored in the analysis, then the results will not be valid.

The M/F ratio generated by a spring and the type of controlled movement that it can maintain is dependent on the degree of geometric nonlinearity. Current springs used in the segmented arch technique, from this point forward termed *segmental* springs, go through two stages of activation. In the first stage, one end of the spring is lifted into an auxiliary tube, while in the second stage the spring is further activated by cinching back on the wire as it exits the auxiliary tube.[2,5,7] This type of spring activation increases the degree of geometric nonlinearity because the spring is exposed to large deflections as it goes from a passive state to an active state. This is the primary reason why current segmental springs display M/F ratios that increase rapidly as the spring deactivates during space closure.[2,5,7]

Efficient tooth movement by means of light continuous forces is the preferred treatment method in contemporary orthodontics.[8-12] Force levels between 75 and 100 grams can typically achieve single tooth movements on the order of 0.5 mm per week for a short time.[12] Many segmental springs, however, are less than optimal because of the design, material properties, or a combination of the two. Springs made of materials such as stainless steel, for example, have high load-deflection rates as a result of the material's high stiffness; they are of low efficiency and require frequent activation.[2,7,13] The incorporation of helices into the design of a spring or the use of materials with low stiffness have helped to reduce the load-deflection rates to an efficient level.

The M/F ratios generated by current segmental springs do not stay reasonably constant over a practical range of tooth movements and may allow tipping during space closure.[5,7] A continuous archwire has been used in conjunction with a segmental spring in order to circumvent these tipping tendencies. Unfortunately, however, this produces sliding friction between the bracket and archwire.[2] As a result of the short lever-arm inherent within the bracket, this sliding friction may significantly reduce the efficiency of the spring mechanism such that tooth movement approaches that experienced with purer forms of continuous arch treatment where a spring is not used to eliminate some of the friction.

During space closure, anterior retraction, posterior protraction or a combination of the two—termed reciprocal attraction—may be desired.[5] A

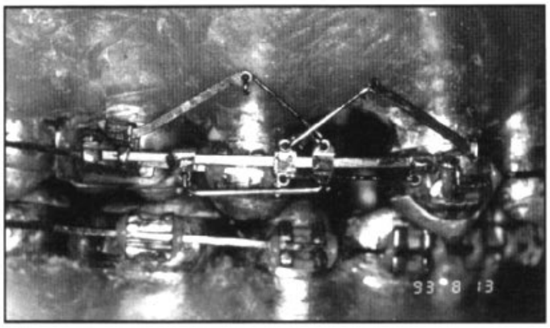


Figure 4

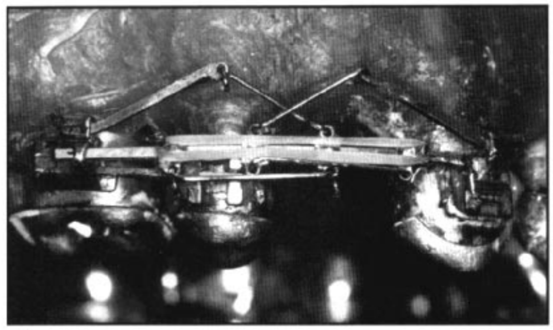


Figure 5

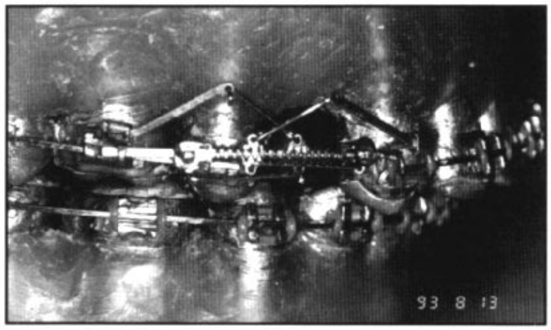


Figure 6

Figure 4
Prototype inactivated

Figure 5
Prototype with an "elastic" activator

Figure 6
Prototype with a coil spring activator

segmental spring mechanism should be able to provide these controlled movements by differentially controlling the anterior and posterior segments.[5] Ideally, this mechanism should be able to deliver these types of controlled movements without round-tripping or relying on the use of a continuous archwire for guidance.

This paper describes the design and testing of a new type of segmental spring mechanism that can maintain a relatively constant M/F ratio throughout space closure without the use of a continuous archwire. The objective of such a design is to extend the advantages of the segmented-arch technique to those clinicians presently using simple sliding mechanics as a means of space closure.

