LOW-FRICTION BRACKETS IN PERSPECTIVE

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The design of self-ligating brackets has fulfilled the purposes of lower friction, lighter force and less treatment time. This article carefully scrutinizes the frictional role in current S-L brackets. Starting with the fundamental friction theory in orthodontic brackets and archwires, and then discuss the low-friction designs for initial leveling and aligning, rotation control, space closure and third-order control for finishing. This article also reveals a critical thinking on the design of self-ligating brackets by extension of the second-order binding theory and anticipated to help the clinicians to better understand the thrust and clinical use of self-ligating brackets. ***(J. Taiwan Assoc. Orthod. 19(4): 5-17, 2007)***

Key words: self-ligating bracket, friction, second-order binding theory, critical contact angle

INTRODUCTION

As orthodontists moved away from multi-loop stainless steel (SS) archwires to high-tech nickel titanium (NiTi) archwires to start leveling and aligning, obviously it's a good time to think about what kind of bracket can couple with those archwires better.[1] Khambay et al.[2] evaluated different methods of ligations in terms of frictional resistance, including self-ligation, elastomeric modules, and SS ligature wires. Results showed self-ligating (S-L) brackets had the lowest frictional forces. Comparing with conventional brackets in the literature, it is not surprising that S-L brackets exhibited superior performance on the resistance to sliding (RS)[3-6], less chair time[7,8], less treatment time[8,9] and higher patient satisfaction[10].

There has been controversy between the S-L bracket with an active clip and the S-L bracket with a passive slide. Generally speaking, the brackets having active spring clips can place an active force on the archwire. The intended benefit of programming a force from the clip is producing more labio-lingual action than a passive slide[11,12]. However, a considerable difference was found that when the active clips were closed, consequent asymmetries of the bracket slots resulted in smaller slot geometries, which actually produced higher RS than the

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brackets with passive slide[13,14].

Based on the necessity and development of low-friction bracket, the bracket with "passive" clips was introduced into the market (The SmartClip S-L bracket,Unitek/3M Coporation, Monrovia, CA), which also featured a S-L design and maintained a twin bracket design with two NiTi clips to restrain the archwire. Those 2 NiTi clips were programmed to release the archwire should the forces on the clips become too high[15]. Study indicated the bracket with 2 passive clips was actually an passive S-L bracket (Fig. 1) and exhibited lower RS than the brackets with passive slides in simulated ideal arch for retraction mechanics[16]. Given that most of the frictional research was carried on the in vitro environment, and most of the results lack of clinical interpretations, it is interesting and important to know: What is the role of friction in clinical orthodontics? Should much lower friction be necessary to accompany orthodontists for daily practices? If low friction is indispensable, where is the balance between better control and lower friction in modern straight wire system?

FRICTIONAL THEORY OVERVIEW

Friction may exist between two solid surfaces, at a solid-fluid interface, or between fluid layers. The resistance that precludes actual motion is termed static friction; the resistance exists during motion is called dynamic friction[17,18]. To comprehend the frictional principle, a classical "block-on plane" model is usually used[17,18] . (Fig 2). The motion does not occur until the frictional force reaches a maximal value corresponding to the critical magnitude of applied force. Any slight additional increase in the applied force beyond this critical magnitude will result in motion of the block. The frictional force will generally decrease slightly from the

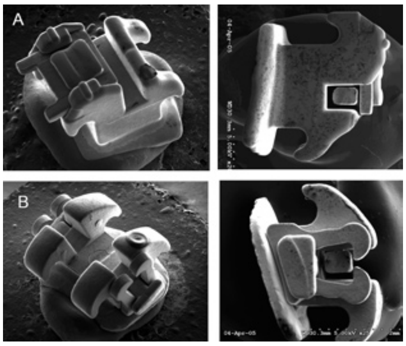


Fig 1. *A. Damon SL II bracket with passive slide. B. SmartClip bracket with 2 NiTI clips. Both of them feature passive self-ligating designs.*

