Second Edition

TEMPORARY ANCHORAGE DEVICES in ORTHODONTICS

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ELSEVIER

Contents

Preface

The new millennium brought about a new era in orthodontics with the advent of temporary anchorage devices (TADs). The realm of possibilities to correct malocclusions that in the past were only treatable by means of orthognathic surgery was made available in a cost-effective manner through the insertion of small screws and miniplates during orthodontic treatment. Clinicians quickly became interested in adopting this new approach in their patients, and precise indications for the use of skeletal anchorage started to shape up. The first edition of *Temporary Anchorage Devices in Orthodontics*, which was compiled in the early days of skeletal anchorage, was a very timely book that introduced many aspects of this new approach. The chapters of this first book described the use of miniplates and screws with emphasis on the multiple locations of placement in the maxilla and mandible and a myriad of screw systems and appliances. The biomechanics involved with new skeletal anchorage orthodontic adjuncts was described in detail, with many case reports illustrating the expanded possibilities to correct complex malocclusions and enhance smile esthetics.

Approximately a decade has transpired since the first edition, and significant refinements to the techniques and appliances have been developed. In this second edition, we wanted to highlight these advances described by multiple authors that had been at the forefront of skeletal anchorage era since the early days. The first chapters in this edition review the biology and interaction of the titanium hardware and bone and the basic biomechanic principles that apply when using skeletal anchorage. The application of space closure, distalization, and overall molar control form palatal appliances is described in depth with different approaches. Later in the book, the versatility of miniplates and infrazygomatic mini-implants is presented by multiple authors managing cases of significant complexity. Finally, the management with skeletal anchorage of anteroposterior and vertical problems, such as the management of the Class III malocclusion, second molar protraction, anterior openbite correction, and the mechanical advantages of TADs in multidisciplinary patients, are described.

A very interesting development in skeletal anchorage presented in this new edition is the integration of three-dimensional (3D) technologies for the placement of mini-implants and the fabrication of TAD-supported appliances. With the advent of 3D-printing, precise palatal appliances are now available as described in this book with the MAPA appliance. Overall, this new approach sets a trend where the application of 3D-printing facilitates the insertion of mini-implants and the delivery of appliances in a single visit in a very precise and predictable manner. Another novel and interesting approach is the combination of clear aligner therapy with skeletal anchorage. Clear aligners are increasingly becoming the elected orthodontic appliance by adults, and a tightly coupled synergy with TADs for the treatment of more complex malocclusions in patients demanding non-visible appliances is described in this book.

We want to thank all the contributors who have invested time and effort to advance our knowledge regarding skeletal anchorage. We also appreciate the contributions of numerous individuals who are not part of this book but who have influenced all of us with their scientific publications. We hope you will enjoy reading it, and various methods of skeletal anchorage usage shown will help in efficient treatment of patients.

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PART I

Biology and Biomechanics of Skeletal Anchorage

1

Biomechanics Principles in Mini-Implant Driven Orthodontics

MADHUR UPADHYAY, RAVINDRA NANDA

Introduction

The physical concepts that form the foundation of orthodontic mechanics are the key in understanding how orthodontic appliances work and are critical in designing the treatment methodologies and appliances that carry out these plans.

Mechanics can be defined as a branch of physics concerned with the mechanical aspects of any system. This can be divided into two categories:

Statics, the study of factors associated with nonmoving (rigid) systems, and

Dynamics, the study of factors associated with systems in motion: a moving car, plane etc. When the knowledge and methods of mechanics are applied to the structure and function of living systems (biology) like, for example, a tooth together with its surrounding oral architecture, it is called ***biomechanics***. It is our belief that the study of biomechanics of tooth movement can help researchers and clinicians optimize their force systems applied on teeth to get better responses at the clinical, tissue, cellular, or molecular level of tooth movement.

Approaches for Studying Tooth Movement

Two approaches are used for studying the biological and mechanical aspects of tooth movement—a quantitative approach and a qualitative approach. The ***quantitative approach*** involves describing movement of teeth or the associated skeletal structures in numerical terms. We all are familiar with terms like 3 millimeters of canine retraction, or 15 degrees of incisor flaring. However merely describing tooth movement quantitatively does not describe the complete nature of the movement. It is also important to understand the type or nature of tooth movement that has occurred. A ***qualitative*** *approach* describes movement in nonnumerical terms (i.e., without measuring or counting any parts of the performance). This approach is often followed at the clinical level or inferred from x-rays and/or stone models like tipping, translation, etc.

Both qualitative and quantitative analyses provide valuable information about a performance; however, a qualitative assessment is the predominant method used by orthodontists in analyzing tooth movement. The impressions gained from a qualitative analysis may be substantiated with quantitative data, and many hypotheses for research projects are formulated in such a manner.

