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Frictional forces related to self-ligating brackets

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SUMMARY Orthodontic tooth movement can be regarded as teeth sliding on a wire like pearls on a string, the force being supplied by springs or elastics. The movement implies friction between wire and bracket, taking up part of the force and leaving an uncontrolled amount to act on the teeth. The friction is likely to depend on bracket construction and wire material. Therefore, in this investigation the friction of self-ligating brackets and beta-titanium wires was evaluated, as opposed to more conventional configurations.

Carried by low-friction linear ball bearings, a bracket was made to slide along an outstretched archwire with minimal (and known) basic friction, either parallel or at an angle to the wire. Two self-ligating brackets were used in their closed position without any normal force. Friction was tested against four wires: stainless steel and beta-titanium, both in round and rectangular cross-sections. The force used to overcome friction and to move the bracket was measured on a testing machine at 10 mm/min, and the basic friction was subtracted.

The results show that round wires had a lower friction than rectangular wires, the beta-titanium wires had a markedly higher friction than stainless steel wires, and friction increased with angulation for all bracket/wire combinations. The self-ligating brackets had a markedly lower friction than conventional brackets at all angulations, and self-ligating brackets, closed by the capping of a conventional design, exhibited a significantly lower friction than self-ligating brackets closed by a spring.

The selection of bracket design, wire material, and wire cross-section significantly influences the forces acting in a continuous arch system.

Introduction

Whenever sliding mechanics are used in orthodontics, friction generated between the bracket and the archwire has a major impact on the force delivered to the teeth (Frank and Nikolai, 1980).

Friction is defined as the resistance to motion which is called into play, when it is attempted to slide one surface over another with which it is in contact (Tweeny and Hughes, 1961). A distinction is made between static frictional force defined as the smallest force needed to start a motion of solid surfaces with respect to each other, and kinetic frictional force defined as the force needed to resist the sliding motion of one solid object over another at a constant speed. Sliding frictional force is the component of total contact force between the surfaces which is in the direction of intended or actual sliding motion and opposing this motion. The other components of the contact force are perpendicular to the frictional component and are referred to as normal force.

Since continuous arch mechanics comprise an overwhelming part of orthodontic treatments, friction influencing the rate and type of tooth movement has attracted considerable interest, resulting in a large number of experiments designed with the purpose of analysing the various aspects of friction. Materials, size and shape of brackets and wires, and type of ligation have been analysed in wet and dry conditions, and at room and mouth temperatures. The influence of the materials comprises two factors, the alloy and the surface structure of both brackets and wire. With regard to the magnitude of the contact surface most authors agree that friction increases with increasing wire dimension and bracket width. It is likewise generally agreed that friction largely depends on surface roughness and coefficient of friction of the involved materials (Angolkar *et al.*, 1990; Kusy *et al.*, 1991; Vaughan *et al.*, 1995). In addition, a linear relationship between the normal force delivered, when the wire is inserted into the bracket, and friction has been demonstrated repeatedly. Lately Yamaguchi *et al.* (1996) focused on the influence of the point of force application with respect to the centre of resistance and stressed, as earlier studies (Drescher *et al.*, 1989; Tidy, 1980), the role the biological resistance of the periodontium plays in relation to friction.

Review of methods

Investigations on friction can be divided into four main groups according to the type of set-up used:

1. Archwires sliding through contact flats, limiting the studies to the influence of materials only (Kusy and Whitley, 1989; Stannard *et al.*, 1986).
2. Archwires sliding through brackets parallel to bracket slot, allowing the analysis of the influence of material, bracket design and wire dimension in addition to impact of saliva and different types of ligation (Garner *et al.*, 1986; Baker *et al.*, 1987; Angolkar *et al.*, 1990; Berger, 1990; Kapila *et al.*, 1990; Kusy and Whitley, 1990; Pratten *et al.*, 1990; Kusy *et al.*, 1991; Sims *et al.*, 1993; Downing *et al.*, 1994, 1995; Saunders and Kusy, 1994; Shivapuja and Berger, 1994; Keith *et al.*, 1994).
3. Archwires sliding through brackets with different second and third order angulations allowed the study of the influence of the variation in interbracket configuration (Andreasen and Quevedo, 1970; Frank and Nikolai, 1980; Peterson *et al.*, 1982; Prosoki *et al.*, 1991; Sims *et al.*, 1994; Tselepis *et al.*, 1994; De Franco *et al.*, 1995).
4. Recently, study designs in which the brackets submitted to a force were allowed a certain freedom of tipping resulting in a 'retarding' of the applied force has attempted to simulate the impact of the biological resistance to tooth movement (Tidy, 1980; Drescher *et al.*, 1989; Yamaguchi *et al.*, 1996; Bednar *et al.*, 1991; Ireland *et al.*, 1991).

