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Miniscrew biomechanics: Guidelines for the use of rigid indirect anchorage mechanics

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Indirect anchorage is an established form of anchorage provided by orthodontic miniscrews. Although there are different ways to set up the mechanics, rigid indirect anchorage offers the greatest biomechanical versatility but is more difficult to install than conventional, nonrigid indirect anchorage or direct anchorage. The purpose of this article was to introduce readers to the concept of rigid indirect anchorage and provide guidelines as to its use. (Am J Orthod Dentofacial Orthop 2017;152:413-9)

Over recent years, studies have reported much improved success rates with orthodontic miniscrew implants, compared with the early reports of success rates that were mediocre at best.[1,2] It seems therefore that some factors affecting success and how to control them have finally been identified—the dark days where high failures were simply accepted as fact seem to slowly be left behind us, despite still not fully understanding the phenomenon of how screws fail.[3-5]

However, a successfully inserted and long-term stable miniscrew is only part of the formula for clinically successful miniscrew use. The other important component is the coupling of the miniscrew to the dentition.[6,7] If this connection were to fail, even a stable miniscrew will not deliver the desired anchorage.

It is generally accepted that there are 2 main methods of connecting miniscrews to the patient's dentition: one resulting in direct loading of the miniscrew, the "direct anchorage" approach, and the other resulting in indirect loading of the miniscrew, the "indirect anchorage" approach.[8-11]

Direct anchorage mechanics comprise a setup where an elastic module spans from the miniscrew to the tooth, or group of teeth, that are supposed to be moved. The miniscrew serves a different purpose when used with indirect anchorage mechanics. Here, a nonelastic element spans from the anchorage screw to the tooth unit that ideally should remain stationary: the traditional "anchorage segment," preventing reciprocal tooth movement resulting from conventional orthodontic mechanics.[11] Whereas this approach as we have used and described it has applications in practice,[6,7] it has never been explored in greater detail in the literature, and scientific guidelines for the proper installation of indirect anchorage based on the underlying mathematics have not yet been published.

The purposes of this article were to explain the mechanics related to the use of rigid indirect anchorage biomechanics by applying physics and bioengineering principles and to derive some clinical guidelines for the proper installation of rigid indirect anchorage.

Indirect anchorage options

Indirect anchorage refers to a setup in which the miniscrew is used to prevent tooth movement in the "anchorage segment." This can be accomplished with either a nonrigid coupling element, such as a steel ligature (Fig 1), or a rigid coupling element such as a stainless steel wire segment (Fig 2).

From an engineering viewpoint, the coupling elements described above can be classified as either struts or ties.[12] The Table gives an overview of the properties of struts and ties for better understanding, but the major

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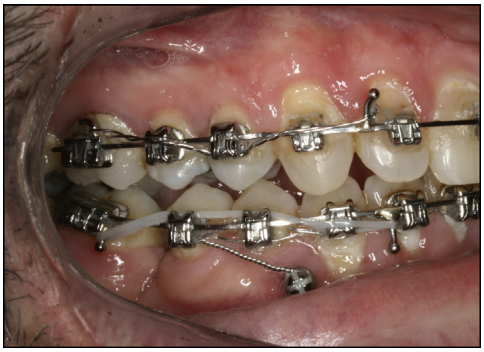

Fig 1. Nonrigid indirect anchorage.

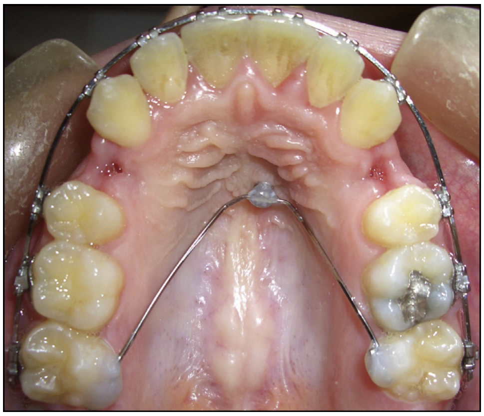

Fig 2. Rigid indirect anchorage: transpalatal arch to second molars.

difference is that ties are tension loaded and aim to keep 2 objects together, whereas struts are compression loaded and serve to keep 2 objects apart (Fig 3).

