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Biomechanics of clear aligners: hidden truths & first principles

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ABSTRACT

Over the past two decades clear aligner-based treatment has received remarkableattention from the orthodontic profession and more so from general practitioners.Different companies have emerged using vigorous advertisement to promote theirproducts mainly to patients and clinicians through social media. A variety of concepts,methods, and adjuncts have been introduced to enhance the efficacy andeffectiveness of clear aligners. However, the accuracy of tooth movement (vspredicted) with aligners still hovers around 50%. Fixed appliances fare much better onaccuracy and predictability of treatment. Why is there a discrepancy betweenexpected and actual outcomes? This paper utilizes 'first principles' and the existingevidence to unravel some of the key drawbacks of aligner-based therapy. Severalshortcomings in the biomechanical properties of aligner material (thermoplastics) thataffect clinical performance are discussed. Based on the first principles of alignerbiomechanics, this paper provides clinical insights for improving predictability and effectiveness of aligner therapy.

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1. Introduction

In the past 2 decades, clear aligners have become an increasingly popular alternative to fixed appliance treatment for mild to moderate malocclusions [1]. The concept of clear aligners evolved in 1940 when Kesling introduced "the positioner to refine the final stages of orthodontic treatment" [2]. In 1971, inspired by Kelsing's positioner, Ponitz introduced "the invisible retainer" [3], which was followed by similar appliances by McNamara and Sheridan [4,5]. The development of computer-aided design (CAD) and rapid prototyping (RP) techniques allowed an industrial approach for both planning orthodontic treatment and manufacturing polymeric aligners [6,7]. In 1998, Align Technology (Santa Clara, CA) introduced Invisalign, a series of removable polyurethane aligners, as an aesthetically appealing alternative to fixed labial braces. This system allowed for movement of multiple teeth simultaneously, to fix various malocclusions [8]. The earliest systems relied primarily on the aligners to achieve desired tooth movement. Recently, the system has evolved remarkably with the introduction of auxiliaries, attachments, and better fabrication material, allowing aligners to produce a greater range of movement in less time [9].

Although professional use of clear aligners continues to increase, questions regarding its efficacy remain [10]. Opponents have pointed out limitations in treating complex malocclusions, for which there has been a consistent mismatch between predicted and clinical outcomes, specifically in terms of amount and type of tooth movement [11]. Over the years, a substantial body of research has focused exclusively on the efficacy of tooth movement with clear-aligner systems [12–15]. The current consensus is that the discrepancy between predicted and clinical outcomes is around 50% or more, requiring multiple stages of refinement or added treatment (Fig. 1). Many orthodontists have reported that 70% to 80% of their patients require midcourse correction, case refinement, or conversion to fixed appliances before the end of treatment [16,17]. Some have reported that patients treated with aligners showed more relapse than those treated with fixed appliances, particularly for the maxillary anterior teeth [18].

2. Reasoning from first principles

Tooth movement with aligners is more complex than it is with fixed appliances. This difference can be attributed to the absence of specific points of force application, tooth anatomy, aligner material properties, mismatch between aligner and dentition geometries, slipping motions between contact shapes, and other biomechanical factors [14,19]. Accurate treatment prediction has long been a challenge for orthodontists, as well as for the many available pre-

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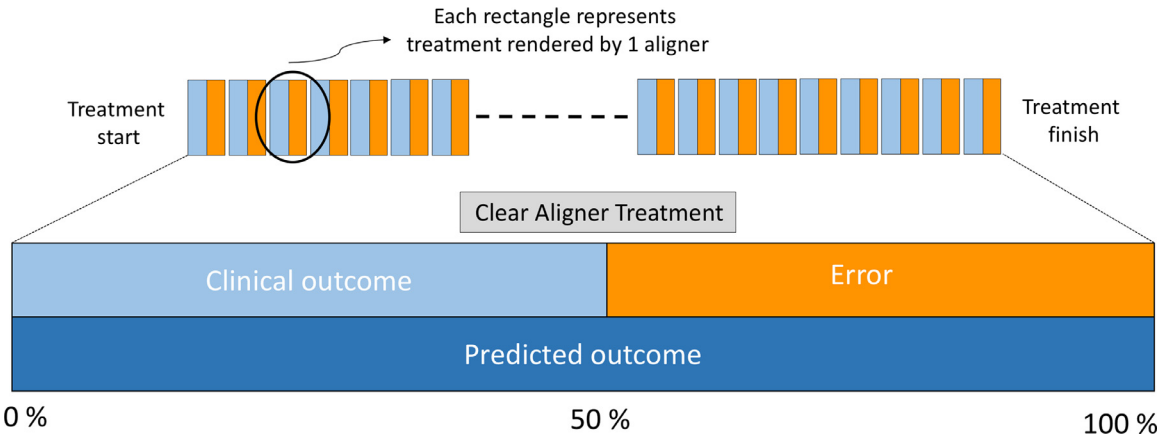

Fig. 1. Predicted versus clinical outcome with aligner-based therapy: Every aligner falls short (orange) of the predicted outcome (blue). The error from each aligner accumulates through the course of treatment, requiring more aligners or refinements to fix.

diction algorithms used by various aligner companies. This paper provides a deep dive to determine why aligners do not provide the expected outcomes. Why is there a huge difference between predicted and clinical outcomes? We approach this question from a "first principles" perspective, to unravel the biomechanical limitations of aligners. A first principle is a foundational proposition or assumption that stands alone and cannot be deduced from any other proposition or assumption. Reasoning from first principles involves breaking down complicated problems into basic elements and then reassembling them from the ground up, in light of existing evidence.