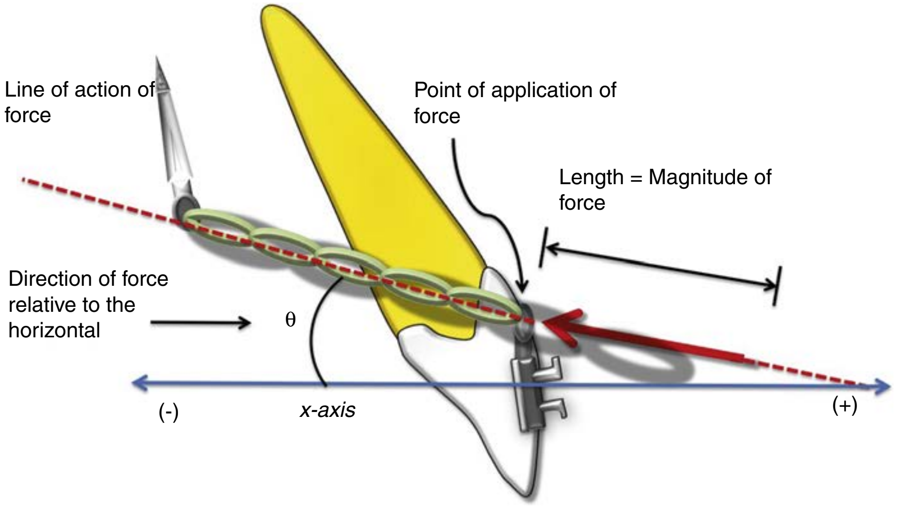
Basic Mechanical Concepts

Force

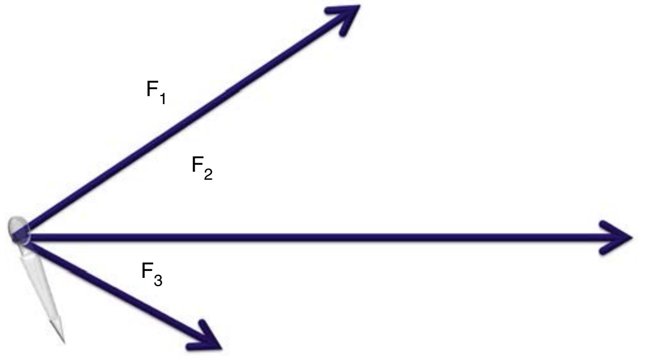
The role of force in everyday life is a familiar one. Indeed, it seems almost superfluous to try to define such a self-evident concept as force. To put it in a simple way, force can be thought of as a measure of the push or pull on an object. However, the study of mechanics of tooth movement demands a precise definition of force. A force is something that causes or tends to cause a change in motion or shape of an object or body. In other words, force causes an object to accelerate or decelerate. It is measured in Newton (N), but in orthodontics nearly always force is measured in grams (g). 1 N = 101.9 g (≈ 102 g) (see appendix).

Force has four unique properties as shown by graphic representation of a force acting at an angle to a central incisor in Fig. 1.1:

- Magnitude: how much force is being applied (e.g., 1 N, 2 N, 5 N).
- Direction: the way the force is being applied or its orientation to the object (e.g., forward, upward, backward).
- Point of application: where the force is applied on the body or system receiving it (e.g., in the center, at the bottom, at the top).
- Line of action/force: the straight line in the direction of force extending through the point of application.



• **Fig. 1.1** The four properties of an external force applied to a tooth illustrated by an elastic chain applying a retraction (distalizing) force on a maxillary incisor to a mini-implant.



• **Fig. 1.2** The length of the force vector describes the magnitude of the force vector. Example: F1 = 2 N, F2 = 3 N, F3 = 1 N.

Force Diagrams and Vectors

Physical properties (such as distance, weight, temperature, and force) are treated mathematically as either scalars or vectors. Scalars, including temperature and weight, do not have a direction and are completely described by their magnitude. Vectors, on the other hand, have both magnitude and direction. Forces may be represented by vectors.

To a move a tooth predictably, a force needs to be applied with an optimal magnitude, in the desired direction, and at the correct point on the tooth. Changing any property of the force will affect the quality of tooth displacement. A force may be represented on paper by an arrow. Each of its four properties may be represented by the arrow whose length is drawn to a scale selected to represent the magnitude of the force—for example, 1 cm = 1 N or 2 cm = 2 N, etc. (Fig. 1.2). The arrow is drawn to point in the direction in which the force is applied, and the tail of the arrow is placed at the force's point of application. The line of action of the force may be imagined as continuing indefinitely in both directions (head and tail end), although the actual arrow, if drawn to scale, must remain of a given length. A graphic representation of a force of 1 N acting at an angle of 30 degrees to a central incisor is shown in Fig. 1.1.