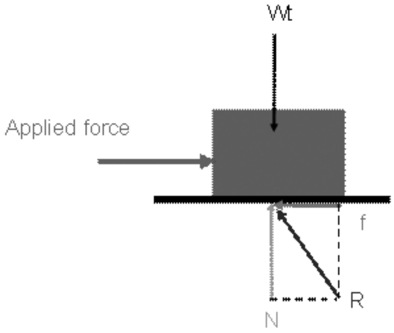


Fig 2. *A classical frictional analysis model. (Wt: the weight of the block; N: the normal force; f: friction; R: resultant force)*

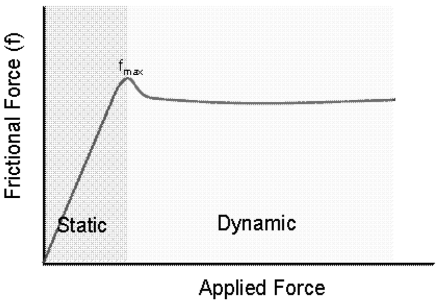


Fig 3. *The applied force and corresponding friction force. The dynamic force starts after the maximum frictional force of the static phase.*

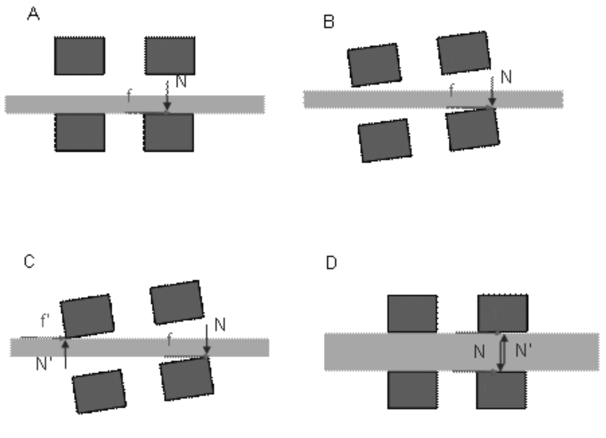


Fig 4. *Buccal view of possible contact modes of the bracket and archwire. A) Zero angulation with clearance; B) One edge contact with clearance; C) Two-edge contact without clearance; D) Snug archwire/bracket fit without clearance.*

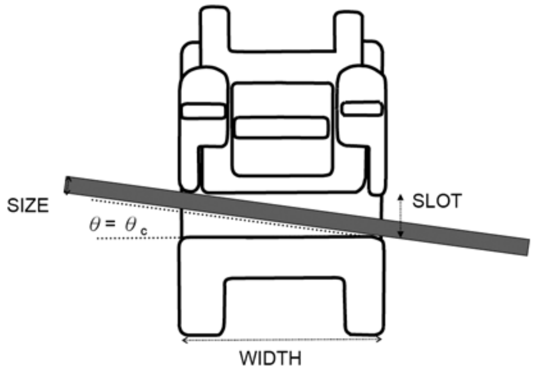


Fig 5. *Schematic illustrations of the second-order critical angle of a bracket/archwire couple: top, in the passive configuration, when contact angle (θ) < critical contact angle for binding (θ c); bottom, in the active configuration, when $\theta \geq \theta$ c.*

maximum as the static situation becomes dynamic after this time point (Fig 3). The frictional force is proportional to the normal force by a constant, called coefficient of the friction, which is independent of the contact area[18].

Nikolai took the canine-retraction mechanism as a frictional example in clinical orthodontics[17]. When the bracket/archwire couples were viewed buccally, there was one or more of four possible separate forms of contact between the bracket slot and the archwire (Fig 4). Therefore, the components of contact force, angulations of the bracket and the archwire and the tightness of the ligation were proposed to be the factors that influenced the overall friction[17,19].

However, above perceived notion that the rougher and greater surface of contact surface area of the bracket to the archwire can result in greater friction was proven to be "incorrect". Kusy and Whitley[20] used three different archwire alloys, including SS, cobalt-chromium-nickel-iron alloy, and nickel-titanium alloy drawn between specially prepared flats SS. Results showed the differences in the values of dynamic coefficient of friction were minimal as the roughness of the flat increased.20 Kusy et al.[21] found similar frictional results occurred when the same archwires with different cross-sectional areas (round, square or rectangular) were coupled with the same bracket slot when clearance of bracket and archwire existed. However, different archwire dimensions influenced the fictional results when binding occurred in the bracket/archwire couples[21].