3. How do aligners move teeth?

Aligner-based orthodontic treatment involves incremental movement of teeth, by use of multiple successive aligners or trays, each of which progressively repositions teeth by small amounts [20]. This incremental movement is brought about by 2 primary mechanisms:

3.1. The shape molding effect

This method has been the primary means of force application since the inception of clear-aligner treatment in the 1940s [11]. The method involves "molding" the movement of the target teeth according to the shape of the aligner used [20,21]. Pre-established mismatches (activation) between the aligner shape and the dental crown geometry generate 3-dimensional (3D) force systems distributed all over the contact surfaces [22]. There are areas of intimate contact and relief between the aligner and the tooth surface. A full treatment consists of a set of aligners with sequentially varying shapes, ranging from the initial anatomic geometry to the final tooth positions [21].

3.2. Auxiliary elements

Auxiliary elements, such as attachments and power ridges, are used to enhance predictability of specific tooth movements [23]. The strategic arrangement of these auxiliaries in aligners or on the teeth can enhance force delivery [24]. They are used strategically to deliver forces at specific areas on the tooth surface.

3.3. Which approach is better?

At the fundamental level, tooth movement is an interplay of the stress created between the appliance and the biological complex consisting of the periodontal ligament and the surrounding bone [25]. For tooth movement, an aligner has to maintain acceptable levels of stress (optimal force) throughout treatment. This force is created and transmitted to the surrounding periodontal complex, by means of either the shape molding effect [20] or attachments [26]. Theoretically, the stress (force/area) exerted by the shape molding effect will be significantly lower than the stress created via an attachment for the same force system [24] (Fig. 2), because tooth movement created via the shape molding effect involves force transmission to a larger surface area of the tooth, compared with that of an attachment, which has a significantly smaller surface area. Between the 2, most of the treatment is executed through the shape molding effect [20,21].

4. How do aligners treat various malocclusions?

Based on the broad mechanism described above, aligners have been used to treat various malocclusions [23].

4.1. Deep bites

Deep-bite correction with aligners can be achieved by 3 methods, alone or in combination (Fig. 3).

4.1.1. Watermelon seed effect

Aligners have the inherent ability to simultaneously engage the occlusal, buccal, and lingual surfaces of teeth. This ability provides them with a unique ability to apply compressive forces from all directions; hence, the term "watermelon seed effect." The idea behind this effect is to create a resultant force vector that is directed through the center of resistance of target teeth [13,27]. However, as good as this may sound, tooth crowns are not symmetrical structures. This asymmetry often creates an uneven distribution of forces, and the resultant force will most likely miss the center of resistance and create a moment. If this moment can be predicted in advance, then certain modifications called "pressure areas" [28] can be added to the aligners to create an additional force that will redirect the net compressive force through the center of resistance.

4.1.2. Bite ramps

Deep-bite correction is also achieved by extrusion of posterior teeth. The key step is to remove occlusal forces. Bite ramps or lingual prominences can be added to the palatal surface of maxillary incisors or canines near the cingulum area, to disocclude the posterior teeth and encourage extrusion [29].

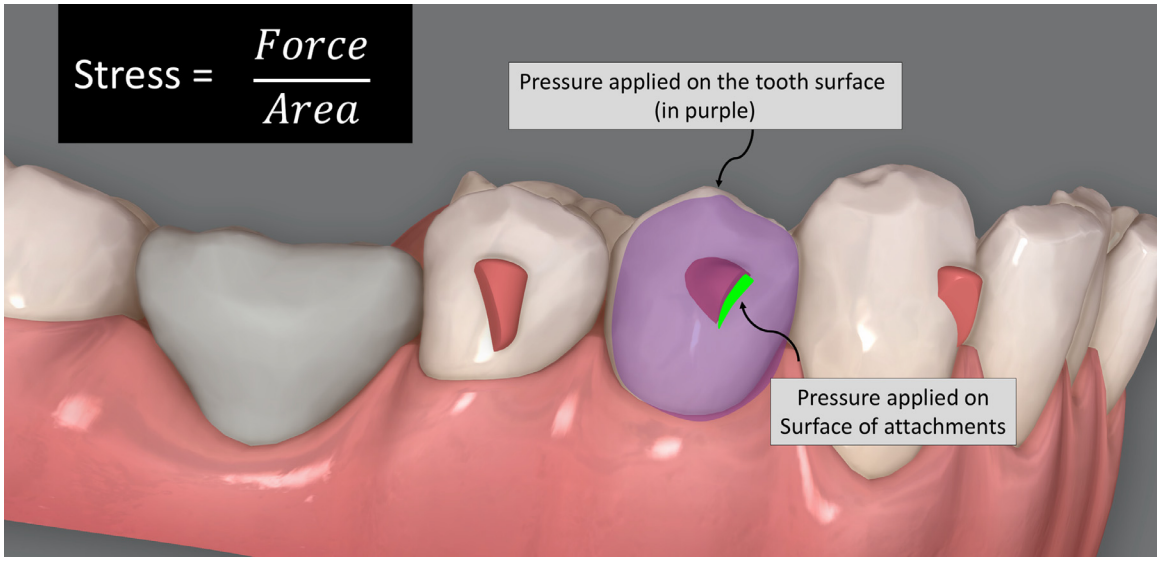

Fig. 2. Let us assume that the first premolar requires a force of 100 g to move lingually. Also assume that the buccal surface area (purple) of the tooth is 100 mm^2, and the attachment surface (green) is 5 mm^2. The stress created by the shape-molding effect [100 g/100 mm^2 (approximately) = 1 g/mm^2]. This is 10 times less than the stress created by the attachment (100/10 mm^2 = 10 g/mm^2) on aligners. A point to note is that greater stress can lead to greater amounts of deformation of the aligner material.

4.1.3. Drawbridge effect

Simple tipping of anterior teeth can lead to pseudo correction of the overbite, known as the "drawbridge effect." This impact does not involve a "true" intrusion of anterior teeth (a movement along the longitudinal axis of teeth) but rather just a relative movement of the incisor crown downward and backward. This method might well be the easiest way to fix an excessive overbite, because directing forces through the center of resistance of target teeth is very difficult [13,30]. "Power ridges" are indents placed on aligners in the gingival third of the crown for enhancing the tipping of incisors [20].