Principle of Transmissibility

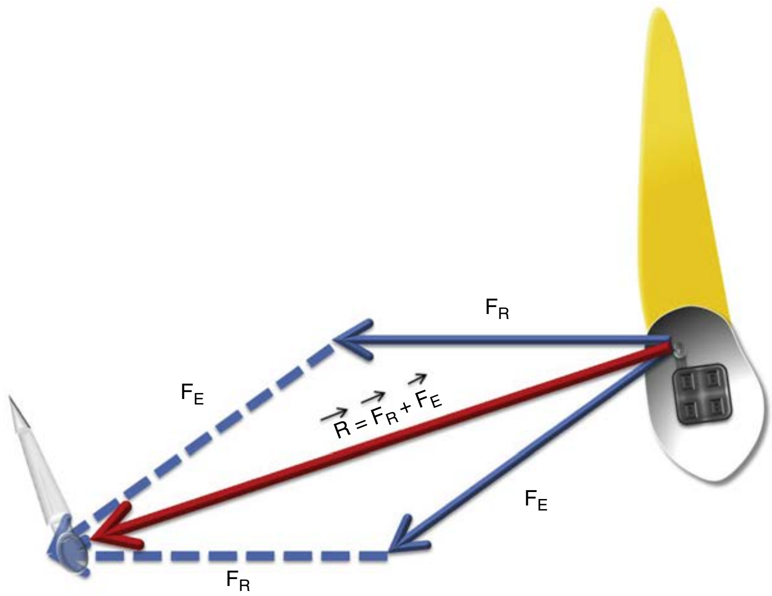
This concept is very important for vector mechanics, especially in understanding equilibrium and equivalent force systems as we will see later. It implies that a force acting on a rigid body results in the same behavior regardless of the point of application of the force vector as long as the force is applied along the same line of action.

The Effect of Two or More Forces on a System: Vector Addition

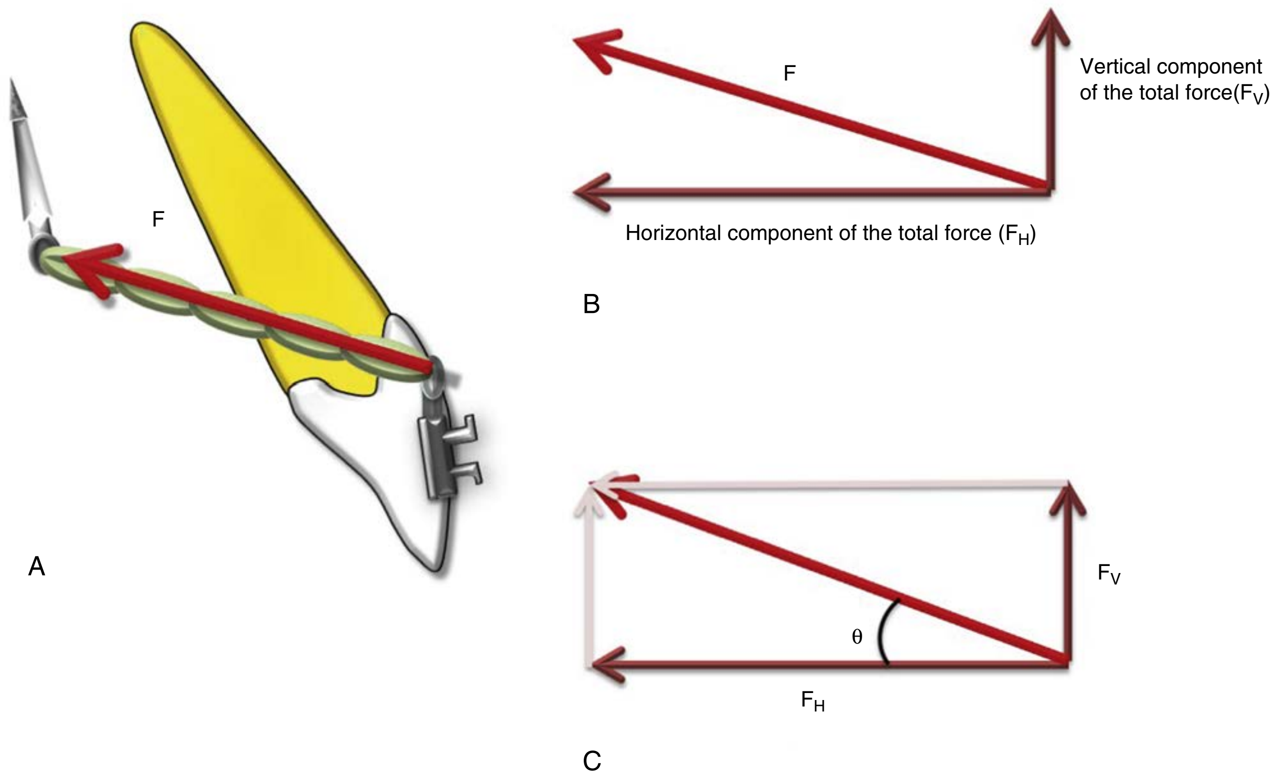
Teeth are often acted on by more than one force. The net effect or the **resultant** of multiple forces acting on a system, in this case teeth, can then be determined by combining all the force vectors. This process of combining all the forces may be found by a geometric rule called ***vector addition***, or ***vector composition***. We place the vectors head to tail, maintaining their magnitudes and directions, and the resultant is the vector drawn from the tail of the first vector to the head of the final vector. Vector addition can be accomplished graphically by drawing diagrams to scale and measuring or by using trigonometry. Fig. 1.3 shows how the two forces are visualized as two sides of a parallelogram and how the opposite sides are then drawn to form the whole parallelogram. The resultant force, R, is represented by the diagonal that is drawn from the corner of the parallelogram formed by the tails of the two force vectors.