As the interaction between the involved variables clearly influences the results, it is important to design any experiment on frictional forces with new brackets and materials using well characterized frictional forces using a known material as a control.

The purpose of the present study was to apply the third type of design to four types of brackets, one well known self-ligating (Speed, Speed System, Cambridge, Ontario, Canada), two conventional brackets to which a standard normal force was applied and one of the latter brackets to which a self-ligating device was added (the Damon SL bracket, Ormco, Glendora, CA, USA); to test these brackets against two known materials in two dimensions and at five different second order angulations.

Material and methods

The wires used for the test were stainless steel and beta titanium in two different dimensions, round 0.018 and rectangular 0.017×0.025 inches. The brackets were one Dentaurum (Dentaurum, Pforzheim, Germany) and two A-Company (A-Company Europe, Amersfoort, The Netherlands) conventional upper premolar brackets without torque. One of the A-Company brackets, the Damon SL bracket, had a specially designed coverage so that the bracket became self-ligating (Figure 1). The last bracket included was the self-ligating Speed bracket to serve as a control for the newly designed Damon SL bracket. All brackets had the same vertical slot size (0.022 inches). The horizontal dimension of the bracket varied as seen in Table 1.

The experiments were carried out using a Tensometer 10 testing machine (Monsanto plc, Swindon, UK) with a 25 N tension load cell and a chart recorder. The measuring device used on the testing machine comprised an aluminium carriage with four smooth linear ball bearings made to run on two vertical, parallel rods of polished, hardened steel (Figures 2 and 3). Along a third rod, parallel to the first two, an archwire was suspended, parallel to the motion of the

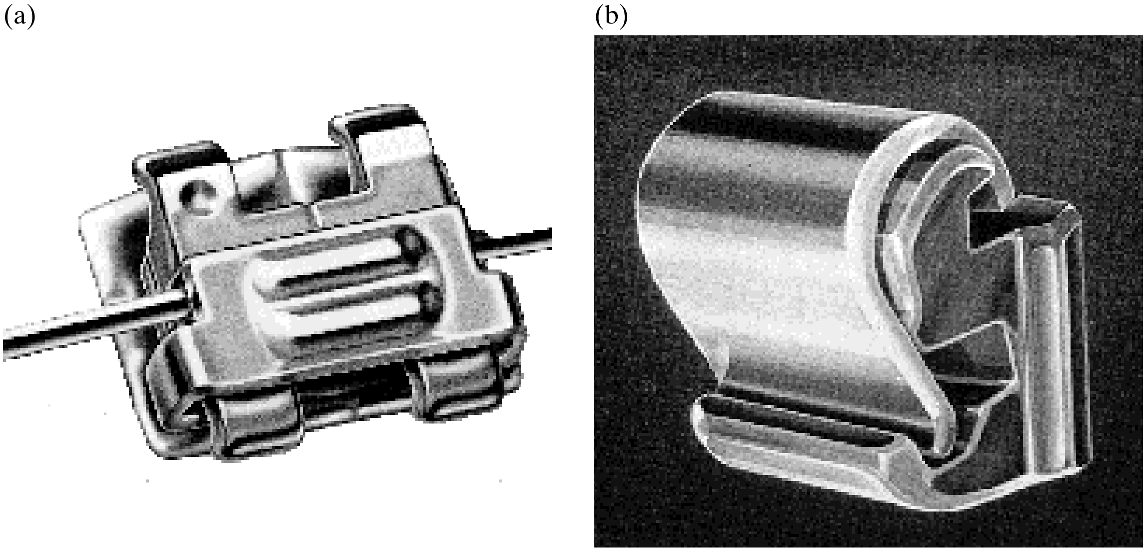

Figure 1 The two self-ligating brackets. (a) The Damon SL bracket. (b) The Speed bracket.