4.2. Open bite

Open-bite correction is essentially the reverse of deep-bite correction. The basic principles are similar as outlined above (Fig. 3). Anterior teeth need extrusion instead of intrusion; posterior teeth need intrusion instead of extrusion; and incisors have to be tipped back or retroclined for pseudo correction of the anterior open bite [31]. The mechanics and auxiliary elements are also similar. The intrusion of posterior teeth will cause a forward and counterclockwise rotation of the mandible, leading to a reduction in open bite [32]. The anterior extrusion and posterior intrusion force pairs complement each other in accordance with Newton's First Law or the Law of Equilibrium, which states that sum of all the forces in any plane should be equal to zero [33]. An extrusive force created by the aligner will be accompanied by an intrusive force on the posterior teeth. Harris et al. [31] have shown that the primary mechanism of open-bite closure comes from the drawbridge effect or simple tipping of incisors, accounting for close to 60% of the correction observed. This closure is followed by autorotation of the mandible caused by posterior teeth intrusion, accounting for another 30% of the total correction. The combination of these 2 effects shows that true extrusion of anterior teeth contributes only 10% or less of the correction. This finding does not come as a surprise. Clinical reports have suggested that vertical extrusion is one of the toughest movements for aligners to accomplish [10,14].

4.3. Alignment/crowding

Several options are available for resolving arch-length discrepancy, such as expanding the dental arch [34], proclining incisors, and/or performing interproximal reduction (IPR) [35]. The primary mechanism of gaining space is through tipping [13]. A single force applied on the crown can create tipping, which is arguably one of the easiest movements to perform. Less precision is required with these movements, as the force vector does not have to be in any particular relationship to the center of resistance. Tipping is a byproduct of the moment of force where the line of force is away from the tooth's center of resistance [36]. Aligners utilize the shape molding effect to achieve this. In fact, the general inability of aligners to direct force through the center of resistance is actually a benefit, as the default tooth movement is simple tipping [14].

4.4. Space closure

Space closure is an interplay between the moment of force, which is created by the force of retraction and the moment of a couple [24]. The moment of a couple plays a dominant role when there is a need to "control" tooth movement. Any tooth movement other than uncontrolled tipping will require a moment of a couple. Optimized root control attachments [37] are preferred for second-order control, whereas power ridges (lingual projections) establish third-order control over tooth movement (Fig. 4).

4.5. Torquing of roots

This type of tooth movement is perhaps the most force-intensive in orthodontics. Higher magnitudes of force have to be sustained through the entire movement. Unfortunately, root movement with aligners has been an arduous task [38–41]. Later in this paper, we demonstrate why this has been the case.

5. How good are aligners at moving teeth?

A good way to estimate the efficiency of aligner-based tooth movement is to find the ratio of the final/achieved tooth move-