Design

The appliance

A new segmental spring mechanism has been designed and is represented schematically in Figures 1, 2, and 3. It is also represented by Figure 4 in the form of a prototype.

The segmental spring mechanism essentially consists of two halves: one half for retracting the anterior segment (multiple teeth) and the other for protracting the posterior segment. Each half consists of an auxiliary wire (Figure 1d), link (Figure 1e), and sleeve link (Figure 1j). The links are guided along a stabilizing wire (Figure 1k) which spans the modified first molar and canine brackets. The stabilizing wire is hinged on one end (Figure 1f) and guided on the other by an oversize ring (Figure 1g) so that a force couple will not be transferred from the stabilizing wire to the teeth. In other words, the stabilizing wire can transfer vertical forces to the brackets without rotational forces (force couples).

The modified brackets have their auxiliary tubes oriented such that bending will take place around the strong axis rather than the weak axis (Figure 1b). This means that the long dimension of the rectangular auxiliary wire is oriented vertically rather than horizontally in the auxiliary tube.

The spring mechanism is not activated by traditional means. It is activated, instead, by stretching elastic (Figure 5), coil spring (Figure 6), or some other type of force-application device (activator) between two hooks (Figure 1c). The segmental spring mechanism then transfers this force through the sleeve link (Figure 1j), link (Figure 1e), auxiliary wire (Figure 1d), and then to the teeth producing controlled tooth movements (Figures 2 and 3).

The spring mechanism is designed so that the angle between the auxiliary wire (Figure 1d) and link (Figure 1e) changes minimally during tooth movement. The applied force from the activator causes structural deflections within the mechanism, thus leading to the angle change. This in turn leads to a fluctuation in the M/F ratio because of the change in geometry. A large deflection analysis is necessary so that this changing geometry can be taken into consideration.

Preliminary design

A combination of intra-arch anchorage or translational movement may be desired in the anterior or posterior segments of an arch in which one or more teeth have been extracted. In order to achieve this, two geometric configurations were used. These configurations are defined and termed the translational and anchorage units. In this paper, interarch anchorage was assumed to occur at an M/F ratio equal to 18 mm, and translational movements were assumed to occur at an M/F equal to 11 mm. Preliminary geometric layouts for the translational and anchorage units were determined using an equation that was derived in terms of a target M/F ratio (Equation 6, Appendix 1). Since the actual M/F ratio determined by testing would be less than the target M/F ratio due to structural deflections (nonlinearities), a higher M/F ratio was used to determine the preliminary layouts. The final layouts were verified through tests using the finite element method and are shown in Figure 7A.

The cross-sectional geometry of the auxiliary wire (Figure 1d) in both the translational and anchorage units was based on a derived equation that describes the maximum longitudinal force that can be applied without exceeding the elastic limit of the material (Equation 7, Appendix 2). Forces which exceed the elastic limit of the material would cause permanent deformation of the spring mechanism's geometry, which in turn would affect its force system and ultimately the types of controlled movements that could be maintained. The equation was derived in terms of the target M/F ratio and elastic limit of the material. The actual M/F ratio acting on the auxiliary wire, as determined through finite-element testing, was checked using this equation to ensure that an elastic response had taken place.

Computer-aided testing using the finite element method

Geometry

Before a test was conducted using the finite element method, the geometries of the translational and anchorage units were defined. The geometries of the units were modeled using Ideas (Structural Dynamics Research Corp.), a general purpose finite element software package. The geometry of each unit was modeled with 42 elements and 43 nodes. Two-dimensional beam elements were used to mesh the geometry, and each beam element had 3 degrees of freedom at each node: one rotational and one translational in both the horizontal (x) and vertical (y) directions. The ends of the link (Figure 1e) were released in the rotational degree of freedom on both ends because the link carries an axial force only. The deflection of the stabilizing wire that spans between the modified canine and first molar brackets was modeled using a rigid surface gap element that was given a stiffness in the vertical (y) direction. Since there are sliding components within the spring mechanism, the rigid surface gap element used in each geometry type was given frictional capability so that the resistance could be taken into consideration. A coefficient of kinetic friction equal to .14 for stainless steel against stainless steel was used.[14]

