REVIEW ARTICLE

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Factors influencing efficiency of sliding mechanics to close extraction space: a systematic review

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Structured Abstract
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Objectives – To review recent literature to determine strength of clinical evidence concerning the influence of various factors on the efficiency (rate of tooth movement) of closing extraction spaces using sliding mechanics.
Design – A comprehensive systematic review on prospective clinical trials. An electronic search (1966–2006) of several databases limiting the searches to English and using several keywords was performed. Also a hand search of five key journals specifically searching for prospective clinical trials relevant to orthodontic space closure using sliding mechanics was completed.
Outcome Measure – Rate of tooth movement.
Results – Ten prospective clinical trials comparing rates of closure under different variables and focusing only on sliding mechanics were selected for review. Of these ten trials on rate of closure, two compared arch wire variables, seven compared material variables used to apply force, and one examined bracket variables. Other articles which were not prospective clinical trials on sliding mechanics, but containing relevant information were examined and included as background information.
Conclusion – The results of clinical research support laboratory results that nickel-titanium coil springs produce a more consistent force and a faster rate of closure when compared with active ligatures as a method of force delivery to close extraction space along a continuous arch wire; however, elastomeric chain produces similar rates of closure when compared with nickel-titanium springs. Clinical and laboratory research suggest little advantage of 200 g nickel-titanium springs over 150 g springs. More clinical research is needed in this area.

Key words: orthodontics; sliding mechanics; space closure; systematic review

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Introduction

Extraction of teeth is a common orthodontic procedure to minimize crowding or to accomplish maximum interarch interdigitation. Methods and materials to close the resulting space can be influenced by manufacturers' claims for products and clinical training and experience. However, decisions to purchase new products or to use particular methods should be based on strong evidence of clinical efficiency.

Understanding of the influence of these products or materials on space closure requires a basic understanding of mechanics.

Closure of extraction space using orthodontic appliances is usually accomplished in one of two general approaches. The first involves using 'closing loops' in a continuous or segmented arch wire. Once the wire is engaged in the brackets, the spring is activated with a distalizing force. The springback properties of the wires cause the springs to 'close' producing the forces necessary to initiate and continue tooth movement. The second technique, termed sliding mechanics, involves pushing or pulling a tooth along a continuous arch wire with a force delivery system adequate to produce and sustain movement. Generally, either a coil spring or a form of elastomeric material is used to accomplish the latter. Both techniques present advantages and disadvantages.

Ideally, space closure results in translation of teeth with little or no tipping. However, the closure force is usually occlusal and buccal to the center of resistance of the tooth and produces moments, resulting in tipping and rotation of the tooth in the direction of the pull. If a closing loop is used on a segmental wire, the wire requires compensating bends to produce translation and counteract the undesired moments. Clinicians frequently place closing loops in continuous arch wire rather than segmental arch wire to minimize the undesired moments. When space is closed with tipping rather than translation, additional time is usually required to upright the roots under the crowns. The advantage to a closing loop is that friction between the arch wire and the bracket or ligature is removed, minimizing the effect of friction on movement.

In sliding mechanics, the stiffness of the continuous arch wire supports the tooth, keeping it from tipping uncontrollably when a force is placed on it. The tooth will tip until the wire contacts the bracket at opposite corners of the slot, stopping the tipping motion. This contact with the corners of the bracket slot appears to produce a counteracting moment that pulls the root of the tooth in the same direction as the crown moved. Thus, a 'ratcheting' movement of the tooth occurs producing net translation, requiring less time for root uprighting following space closure(1). Numerous *in vitro* studies (2–5) suggest that variables such as coefficient of friction, size of wire, and force degradation affect the efficiency of sliding mechanics. Attempts to maximize efficiency of sliding mechanics by controlling these variables have produced numerous commercially available products.