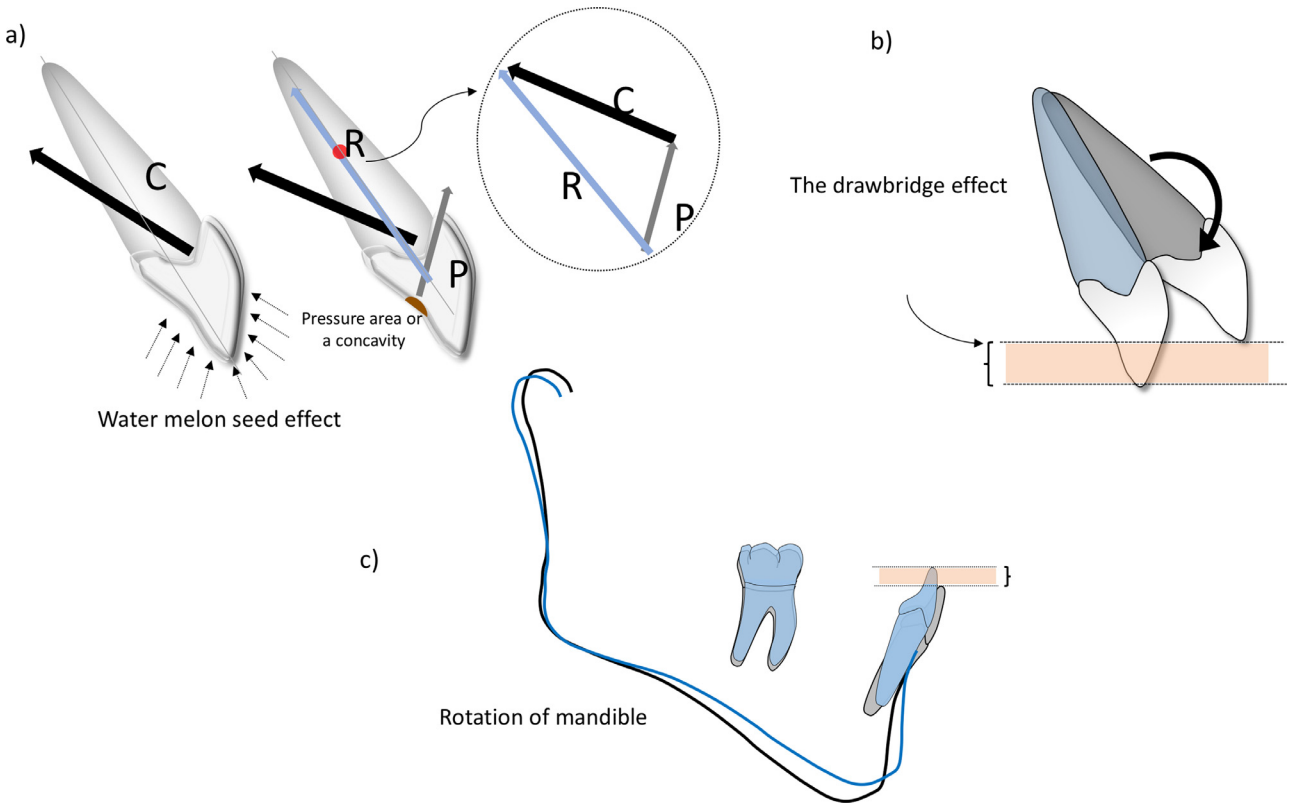

Fig. 3. Mechanisms of vertical correction by aligners. (A) "True" vertical correction by vertical movement of anterior (for deep bite) or posterior teeth (for open bite). (B) The drawbridge effect by tipping of anterior teeth. (C) Rotation of the mandible upward (intrusion of posterior teeth) or downward (extrusion of posterior teeth) will result in vertical movement of lower anterior teeth. Note: (B) and (C) are categorized as "pseudo" correction of overbite. C = Compressive force. P = Force from the pressure area. R = Resultant force.

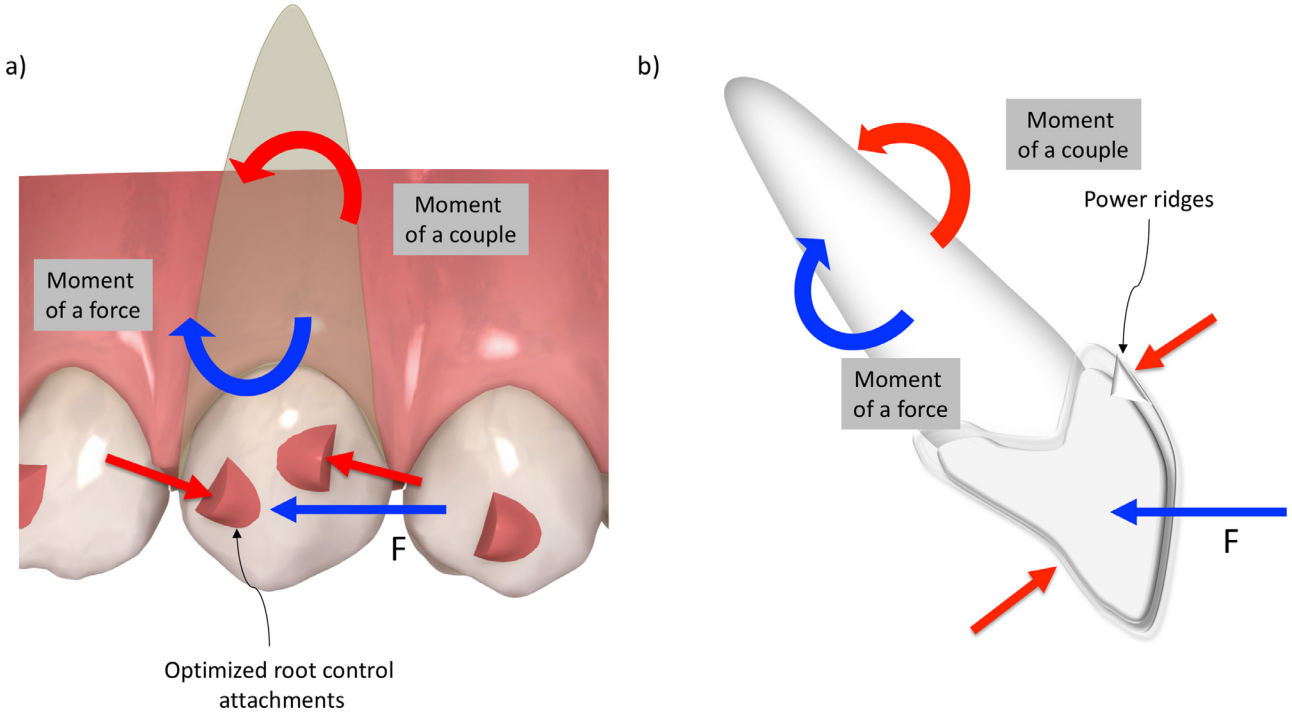

Fig. 4. Controlling root movement during space closure: (A) Attachments for applying moment of a couple in the second order. (B) Third-order control achieved with the help of "power ridges."