Cross-sectional and material properties

The translational and anchorage units were modeled out of stainless steel. A module of elasticity equal to 2.00×10^7 gm/mm^2 was used.[15] The cross-sectional properties of the auxiliary wires (Figure 1d) in both the translational and anchorage units were based on equation 7 (Appendix 2) with an elastic limit for stainless steel equal to 140,614 gm/mm^2.[1,15] These wires were modeled as .5461 x .7112 mm (.0215 x .028 in.) stainless steel rectangular wire with the larger dimension taken as the height. A moment of inertia equal to .0164 mm^4, and a cross-sectional area equal to .388 mm^2 were used. The links (Figure 1e) were modeled as .3556 mm (.014 in.) diameter stainless steel wire with a cross-sectional area equal to .0993 mm^2. The stabilizing wire (Figure 1k) was a .5461 x .7112 mm (.0215 x .028 in.) stainless steel rectangular wire.

Assumptions

In any finite element analysis, assumptions need to be made for the purpose of simplicity. There is nothing wrong with this as long as the assumptions made have a relatively insignificant effect on the results. The insignificant nature of the assumption is generally a judgment call from an experienced designer.

In the analysis of this spring the following assumptions were made: (1) It was assumed that the spring material did not exceed its elastic limit. This assumption was verified using equation 7 in Appendix 2. If it had been wrong, then the forces reported would be invalid. (2) It was assumed that the spring would operate in a two-dimensional plane. This is clearly not the case, because it is adapted to an arch form. However, this fact was considered to be insignificant because the curvature was slight. (3) The deflections within the spring mechanism's structure were considered to be the largest when the teeth are farthest apart, i.e., the point at which space closure is initiated. Since structural deflections have such a significant effect on the M/F ratios, only this case was considered. (4) Friction was taken into consideration. However, its magnitude is independent of whether space closure is being initiated or is complete. The friction is dependent on the magnitude of the applied force only. So, if the applied force decreases as the space closes, so does the friction.

Analyses

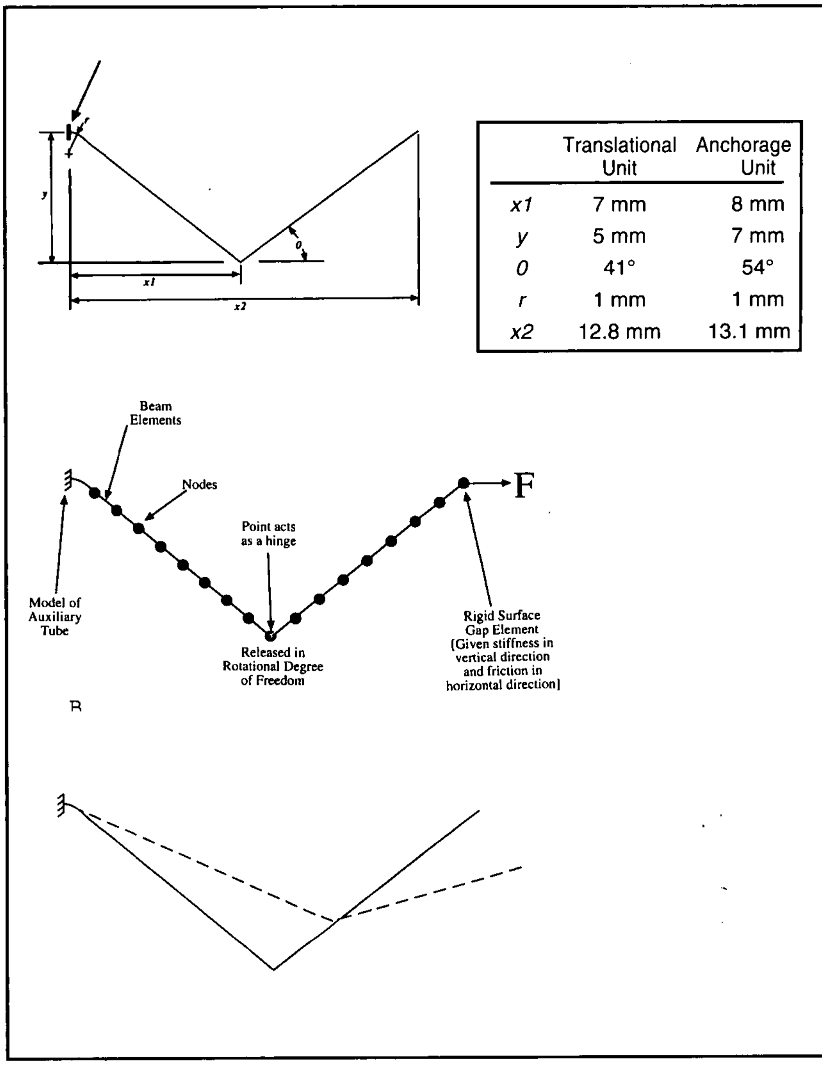
Ansys (Version 4.4a; Swansin Analysis Systems), a general purpose finite element package, was used to analyze both the translational and anchorage units. Loads from 50 to 450 grams in steps of 50 grams were applied to each unit. The nonlinearities arising from the large deflections within the structure induced by the applied loads were taken into consideration by using a Full Newton Raphson Method.[16] Since the stress in the stainless steel varies linearly with strain up to its elastic limit, material nonlinearities were not taken into consideration.[15] All computations were performed on a VAX-750 computer. A typical finite element model for one of the units used to produce controlled tooth movement is presented in conjunction with the structural deflections resulting from an applied force (Figure 7B-C).

