Fact or Friction: The Clinical Relevance of In Vitro Steady-State Friction Studies

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The subject of friction in orthodontic treatment mechanics has attracted considerable attention in recent years.[1-59] Appliance manufacturers have battled over whose bracket or system has the least friction. Treatment principles and modalities have been developed to account for the effects of friction on tooth movement and biological response. In spite of the volumes that have been written on the subject, however, there is little agreement on how best to measure friction and determine its clinical significance.

Defining Friction in Orthodontics

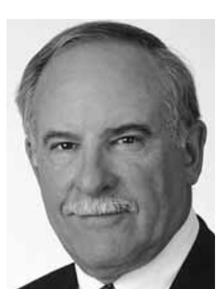
Friction can be defined as a force that resists the relative motion or tendency to motion of two bodies in contact. Orthodontics involves sliding friction—the interaction between the archwire and the bracket or the bracket-archwire retaining mechanism. The archwire and the bracket are in intermittent contact, and the frequency of that contact is unknown and highly variable. Not only is there freedom of movement between the two bodies as a result of the size difference between the archwire and the bracket slot (as well as other bodies such as the ligature wire), but the two bodies themselves can move. The teeth and attached brackets have varying degrees of mobility and react to the forces and moments applied to them. Moreover, the archwires flex to varying degrees. Therefore, a more accurate term for friction in orthodontics is "resistance to sliding", which encompasses a frictional component as well as factors such as biomechanical dynamics, the binding of the archwire to the bracket complex, and the release of that binding by tooth movement and other motion within the system.

As treatment progresses and the brackets align, the relative amount of archwire-bracket binding changes. Even during the initial stages of treatment, involving considerable deflection within the arch, it can be assumed that the amount of friction is not constant; the binding is intermittently released as a result of the mobility of the teeth, the flexure of the archwire, and the yielding of ligatures. The exact amounts and timing of this release are unknown, but it likely involves a dynamic series of interactions.

In Vitro and In Vivo Studies

The vast majority of studies that have measured resistance to sliding under various conditions have been conducted using a steady-state laboratory model.[1-59] Typically, an archwire is pulled through a series of immovable brackets. The archwire and the brackets are in constant contact as the wire is drawn through and the force is measured. Thus, this test design measures the frictional component of the resistance to sliding between the archwire and the brackets during continuous binding. It does not allow for movement of the brackets or release of the binding.

Only a few researchers have questioned the clinical validity of the steady-state laboratory



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model. One of the earliest references to "dynamic friction" was by Hixon and colleagues in 1970.[60] To test theories of optimal and differential forces, they placed specially designed space-closing devices on six patients who had each had four premolars extracted, then replicated the same devices (.045" wires and tubes) in the laboratory. They found that "static friction" varied from 10% of the applied force at 50g to 20% at 1,400g in the laboratory, but did not observe this proportional loss of force through the system's resistance to sliding in the six patients: "When this apparatus was employed in the patient, however, it was subject to a variety of oral forces, especially from mastication, which produced other motions and permitted the wire to slide through the tube more easily. An estimate of this dynamic (or kinetic) friction was obtained by repeating the above procedure but vibrating the apparatus with an electrical (60 cycle) vibrator. After computation of the linear regression of the equation describing the results, the slope was so minute (.0005) that dynamic or kinetic friction was accepted as 5% of the applied force, irrespective of the force magnitude." In other words, the steady-state laboratory model did not accurately replicate the clinical conditions until it was vibrated. Under vibration, the resistance to sliding was less than 5% of the applied force and was not proportional to that force.

Jost-Brinkmann and Miethke also measured bracket-archwire sliding with both laboratory and clinical devices.[61] They cemented custom-made partial dentures in six volunteers with anterior diastemas and normal tooth mobility (Fig. 1A). In each patient, a single bracket was bonded to a central incisor, and an archwire with a laser-drawn reference line was inserted (Fig. 1B). These cemented fixtures allowed for measurement, in microns, of the archwire movement relative to the bonded bracket as well as the load placed on the archwire (Fig. 1C). Measurements were made with and without occlusal loading, in which the patient was asked to clench on the central incisor every 20 seconds. An identical fixture was fabricated in the laboratory for comparison. The authors concluded: "While the friction measured in vitro with immovable brackets and in vivo without occlusal load did not differ significantly, additional tooth movement by occlusal load resulted in significant reduction of friction magnitude. It should be kept in mind that the mobility of those teeth investigated was absolutely normal, while it is usually increased during orthodontic treatment. Due to this effect and influences resulting from chewing various kinds of food, it can be estimated that the frictional forces occurring with orthodontic treatment are even smaller in comparison to in vitro experiments with immovable brackets." This is the only study to date that has directly measured friction under comparable in vivo and in vitro conditions. Although only one bracket-archwire interaction was tested, the difference between the two conditions was clearly demonstrated.