The Directional Effects of Force: Vector Resolution

Often an occasion arises in which the observed movement of a system or single force acting on a system is to be analyzed in terms of identifying its component directions. In such cases, the single vector quantity given is divided into two components: a horizontal component and a vertical component. The directions of these components are relative to some reference frame, such as the occlusal plane or the Frankfort horizontal plane (FHP), or to some axis in the system itself. The horizontal and vertical components are usually perpendicular to each other. Such a process maybe thought of as the reverse of the process of vector



• **Fig. 1.3** Illustration showing the law of vector addition by the parallelogram method. Here, FR can be thought of as a retractive force on the incisor and FE as a force from a Class II elastics. The net effect of the two forces is represented by the resultant R.



• **Fig. 1.4** The process of vector resolution.

composition. The operation is called ***vector resolution*** and is the method for determining two component vectors that form the one vector given initially.

For example, a mini-implant as shown in Fig. 1.4A is being used for retraction of anterior teeth. It may be useful to resolve this force into the components that are parallel and perpendicular to the occlusal plane, to determine the magnitude of force in each of these directions. Resolution consists of these steps (Fig. 1.4B–C): (1) draw the vector given initially to a selected scale; (2) from the tail of the vector, draw lines representing the desired directions of the two perpendicular components; (3) from the head of the vector, draw lines parallel to each of the two direction lines so that a rectangle is formed. Note that the new parallel lines constructed have the same magnitude and direction as the corresponding lines on the opposite side of the rectangle.

It is important to note that if it is desirable to estimate the magnitude of the components, then simple trigonometric rules can be invoked to do so. The sine and cosine are in particular very useful in finding the horizontal and vertical components of the force vector. In this case if, for example, the horizontal component of magnitude F_H makes an angle θ with the force (F), we can derive the components using the definitions of sine and cosine:

Horizontal component (F_H): $F_H/F = \cos\theta$; $F_H = F \cos\theta$
Vertical component (F_V): $F_V/F = \sin\theta$; $F_V = F \sin\theta$

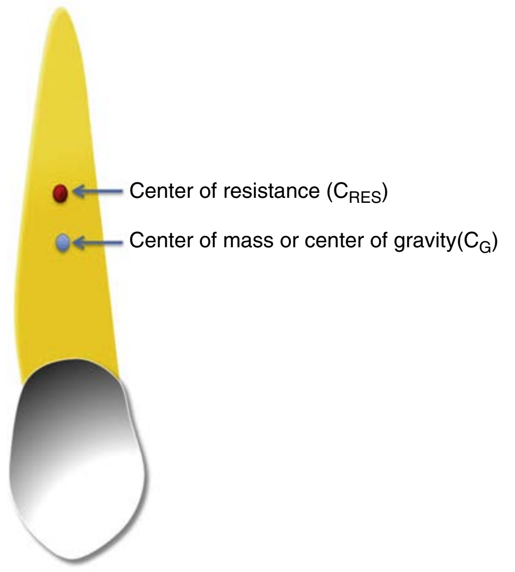
With a little practice, it is easy to get the component directly as a product, skipping the step involving the proportion. Think of sin θ and cos θ as fractions that are used to calculate the sides of a right triangle when the hypotenuse is known. The side is always less than the hypotenuse and the sine and cosine are always less than one. To get the side opposite the angle, simply multiply the hypotenuse by the sine of the angle. To get the side adjacent to the angle, multiply the hypotenuse by the cosine of the angle.

Center of Resistance, Center of Gravity, and Center of Mass

The **center of mass** of a system may be thought of as that point at which all the body's mass seems to be concentrated (i.e., if a force is applied through this point, the system or body will move in a straight line). On similar lines recall that the earth exerts a force on each segment of a system in direct proportion to each segment's mass. The total effect of the force of gravity on a whole body, or system, is as if the force of gravity were concentrated at a single point called the ***center of gravity.*** Again, if a force is applied through this point, it will cause the body to move in a straight line without any rotation. The difference between the center of mass and center of gravity is that the system in question in the latter is a 'restrained system' (restrained by the force of gravity).

Teeth are also a part of a restrained system. Besides gravity, they are more dominantly restrained by periodontal structures that are not uniform (involving the root but not the crown) around the tooth. Therefore the center of mass or the center of gravity will not yield a straight line motion if a force is applied through it because the surrounding structures and their composition alter this point. A new point analogous to the center of gravity is required to yield a straight-line motion; this is called the ***center of resistance* (C$_{RES}$)** of the tooth (Fig. 1.5).

The C_{RES} can also be defined by its relationship to the force: a force for which the line of action passes through the C_{RES} producing a movement of pure translation. It must be noted that, for a given tooth, this movement may be mesiodistal or vestibulolingual, intrusive or extrusive. The position of the C_{RES} is directly dependent on what may be called the "clinical root" of the tooth. This concept considers the root volume, including the periodontal bone (i.e., the distance between the alveolar crest and the apex), incrementing this value with the thickness (i.e., the surface) of the root.[1]



• **Fig. 1.5** The center of resistance (C_{RES}) of a tooth is usually located slightly apical to the center of gravity (CG). The periodontal structures surrounding the tooth root cause this apical migration of the CRES.

Thus the position of the C_{RES} is also a function of the nature of the periodontal structures, and the density of the alveolar bone and the elasticity of the desmodontal structures that are strongly related to the patient's age.[2–4] These considerations implore us to speak of the "C_{RES} associated with the tooth," rather than of "the C_{RES} of the tooth."