Results

The numeric results from both the translational and anchorage units were combined so that anterior retraction, posterior protraction, or reciprocal attraction could be achieved. These are presented in Table 1. The spring was designed to be used in either the maxillary or mandibular arch, and the results of the analyses for each arch are presented in a format suggested by Burstone.[5,17] This format has been slightly modified to take into account the friction developed by the sliding components within each segmental spring mechanism. The applied force represents the force actually delivered to the segmental spring (at hooks Figure 1c) by the activator, while the effective force represents the force actually applied to the teeth after frictional losses. In the case where anterior retraction was desired, a translational unit in the anterior position (alpha) was combined with an anchorage unit placed in the posterior position (beta). The opposite was true in the case where posterior protraction was desired in which an anchorage unit in the anterior position was combined with a translational unit placed in the posterior position. In the case where reciprocal attraction was desired, two translational units were combined by placing them in both the anterior and posterior positions.

An examination of the data for the frequently used reciprocal attraction spring shows an M/F ratio equal to 12.0 mm at an applied force of 50 grams that decreases to 10.4 mm at an applied force of 450 grams in both the alpha and beta positions. This means that as the activating element deactivates, the M/F ratios go up. The force in the M/F ratio is the effective horizontal force that is transferred to the teeth after frictional losses. This force is noted as the alpha or beta effective horizontal force. A graph displays the consistency in the M/F ratios in both the alpha and beta positions over a wide range of applied forces (Figure 8). A further examination of the data shows that the effective horizontal forces start at 39 grams for an applied force of 50 grams and increase to 374 grams for an applied force 450 grams. Frictional losses account for the differences between the applied and effective forces. The data also show that the effective vertical forces are equal to 0 grams at all applied force levels. This is because the vertical force transferred by the stabilizing wire (Figure 1k), and the auxiliary wire (Figure 1d), are equal and opposite such that the resultant or effective vertical force acting on the teeth is equal to zero grams.

An examination of the data for the anterior-retraction or posterior-protraction springs shows a narrow fluctuation in the M/F ratios at both the alpha and beta positions. In the posterior protraction spring, the beta M/F ratio starts off at 12.4 mm for an applied force of 50 grams and drops to 10.6 mm at an applied force of 450



	Translational Unit	Anchorage Unit
x1	7 mm	8 mm
y	5 mm	7 mm
θ	41°	54°
r	1 mm	1 mm
x2	12.8 mm	13.1 mm

Figure 7A-C

Figure 7A-C
A. Geometric configuration of translational and anchorage unit before applied force.

B. Typical finite element model of translational and anchorage unit.

C. Geometry of translational or anchorage unit before (solid) and after (dashed) testing.

Table 1
Result of activation for three conditions of maxillary/mandibular segmental springs