Although laboratory studies can support the claims of a product, the relevance to clinical situations can be difficult to establish because laboratory studies tightly control the multiple variables present in a clinical situation. Hopefully, the benefit of a product should be greater than the cost or other problems associated with the product. Burstone et al. (6) suggested that optimal force delivery for tooth movement is a constant force. Although a constant force is rarely produced with a closing loop, super-elastic nickel-titanium coil springs used as part of a sliding force system on a straight wire approach this ideal constant force system in the laboratory (7). These springs are costly, though (retailing over $80 for a set of 10), and many clinicians prefer a less expensive product, elastomeric powerchain, as an alternate. This presents a problem as an elastomeric powerchain and other elastic orthodontic materials can show a significant degradation of force within a short time after placement in the mouth (8). It is unclear whether there is a clinical advantage of the nickel-titanium spring over the elastomeric powerchain in closing space.

Although the concepts of optimal force (9) and light continuous forces (10) have been accepted for many years, it still remains unclear as to how much push and pull is actually required to move a tooth optimally. A recent review (11) attempted to clarify this enigma, but the authors were unable to come to any hard conclusion and were unable to perform a meta-analysis because of lack of consistency of the control of variables. Quinn et al (12) suggested a force of 100–200 g as optimum, and other authors (10) have previously suggested similar levels for optimal tooth movement. However, a 200 g force is not only enough to move a single tooth such as a canine, but it is enough to retract all anterior teeth en masse following extraction (13–17). It is also worthwhile to note that en masse retraction was accomplished with nickel-titanium springs, which have been shown to produce the least amount of force of any retraction mechanism (18). Prospective clinical trials demonstrate the effectiveness of closing extraction spaces with force delivery methods, such as elastomeric powerchain, nickel-titanium springs, and elastic modules (a steel ligature combined with an elastic ligature). As it is well demonstrated that space closure can be accomplished with all of these devices, it is prudent not to focus only on the force requirements of tooth movement, especially as biologic variability from patient to patient appears to be one of the major deciding factors in rate of tooth movement (19, 20) Rather, focus should be directed on the rates of movement that can be achieved clinically using different combinations of archwire cross sectional size and material, bracket design, and different methods of force delivery systems. This review will focus on the amount and strength of clinical evidence supporting the effect of various factors on the efficiency or rate of space closure using sliding mechanics.

Materials and methods

Search strategy

Using the keywords 'orthodontic space closure', 'space closure', 'canine retraction', 'nickel-titanium springs', 'sliding mechanics', 'orthodontics', 'dental', 'clinical trials', 'systematic review', and 'meta-analysis', an electronic search in several databases (Medline – 1966 to 2006; PubMed – 1966 to 2006; and Cochrane Central Register of Controlled Trials) was performed limiting the searches to English. Each of the words 'clinical trials', 'systematic review', and 'meta-analysis' was combined with each of the other words to find pertinent articles.

The results were examined searching for prospective clinical trials related to space closure using sliding mechanics. A hand search from 1993 to 2006 of the tables of contents in the American Journal of Orthodontics and Dentofacial Orthopedics, European Journal of Orthodontics, Angle Orthodontist, British Journal of Orthodontics, and The Australian Journal of Orthodontics was also performed, specifically searching for clinical trials relevant to the subject of sliding mechanics in orthodontic space closure. Two investigators selected the studies included in the review.

Inclusion criteria

Inclusion for this review was limited to clinical trials that focused only on the subject of closing extraction spaces using sliding mechanics, comparing efficiency under different variables. Emphasis in the review was placed on prospective, randomized clinical trials. The selection process was not weighted because of the lack of similar studies and the transition stage of the Cochrane Review process. Searches were limited to the English language and only human studies were considered for review. English was selected as several journals originating in non-English speaking countries are published in both English and another language (e.g., The Korean Journal of Orthodontics and Journal of Orofacial Orthopedics).

Results

Ten prospective clinical trials (Table 1) focusing exclusively on the subjects were identified. Two compared arch wire variables (13, 21), seven compared material variables used to apply force (14–17, 22–24), and one examined bracket variables (25). A meta-analysis of the data in these studies could not be performed because of inhomogeneity of the data from the different studies. Details on the design of the studies are presented in Table 1.

The rates of space closure given in each study were normalized to mm/day (assuming 28 days/month for normalizing) and compiled (Table 2). Despite the multiple debates about the amount of force necessary for optimum tooth movement, few randomized, prospective clinical trials on the effect of factors influencing the efficiency of space closure using sliding mechanics could be found.