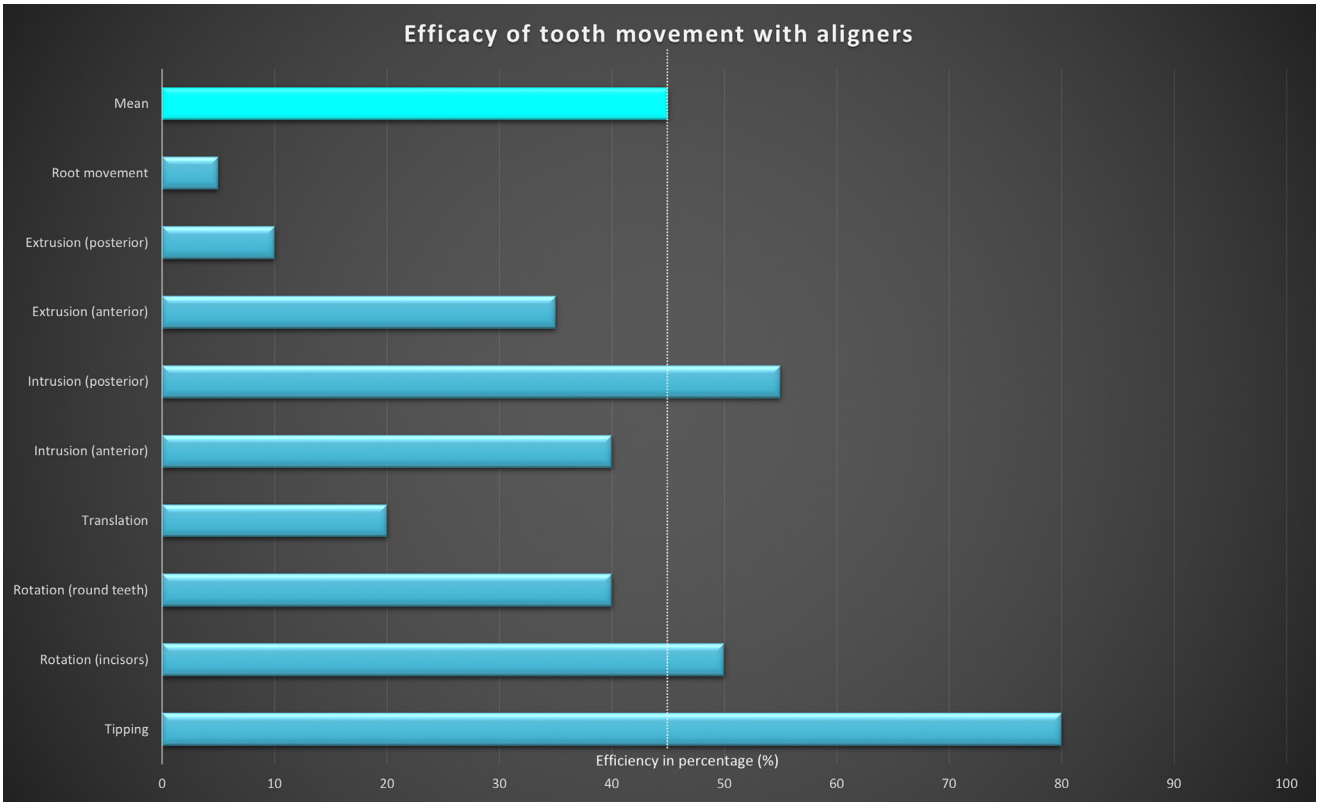

Fig. 5. Aligner efficiency (%) for different types of tooth movement. This graph was constructed to approximate the consensus from the available literature on how good aligners are at moving teeth [9,10,14,16,24,30,42,43,45]. Tipping is the most predictable tooth movement, whereas root movement or torquing is the least predictable. Recent literature has shown the mean efficiency to be 50%.

ment to the desired/predicted tooth movement [16,24,42,43], as follows:

$$\text{Efficiency of aligners (in \%)} = \frac{\text{Clinical tooth movement}}{\text{Predicted or desired tooth movement}} \times 100.$$

Figure 5 represents a quantitative description of the efficiency of aligners for various types of tooth movement. These data provide a simplified version of the data in the literature [1,9,10,14–17,21,24,30,37,42–45]. Shown are absolute, not relative, tooth movements. For example, in the previous section, we showed that overbite correction can be obtained by tipping teeth; however, such tipping does not indicate a true intrusion or extrusion along the long axis [46]. Aligners move teeth by pushing rather than pulling [44], allowing for intimate contact between the tooth surface and the aligner. This facilitates uniform stress distribution and better force application, transmission, and control over tooth movement [47]. No wonder aligners are better at intruding rather than extruding teeth [14]—they work better for closing rather than opening bites [31].

An integrated assessment of the literature shows that the mean efficiency of aligners is around 50% [43]. For many, this result can be surprising, but it is expected—let's find out why. Just because teeth can be easily moved around with some software, they will not necessarily react the same way in reality. However, with advancements in aligner technology and a better understanding of biomechanics, the efficacy of aligners has been improved in recent years [42]. An evaluation of integrated 3D digital models with crown and root showed that clear aligners moved teeth by means of a tilting motion, and crowns, but not roots, of anterior teeth could be moved to designated positions, making tipping the most predictable tooth movement, and root torquing the least predictable [40]. Here, torquing does not refer to any type of root movement. Root movement can take place while tipping is occurring too (uncontrolled tipping). Torquing specifically means root movement with minimal or no movement of the crown. In other words, the center of rotation is located at the crown [48]. Attempts at creating pure root movement with aligners have not been successful [21,38,40,44].

Other types of tooth movement fall between tipping and root torquing [10]. Rotation of rounded teeth such as premolars and molars is harder than it is for incisors [9,10,42,43]. This difference is further amplified by situations in which $>$ 15 degrees of rotation is desired [24,[45]. Translation by aligners is only observed for very small displacements ($<$ 1 mm) [13].

6. Why can't aligners move teeth as efficiently as fixed appliances?

Reviewing literature on aligner biomechanics, as noted in the previous sections, indicates that the most predictable tooth movement is pure tipping [9,24,13,42,43,47]. Any other type of movement that requires any amount of root control has poor predictability (50% or less), including controlled tipping [1,9,10,14]. More than half of Invisalign cases need refinement, midcourse correction, adjunct fixed appliances, and sometimes retreatment with fixed appliances [16,49]. The lackluster treatment efficacy of clear-aligner therapy can be explained by noting some of its limitations, as follows.

6.1. The 'default' tooth movement

Simple tipping or uncontrolled tipping is the 'default' tooth movement in orthodontics, for both aligners and fixed appliances. A single force applied labio-lingually at the crown creates this output [48]. A clinician does not have to intricately calibrate the type, amount, method, or direction of force application. On the other hand, specific tooth movements, such as extrusion and intrusion, require detailed planning to redirect the force system through the center of resistance, whereas others, such as controlled tipping, translation, and root movement, require careful titration of the force with the application of a counterbalancing moment (moment of a couple) to optimize tooth movement [50–52].

6.2. Force delivery

Fixed appliances give clinicians various options to engineer different types of force systems. Changing the type (modulus of elasticity, E) of archwire (nickel titanium or stainless steel) [53] and /or the dimensions (moment of inertia, I) [54] in conjunction with using different types of bracket systems (prescriptions; tip/torque) [55,56] can create the desired type of tooth movement. These combinations give varying intensities of a force system to choose from. Aligners do not offer this flexibility. The thermoplastics used for aligners come with a set flexural rigidity (E, I) that cannot be significantly altered [57,58]. Additionally, degradation of the polymer molecular structure by water absorption might occur in the oral environment, which can cause a decrease in the actual orthodontic forces delivered by aligners over time [59].