Applied Force (gm)	Effective Forces α–Horizontal force (gm)	β–Horizontal force (gm)	Vertical force (gm)	α-moment (gm-mm)	β–moment (gm-mm)	α-M/F (mm)	β–M/F (mm)
Maxillary/mandibular anterior retraction spring							
50	36	34	9	481	731	13.4	21.5
100	73	69	17	947	1426	13.0	20.7
150	112	105	24	1402	2088	12.5	19.9
200	150	143	30	1844	2727	12.3	19.1
250	190	181	34	2275	3340	12.0	18.5
300	230	221	39	2695	3935	11.7	17.8
350	271	260	43	3105	4512	11.5	17.4
400	313	301	46	3506	5073	11.2	16.9
450	355	342	49	3898	5618	11.0	16.4
Maxillary/mandibular reciprocal attraction spring							
50	39	39	0	481	481	12.0	12.0
100	80	80	0	947	947	11.8	11.8
150	121	121	0	1402	1402	11.6	11.6
200	162	162	0	1844	1844	11.4	11.4
250	203	203	0	2275	2275	11.2	11.2
300	245	245	0	2695	2695	11.0	11.0
350	288	288	0	3105	3105	10.8	10.8
400	331	331	0	3506	3506	10.6	10.6
450	374	374	0	3898	3898	10.4	10.4
Maxillary/mandibular posterior protraction spring							
50	36	39	9	731	481	20.2	12.4
100	73	78	17	1426	947	19.5	12.2
150	111	118	24	2088	1402	18.8	11.9
200	150	158	30	2727	1844	18.1	11.7
250	190	198	34	3340	2275	17.6	11.5
300	230	240	39	3935	2695	17.1	11.2
350	271	282	43	4512	3105	16.7	11.0
400	312	325	46	5073	3506	16.2	10.8
450	354	367	49	5619	3898	15.9	10.6

grams. The alpha M/F ratio starts off at 20.2 mm for an applied force of 50 grams and drops to 15.9 mm for an applied force of 450 grams. Similar results are presented for the anterior retraction spring. However, the two springs are not exactly opposites due to the effects of friction. The results for both springs have been graphed to demonstrate the narrow fluctuations in the alpha and beta M/F ratios (Figures 9 and 10). The data also shows that vertical forces are present. This is because of the differential moments that exist between the alpha and beta positions.

The friction can be calculated as the difference between the applied force and the effective horizontal force from the data shown in Table 1. The friction is coming from a number of places within the mechanism. The slide sleeves (Figure 1i) create friction as they slide on the stabilizing wire (Figure 1k). The binding of these sleeves is not a problem because they are short enough to track

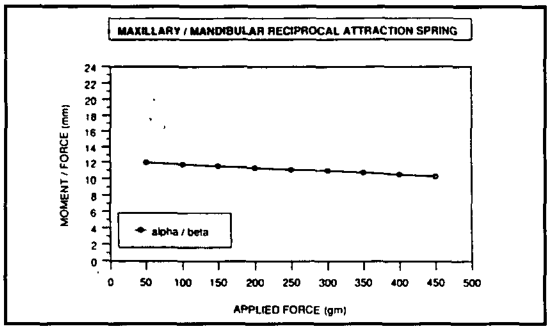


Figure 8

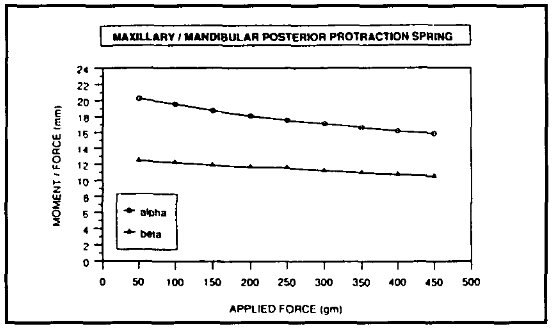


Figure 9

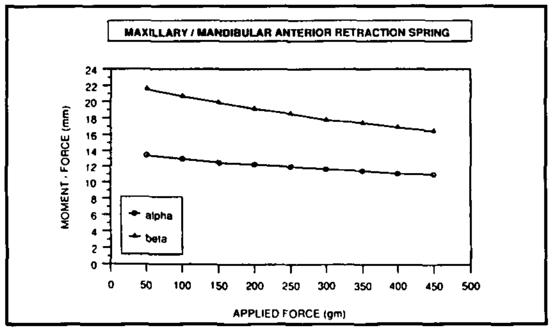


Figure 10

Figure 8
Moment/force ratio versus applied force for reciprocal closure.

Figure 9
Moment/force ratio versus applied force for posterior protraction.

Figure 10
Moment/force ratio versus applied force for anterior retraction.

around a radius. It's kind of like train cars on a train track. Remember this is not a two-dimensional system because the mechanism is adapted to an arch form. Friction is additionally created between the oversized ring (Figure 1g) and the stabilizing wire (Figure 1k). The stabilizing wire transfers vertical force. Hence, this wire is pressed against the part of the oversize ring adjacent to the auxiliary tube. Friction is therefore created when the teeth move together because the stabilizing wire slides through the ring. It does not engage the ring by means of a force couple to create friction by some sort of binding action. The whole purpose of the ring being oversize is so a moment will not be transferred to the bracket. The stabilizing wire can be clipped off as it comes through the ring so it does not cause the patient discomfort.