Actually, the fundamental frictional concept based on the behavior of the bracket/archwire couples at second-order angulations was being brought out. Kusy and Whitley proposed "the critical contact angle" concept of bracket/archwire couple to explain the frictional phenomena. There were three parameters involved in the second-order bracket/archwire couple for binding: the bracket slot height (SLOT), the archwire height (SIZE) and the bracket width (WIDTH)[22]. The equation of calculation of critical contact angle (θ_c) was expressed as (Fig 5):

$$\theta_c = \cos^{-1} \frac{(SIZE)^2 - (WIDTH)^2}{(SIZE)(SLOT) \pm ((WIDTH)^2((SLOT)^2 + (WIDTH)^2 - (SIZE)^2)^{0.5}} \quad (1)$$

which can also be simplified to

$$\theta_c = \frac{57.3(1\text{-}(SIZE / SLOT))}{(WIDTH / SLOT)} \quad (2)$$

Based on above equation, three frictional stages were proposed theoretically: 1) When the contact angle between the bracket slot and archwire (θ) equals or just exceeds θ_c, the classical friction and binding solely contributes to the RS (RS). That is, RS = classical friction (FR) + binding (BI). 2) When θ is clearly greater than θ_c, binding increasingly restricts sliding as the classical friction becomes only a small part of binding. That is, RS ≈ BI. 3) When θ is much greater than θ_c, both classical friction and binding become negligible because notching occurs. As a consequence, sliding is impossible, which makes RS approach infinity. That is, RS ≈ notching (NO) ≈ ∞.

Interestingly, Kusy and Whitley[23] further evidenced above assumptions were correct and effective. Four different archwires with the same dimension (0.016 × 0.022 -in SS, cobalt chromium, beta-NiTi and NiTi) were coupled with the same SS bracket slots with 2 different dimensions (nominal 0.018-in and 0.022-in). A 0.010 inch SS ligature wire was tied on the bracket with a constant normal force of 300gm while the second-order angulation (θ) was adjusted from -12º to +12º. The frictional tests were run in dry and wet states with human saliva at 34ºC. Different interbracket distances were also incorporated into the study. The theoretical critical angles (θ_c) were found in a good agreement with the "experimental" critical angles determined via the frictional results. The θ_c was identified as the boundary between the classical friction and the binding for bracket/archwire couples. Once the θ exceeded θ_c, the RS was independent of the bracket slot height (SLOT). Stiffer archwires and shorter interbracket distances exacerbated the binding phenomena. NiTi and beta-NiTi archwires had greater RS value in wet than in dry state when they were in active configuration ($\theta > \theta_c$).

FRICTIONAL EXPERIMENTS

Usually the frictional tests were performed by drawing the archwires through the bracket slots by attached to the crosshead of an Instron mechanical testing machine[3-5,11,13,14,16,18,20-23]. For single-bracket studies, the bracket was placed in a linear arrangement with two sets of Teflon® bearings that simulated the adjacent teeth[5,13,14]. Artificial saliva was dropped to the archwire from a saliva drip to simulate the wet-state tests[5,13]. Because a ligation force may be present from a elastic tie or the ligature wire for the conventional brackets, the consistency of normal force can be maintained by archwire-on-flat methodology and archwire-bracket-ligature methodlogy[18,24]. However, difference in experimental settings, acquisition systems, angulations between brackets and archwires made a direct comparison of the frictional results of various published studies still impossible.