6.3. Stress relaxation

Stress relaxation is arguably the single biggest factor in determining the efficiency of aligners; it is a time-dependent decrease in stress under a constant strain. This characteristic behavior is studied by applying a fixed amount of deformation to a material and measuring the load required to maintain it, as a function of time [60]. Stress relaxation is a measure of the constancy of force delivered over a period of time [60]. Maintaining a constant force is desirable in orthodontics [61], but aligners are not good at such maintenance. The decrease in force is not linear with time, but rather is "exponential" (Fig. 6). In fact, the force drop is quite dramatic in the first few hours of use, indicative of material fatigue [58]. A similar rapid drop is also observed when torque is applied [24]. In comparison, a nickel–titanium archwire at similar or greater stress levels remains active for weeks [62]. This force drop should be taken into consideration while planning treatment with aligners [63].

6.4. Activation

As noted previously, complex tooth movements such as translation and root correction require higher magnitudes of force [48]. One way to achieve this force is by increasing the activation of the aligners [64]. Archwires are routinely activated by wire bending, wire twisting, or bracket repositioning. More activation creates a higher force magnitude. However, the same is not true for aligners. Aligner activation causes a decrease in force magnitude [65]. In fact, the higher the activation, the steeper the force drop [66]. This tendency should favor application of the "shape-molding effect" of moving teeth, rather than using attachments, which provide sudden bursts of force activation followed by steep drops in the force magnitude. We saw previously that these drops become exponential over time [58].

6.5. Prediction system (algorithm) with unknown variables

As treatment progresses, the mechanics of aligners cannot be adjusted, as they can with fixed appliances. Rather, the force system and resulting tooth movement has to be predicted in advance for the entire treatment period [21,67]. Such prediction requires a firm understanding of not only the material properties and force system but also the surrounding biological structures. Any gaps in knowledge can pose a serious challenge for the prediction algorithms. For example, none of the aligner systems takes into consideration the anatomy of the root, specifically the location of the center of resistance (Cres). As a result, prediction for the force system is poor, specifically the moment of a force (force applied x perpendicular distance to the Cres). This prediction is critical for estimating the force system for a specific tooth movement, as the application of the moment of a couple depends on it. Remember, it is the moment of a couple that controls root movement and is responsible for creating the various types of tooth movement [13,40,41,44].

6.6. Intraoral degradation of mechanical properties

Aligner material intraorally shows signs of abrasion, delamination, adsorption of integuments, and localized calcified biofilm deposits at stagnation sites [68]. These effects can decrease the elastic modulus of aligners, making them brittle and prone to developing cracks [69,70]. Such occurrences are frequent with prolonged use of aligners as retainers [71]. Also, unlike archwires and brackets, aligners undergo degradation of their polymer molecular structure by water sorption in the oral environment. This degradation can cause a decrease in the orthodontic forces delivered by aligners over time [57,59,72].

7. What is missing in the aligner material?

Stress levels of 0.5–1 MPa might be sufficient for tipping movements, but they fall short for controlling root movements [64]. Ideally, an aligner should be able to not only deliver light constant force over time, but also be stiff, have a high-yield strength, and ensure force delivery within the elastic range [58,73,74]. In other words, a material should tolerate varying degrees of deformation and still be able to create the desired force system [53,75]. These characteristics are closely related to an internal mechanical property—E —which measures a material's resistance to being elastically deformed [76]. A stiff material has a high E and can create heavier force systems with minimal deformation. A flexible material will have a lower E and can easily deform. For example, NiTi archwires are flexible, have a low E, and create lower force levels. In comparison stainless steel archwires are stiff, have a higher E, and create heavier force systems [76]. On a similar scale, aligners have an E that is 40–50 times lower than that of a typical NiTi archwire [77] (Fig. 7). This E level means that it can deform easily with little force, which is surprising to many. Aligners offer far less resistance to permanent deformation than do all the different types of archwires. This characteristic explains why a series of aligners is required to fix malocclusions as simple as minor crowding, which can be corrected by a single NiTi archwire.

8. Aligners are "viscoelastic" materials

The factors highlighted provide a fundamental understanding of what to expect from aligners in terms of force delivery, constancy, magnitude, and decay. Aligners are known to do the following: (i) apply low force; (ii) work better with less activation; (iii) exhibit low flexibility; and (iv) undergo rapid force decay [73]. A material