Discussion

The type of activator used in conjunction with the spring will determine the efficiency at which controlled movements take place. The hooks (Figure 1c) can be spaced as far apart as the interbracket distance between the modified canine and first molar auxiliary tubes. This spacing allows for the use of low load-deflection-rate springs that may require large activations in order to generate enough force to move teeth, but have the desirable quality of being able to provide force levels that decay slowly over a wide range of tooth movements. It may be possible to close an extraction space of 7 mm in just one activation by using the correct activator in conjunction with the spring mechanism.

Nickel-titanium-alloy springs have been shown to provide nearly constant forces over large activations and can be used as activators.[18] A force between 270 and 360 grams might be ideal for en masse (multiple teeth) space closure with just one activation. Approximately 20 grams per 100 grams of applied force would be dissipated by frictional losses within the segmental spring mechanism.

Rotations from an occlusal view (first order rotations) were taken into consideration in the spring design. The posterior segments are connected lingually by the use of a transpalatal archwire (Figure 11). This prevents the posterior segments from rotating during space closure. Rotations of the anterior segment are controlled similarly by using an archwire to tie the anterior teeth together. If single tooth canine retraction is desired, then first order rotations can only be controlled with an archwire that connects the canine to the posterior segment.

The free ends of the anterior and posterior auxiliary wires (Figure 1d) are spaced apart so that the distance between them is greater than the size of the extraction space. If this were not the case then space closure could be impeded as it nears completion. Therefore, tooth anatomy, as it relates to the mesial distal dimension, is a very important parameter in the layout of the spring mechanism's geometry.

Haskell, Spencer, and Day[2] designed a spring that offers improved reliability. The spring's reliability, as it relates to preventing the teeth from tipping, was achieved by using it in conjunction with a continuous archwire. This was essentially a modification of simple sliding mechanics in which a spring is used to relieve some of the friction experienced with purer forms of the technique in which no spring is used. An evaluation of the data presented for the reciprocal attraction spring shows an M/F ratio of approximately 20 mm at 50 grams of horizontal force that decreases to 5 mm at 450 grams of force. This is a fluctua-

Figure 11
Prototype inactivated from an occlusal view showing trans-palatal archwire.

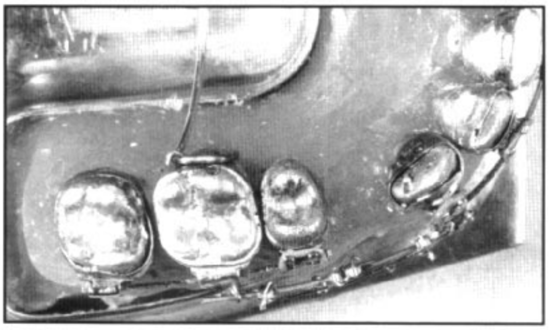


Figure 11

tion in the M/F ratio equal to 15 mm as compared with 1 mm for the same spring presented in this paper. Therefore, the continuous archwire plays a very important role in preventing the teeth from tipping.

The efficiency of the stainless steel spring proposed previously[2] may have been compromised by the material properties. The problem is that stainless steel has a much larger modulus of elasticity than other materials. In order to compensate for this, a number of helices had to be incorporated into its design. Unfortunately, the spring still has a load-deflection rate which is reported at approximately 225 gm/mm for the reciprocal attraction spring. In addition to the load deflection rate, the limit of activation appears to be 2 mm according to equation 7, Appendix 2. The limit of activation is defined as the maximum amount a spring can be activated without exceeding the elastic limit of the material. This means that all the data reported above 2 mm of activation would be in excess of the material's elastic limit, hence not clinically feasible. Because the load deflection rate is so sensitive and the limit of activation is only 2 mm, the clinician would most likely over-activate the spring by accident, deform it slightly (exceed the elastic limit of the material), and thus change its force characteristics. The segmental spring presented in this paper uses a different activation technique. The clinician could select a high-load deflection rate or a low-load deflection rate activator. The limit of activation would not be exceeded unless the clinician used an activator that exceeded 450 gm of force.