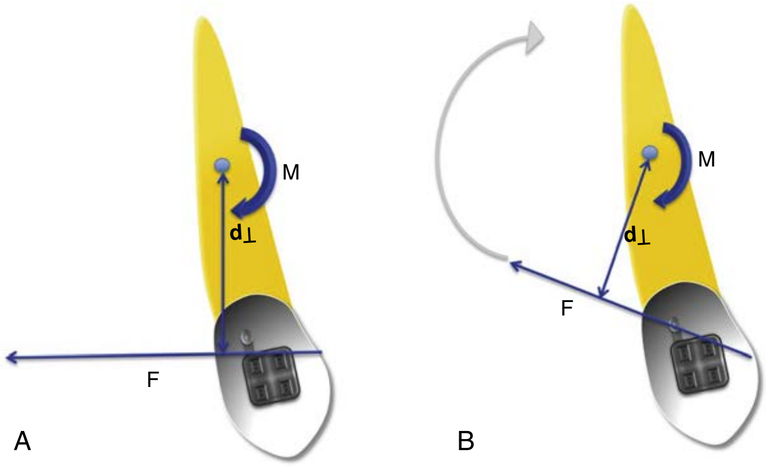
Moment (Torque)

When an external force acts on a body at its center of gravity (CG), it causes that body to move in a linear path. Such a type of force with its **line of action** through the CG or C_{RES} of a body is called a ***centric force***. On similar lines, eccentric **forces** (off-center) act away from the C_{RES} of a body.

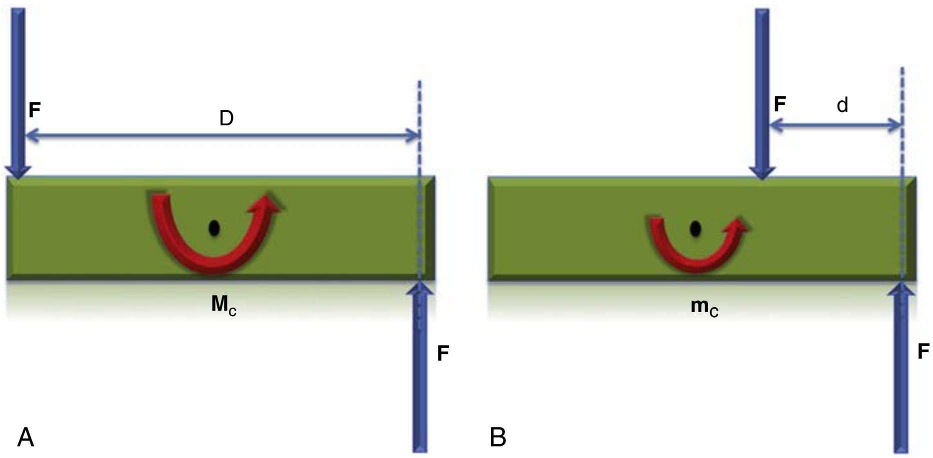
What kind of effect will these forces have? Besides causing the body to move in a linear path, it will have a turning effect on the body called *torque*, or in other words the force will also impart a "**moment**" on the body. The off-axis distance of the force's line of action is called the ***force arm*** (or sometimes the *moment arm, lever arm,* or *torque arm*). The greater this distance, the greater the torque produced by the force. The specifications of the force arm are critical. The force arm is the shortest distance from the axis of rotation to the line of action of force. Invariably the shortest distance is always the length of the line that is perpendicular (90 degrees) to the force's line of action ($d\perp$). The symbol "$\perp$" designates perpendicular. Force arm is critical in determining the amount of moment acting on the system.

The amount of moment (M) acting to rotate a system is found by multiplying the magnitude of the applied force (F) by the force arm distance ($d\perp$):

$\mathbf{M = F(d\perp)}$, where F is measured in Newton and $d\perp$ in millimeter (Fig. 1.6A). Therefore the unit for moment as used in orthodontics is Newton millimeter (Nmm). As mentioned previously, often for force Newton is replaced



• **Fig. 1.6** (A) The moment of a force is equal to the magnitude of the force multiplied by the perpendicular distance from its line of action to the center of resistance. (B) The direction of the moment of a force can be determined by continuing the line of action around the center of resistance.



• **Fig. 1.7** (A) The moment created by a couple is always around the center of resistance (C_{RES}) or center of gravity (CG) (M_C = F × D). (B) No matter where the pair of force are applied, the couple created will always act around the C_{RES} or CG. As the distance between the two forces decreases (d<D), the overall magnitude of the couple decreases ($m_c < M_C$).

with gram (g), therefore the unit for moment becomes: Grammillimeter (gm-mm). The larger the force and/or longer the force arm, larger the moment. Because of this intrinsic relationship of the moment and the associated force, it is also known as *moment of the force* (M_F).

If forces are indicated by straight arrows, moments can be symbolized by curved arrows. With two-dimensional diagrams, clockwise moments will be arbitrarily defined as positive and counterclockwise moments negative or vice versa. Values can then be added together to determine the net moment on a tooth relative to a particular point, such as the C_{RES}.