Nonrigid indirect anchorage is typically achieved by running a tightly wound steel ligature tie from an undercut in the miniscrew head to the tooth one aims to stabilize. This may be a popular option because of the simplicity of the setup; however, despite the simplicity, one should be aware of the proper ways to install this anchorage option to avoid negative outcomes.

First, due to the nonrigid nature of steel ligatures, they can only be tension loaded and hence are structurally classified as ties. This means that their purpose is to keep the miniscrew and the tooth together. When this rule of thumb is kept in mind, it becomes apparent how the setup is best constructed.

Clearly, the screw should be inserted in a position that allows the ligature to span in the direction of the undesired tooth movement. Only then can the ligature wire serve its purpose to resist the applied force and maintain the distance between the screw and the tooth in the plane of the force. In other words, if anteroposterior tooth movement is supposed to be prevented, the ligature tie should also run in an anteroposterior direction, with the screw obviously placed on the opposite side of the force application (Fig 1).

Table. Characteristics of struts and ties

Struts	*Ties*
Part of a framework	Part of a framework
Provide outward-facing support	Provide inward-facing support
Keep 2 objects apart	Keep 2 objects together
Loaded lengthwise	Loaded lengthwise
Load: compression force	Load: Tension force
Rigid structure	Rigid or nonrigid structure

Improper installation of nonrigid indirect anchorage carries the risk of anchorage loss.

Using rigid coupling elements from the screw to the dentition allows the installation of rigid indirect anchorage. Because the connectors are rigid, the miniscrew can be placed on either side of the tooth, disregarding the side to which force is applied. Hence, these coupling elements can function either as struts if the screw is placed on the side of the force application since they are compression loaded or as ties if the screw is placed opposite the side of force application; as a result, they are tension loaded, similar to the way steel ligature ties are loaded.

A tremendous advantage of the rigid indirect setup is that there is more freedom when choosing the insertion site. Since the same element can serve structurally as both a strut and a tie, biomechanical considerations are less important. One can put more emphasis on ideal anatomic parameters for the insertion site vs being forced by the indication to select a certain spot for the screw insertion.

However, because of the coupling element's double function, the setup guidelines are slightly more complex and require a deeper understanding of the element's static properties and its strength. A better understanding of the thought process required to determine the best design of the anchorage setup can be gained by using some clinical examples.

When attempting to retract anterior teeth en masse after first premolar extraction while maintaining the molar position with an orthodontic miniscrew, one may chose a Nance appliance-inspired setup. Although it should be clear to the informed reader that the proper insertion site for the screw is the anterior palate with a paramedian screw position, the question arises if it is more favorable to have the stabilizing wire run more horizontally, for example to the second molars (Fig 2) or more vertically to the second premolars (Fig 4).[13] The mathematics to answer this question will explain how to best construct this indirect anchorage setup.

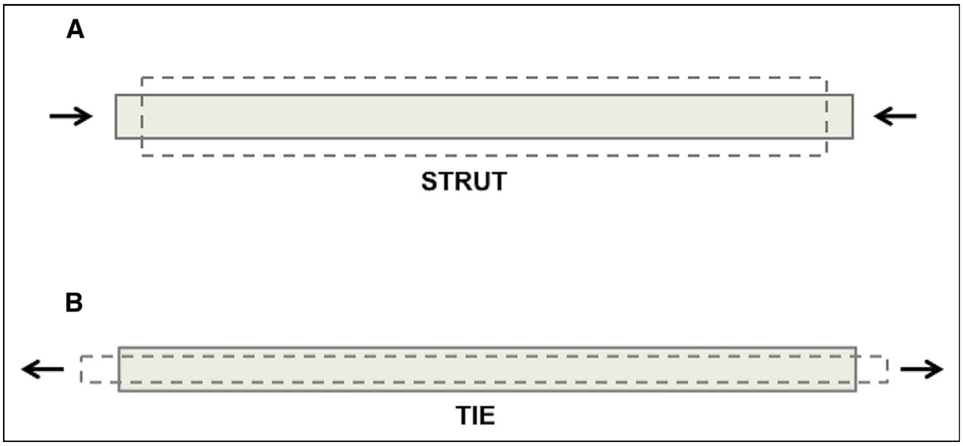

Fig 3. A, Strut: part of a framework with a compressive force acting on it; **B,** tie: part of a framework with a tensile force acting on it.