Burstone[5] recommends using a segmental spring without a continuous archwire. The spring is more efficient than the Haskell-Spencer-Day spring, but it is not more reliable. Like the Haskell-Spencer-Day spring, this spring's reliability is linked directly to its activation technique; as a result, its M/F ratio changes rather significantly as tooth movement takes place. Burstone addressed the wide fluctuation in the M/F ratio by suggesting that the spring is designed to move the teeth in a precise manner by "round-tripping" the segments. We disagree with this philosophy and have demonstrated analytically that translational tooth movements may be able to take place without round tripping the segments.

The load-deflection rate reported for Burstone's reciprocal attraction spring is approximately 45 gm per mm, which can be attributed to the beta-titanium alloy wire of which it is made. This low load deflection rate significantly reduces the risk of over-activating the spring as would be the case if the same spring were made of stainless steel. A nickel-titanium-alloy spring might offer even better performance characteristics, in terms of efficiency, than a beta-titanium alloy spring because the nickel-titanium alloy can provide nearly constant force levels. Therefore, when a nickel-titanium-alloy coil spring is used as an activator with this new spring, efficiency is significantly increased. It may even be possible to close an extraction space with just one activation. As a matter of economics, however, an activator made of a less expensive material may be desired. This gives the spring mechanism presented economic versatility without compromising reliability.

Conclusion

By reducing geometric nonlinearities, the reliability of a segmental spring can be significantly improved. This reliability should be verified through test results that show a narrow deviation in the alpha and beta M/F ratios over a wide range of effective forces. The deviation in the M/F ratios generated by a segmental spring should not be linked to the material out of which it is made. Therefore, a segmental spring mechanism must fulfill two functions: (1) The spring's geometry should be such that nearly constant M/F ratios are generated. (2) The spring mechanism should provide a means for efficient tooth movement. By separating these two important functions, a segmental spring mechanism, such as the one described in this paper, can extend the advantages of the segmented arch technique to those clinicians presently using simple sliding mechanics as a means of space closure.

This new space-closure mechanism should be thought of as being between pure segmental mechanics and pure simple sliding mechanics. It was designed using both schools of thought, and as a next step in its evolution should undergo refinement in its design, wax typodont testing, and extensive clinical trials so that it can become a valuable tool for the clinician.

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Appendix 1

The purpose of this appendix is to derive an equation that will serve as a starting point for the dimensions of the translational and anchorage units.

The following equation represents the sum of the moments about the auxiliary tube (Figure A1):

$$M = X(F \sin \theta) + Y(F \cos \theta) \qquad (1)$$

The moment can be represented in terms of the M/F_x ratio. F in this ratio is the horizontal force F_x acting on the bracket and delivered from the auxiliary wire. The force couple (M) is the force couple acting on the bracket from the auxiliary wire.

$$M = \left(\frac{M}{F_x}\right)_{ratio} F_x \qquad (2)$$

Equation (2) can be thought of as multiplying the top and bottom of the force couple(M) in equation (1) by F_x

Substituting equation (1) into equation (2) gives

$$\left(\frac{M}{F_x}\right)_{ratio} F_x = x(F \sin \theta) + y(F \cos \theta) \qquad (3)$$

Since F_x is a component of F, it can be written as

$$F_x = F \cos \theta \qquad (4)$$

Substituting equation (4) into equation (3) gives

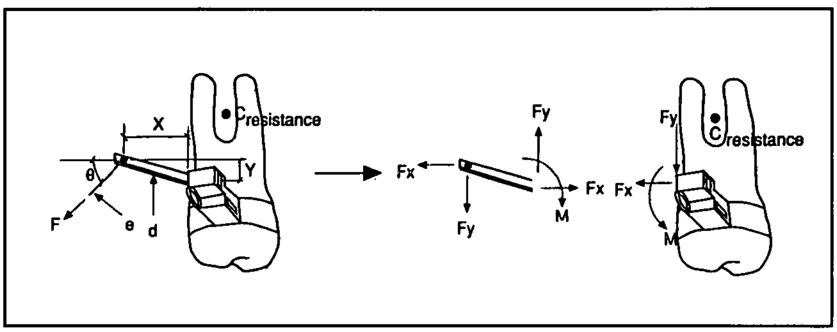
$$\left(\frac{M}{F_x}\right)_{ratio} F \cos \theta = x(F \sin \theta) + y(F \sin \theta) \qquad (5)$$

Rearranging equation (5) gives

$$\theta = \tan^{-1}\left(\frac{\left(\frac{M}{F_x}\right)_{ratio} - y}{x}\right) \qquad (6)$$

Equation (6) can now be used to calculate the orientation of the coupling mechanism(Figure 1e) with respect to the horizontal given the desired M/F ratio and the x and y dimensions of the auxiliary wire (Figure 1d). It is important to realize that equation (6) is an exact geometric relationship. This relationship will change when the spring mechanism is subjected to the structural deflections, and as a result the M/F ratio will also change. The degree to which the M/F ratio will vary depends on how stiff the spring mechanism is. The stiffness largely depends on the material, cross sectional geometry, and length of the auxiliary wire.