A typical drawing force vs. displacement graph was shown in Fig 6. Similar to the block-on-plane model, when the archwire is pulled through the bracket slots, the drawing force builds up gradually to a maximum point, where is recorded as initial maximum drawing force (IMDF). IMDF is a static force, which represents the amount of force needed to overcome the static phase to slide the archwire through the bracket slots. After that, the drawing force may drop somewhat and oscillate more

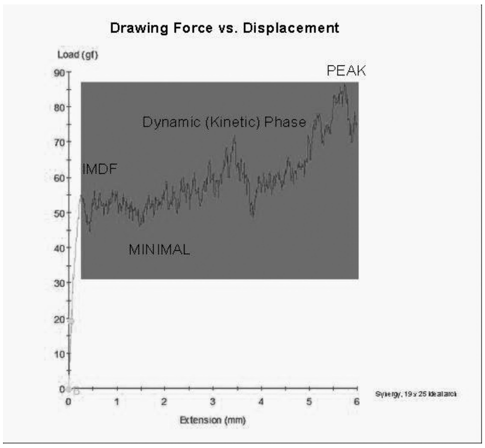


Fig 6. *A typical drawing force vs. displacement graph. IMDF was the initial maximum drawing force of static phase. After IMDF, the dynamic phase began. MINIMAL was the minimal drawing force in the dynamic phase; PEAK is the peak drawing force in the dynamic phase.*

or less and recorded as dynamic force, depending on different kinds of bracket/archwire couples.

Different opinions regarding the frictional measurements arose from different interpretation and comprehension about the testing models. Most of testing apparatuses did not permit tipping[25], disregarded the vibration from chewing[26], or were tested in the dry state. More importantly, the realistic tooth movement is not continuous[17]. Therefore, some investigators simply measured the static friction[16,19,27,28]. However, other investigators[13,14,18], thought the IMDF represented only one data point of whole measurements and not sufficient for data collection; whereas dynamic frictional forces can be measured from hundreds of data points. Although one would expect to see static frictional force larger than dynamic frictional force, the outcome actually is seldom observed because a more complex situation occurs in the dynamic phase.

DIFFERENT SELF-LIGATING DESIGNS

Stolzenberg[29] developed the first S-L bracket in the early 1930s, the Russel attachment. Although shorter office visits, shorter total treatment time, and patient comfort were reported, the concept of low-friction and self-ligation did not get widespread notice and acceptance until the introduction of following S-L bracket variations in the 1970s, such as Edgelok brackets (Ormco/ "A" Company, Orange, CA) by Wildman[30] and the SPEED bracket (Strite Industries Ltd, Cambridge, Ontario, Canada) by Hanson[31]. The Edgelok brackets featured a round body with a rigid labial sliding cap. A special opening tool was needed to open the bracket cap for insertion of the archwire. When the cap was closed, the bracket converted into a tube with an outer bracket slot wall. In the history of prevalent edgewise bracket systems, the Edgelok bracket was conceded the first S-L bracket having the passive S-L design and the first to enjoy any sort of commercial success[32]. In 1976, Hanson created prototypes of the SPEED bracket and was introduced in the market in 1980, which featured a curved, flexible "Super-Elastic" spring as the flexible outer fourth wall of the bracket slot. The labial arm of the SPEED bracket not only constrained the archwire but interacted with the archwire as the archwire dimension went up to certain size. This set the SPEED bracket apart from all other available S-L brackets at that time as the only "active" S-L bracket system. Following S-L bracket designs were variations of those two major types.

The RS generated from different types of S-L brackets was compared in vitro by Thorstenson and Kusy[13]. This study was conducted with single bracket at different second-order angulations in both dry and wet states. 3 passive S-L brackets (Activa, Damon SL II, Twinlock) and 3 active S-L brackets (SPEED, In-Ovation, Time) were compared. Results showed below each characteristic critical angle, brackets with passive slides exhibited negligible friction; bracket with active clips exhibited frictional forces as great as 50 gm. Above each characteristic critical contact angle for binding, the elastic binding forces of all brackets increased at similar rates, which were independent of the bracket design. This study concluded that the brackets with passive slides and bigger critical contact angles exhibited the lowest RS. The brackets with active clips and smaller critical contact angles had higher RS values than that with larger critical contact angle.

Obviously, single bracket study may not mimic the realistic situation of malocclusions in the oral cavity, even though better idea of active clip resulting in smaller slot geometry and smaller critical angle for binding had been obtained. The dental typodonts duplicated from the patient's oral cavity were used for the frictional evaluation by Henao and Kusy[4]. Results indicated that the S-L brackets had lower RS than conventional brackets when coupled with smaller archwires. However, no significant differences were found between different types of S-L brackets. Interestingly, the irregularities of the malocclusions influenced the RS for all types of brackets.