Table 1 Survey of the materials used.

	Dentaurum	A-Comp.	A-Comp.	Speed
Ligation	conventional	conventional	self-ligating	self-ligating
Slot size (inches)	0.022 × 0.030	0.022 × 0.028	0.022 × 0.028	0.022 × 0.025
Slot length (inches)	0.145	0.125	0.120	0.089

carriage; the wire was fixed at the lower end (where carriage motion starts) and kept under 3 N tension by a spring at the upper end.

Each bracket was mounted with cyanoacrylate glue on the end of an acrylic rod with a diameter of 6 × 15 mm, which was fixed to the carriage, facing the archwire, and adjusted in two planes of space so the bracket slot would engage the wire and slide along it with minimal friction (Figures 2 and 3).

The self-ligating brackets were used in the closed position. Over the conventional brackets a small brass tube with two 5-mm lengths of 0.010 inches soft stainless steel wire resting at an angle of 90 degrees on the archwire was placed so that a normal force of 2 N perpendicular to the base of the bracket was delivered to the archwire. This force was generated by a spring fixed to the carriage. The first test was carried out with the bracket slot parallel to the direction of displacement, while the bracket in the subsequent experiments was rotated from this initial position (slot parallel to the wire) to a fixed angulation of 3, 6, 9, and 12 degrees with respect to the wire.

The weight of the carriage was balanced by two symmetrically positioned counterweights with strings and ball bearing pulleys, allowing the carriage to be moved vertically with the least possible force. The measuring device frame was attached to the testing machine frame, and the carriage was connected to the cross-head by a thin wire. Four archwires and four types of brackets and five different angulations resulted in a total of 80 combinations. Each combination was tested for 80 mm movement at 10 mm/min cross-head speed; two runs were made for each

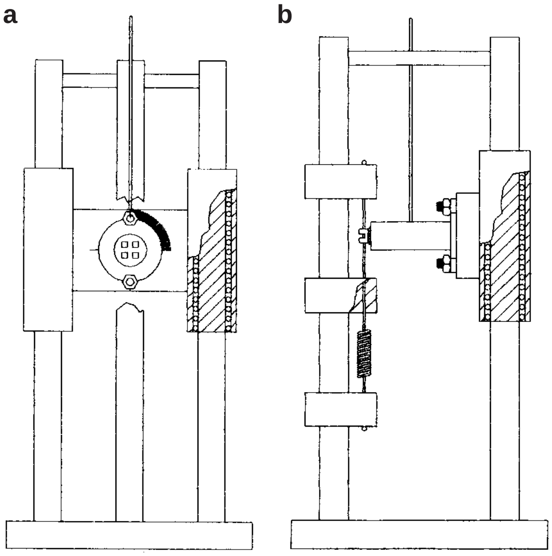

Figure 2 Schematic drawing of the experimental set-up. (a) Frontal view illustrating the possibilities for angulation. (b) Lateral view illustrating the sliding mechanics.

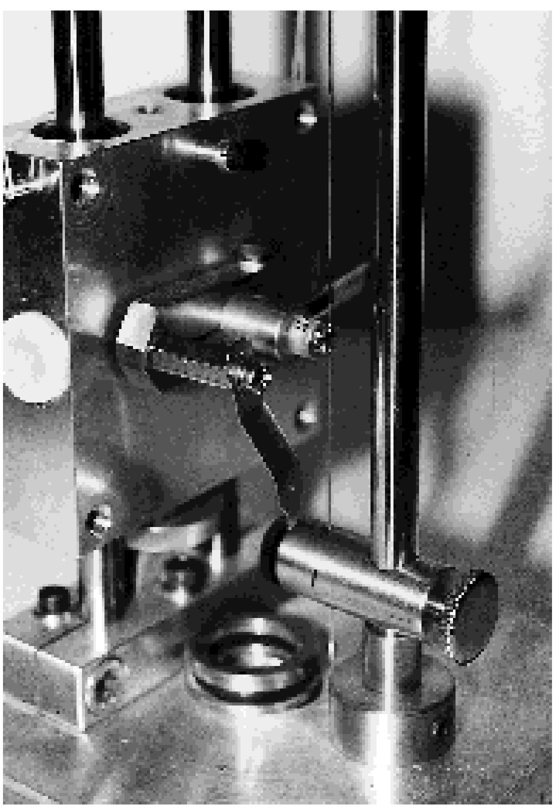

Figure 3 Photographic illustration of the experimental set-up.

possible combination. The tests were made at room temperature and in the dry state.