Discussion

Although anchorage loss was measured in two of the reviewed articles (22, 25) to partly explain space closure, the clinician currently can obtain absolute anchorage control through the use of micro implants (26) as well as to varying degrees with other appliances (e.g., Nance, headgear). Therefore, this topic will not be discussed further in this article.

Arch wire properties

In vitro studies testing the frictional properties of different materials used in sliding mechanics are abundant (27–29). While these properties are important,

Table 1. **Summary of literature reporting rates of space closure using sliding mechanics**

Reference No	First author	Year	Random (method)	Variable	Control	Power analysis	No	No. of groups	Quadrants or participants/group	Observer blinded	Intra-rater reliability
Force delivery variables											
15	Samuels	1993	Yes	100 and 200 g Ni-Ti springs	No control (elastics of earlier study)	No	18	2 (split-mouth)	18 quadrants/group	No	Yes
17	Nightingale	2003	Yes (coin toss)	9-mm Ni-Ti spring	Powerchain	No	8 in closure study (15 total)	2 (split-mouth)	20 quadrants/group	Yes	Yes
16	Samuels	1998	Yes	150 g Ni-Ti spring	Elastic module	No	17	2 (split-mouth)	19 quadrants/group	No	Yes
24	Sonis	1994	Yes (coin toss)	150 g Ni-Ti spring	3/16′ elastics	No	27	2	50 quadrants/group	No	No (triple determination)
22	Bokas	2006	Yes	9-mm Ni-Ti spring activated to 200 g	Powerchain	No	12	2 (split-mouth)	12 quadrants/group	Yes	Yes
23	Sonis	1986	Not available	Elastic thread	Powerchain (2 brands: Unitek and RM)	No	25	3	40 quadrants; elastic thread 30 quadrants; Unitek powerchain 10 quadrants; RM powerchain	No	No
14	Dixon	2002	Yes (die)	200 g Ni-Ti spring and powerchain	Active ligature	No	33	3	48 quadrants; active ligature 40 quadrants; powerchain 44 quadrants; Ni-Ti	Yes	Yes
Archwire variables											
13	Kula	1998	Yes	Ion implanted TMA archwire	Non-implanted TMA archwire	Yes	30	2 (split-mouth)	30 quadrants/group	Yes	Yes
21	Huffman	1983	Yes	0.020′ round wire	0.016′ round wire	Yes	16	2 (split-mouth)	25 quadrants/group	No	No
Bracket variables											
25	Lotzof	1996	Yes	Tip-Edge brackets (TP ortho)	A-Company Roth straight wire brackets	Yes	12	2 (split-mouth)	12 quadrants/group	No	No (double determination)

Ni-Ti, nickel-titanium; TMA, titanium molybdenum alloy.

Table 2. **Rates of space closure[†] reported for different sliding systems**

Reference No	First author	Year	Archwire size and material[‡]	Bracket slot size	Rates of closure (mm/day) Conventional elastics	Elastomeric chain	Ni-Ti coils (100 g)	Ni-Ti coils (150 g)	Ni-Ti coils (200 g)
14	Dixon	2002	0.019 × 0.025′ SS	§	0.011	0.019	N/A	0.027	N/A
24	Sonis	1994	0.016 × 0.022′ SS	–	0.039	N/A	N/A	0.073	N/A
15	Samuels	1993	0.019 × 0.025′ SS	0.022 × 0.028′	0.025	N/A	N/A	0.038	N/A
16	Samuels	1998	0.019 × 0.025′ SS	0.022 × 0.028′	N/A	N/A	0.022	N/A	0.034
13	Kula	1998	0.019 × 0.025′ ion implanted TMA	0.022 × 0.028′	N/A	N/A	N/A	0.031	N/A
			0.019 × 0.025 TMA	0.022 × 0.028′	N/A	N/A	N/A	0.03	N/A
17	Nightingale	2003	0.019 × 0.025′ SS	§	N/A	0.03	N/A	0.037[¶]	N/A

Ni-Ti, nickel-titanium; N/A, not applicable.
[†]Converted to mm/day.
[‡]SS, stainless steel; TMA, titanium molybdenum alloy.
[§]Assumed 0.022 × 0.028 inch slot size.
[¶]Utilized a 9 mm Ni-Ti coil.