Manufacturers argued the investigators had to follow recommended archwire sequencing of each bracket system to conduct the study. Study further revealed that the RS was influenced by a combination of bracket design, archwire size, degrees of malocclusion, and archwire stiffness. The S-L brackets with passive slides had lower values of RS than S-L brackets with active clips when clearances were substantial. However, as malocclusion became more severe and archwire size reduced overall clearance, active and passive S-L brackets lost distinction[3].

LOW-FRICTION DEMAND VS DIFFERENT STAGES OF OBECTIVES

Although the pattern of ligating the brackets without the ligature wires or elastic O-ring have been known to enjoy great convenience for the orthodontists, effective control of those innovative bracket systems did not come to maturity until last decade. Various self-ligating brackets, including ligating type, bracket dimensions, and associated second-order critical angle are shown in Table I.

Initial leveling and aligning

The goals of initial stage of orthodontic treatment are to bring the malaligned teeth into alignment and correct vertical discrepancies by leveling the arches as quick as possible by using a light highly flexible round archwire. Proper alignment should bring malposed teeth into the arch, without jeopardizing the adjacent anchored teeth. Any heavy force created from initial irregularity of alignment and the bracket/archwire couples, such as binding, can cut off the blood supply of the periodontal ligament and a hyalinized and avascular area can be formed. The teeth can not move until vascularization again.33 Therefore, Kusy[23] suggested a larger slot lumen with a larger critical contact angle can efficiently implement sliding mechanism because the binding phenomena can be reduced with larger bracket/archwire clearance. Damon also pointed out example of sliding mechanism should not only be used in the space closure, but also in the initial leveling and aligning stage, because "the archwire has to slide to the brackets[1]".

In the situation of absence of ligating force (or only a small amount exists), S-L brackets with larger slot lumen in whatever order space facilitate the sliding mechanism in the initial stage of treatment. Take the critical angle/distance models for example, the initial tooth irregularities can be up-and-down, rotations, tipping and third order angulations (Fig 7). Wider bracket width decreases the inter-bracket span and the flexibility of the archwire. Smaller slot height and slot depth increases the possibility of binding with the archwires. All of which increase the RS and hinder the highly flexible archwires from sliding through the bracket slots[16,19,23].

S-L brackets with active clips are programmed in a passive state when coupling with small dimensional archwires. The labial clip of fourth slot wall actually helps the archwire to correct possible first-order in-and-out and rotations, rendering the archwire slide freely in the bracket slots. Less labio-lingual action are proposed for the S-L bracket with passive slides in the same situation[11]. However, the arguments for the S-L brackets with passive slides are 1) the energy expressed to correct first-order mal-alignments is not in the slide but in the high-tech archwires 2) the clip design encroaches on the slot lumens, which produced a smaller and asymmetry slot dimension, actually increases the friction[1]. Given that in-vitro studies revealed that higher RS was found in S-L brackets with active clips when the archwires contact the clip, the in-vivo comparison of biological response for those two types of S-L brackets remain unknown.

Elimination of Rotations

The rectangular archwire is often used to complete the initial stage leveling and aligning, express the rotation control, and start the torque control. At this transition stage, the rotation control is expressed by the first-order dimensions of bracket/archwire couples (Fig 7A), which means the ligation method, bracket slot depth, the bracket width and the archwire thickness are determinants for elimination of any rotations to prepare the next stage of space closure or finishing. For a conventional twin bracket tied by a stainless steel or elastomeric ligation, actually the ligation force renders the bracket/archwire couple antirotation control. However, for S-L brackets, depending on active or passive self-ligation, the rotational control is different. For passive S-L brackets without the ligation force, the clearance between the bracket and archwire becomes critical, because the archwire has to nearly fill the bracket slot depth in a labial-lingual (buccolingual) direction to produce the necessary moments for correction of rotation. A 0.016 × 0.025 archwire is preferred for rotation control in the nominal 0.022-in Damon brackets[1]. Damon believed an approximate 0.003-in slot depth clearance has to be maintained because any larger archwire dimension encroaching on this clearance increases the friction[1]. For active S-L brackets, Voudouris[11] claimed rotational control can be created in a very initial stage of treatment through the interactive arm of the clip when the brackets were still coupled with smaller archwires. After passivation of movement, frictional force produced from larger archwire (above 0.018-in in 0.022 × 0.028-in In-Ovation brackets) helps maintain control effectively.