Figure A1
Free body diagram of translational or anchorage unit.



Appendix 2

Appendix 1 and Appendix 2 are not related. The reader should not relate the notations used in Appendix 1 to Appendix 2. The first appendix was used to determine a starting point for the geometric layout of the translational and anchorage units. Appendix 2 looks at a cross-section of the auxiliary wire before it enters the auxiliary tube. This is done so that a starting point for the cross-sectional geometry of the auxiliary wire can be determined, such that the wire material does not exceed its elastic limit. It also serves as a check for the assumption of linear elasticity. Remember, if the material exceeds its elastic limit, the auxiliary wire will be permanently deformed and the spring will not behave as predicted.

The elastic limit on a cross-section of material with an axial force and a bending moment can be determined by the following (Figure A2):

$$\sigma_{el} = \frac{MC_{max}}{I} + \frac{F_{max}}{A} \tag{1}$$

Where:

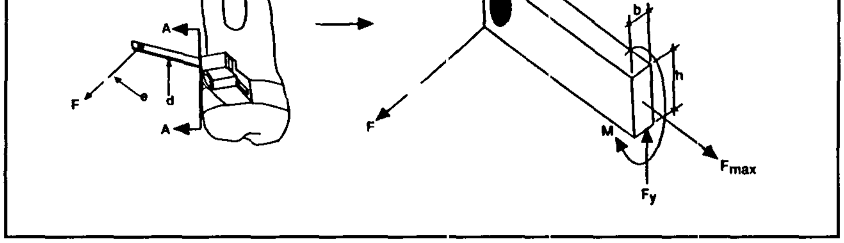
σ_{el} = elastic limit of the material $(\frac{gm}{mm^2})$

-M = force couple acting on the cross-section (gm-mm)

-I = moment of inertia of the cross-sectional area about the centroidal axis of which bending is taking place (mm^4)

-c_{max}maximum perpendicular distance from the centroidal axis about which bending is occurring to a point of maximum normal stress (mm)

Figure A2
Free body diagram of auxiliary wire in section.



-$F_{max}$is the maximum allowed force before the elastic limit is exceeded(gm) (F_x in Appendix 1)

-A is the cross-sectional area (mm^2)

For rectangular cross-sections:

$$I = \frac{bh^3}{12} \tag{2}$$

Where:

-h = is the larger dimension of the cross-section perpendicular to the centroidal axis (mm)

-b = is the width of the cross-section parallel to the centroidal axis (mm)

Note:b and h would be the same for square cross sections.

Combining (1) and (2) gives:

$$\sigma_{el} = \frac{12MC_{max}}{bh^3} + \frac{F_{max}}{A} \tag{3}$$

c_{max} for a rectangular section is equal to $\frac{h}{2}$.

The area "A" for a rectangular cross-section is equal to b x h. Substituting for c_{max} and A in (3) gives:

$$\sigma_{el} = \frac{6M}{bh^2} + \frac{F_{max}}{bh} \tag{4}$$

M can be substituted by the following:

$$M = (\frac{M}{F_{max}})_{ratio} \times F_{max} \tag{5}$$

Combining (4) and (5):

$$\sigma_{el} = \frac{6(\frac{M}{F_{max}})_{ratio} F_{max}}{bh^2} + \frac{F_{max}}{bh} \tag{6}$$

Rearranging (6) gives:

$$F_{max} = \frac{\sigma_{el}(bh^2)}{h + 6(\frac{M}{F_{max}})_{ratio}} \tag{7}$$

Equation (7) can be applied to various combinations of M/F_{max} ratios, cross-sections of wire and elastic limits of material to determine the maximum horizontal force the auxiliary wire can provide to the bracket without permanently deforming its structure. Shear (vertical) forces acting at the point of section were not considered.