in vitro studies limit the information for the practicing clinician because of the strict control of variables. For example, one *in vitro* study has shown that the frictional forces of titanium molybdenum alloy (TMA) wires could be reduced by ion implantation (30). In a prospective randomized clinical trial, the effects of nitrogen ion implantation on the surface of a 0.019 × 0.025′ TMA arch wire on the rate of space closure was tested clinically in a split-mouth design (13). The steps the authors took to maintain validity offer results with little bias (Table 1). As the mean rates of space closure for the two sides were not statistically different, the authors suggested that changing the frictional coefficient of TMA orthodontic wires did not influence the rate of space closure, in contrast to what is suggested by the *in vitro* study (30). These findings pose an interesting question as to the clinical relevance of friction to space closure. It might be that other arch wire material types (e.g., TMA) are as efficient as stainless steel in space closure because of the ratcheting effect.

The size of an arch wire also influences friction (5) *in vitro*. The clinical significance of arch wire size can be demonstrated by a randomized split-mouth clinical trial (21) evaluating rate of retraction and amount of tipping of canines retracted along two different size segmental stainless steel arch wire (0.016′ and 0.020′). Canine retraction was accomplished with 200 g pletcher springs. Although the mean rate of closure was higher for the 0.016′ wire (1.37 mm/month) than for the 0.020′ wire (1.20 mm/month), there was no statistically significant difference between the two. Similar to many of the articles in this review, the variability in the results was large and the sample size small, i.e., the study lacked adequate power. In addition, the examiner was not blinded to the variables nor was intra-rater reliability tests performed. The stiffer 0.020′ arch wire (21) probably allowed less tipping and therefore seemed more advantageous to use by the authors. The increased tipping by the smaller wire might explain the slightly greater rate of space closure. *In vitro* studies (1, 5) indicate that the angle of the arch wire in the slot appears to affect the sliding of a wire because of an increase in friction. A larger diameter arch wire will engage the corners of a tipped slot faster than a smaller wire, causing more ratcheting and root uprighting. More studies are needed to verify whether continuous arch wires of various cross-sectional sizes influence space closure, as the results of this study (21) are not conclusive.

Although many *in vitro* studies have also been performed on the effects of different ligation on friction (31–34), this topic has not been explored in a prospective clinical study of extraction space closure. The recent popularity of self-ligating systems (both passive and active types) would warrant investigation on their effects on space closure with sliding mechanics.

Bracket design

The effect of bracket design on closure of extraction space is also without much clinical evidence. The only published clinical study (25) reported no statistical difference in rate of canine retraction or anchorage loss when two different pre-adjusted bracket systems (Tip-Edge and A-Company Roth) were compared. However, the study design cannot be considered a true split-mouth design as there was not an entire quadrant of Tip-Edge vs. an entire quadrant of A-Company Roth. The bracket on only one canine for each patient was a Tip-Edge bracket with the rest of the teeth in the quadrant A-Company Roth.

Force delivery systems

The variables examined most frequently were force delivery methods/systems (14–17, 22–24). Although a meta-analysis of the data was not undertaken because of the lack of studies with a constant variable, one can infer some intriguing conclusions of this published research from which a practicing clinician can certainly benefit.

Of the seven studies examining the method of force delivery and how it pertains to rate of closure, five compared a nickel-titanium closed coil spring to some sort of elastomeric material such as an elastomeric chain or active ligature (module activated with a ligature wire). The nickel-titanium coil spring *in vitro* delivers a constant force over a long deactivation range (7); however, because of their cost, and the associated hygiene problems of the springs, many clinicians utilize alternative techniques such as elastomeric chain to close extraction spaces. Laboratory studies have shown that the force of elastomeric chain can degrade quickly (8). The questions would seem to be whether the extra cost of nickel-titanium springs is warranted by an increase in space closure, or are elastomeric materials (either in chain form or other) just as efficient?

Nickel-titanium springs vs. active ligatures

It can be inferred from the available literature (14, 15, 24) that 150 and 200 g nickel-titanium springs produce a faster rate of retraction whether en masse or simple canine retraction when compared with elastics in an active ligature form.