The validity of the measurements was established through the evaluation of the inherent friction of the measuring device. This was calculated as an average of 10 dry runs with no engagement between bracket and wire. These results served as the generation of a correction factor by which the test results were adjusted.

The analogue output from the Tensometer 10 testing machine was connected to an X-T recorder for visual control of the measurement values, and to an analogue-digital converter and a PC for precise data acquisition. The stick-slip nature of friction tended to yield values expressing spikes and glitches. To overcome this, an electronic low pass filter was inserted in the analogue output path. The action of the filter was a short-term averaging of signal, rendering data more readable without affecting the long term variation and the absolute values.

The A–D conversion was carried out with a 10-bit resolution, dividing the measurement range into 1024 steps. Sampling intervals were 250 milliseconds, yielding a total of 1920 measurements sampled per run.

Results

The results illustrated in Figure 4a–d represent the four different types of wire included in the experiments. The variation within the individual combination of the tests appears in Table 2. It was obvious that both alloy and wire dimension had a major impact on friction. As expected TMA showed a considerably higher friction than stainless steel at all angles and with all brackets. In addition, the wire dimension also affected frictional forces, but not always in a predictable manner. Wire dimension and alloy exhibited a clear interaction with angulation.

Whereas a linear relationship between frictional forces and increasing angulation seemed to exist in the case of the conventional brackets, the self-ligated behaved differently. With a rectangular wire the frictional forces observed with the self-ligating brackets increased dramatically when the angulation was 9 and 12 degrees. The impact of wire dimension and alloy was likewise

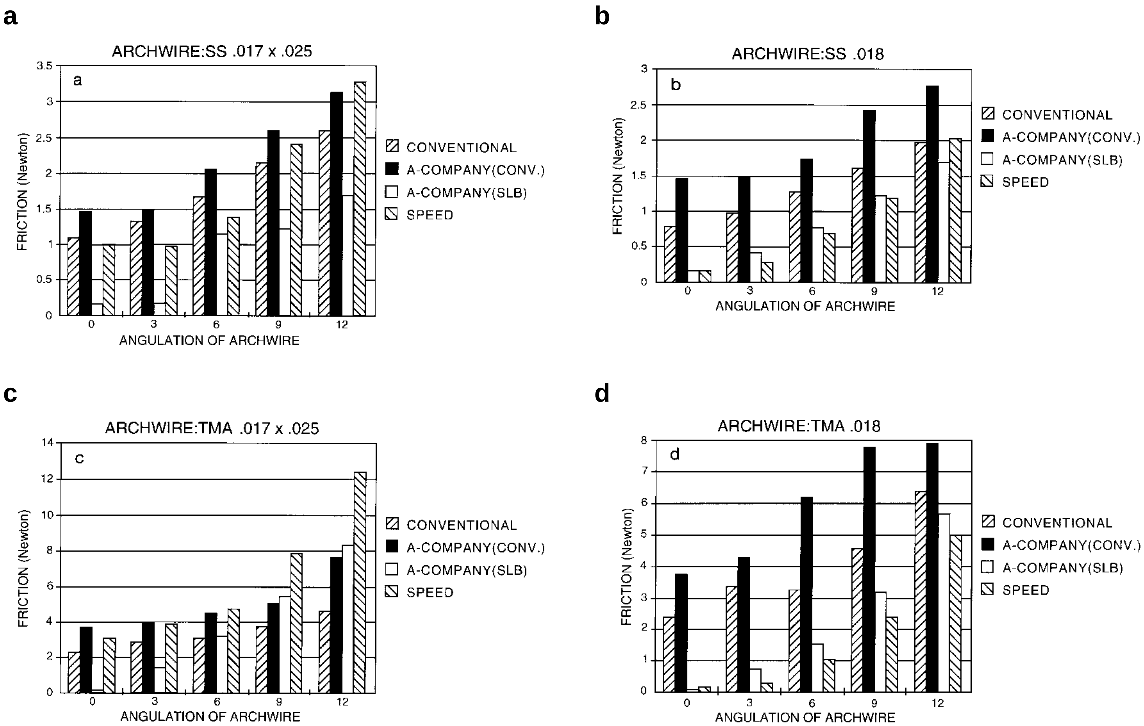

Figure 4 (a–d) Bar charts showing the results of the different combinations. Note that the scale of the *y*-axis varies between the graphs.