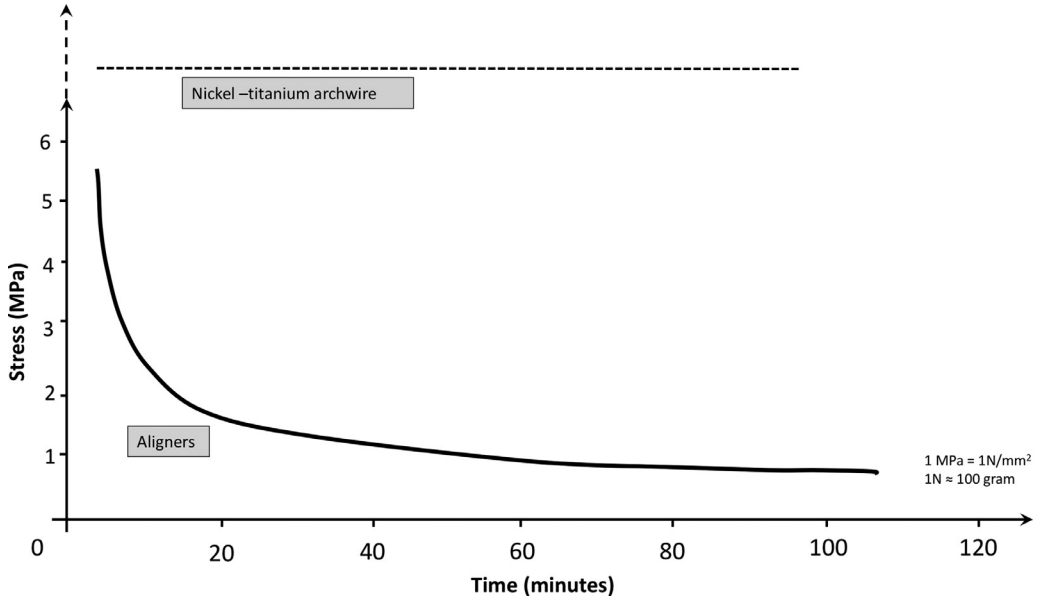

Fig. 6. Stress relaxation (deactivation) curve of aligners in comparison with an austenitic NiTi archwire. Note the exponential decrease in the stress (force/area). More than 90% of the force is lost in the first couple of hours. (This graph is a summary representation of the available data [24,58,63]).

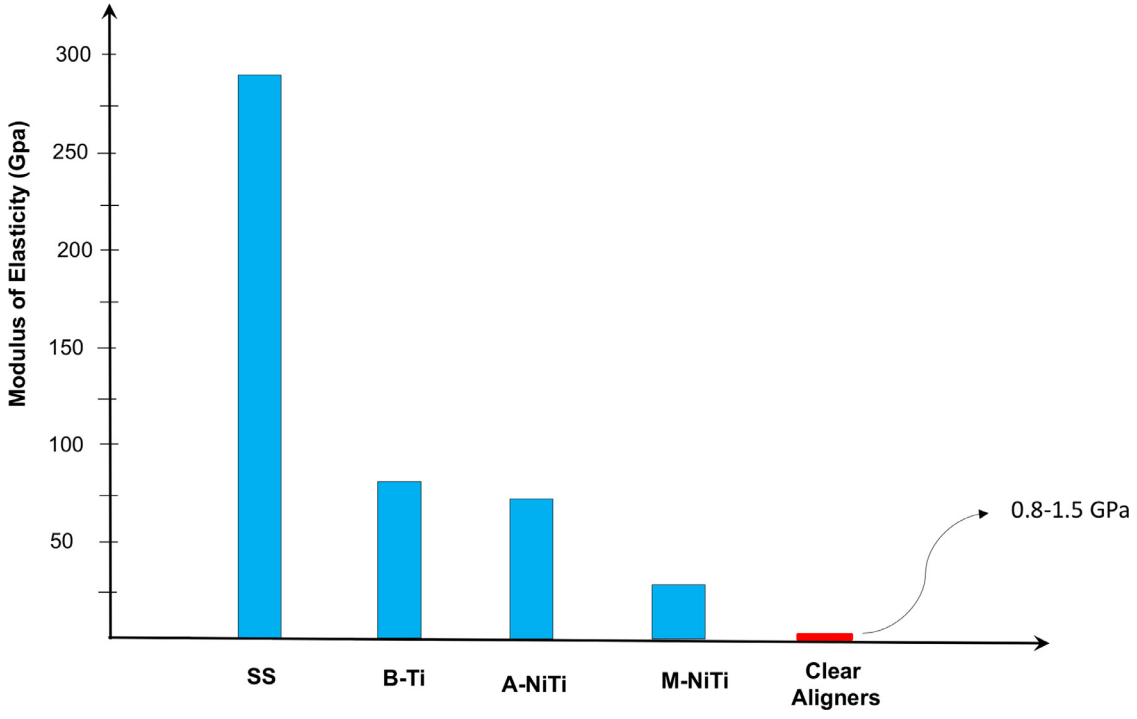

Fig. 7. A summary of the modulus of elasticity (E) of different material types used in orthodontics, which shows the huge gap between aligner material and any of the other archwire types. (Note: This is a relative comparison. The graphs are approximations and do not reflect accurate values.) SS= Stainless Steel. B-Ti = Beta Titanuim. NiTi = Nickel Titanuim. A- NiTi = Austenitic Nickel Titanuim. M-NiTi = Martensitic Nickel Titanuim. GPa = Gigapascal.

that can easily deform with little force has low resiliency, which is the ability of an object to absorb energy when it is elastically "loaded" or deformed, and release that energy when "unloaded," without causing permanent deformation of the material. Resiliency is represented by the shaded area under the stress–strain curve up to the elastic limit (after this point the material undergoes some amount of permanent deformation; Fig. 8). Unloading is the measure of force exerted by a material to move teeth [78]. Aligners absorb less energy because under moderate-to-heavy load they permanently deform [79]. They have considerably less resiliency as compared to archwires [57] (Fig. 8). Clinically, this difference is obvious. Crowded dentition that can be corrected by a single NiTi archwire requires multiple aligners to correct. Metal archwires are good at storing energy (loading) and transferring (unloading) this energy to teeth over a period of time, while undergoing minimal fatigue. By contrast, the little energy aligners absorb is mostly dis-