In one reasonably well-designed study, Dixon et al. (14) reported that 200 g nickel-titanium springs produced a significantly faster rate of retraction than 'active ligatures' (a gray elastic module and a long ligature). While the methodology was reasonably sound, measurements were taken only at two times (pre-space closure and at 4 months or earlier if closure completed) and it remains unclear as how many cases had complete space closure nor the initial amount of the space to be closed. This could alter the accuracy of the recorded data because it is not known whether spaces closed at a continuous rate. Lastly, intra-arch elastics were utilized in some patients and this could obviously alter the results.

In another well-designed study (15), a 150 g Sentalloy closed-coil spring closed spaces significantly faster than a ligature-activated appliance activated to 400–450 g. Although this study did have a few problems (Table 1), it does support the use of coil springs over modules for closing space requirements.

In a second study, Samuels et al (16) compared the efficiency of 100 and 200 g springs for closing extraction space. The 200 g springs are significantly more efficient at closing spaces than 100 g nickel-titanium springs. These authors also concluded that utilizing a 200 g nickel-titanium spring produces no advantage to using a 150 g spring (15, 16) and that 100 g nickel-titanium spring had no benefit over the elastic module. However, the authors combined the data from the first study with the second study in their statistical analysis, invalidating the conclusions. Unfortunately, their methods of measurement varied between the two studies. Although laboratory data (7) supports their conclusion that there is no difference between the 150 and 200 g springs, the combining of the data from the two studies is a definite methodological weakness. Additional clinical studies are needed.

Nickel-titanium coil springs vs. elastics

Nickel-titanium closed coil springs (150 g) appear to be more efficient than 3/16″ elastics in closing extraction spaces. Sonis (24) found a significantly faster rate of closure with 150 g nickel-titanium springs when compared with 3/16″ Class I elastics stretched from molar hook to canine hook. However, patient compliance as a clinical variable for the elastics, which produces a significant flaw in the methodology was not noted. There is no indication that the investigator was blinded to the variables during the measurements. Again, more clinical studies are needed.

Nickel-titanium coil springs vs. elastomeric chain

As many practicing clinicians utilize an elastomeric chain to close space along a straight wire, another important question to examine is how this method compares with different force nickel-titanium springs. The results of three studies (14, 17, 22) are intriguing. Although the rates of closure using nickel-titanium springs were faster than elastomeric chain in all the studies, there was no statistical difference in two of the studies (14, 17) and the difference in the third study did not show a clinically relevant difference between the two. The cost difference between the two is such that there would have to be marked advantage of the springs for clinicians to readily adopt nickel-titanium springs.

Two hundred gram nickel-titanium springs were equally efficient as power chain and were significantly more efficient than an active ligature (module tied with a ligature and activated) in one well-designed study (14). Thirty-three patients with premolar extractions in every quadrant were involved in this study and nickel-titanium springs were compared to powerchain and 'active ligatures'. Although a split-mouth design was not utilized to eliminate biological variables between the patients, the assignment of each quadrant was randomized. Nickel-titanium springs (200 g) showed the fastest rate of closure when stretched within their constant activation range but were not statistically better than power chain. The only statistically significant difference found was between nickel-titanium springs and active ligatures as reported previously. The methodological issues discussed previously pertain here as well.

Bokas et al. (22) did find a small but statistically significant difference (0.17 mm/months) between 9-mm nickel-titanium springs activated to 200 g and elastomeric chains in a split-mouth design. However, their sample size was small and no power analysis was performed. Additional laboratory information shows that the pre-calibrated spring was extended considerably beyond its constant force activation and into a range which would allow quick force decay. The authors do not indicate the pre-determined activation force suggested by the company. Thus, the clinical relevance of the study is questionable. Although the difference in anchorage loss was not significant, it accounted for almost a third of the entire space closure each month.

Nightingale and Jones (17) also found a small, statistically insignificant difference in rate of space closure between a 9-mm nickel-titanium spring and elastomeric chain when their rates are normalized to mm/month. In this study, the coil spring was attached directly to molar and lateral incisor hooks without standardizing either the force or the distance. Presumably, the coil spring was activated beyond its constant force point as the authors measured initial forces ranging from 70 to 450 g. The force of the elastomeric chain was activated similarly to that of the coil spring. The study is difficult to analyze because of the inconsistencies in number of patients and the types of subsets of studies within the study. It appears that both mandibular and maxillary arches were used in the study but rate of closure was not compared between the two arches.