highly dependent on the type of bracket. Generally, the self-ligating brackets exhibited less friction than the conventional brackets. At no or small angulations and with round wires these brackets demonstrated a very low friction compared with the conventional brackets loaded with a normal force. At larger angulations between the brackets and the wire the Speed bracket exhibited a significantly greater increase in friction than the other brackets. Among the conventional brackets the Dentaurum bracket exerted less friction than the A-Company bracket of the same dimension.

The dependency of the frictional forces on the angulation was noteworthy, indicating that the increase in frictional forces with increasing angulation was more pronounced in the case of stainless steel than TMA wires. The dimension likewise played a more important role in the case of stainless steel than in the case of TMA wires. Apart from the combination of zero degree angulation and rectangular wire where the Speed bracket exhibited higher friction, probably related to its smaller horizontal dimension and the special spring design, both the self-ligating brackets were superior than the conventional brackets. The Damon SL bracket from A-Company exhibited even less friction than the Speed bracket with respect to all wire types (Figure 4a–d).

Discussion

In the selection of orthodontic materials a thorough knowledge of their physical properties is crucial. New materials should therefore be submitted to testing, allowing for comparison with known materials. In the present study a new self-ligating bracket and three known brackets were tested against two materials, two wire dimensions and five different angulations. It was confirmed, as previously demonstrated (Angolkar *et al.*, 1980; Tidy 1980; Drescher *et al.*, 1989;

Table 2 Frictional forces expressed as mean and SD (below) for each combination.

Bracket	Wire	0°	3°	6°	9°	12°
Dentaurum	0.018	0.769	0.968	1.269	1.617	1.985
convent.	SS	0.048	0.052	0.056	0.068	0.082
Dentaurum	0.017 × 0.025	1.107	1.333	1.716	2.139	2.591
convent.	SS	0.054	0.052	0.142	0.163	0.152
Dentaurum	0.018	2.462	3.445	3.396	4.598	6.395
convent.	TMA	0.298	0.406	0.446	0.440	0.534
Dentaurum	0.017 × 0.025	2.255	3.052	3.272	3.786	4.602
convent.	TMA	0.564	0.544	0.288	0.368	0.578
A-Comp.	0.018	1.441	1.494	1.742	2.440	2.775
convent.	SS	0.070	0.152	0.130	0.239	0.185
A-Comp.	0.017 × 0.025	1.471	1.501	2.050	2.601	3.137
convent.	SS	0.106	0.162	0.156	0.198	0.223
A-Comp.	0.018	3.712	4.342	6.220	7.670	7.880
convent.	TMA	0.728	0.724	1.048	0.934	0.994
A-Comp.	0.017 × 0.025	3.678	4.002	4.444	5.016	7.706
convent.	TMA	0.415	0.336	0.314	0.378	0.736
Damon	0.018	0.156	0.413	0.782	1.250	1.718
A-Comp.	SS	0.025	0.030	0.044	0.050	0.079
Damon	0.017 × 0.025	0.130	0.119	0.656	1.188	1.749
A-Comp.	SS	0.021	0.033	0.043	0.062	0.088
Damon	0.018	0.111	0.700	1.529	3.325	5.664
A-Comp.	TMA	0.021	0.104	0.227	0.394	0.626
Damon	0.017 × 0.025	0.116	1.252	3.387	5.464	8.398
A-Comp.	TMA	0.029	0.163	0.388	0.594	0.996
Speed	0.018	0.152	0.278	0.704	1.207	2.009
	SS	0.026	0.031	0.044	0.044	0.082
Speed	0.017 × 0.025	1.002	0.975	1.431	2.371	3.278
	SS	0.081	0.074	0.123	0.107	0.168
Speed	0.018	0.173	0.273	1.025	2.432	5.006
	TMA	0.025	0.062	0.100	0.272	0.384
Speed	0.017 × 0.025	3.208	3.952	4.682	7.866	12.711
	TMA	0.398	0.326	0.486	0.748	0.705