Most of the in vitro (steady-state) studies

Fig. 1 A. Custom-made partial denture cemented on cast. B. Bonded bracket with archwire and test fixture in place. C. Assembled test fixture allowing measurement of archwire movement relative to bonded bracket and force load. (Reprinted by permission.[61])

comparing the resistance to sliding of stainless steel archwires to that of titanium alloy archwires have reported that a beta titanium wire has four to six times the friction of a stainless steel wire of the same size. As a result, beta titanium wires began to be manufactured with a hydrogen ion impregnation process to make the surface harder and smoother, so that the friction coefficient would be similar to that of stainless steel. Subsequent steady-state laboratory studies confirmed that the ion-impregnated beta titanium wires had a lower resistance to sliding than the non-impregnated beta titanium wires.[34] A clinical study in which .019" × .025" beta titanium wire was ion-impregnated in only half of each patient's arch, however, found no significant difference in the rate of extraction space closure between the two sides, and a similar closure rate to that reported for stainless steel archwires.[62] This is yet another example of how the results of in vitro studies can be clinically insignificant and even misleading.

Simulation of Intraoral Dynamics

In an attempt to better emulate actual biomechanical dynamics, some researchers, including Hixon and colleagues,[60] have designed laboratory devices that incorporate movement within the brackets, archwires, or both while measuring resistance to sliding. Liew placed an oscillating force of 25-400g at 90Hz on the archwire as it was drawn through a bracket.[63] The resistance to sliding was reduced by 60% with 25g of wire-displacement force, as compared to a steady state with no wire displacement, and by 85% with 100g of wire-displacement force. Liew concluded: "The effective frictional resistance between orthodontic brackets and archwires is substantially reduced by the disturbance of the wire produced by masticatory forces and other oral functions. Small forces, well within the range exerted in the mouth, are sufficient to produce this effect. This suggests that there will be less friction between wires and brackets in the mouth than is indicated by the laboratory sliding tests in a steady mode. It follows that friction in vivo is not as significant as shown in conventional (steady state) studies."

In a similar laboratory study, Braun and colleagues measured frictional resistance with various wire sizes, degrees of wire binding, and ligation methods.[64] As the archwire was drawn through the bracket, either the wire or the bracket was tapped with a finger. These "perturbations" (20-200g of force, with a mean of 87g) were applied to the bracket or archwire in random frequencies and in random directions in all three planes of space. In every instance, independent of wire size, ligation method, and 2nd-order wire deflection of as much as 25°, the resistance to sliding was reduced to zero when the wire or bracket was displaced. The authors concluded: "Frictional resistance was effectively reduced to zero each time minute relative movements occurred at the bracket/wire interfaces. Factors such as the degree of dental tipping, relative archwire/slot clearances, and method of tying did not have a measurable effect on frictional resistance in the simulated dynamics of the oral environment." They also noted that this was a simple model of a single bracket-archwire interaction, and that the intraoral biomechanical environment would be far more complex.

In yet another laboratory study attempting to simulate the dynamics of the oral environment, O'Reilly and colleagues oscillated the test bracket while measuring sliding resistance.[65] They wrote: "If one considers the clinical situation, where there is intermittent movement between the bracket and archwire, then clinically we may not be looking at true friction, but rather a binding and releasing phenomenon. In the present study, it was found that repeated displacement of a bracket, equivalent to as little as .16mm of mesiodistal crown movement, could reduce the sliding resistance by as much as 85%." They concluded: "The influence of friction, given the likelihood of bracket and/or wire displacements in vivo, is thought to be small and may have significantly less clinical importance than previously stressed."

Spontaneous Sliding of Titanium Wires

Although neither the steady-state laboratory model nor the simple single-interaction dynamic model can replicate complex oral biomechanics, further evidence that friction may have less influence than orthodontists have been led to believe is provided by the common clinical observation of the spontaneous sliding of titanium alloy archwires (Fig. 2). Unless a stop is placed in the wire or the distal ends are bent back, the wire routinely rotates around the arch, usually in the same direction on a particular patient. Stainless steel archwires, which have a lower coefficient of friction, rarely exhibit spontaneous sliding.

Such a phenomenon undermines the implication of steady-state studies that high-friction wires should be less prone to sliding than low-friction wires. A possible explanation is that because titanium alloy archwires are more resilient and flexible than stainless steel wires, they are more readily released from binding in the dynamic oral environment, despite their higher coefficient of friction. This theory supports the conclusion of Articolo and Kusy that the binding and releasing components may be more significant than the frictional component of resistance to sliding.[39]

Fig. 2 Spontaneous sliding of .019" × .025" beta titanium archwire in ligated ceramic brackets.

Conclusion

The simpification of complex biomechanical interactions that inevitably occurs in steady-state laboratory testing may have resulted in an overestimation of the clinical significance of friction. Entire bracket systems, treatment modalities, and treatment-planning decisions have been based on beliefs about friction that may be mistaken. Additional studies that focus on the dynamic oral environment are needed to determine the true influence of friction in orthodontic treatment and to guide future appliance development.

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