While there are only three clinical prospective studies currently available to compare these two methods of force delivery, the conclusion seems to be that elastomeric powerchain is as effective and is certainly a cheaper alternate to the nickel-titanium coil spring. However, considering the lack of studies, more evidence in this area is needed. A summary of the rates of retraction produced during these studies under different conditions is given in Table 2 that reports additional rates of retraction for powerchain along with the rates produced in one study that has not been previously discussed (23).

Conclusions

From the current literature, one could conclude but with varying confidence that clinically:

- Elastomeric powerchain produces similar rates of retraction as 150 and 200 g nickel-titanium springs;
- nickel-titanium springs of 150 and 200 g are more effective at closing space than active ligatures;
- nickel-titanium springs of 200 and 150 g are equally effective in space closure;

- arch wire size might have no effect on the rate of closure, but larger sizes control tipping better; and
- frictional differences of arch wire type might not be the major factor in rate of closure.

While it is certain that materials have come a long way, more clinical research is needed in many areas of sliding mechanics space closure. It would seem prudent to direct less effort towards studying friction effects in a laboratory setting, and to direct more energy at well-designed randomized prospective trials identifying variables that are clinically relevant in space closure using straight wire mechanics.

References

1. Loftus BP, Artun J. A model for evaluating friction during orthodontic tooth movement. *European Journal of Orthodontics* 2001;23:253–61.
2. Frank CA, Nikolai RJ. A comparative study of frictional resistances between orthodontic bracket and arch wire. *American Journal of Orthodontics and Dentofacial Orthopedics* 1980;78:593–609.
3. Downing A, McCabe J, Gordon P. A study of frictional forces between orthodontic brackets and archwires. *Journal of Orthodontics* 1994;21:349–57.
4. Bednar JR, Gruendeman GW, Sandrik JL. A comparative study of frictional forces between orthodontic brackets and archwires. *American Journal of Orthodontics and Dentofacial Orthopedics* 1991;100:513–22.
5. Ho KS, West VC. Friction resistance between edgewise brackets and archwires. *Australian Orthodontic Journal* 1991;12: 95–9.
6. Burstone CJ, Baldwin JJ, Lawless DT. The application of continuous forces in orthodontics. *Angle Orthodontist* 1961;31: 1–14.
7. Tripolt H, Burstone CJ, Bantleon P, Manschiebel W. Force characteristics of nickel-titanium tension coil springs. *American Journal of Orthodontics and Dentofacial Orthopedics* 1999;15:498–507.
8. Lu TC, Wang WN, Tarng TH, Chen JW. Force decay of elastomeric chain-A serial study. *American Journal of Orthodontics and Dentofacial Orthopedics* 1993;104:373–7.
9. Schwarz AM. Tissue changes incidental to orthodontic tooth movement. *International Journal of Orthodontics, Oral Surgery and Radiology* 1932;18:331–52.
10. Storey E, Smith R. Force in orthodontics and its relation to tooth movement. *The Australian Journal of Dentistry* 1952;56:11–8.
11. Ren Y, Maltha JC, Kuijpers-Jagtman AM. Optimum force magnitude for orthodontic tooth movement: a systemic literature review. *Angle Orthodontist* 2003;73:86–92.
12. Quinn RS, Yoshikawa DK. A reassessment of force magnitude in orthodontics. *American Journal of Orthodontics* 1985;88:252–60.
13. Kula K, Phillips C, Gibilaro A, Proffit WR. Effect of ion implantation of TMA archwires on the rate of orthodontic sliding space closure. *American Journal of Orthodontics and Dentofacial Orthopedics* 1998;114:577–81.
14. Dixon V, Read MJF, O'Brien KD, Worthington HV, Mandall NA. A randomized clinical trial to compare three methods of orthodontic space closure. *Journal of Orthodontics* 2002;29:31–6.