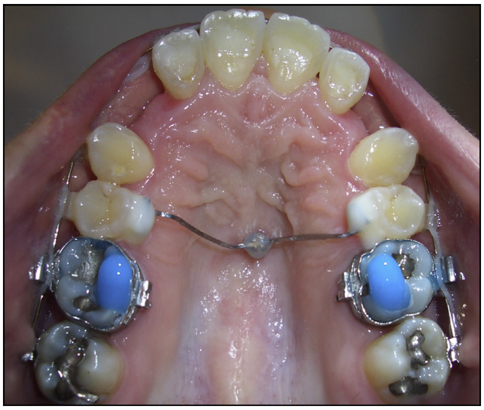

Fig 4. Rigid indirect anchorage: transpalatal arch to second premolars.

For the horizontal wire direction to the second molars, to calculate the internal forces of the stabilizing wire when acting only as a strut, the assumption needs to be made that it is part of a framework in which all joints are pin jointed and frictionless, the wire is not deformed under a force, the effect of gravity is negligible in this situation, and the system is in static equilibrium, which means that the sum of the forces acting on a body must be zero (Newton's first law).[14] Also, we will project the setup into the sagittal plane (2 dimensional) as seen on a cephalometric radiograph to simplify the mathematics resulting in what is known as a free-body diagram.

We will first calculate the internal forces for the scenario in which the connecting wire runs from a miniscrew in the anterior palate to the second molars. Force application in the plane of the wire is assumed to be at a physiologic level of 1.5 N (F_1), and the angle between the archwire and the stabilizing wire will be 30°, a clinically realistic assumption. Using the free-body diagram, Figure 5 is a schematic of the joint resulting from our clinical setup. To understand the internal forces in the stabilizing wire, we apply Newton's laws[14] and the rules of trigonometry.

Because the system is in static equilibrium, according to Newton's laws, there cannot be any unbalanced applied forces on the wire; therefore, the following holds true.

$$\Sigma \text{Forces} = 0$$

This can be expanded as follows.

$$\Sigma Fx = 0$$
$$\Sigma Fy = 0$$

where Fx indicates the force acting on the x-axis direction and Fy indicates the force acting on the y-axis direction. Using Figure 5, the following equations can be written.

$$\Sigma Fx = 0$$

$$F_1 + F_{2x} = 0 \qquad \text{where } F_{2x} = F_2 \cos 30^\circ$$

$$F_1 + F_2 \cos 30^\circ = 0 \qquad \text{Force } F_1 \text{ is known: } 1.5\text{ N}$$

$$\text{Thus, } -1.5/\cos 30^\circ = F_2.$$

$F_2 = -1.73$ N (negative indicates that the force acts in the opposite direction from the originally chosen direction, which is a compression force in this situation).

By introducing a strut that is not solely in the plane of the force application, a vertical force component R (reaction force) is created according to Newton's third law.[14] Using Newton's laws again, the following equation can be written.

$$\begin{aligned} \Sigma FY &= 0 \\ R + F_{2y} &= 0 \qquad \text{where } F_{2y} = F_2 \sin 30^\circ \\ R + F_2 \sin 30^\circ &= 0 \\ R &= -1.73\ \text{N} \sin 30^\circ \\ R &= -0.86\ \text{N} (\text{negative indicates downward direction}) \end{aligned}$$

This vertical force component will easily be counteracted by occlusal forces, avoiding extrusion, whereas the internal force in the stabilizing wire can easily be absorbed without major deformation, explaining why this strut setup provides good molar stability.