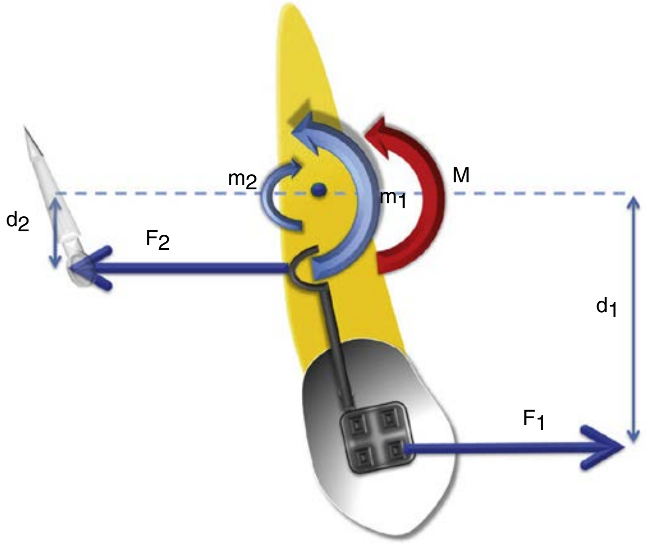
Point of application and line of action are not needed; nor are graphic methods of addition. The direction of a moment can be determined by continuing the line of action of the force around the C_{RES}, as shown in Fig. 1.6B.

Couple (A Type of Moment)

A couple is a form of moment. It is created by a pair of forces having equal magnitudes but opposite sense (direction) to one another with noncoincidental line of action (parallel forces). Because the forces have the same magnitude but are oppositely directed, the net potential of this special force system to translate the body on which it acts is nil and there is only rotation.

A typical couple is shown in Fig. 1.7A. Although the couple's vector representation is shown midway between the two forces, the vector has no particular line-of-action location and maybe drawn through any point of the plane of the couple. Therefore a couple is also known as a *free vector*. This freedom associated with the couple vector has far reaching implications in clinical orthodontics and to certain force analysis procedures (Fig. 1.7B). As an example, no matter where a bracket is placed on a tooth, a couple applied at that bracket can only cause the tooth to feel a tendency to rotate around its C_{RES}. This is also referred to as the ***moment of the couple*** (M_C).

The magnitude of the moment of the couple (M_C) is dependent on both force magnitude and distance between the two forces. The moment created by a couple is actually the sum of the moments created by each of the two forces. Now if the two forces of the couple act on opposite sides of the C_{RES}, their effect to create a moment is additive. If they are on the same side of the C_{RES}, they are subtractive



• **Fig. 1.8** A couple created by two equal and opposite forces acting on a tooth. The total moment (M_C) is the vector addition of the two moments (m1, m2) generated by the two forces (F1, F2). Here, m1 = F1 × d1, m2 = F2 × d2. Because the two moments are in the opposite direction, one of the moments will be assigned a negative sign and the other positive. The net moment (M) will be obtained by adding the two: M = m1+ (–m2)

(Fig. 1.8). Either way, no net force is felt by the tooth, only a tendency to undergo pure rotation.

Concept of Equilibrium

The word "equilibrium" has several different meanings, but in statics it is basically defined as state of rest; in particular it means that an object or system is not experiencing any acceleration. Therefore statics is that branch of physics that deals with the mechanics of nonaccelerating objects or for our convenience and understanding "nonmoving" objects. Such a system is said to be in equilibrium. To achieve equilibrium, we must see to it that no unbalanced force is applied to the body in question or in other words any force acting on a system should be balanced by contrary forces.

Therefore sum of all the forces should be zero (i.e., $\Sigma F = 0$), (according to Newton's second law if a system is not accelerating then a = 0, so F = ma, or F = m(0); $\Sigma F = 0$, i.e., there is no net force acting on the system).

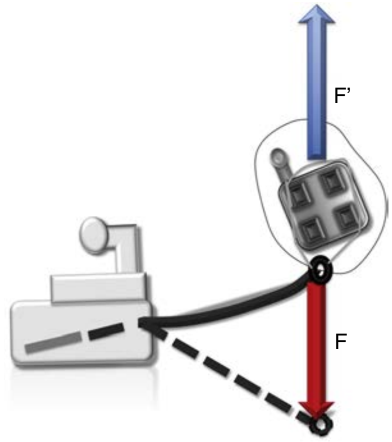
A vector can only be zero if each of its perpendicular components is zero; thus the single vector equation $\Sigma F = 0$ is equivalent to three component equations:

$\Sigma Fx = 0$, $\Sigma Fy = 0$, $\Sigma Fz = 0$ (x,y,z are the three spatial axes described previously).

On similar lines, the net moment too in all the three planes should be equal to zero, i.e., $\Sigma Mx = 0$, $\Sigma My = 0$, $\Sigma Mz = 0$.