Although it is hard to judge which type of S-L brackets controls the rotation more effectively, the basic idea of “twin” S-L designs are used produce a necessary

Table 1. *Dimensional Evaluation of Active and Passive Self-ligating Bracket Systems*

Bracket	Manufacturer	Self-ligation	Bracket Width(“)	Slot height(“)	Theoretical critical angle (second-order)
In-Ovation	GAC Int., Islandia, NY	Active clip (Elgiloy)	0.127	0.0228	2.2
Speed	Strite Industries Limited, Cambridge, Ontario, Canada	Active clip (Super-elastic spring)	0.093	0.0215	2.2
Time	American Orthodontics, Sheboygan, WI	Passive clip	0.105	0.0227	3.0
Twinlock	Sybron Dental Specialties Ormco, Orange, CA	Passive slide	0.117	0.0224	2.2
Damon SL II	Sybron Dental Specialties Ormco, Orange, CA	Passive slide	0.102	0.0230	3.6
Damon SL III*	Sybron Dental Specialties Ormco, Orange, CA	Passive slide	0.089	0.0224	2.9
SmartClip*	Unitek/3M Coporation, Monrovia, CA	Passive clips (NiTi)	0.1349	0.0230	2.2

All second-order critical angles were calculated with 0.0179-in archwire[13].

**Data of Damon III and SmartClip are from Yeh CL, The resistance to sliding of low-friction brackets in simulated malocclusions, Master's Thesis, University of Illinois at Chicgao* moment in the rotational plane of the space. However, the rotational moment may not be sufficient for those brackets. In addition to the bracket slot depth, the bracket width also plays an important role on rotational control (Fig 7A). The narrower bracket and larger slot depth increase the first-order critical angle for rotation and reduce the binding. However, this might be at the expanse of necessary moment of rotational control. Using larger dimension of archwire can compensate this problem but at the same time increases the RS. The concept of the best archwire and bracket couples either for active or passive S-L bracket systems has been proposed from various studies and it is worthy to follow.

Space Closure Strategy

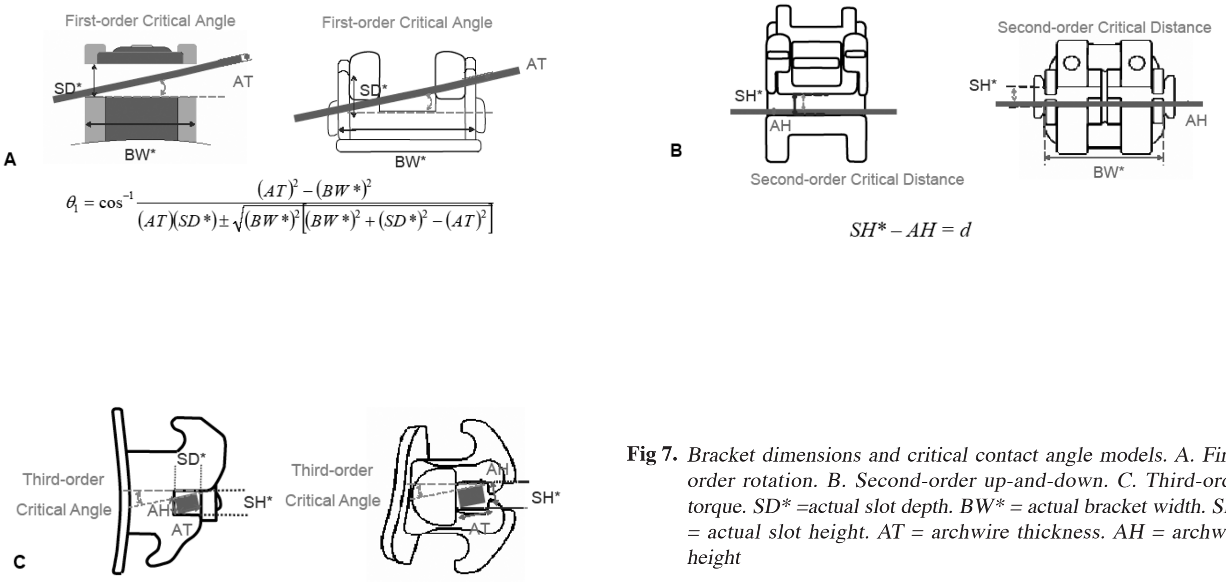
A clinical circumstance, space closure, renders the role of friction prominent. Kojima and Fukui[35] simulated the maxillary canine retraction mechanism by using 3D finite element study. In this model, the absorption and apposition of the alveolar bone were simulated according to the stress distribution of the periodontal ligament. The magnitude changes of applied forces were calculated from the positional changes of the canine and anchorage teeth. 2N force was applied for retraction of the canine. The ligation force was assumed not to exist. Interestingly, the decrease in applied force by friction was estimated to be from 60% to 80%. The tipping of retracted canine can be decreased when the archwire size increased. The square archwire was more effective to decrease the movements of the anchor teeth than the round wire.