However, since we are not dealing with a system that completely adheres to our assumptions above, instead of viewing the stabilizing wire as a strut only, it could also be viewed as a uniform and unilaterally supported (cantilever) beam. To understand the deflection it will undergo in our clinical scenario, it will be beneficial to split our protraction force of 1.5 N along the plane of the archwire into 2 separate forces along and at 90° to the plane of the stabilizing wire through vector resolution. Figure 6 illustrates the clinical scenario, in which F_1 is the force along the archwire, F_2 represents the vector component along the stabilizing wire (at 30° to the archwire), and F_3 acts perpendicular to the stabilizing wire. Using the vector resolution in Figure 6, the math is as follows.

$$\frac{F_2}{F_1} = \cos 30^\circ \text{ and therefore } F_2 = 1.5\ \text{N} \cos 30^\circ = 1.3\ \text{N}$$

$$\frac{F_3}{F_1} = \sin 30^\circ \text{ and therefore } F_3 = 1.5\ \text{N} \sin 30^\circ = 0.75\ \text{N}$$

In other words, the majority of the protraction vector will act along the stabilizing wire, being absorbed as it acts as a strut. However, there is still a sizable force component that will act perpendicular to the stabilizing wire (0.75 N), leading to its deformation. This deformation can be calculated by applying Euler-Bernoulli beam theory's beam deflection formula[15] for a cantilever beam concentrated load F at the free end.

$\partial_{max} = P\,F\,L^3/E\,I$ where ∂_{max} is the maximum deflection at the free end of the beam, P is the constant based on the suspension of the wire (1/3 for unilateral suspension), F is the bending force (0.75 N as calculated above), L is the total wire length (here, 25 mm), E is the modulus of elasticity (here, stainless steel: 180 kN/mm^2), and I is the axial moment of inertia.

The latter is calculated for a rectangular wire by: $I = h\,w^3/12 = 0.08\,h\,w^3$ where h is the wire height (dimension perpendicular to force application), and w is the wire width (dimension parallel to force application).

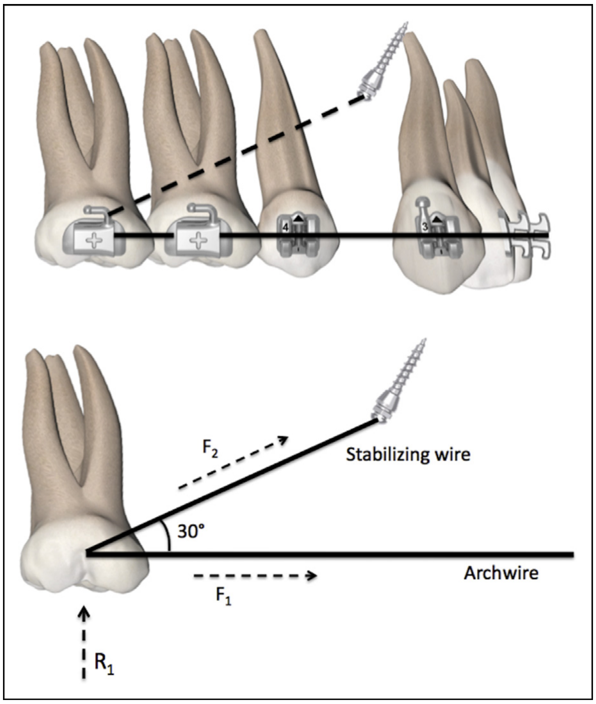

Fig 5. Free-form diagram, with the stabilizing wire acting as a strut.