Equilibrium in Orthodontics (The Quasi-Static System)

Equilibrium only applies to static systems (nonaccelerating systems). However, in orthodontics, we do move teeth. They move, stop, tip, upright. So how can they be governed by



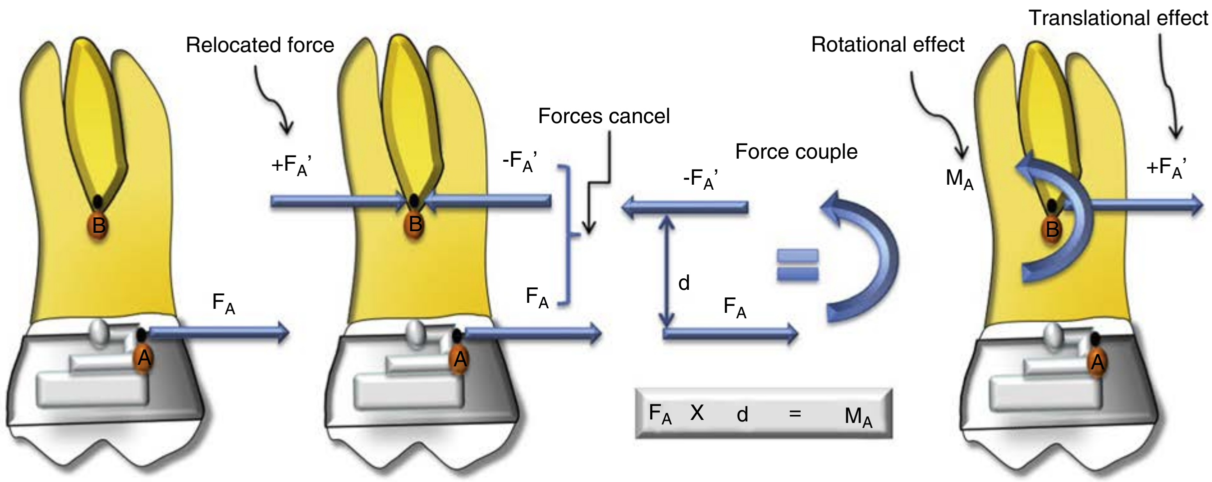
• **Fig. 1.9** A cantilever spring exerting a force (F) on the bracket *(in red)*. As per the third law of Newton, the bracket will put an equal and opposite force (F') on the cantilever wire *(in blue)*.

the laws of statics? To answer this question, we will have to redefine the state of the teeth subjected to orthodontic forces as a **Quasi Static System**. This can be defined as a system or process that goes through a sequence of states that are infinitesimally close to equilibrium (i.e., the system remains in quasi-static equilibrium). When orthodontic appliances are activated and inserted, the tooth displacement that take place is very small and take place over a relatively long period of time. At any point of time if you look in the patient's mouth, you do not see any movement, however after waiting for a sufficient period of time, the movement can be appreciated. Therefore at any instant, a force analysis may be carried out by invoking the laws of equilibrium without erring appreciably. In other words, the inertia of any appliance element or a tooth is negligibly smaller and may be neglected. For this reason, the physical laws of statics are considered adequate to describe the instantaneous force systems produced by orthodontic appliances. However, these laws cannot be used to describe how the force systems will change as the teeth move and an appliance deactivates and alters its configuration.

The solution of problems in statics involving forces and moments calls for ingenuity and common sense. There are no simple rules of procedure. The most common source of error is failure to identify the object whose equilibrium is being considered. You must learn to consider all the forces acting on the body. Of course, Newton's second and third law is of great help in this regard. By using the third law it can be easily figured out that if an appliance is exerting a force on a tooth, the same force the tooth is exerting on the appliance (Fig. 1.9), and the same applies to all the other teeth to which the appliance is connected to. Because the appliance is not moving (static), the sum of all the forces and moments produced by the appliance should be zero.

Principle of Equivalent Force Systems

This principle is an elegant way of redefining the forces and moments acting on a body. It helps visualize not only the bodily movement of a tooth but also the rotation, tip, and torque experienced. An equivalent system is a system of



• **Fig. 1.10** Creating equivalent force systems. The net effect of the force system depicted in (A) and (D) is same. (B) and (C) show how to transform (A) to (D).

forces and/or moments that you can replace with a different set of forces and/or moments and still achieve the same basic translational and rotational behavior. To understand the practical implication of this principle, lets discuss relocating a force system on a molar.

Application of Equivalent Force Systems: Moving the Force System to a Different Location

In Fig. 1.10, there is a force F_A acting on the tooth at Point A. Now suppose you want to compute the effects of this force system at a different location, such as Point B, which in this case is the C_{RES} of the molar (remember C_{RES} of the molar has been arbitrarily chosen; point B can be any other point on the molar). To determine the required translational effect, introduce two equal but opposite forces (+F_A, and –F_A,) at point B. We can easily do this because such an introduction of forces will not affect the system in any way, as these forces are equal and opposite, therefore the result of these newly added forces is F_A, +(–F_A,) = 0, or zero net translational effect. Make sure that the magnitude of these new forces is equal to F_A acting at point A. Now by applying law of vector addition, the original force F_A plus the new negative force –F_A, will cancel each other out. With this in mind, you can see that the only force that now remains on the molar is the newly relocated force F_A, which is now acting at point B. Congratulations! You have relocated the force.