In terms of sliding mechanism for space closure, given that the scenario of anchorage control is similar, a notable difference of frictional demand is between one-step and two-step space closure. For en-masse retraction of moving anterior teeth as a unit, if take maximum-anchorage for example, the brackets/tubes of posterior teeth have to provide a frictionless environment to allow the archwire slide through the bracket slots (Fig 8A). However, for the two-step space closure and retraction of the canine first, the frictionless demand initially is in the canine bracket. The posterior teeth, on the other hand, need more friction for consolidation of the anchorage (Fig 8B).

A 0.019 × 0.025-in archwire is usually selected as the working wire in different 0.022-in S-L bracket systems at this stage[1,11,15]. The main reasons basically include maintaining the necessary clearance between bracket slots and archwire exists for the sliding mechanism and keeping the archform intact without distortions from the retraction. A twin design of the S-L brackets is surely programmed to provide the necessary moments for root paralleling. However, during the process of retraction, over-sized S-L bracket slots may accompany unwanted lingual tipping and distal rotation if the archwire is not coupled correctly. Larger slot lumen of S-L bracket without ligation force makes the bracket move more freely along the archwire in this stage. Although the active S-L brackets have higher RS level than passive S-L brackets, the clinicians need to know that those 2 types of brackets have far less RS than the brackets with conventional ties. With lower RS level, the net force has been greatly decreased. Herewith, applying a heavy force is very easily overpowering the force system of S-L brackets and leaves an unwanted net force on the anchored teeth, which may cause anchorage loss. Light force and low friction are the thrust throughout the S-L bracket systems.

Third-order Torque Control and Finishing

A third-order torque control has little to do with the frictional concern in the clinical orthodontics. After all, the archwire is not necessary to slide through the bracket slots for torque. However, in order to start the third-order control earlier, the clinicians do use square or rectangular archwires far before the finishing stages. Meling and ødegaard[36] study the interaction of force couples between second-order and third order angulations. When the second-order and third-order angulations were both present, the rectangular archwire exerted a third-order



$$\theta_1 = \cos^{-1}\frac{(AT)^2-(BW*)^2}{(AT)(SD*)\pm\sqrt{(BW*)^2\left[(BW*)^2+(SD*)^2-(AT)^2\right]}}$$

$$SH* - AH = d$$

$$\cos\phi_3(AH)+\sin\phi_3(AT) = SH\,*$$

Fig 7. *Bracket dimensions and critical contact angle models. A. First-order rotation. B. Second-order up-and-down. C. Third-order torque. SD* =actual slot depth. BW* = actual bracket width. SH* = actual slot height. AT = archwire thickness. AH = archwire height*