If I is replaced by the above formula in the beam equation, we receive: $\partial_{max} = P\,F\,L^3/0.08\,E\,h\,w^3$

Assuming that we are using a .021 × .025-inch stainless steel wire in a cross-slot miniscrew, the wire height is 0.53 inches, and the wire width is 0.64 inches. We can now calculate the maximum deformation (∂_{max}).

$$\begin{aligned} \partial_{max} &= \frac{0.75\ \text{N}\ (25\ \text{mm})^3 (\text{mm}^2)}{3\ (0.08)\ (180000\ \text{N})\ (0.53\ \text{mm})\ (0.64\ \text{mm})^3} \\ &= \frac{11718.75\ \text{Nmm}^5}{6002.05\ \text{Nmm}^4} \\ &= 1.95\ \text{mm} \end{aligned}$$

We can see that the stabilizing wire will most likely experience approximately 1.95 mm of deformation at the end of the wire. As this occurs at a 60° angle to the occlusal plane, the majority of the deflection would occur in the vertical direction, which again, assuming normal occlusal forces, would be counteracted easily, at which point the anteroposterior component could not express either. Take into account the bracing effect provided by the stiff archwire connecting the entire dentition, and it becomes conceivable why this anchorage setup will result in near complete anchorage preservation.

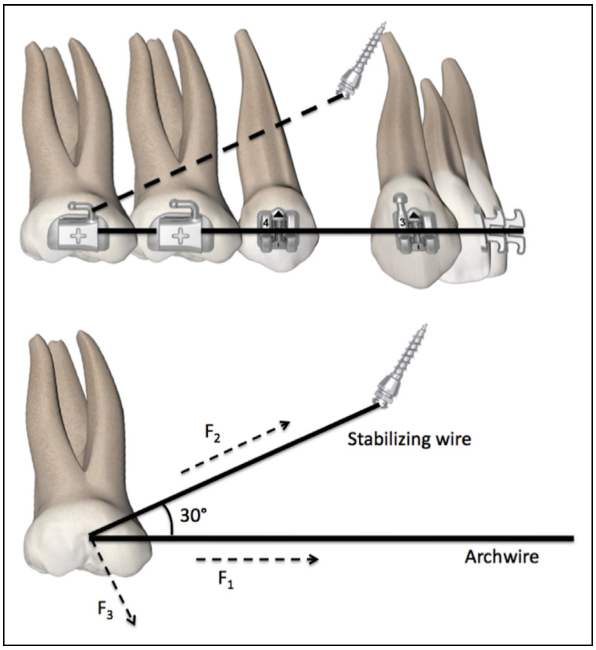

Fig 6. Free-form diagram, with the stabilizing wire acting as a unilaterally supported beam.

Since orthodontists are quite familiar with the impact of wire length on the axial moment of inertia of a wire (about–L^3), it seems likely that a setup with a shorter stabilizing wire would be preferred by most colleagues (eg, to the second premolars; Fig 4). However, the following thoughts will show that this setup will result in a slightly greater anchorage loss. In this scenario, the stabilizing wire runs perpendicular to the base archwire; hence, it acts only as a unilaterally supported beam and has no strut function. Assuming that the length of the stabilizing wire is 15 mm, the beam deflection formula would be identical to the example above, except for the factor length and the fact that the entire 1.5-N load is now applied to the stabilizing wire. In addition, due to the way the stabilizing wire is bent, the wire dimensions are now swapped so that 0.53 mm represents the wire width, and 0.64 mm is the wire height.

$$
\begin{aligned}
\partial_{\max} &= \frac{1.5\ \mathrm{N}\ (15\ \mathrm{mm})^3\ (\mathrm{mm}^2)}{3\ (0.08)\ (180000\ \mathrm{N})\ (0.64\ \mathrm{mm})\ (0.53\ \mathrm{mm})^3} \\
&= \frac{5062.5\ \mathrm{Nmm}^5}{4116.15\ \mathrm{Nmm}^4} \\
&= 1.23\ \mathrm{mm}
\end{aligned}
$$

DISCUSSION

Indirect anchorage as outlined above is a clinical setup preferred and hence frequently used by the authors for anterior en-masse retraction. Naturally, there are many possible setups for indirect anchorage that should result in equally good results, if installed properly.[16,17] That applies to anchorage setups using buccal or palatal insertion sites, as long as the miniscrews are stable. However, regardless of the design of the anchorage mechanics, the resulting setup will be built from either struts, ties, unilaterally supported beams, or a combination thereof. That is why, although the mathematics as outlined above only pertain to the anchorage mechanics described in this article, the concept applies to all indirect anchorage mechanics.