15. Samuels RH, Rudge SJ, Mair LH. A comparison of the rate of space closure using a nickel-titanium spring and an elastic module: a clinical study. *American Journal of Orthodontics and Dentofacial Orthopedics* 1993;103:464–7.
16. Samuels RH, Rudge SJ, Mair LH. A clinical study of space closure with nickel-titanium closed coil springs and an elastic module. *American Journal of Orthodontics and Dentofacial Orthopedics* 1998;114:73–9.
17. Nightingale C, Jones SP. A clinical investigation of force delivery systems for orthodontic space closure. *Journal of Orthodontics* 2003;30:229–36.
18. Nattrass C, Ireland AJ, Sherriff M. An investigation into the placement of force delivery systems and the initial forces applied by clinicians during space closure. *British Journal of Orthodontics* 1997;24:127–31.
19. Iwasaki LR, Haack JE, Nickel JC, Morton J. Human tooth movement in response to continuous stress of low magnitude. *American Journal of Orthodontics and Dentofacial Orthopedics* 2000;117:175–83.
20. Pilon JJ, Kuijpers-Jagtman AM, Maltha JC. Magnitude of orthodontic forces and rate of bodily movement. An experimental study. *American Journal of Orthodontics and Dentofacial Orthopedics* 1996;110:16–23.
21. Huffman JD, Way DC. A clinical evaluation of tooth movement along arch wires of two different sizes. *American Journal of Orthodontics* 1983;6:453–9.
22. Bokas J, Woods M. A clinical comparison between nickel titanium springs and elastomeric chains. *Australian Orthodontic Journal* 2006;22:39–46.
23. Sonis AL, Van der Plas E, Gianelly A. A comparison of elastomeric auxiliaries versus elastic thread on premolar extraction site closure: an *in vivo* study. *American Journal of Orthodontics* 1986;89:73–8.
24. Sonis AL. Comparison of niti coil springs vs. elastics in canine retraction. *Journal of Clinical Orthodontics* 1994;28:293–5.
25. Lotzof LP, Fine HA, Cisneros GJ. A comparison of two preadusted bracket systems. *American Journal of Orthodontics and Dentofacial Orthopedics* 1996;110:191–6.
26. Thiruvenkatachari B, Pavithranand A, Rajasigamani K, Kyung HM. Comparison and measurement of the amount of anchorage loss of the molars with and without the use of implant anchorage during canine retraction. *American Journal of Orthodontics and Dentofacial Orthopedics* 2006;129:551–4.
27. Angolkar PV, Kapila S, Duncanson MG, Nanda RS. Evaluation of friction between ceramic brackets and orthodontic wires of four alloys. *American Journal of Orthodontics and Dentofacial Orthopedics* 1990;98:499–506.
28. Prososki RR, Bagby MD, Erickson LC. Static frictional force and surface roughness of nickel-titanium archwires. *American Journal of Orthodontics and Dentofacial Orthopedics* 1991;100: 341–8.
29. Kusy RP, Whitley JQ. Coefficients of friction for archwires in stainless steel and polycrystalline alumina bracket slots. I. The dry state. *American Journal of Orthodontics and Dentofacial Orthopedics* 1990;98:300–12.
30. Kusy RP, Tobin EJ, Whitley EQ, Sioshansi P. Frictional coefficients of ion-implanted alumina against ion implanted beta-titanium in

the low load, low velocity, single pass regime. *Dental Materials* 1992;8:167–72.

31. Griffiths HS, Sherriff M, Ireland AJ. Resistance to sliding with 3 types of elastomeric modules. *American Journal of Orthodontics and Dentofacial Orthopedics* 2005;127:670–5.
32. Hain M, Dhopatkar A, Rock P. The effect of ligation method on friction in sliding mechanics. *American Journal of Orthodontics and Dentofacial Orthopedics* 2003;123:416–22.
33. Hain M, Dhopatkar A, Rock P. A comparison of different ligation methods on friction. *American Journal of Orthodontics and Dentofacial Orthopedics* 2006;130:666–70.
34. Cacciafesta V, Sfondrini MF, Ricciardi A, Scribante A, Klersy C, Auricchio F. Evaluation of friction of stainless steel and esthetic self-ligating brackets in various bracket-archwire combinations. *American Journal of Orthodontics and Dentofacial Orthopedics* 2003;124:395–402.