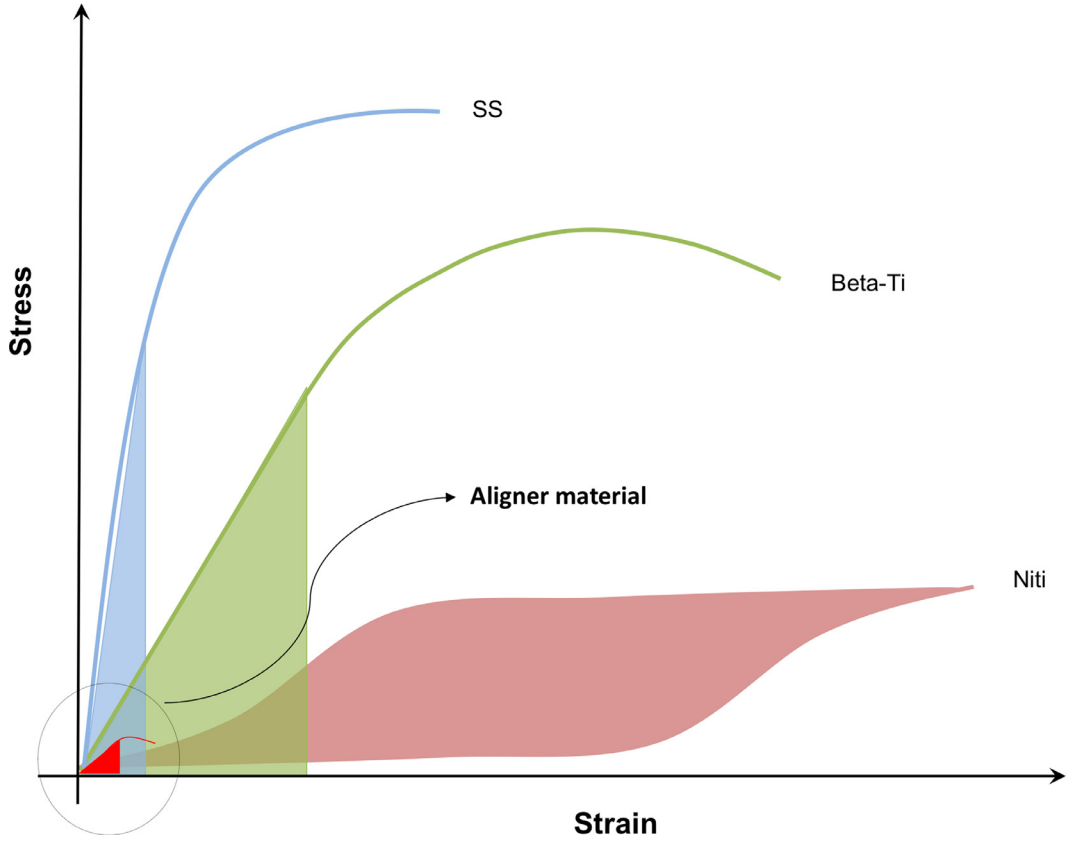

Fig. 8. Aligners have very low resiliency compared to r archwires. This graph shows a relative comparison of the stress/strain curves and does not reflect absolute values. It has been constructed by interpretation of data from the literature [47,85]. SS= Stainless Steel. B-Ti = Beta Titanuim. NiTi = Nickel Titanuim. A- NiTi = Austenitic Nickel Titanuim. M-NiTi = Martensitic Nickel Titanuim. GPa = Gigapascal.

sipated as heat, and a relatively small amount is transferred to teeth. They are therefore "viscoelastic" in nature [80]. Viscoelastic materials are better at absorbing shock, vibrations, and force [58]. A perfect application of such materials can be as "retainers."

9. Conclusions

This paper utilizes first principles and current evidence to identify limitations of clear-aligner mechanics. Most are specific to the aligner material itself. Innovations in the biochemistry of aligner material can bring about radical changes in its therapeutic application. Without such innovation, aligners will always be limited by biomechanical constraints and will underperform, compared with fixed appliances. However, in the meantime, we have outlined certain modifications that can be made to optimize the application of aligners. These changes are based on the first principles discussed in this paper, and they will improve predictability in producing the desired results.

9.1. Make tipping the primary tooth movement

The material properties of clear aligners are primarily responsible for their inability to apply root control [38,77,81,82]. "Simple tipping" is the most easily achievable tooth movement [16,40,45]. Case selection should take account of this factor. Any malocclusion that can be corrected by tipping teeth will have better treatment predictability—that is, most malocclusions, such as crowding, spacing, open bite, deep bite, and narrow arches. However, if similar malocclusions need movement requiring control over the roots, then alternate options must be considered. For example, a huge difference in the force system is required for space closure by tipping versus translation. The M/F ratio required to fix the former is much lower than that for the latter [52,83].

9.2. Add less activation per aligner

Higher stress causes accumulation of fatigue in aligners. In 'fact, optimizing aligners for more activation leads to a sharper decline in the force system and the resulting stress on the aligners [65]. Building less tooth/aligner movement will help in flattening the steep decline in force over time [77] and will create a consistent and continuous force system through the duration of aligner wear.

9.3. Use more aligners per patient

As follows from the above, if less movement is being built into each aligner, then more aligners will be required for treatment [81,84]. This increase, however, does not mean more treatment time is required. The duration of aligner wear should accordingly decrease. For example, let us assume a 1-mm movement is being carried out by a single aligner in 10 days. If the number of aligners is increased to 5 for the same 1-mm movement, each aligner has to be worn for only 2 days. Of course, this is assuming the software is distributing the 1-mm movement equally among the 5 aligners. Changing aligners frequently has numerous other advantages related to hygiene, appearance, and decreased degradation of the material.

9.4. Utilize the shape-molding effect

The shape-molding effect creates better force distribution than do attachments and/or power ridges. The initial force magnitude is similar for both; however, the stress on the material is lower for the former. Theoretically, this difference should result in smaller drops in the force system as the treatment progresses for the same aligner. The lower level of stress will also help in preserving the elastic properties of the aligners longer.

9.5. Material thickness

Clear aligners have different thicknesses, ranging from 0.50 to 1.5 mm, which can affect their properties and performance while they are inducing tooth movement [65,66]. Thinner materials are more suited to producing light forces that are good for tipping, whereas translation or root movement might require thicker aligner material [65].

[Note: Portions of this paper have been presented at Indian Orthodontic Society's Ortho trends, Master Class (July, 2021), Saudi Orthodontic Society's Webinar series (September, 2021) and orthodontic biomechanics courses at University of Illinois, University of Connecticut & Montefiore Medical Center].

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