We were able to demonstrate that with the shorter wire length of the unilaterally supported beam setup comes a slight reduction in the absolute amount of wire deflection, compared with the strut setup. However, here the entire amount expresses in the anteroposterior direction, which results in greater anchorage loss. Conversely, the strut setup, with its horizontal wire direction, will maintain anchorage better, because it prevents nearly all anteroposterior tooth movement.

Even though the latter was loaded as both a strut and a unilaterally supported beam, occlusal forces help to counteract the vertical results maintaining equilibrium and ensuring a near constant molar position.

It can be stated therefore that when installing indirect anchorage, preference should be given to a setup in which the coupling part is mainly either tension or compression loaded and therefore acts as either a tie or a strut, and the unilaterally supported beam should be avoided. This can be achieved clinically by installing coupling elements in which the majority of the course is in the plane of the orthodontic force application or parallel to it. The angle between the coupling element and the plane of force application can be conveniently called the "anchorage angle." It should be more obtuse than 135° for ties and more acute than 45° for struts, to ensure that these coupling elements can provide the best indirect anchorage possible (Fig 7). For nonrigid indirect anchorage angles between 135° and 90°, it will result in rotation of the element and anchorage loss until the 135° angle is established. For rigid indirect anchorage angles between 135° and 45°, it will load the anchorage element more like a unilaterally supported cantilever beam than a strut, resulting in the effects described above.

At times, however, a unilateral beam setup cannot be avoided, for example, when the patient lacks the posterior dentition, but anterior retraction is still desired. Here even a 21 × 25-inch stainless steel wire is not rigid enough to ensure reliable anchorage as demonstrated

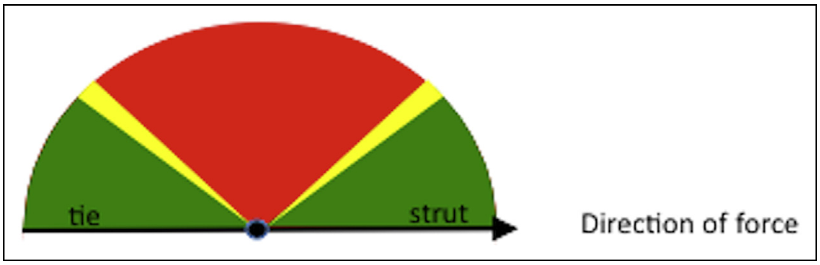

Fig 7. Anchor-O-meter: illustration of tie and strut function (*green zones*) and beam function (*red zone*).

Fig 8. Rigid indirect anchorage using an anchorage auxiliary (Dentaurum, Ispringen, Germany) for a unilaterally supported beam setup.

above. So, the beam dimensions should be changed by using either a laboratory-fabricated framework or a ready-made, chair-side adjustable alternative that has a dedicated mechanism for mechanically attaching it to the miniscrew head (Fig 8).

Certainly, under clinical conditions with the fixed multibracket appliance, one can argue that the side effects mentioned above, when using the cantilever beam approach, can be controlled rather easily by other means. The goal of this article was, however, to illustrate, using mathematics and engineering principles, the most ideal way to construct rigid indirect anchorage in the anteroposterior and vertical planes of space as can be analyzed on a cephalometric radiograph. Certainly, there may be transverse effects that were disregarded for the purposes of the model discussed here. This thought process becomes increasingly important as more clinicians move away from the fixed appliance treatment approach and instead use clear aligners for even more complex orthodontic treatment.[18]

CONCLUSIONS

The predictability of indirect anchorage can be improved if the concept of struts and ties is understood. The "anchorage angle" plays a pivotal role in creating these struts and ties that will increase the anchorage capability of rigid or nonrigid anchorage elements such as stainless steel wire segments or ligature ties.

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