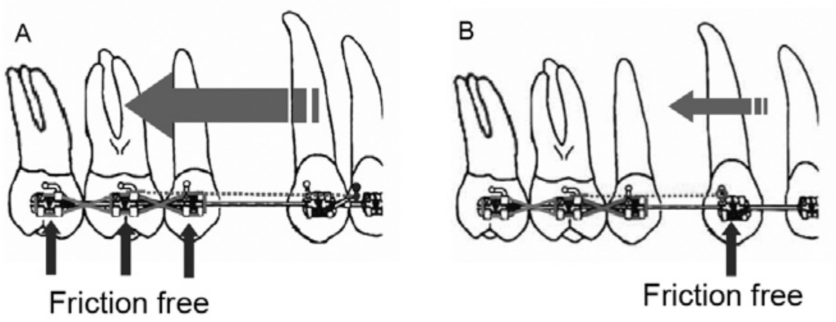


Fig 8. *Different frictional demand in space-closure (maximum anchorage). A. En-masse retraction. B. Canine retraction.*

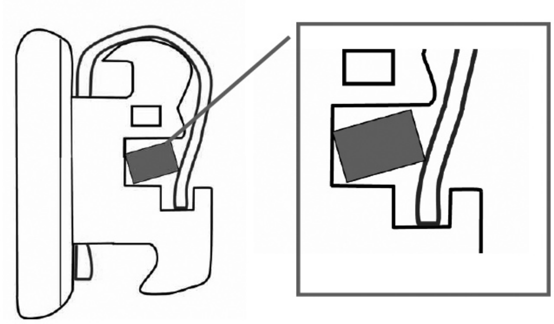


Fig 9. *Third-order control from an active clip. The occlusal and gingival walls of bracket slot are not equal. One edge of the archwire is exerted by the clip.*

force couple but far below the torsional play. The torsional play was recorded twice the third-order clearance, because activation initially required elimination of one third-order clearance at each site of the bracket slot, which are the occlusal and gingival walls of the bracket slot.

For the S-L brackets with active clips, arguments arouse from that the active clip provides not only the labio-lingual action, but can get better third-order control in terms of third order. An interesting opinion about the third-order control was indicated by Harradine[9]. The design of active clip encroaches the bracket slot, reduces the available slot depth and makes the bracket superior and inferior slot walls not equal. The clip provided a lingually directed force to seat the archwire to the base of bracket slot, However, because the rectangular archwire cannot be fully engaged, the actual torque delivery is questionable (Fig 9). Couples of investogators[17,34,37] believed that the third-order clearance is governed by the bracket slot height and the dimension of the rectangular archwire, and is independent of bracket width (Fig 7C). The bracket slot height is related to 2 point contact with the archwire. Obviously, the clip coverage may not be solid enough to firmly twist the archwire if the bracket slot wall is shortened. On the other hand, for the S-L brackets with passive-ligating design, the torque control may be more like the conventional edgewise bracket or tube. The torque control of passive S-L brackets can be activated as long as using appropriate dimension of archwire without leaving too much third-order clearance. However, the difference in the clinical performance of those high-tech bracket systems still need to be further evidenced.

Conclusion

The S-L bracket systems provide a lower friction and net force environment for the clinicians to perform orthodontic treatment. The laboratory data also provided a strong background for supporting those innovative designs. There should not be too many changes in the biomechanics for S-L brackets, compared with conventional brackets. Rather, accompanied simplified technique, low RS level, anchorage requirement, and patient's oral hygiene from S-L brackets let the orthodontists treat patients surely different than usual.

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透視低摩擦力矯正器

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現行矯正裝置中self-ligating的設計已經能滿足低摩擦阻力、輕作用力、以及縮短治療時間等目標。本文謹慎地探討摩擦力於現行self-ligating矯正器系統中所扮演的角色。由基礎的摩擦理論出發、並以二級空間上得到的binding theory做延伸，從而討論低摩擦力矯正器在設計上對各種不同矯正治療階段的控制與影響。目的在於提供矯正醫師在使用self-ligating矯正器時能具有審慎的思考以善加利用，並期待矯正醫師能更進一步了解self-ligating矯正器之精髓以發揮其最大功效。***(J. Taiwan Assoc. Orthod. 19(4): 5-17, 2007)***

關鍵詞：self-ligating bracket, friction, second-order binding theory, critical contact angle

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