Kapila *et al*., 1990; Kusy and Whitley, 1990a,b; Kusy *et al*., 1991; Downing *et al*., 1994) that TMA exhibited an unacceptably high friction which was only to a limited degree dependent on the dimension. The friction was clearly related to the surface structure of TMA and has recently led to surface treatment with ion beam implantation reducing the friction significantly (Kusy *et al*., 1992). The dependence on angulation was more pronounced in the case of stainless steel than TMA, a possible reason being the lower stiffness of the latter wire. The importance of wire stiffness as a factor affecting frictional forces (Nikolai and Frank, 1980) was confirmed in our experiment, where stiffer wires exhibited increased friction at all angulations probably due to the normal force which increases at the contact point. In the case of the Damon SL bracket no normal force was present at zero angulation and the binding which started at 6 degrees was most pronounced with rectangular wires, leading to a rapid increase in friction with respect to all wires.

Within the same type of bracket, except in the case of the Speed bracket, friction with round wires exhibited higher dependency of angulation than friction with rectangular wires. The low friction related to the self-ligating bracket reflected the lack of normal force in the case of these brackets. As the wire was 'undersize' and no friction could be anticipated in the experiments without angulation, consequently only insignificant obstruction to a free movement could be verified in the case of the Damon SL bracket. For the Speed bracket, the 'spring' coverage could account for the friction related to this bracket at zero angulation as the spring delivers a normal force depending on the dimension of the bracket. While Berger (1990) found Speed brackets to generate a significantly lower friction than conventional brackets at wire dimensions up to 0.016 × 0.022 inches, Sims *et al.* (1993) reported higher frictional forces with increasing wire dimensions up to 0.019 × 0.025 inches. These findings suggest that friction in relation to Speed brackets could possibly be related to the slot depth and spring tension rather than archwire width. This conclusion is consistent with the discrepancy between the extremely low friction related to round wires and high friction related to rectangular wires found in this study. The effect of the flexible coverage depends on the presence and absence of contact between wire and spring, and thus is dependent on the surface structure of the wire and the force delivered by the spring. This also may explain the perceived need for the development of a special wire cross-section. In the case of the Damon SL bracket no normal force is delivered as the bracket is transformed into a tube 0.022 × 0.028 inches when closed. This accounts for the negligible friction at zero degree found in this study and that for the Activa Bracket in previous studies (Sims *et al.*, 1993, 1994). The dependence on angulation, independent of bracket type stresses the need for alignment before sliding mechanics are used (Tidy, 1980; Drescher *et al.*, 1989; Sims *et al.*, 1994). The comparison between the Damon SL bracket and the conventional A-Company bracket is noteworthy as the brackets are identical apart from the method of ligation. This makes it possible to focus on the influence from the normal force which is often high even at zero angulation.

In the present study only the presence or absence of a normal force was evaluated, however, the type of ligation may also be important (Frank and Nikolai, 1980; Peterson *et al.*, 1982; Stannard *et al.*, 1986; Kusy and Whitley, 1990; Bednar *et al.*, 1991; Shivapuja and Berger, 1994) and an interaction between ligation with elastomers and the width of the brackets may contribute to the explanation of the diverging results on bracket width and friction (Kapila *et al.*, 1990). Another factor of importance may be the springiness of the wire, which would explain the difference in behaviour. In our experiment the normal force was always kept at 2 N, in the clinical situation the friction would increase even further, where ligation of rotated teeth may generate a higher normal force and elastomers may generate both a higher and a lower force depending on the stretching of the elastics.

Conclusions

The present study confirmed that friction is a product of factors that may interact in various ways. The mechanism of these interactions may explain the often conflicting results reported by different authors. The importance of the surface structure was clearly confirmed as the TMA gave rise to significantly more friction than stainless steel. Both stiffness and springback of the wire was of importance when the bracket was sliding along a wire at a certain angle. The stiffer the wire and the lower the springback, the higher the friction generated. The spring design of the Speed bracket resulted in significant friction even at small angles between brackets and wire. The wire dimension also exerted a significant influence. In the case of an undersize round wire the Speed and the Damon self-ligating brackets resulted in significantly less friction than any of the conventional brackets. In the case of rectangular wires the Damon bracket was significantly better than any of the other brackets and should be preferred if sliding mechanics is the technique of choice.

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