Now that you have relocated the force, examine the two other forces on the molar, namely F_A acting at point A and –F_A, acting at point B. These two forces are parallel, acting in opposite directions and separated by a distance "d." This setup is the very definition of a moment (couple) that we have previously discussed. Remember, moments and couples cause rotation of a body, therefore the added rotational effect of this couple is what you have to include when you move a force. Also a couple is a free vector, therefore they apply the same rotational behavior regardless of where on the body it is acting. As a result, you can freely move the moment of the couple to point B on the molar as long as the magnitude and sense of the moment vector remains unchanged. The magnitude of this moment can be calculated by multiplying the force F_A or –F_A, by d ($M_A = F_A \times d$). The point of application of a moment or couple does not matter when creating an equivalent force system. If you want to move a moment, just move it.

In summary, to relocate a force system, you simply need to take the original force and apply it to the new location, plus compute the newly applied moment (which is the product of the force and the distance between the two points) and apply that at the new location maintaining its sense/direction.

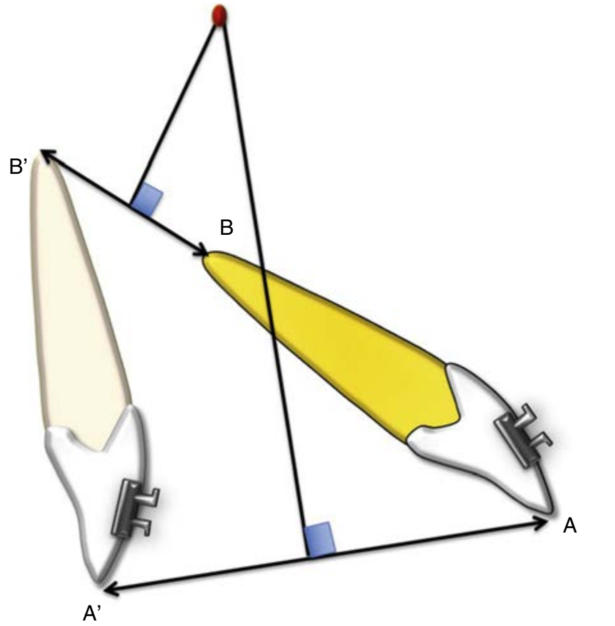
There are three simple rules that allow the calculation of equivalent force systems. Two force systems are equivalent if: (1) the sums of the forces in all the three planes of space (X, Y, and Z) are equal, and (2) the sum of moments about any point are identical.

Center of Rotation

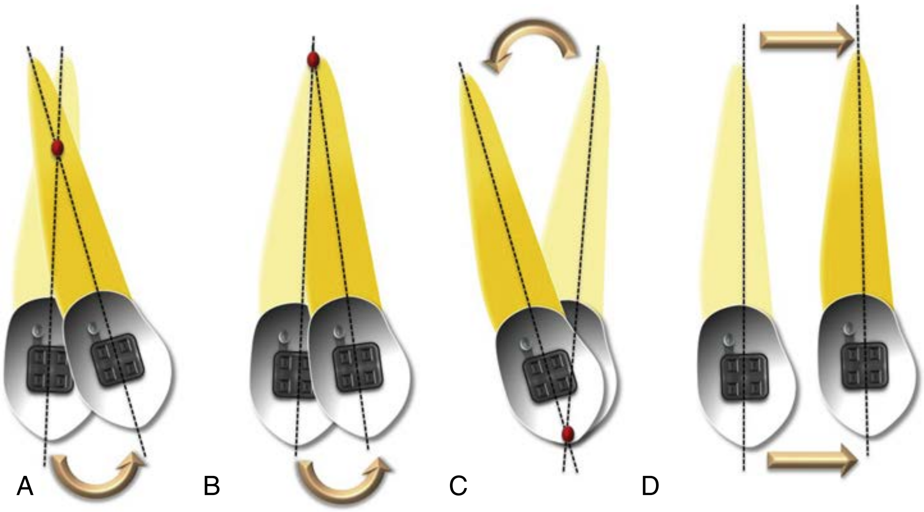
Centre of Rotation (C_{ROT}) is a fixed point around which a two-dimensional figure appears to be rotated as determined from its initial and final position (note: a two-dimensional figure always rotates around a point, while a three-dimensional figure rotates around an axis [i.e., a two-dimensional object has a C_{ROT}, while a three-dimensional object has an axis of rotation]). In other words, in rotation the only point that does not move is called the C_{ROT} (Fig. 1.11). The rest of the plane rotates around this one fixed point.

Although a single C_{ROT} can be constructed for any starting and ending positions of a tooth, it does not follow that the single point actually acted as the C_{ROT} for the entire movement. The tooth might have arrived at its final position by following an irregular path, tipping first one way and then another. As a tooth moves, the forces on it continuously undergo slight changes, so that a changing C_{ROT} is the rule rather than the exception. In determining the relationship between a force system and the C_{ROT} of the resulting movement, all that can really be determined is an "instantaneous" C_{ROT}.[5]

• **Fig. 1.11** Center of rotation *(red dot)* of a tooth. Note how the center of rotation is the only point that has remained stationary.



• **Fig. 1.12** (A) and (B) represent the cusp tip and the root apex before and after movement. A line has been drawn connecting these points. At the midpoint of this line a perpendicular has been constructed. The point at which this perpendicular intersects any other perpendicular constructed in a similar manner (the apex has been selected as the other point) is the center of rotation.



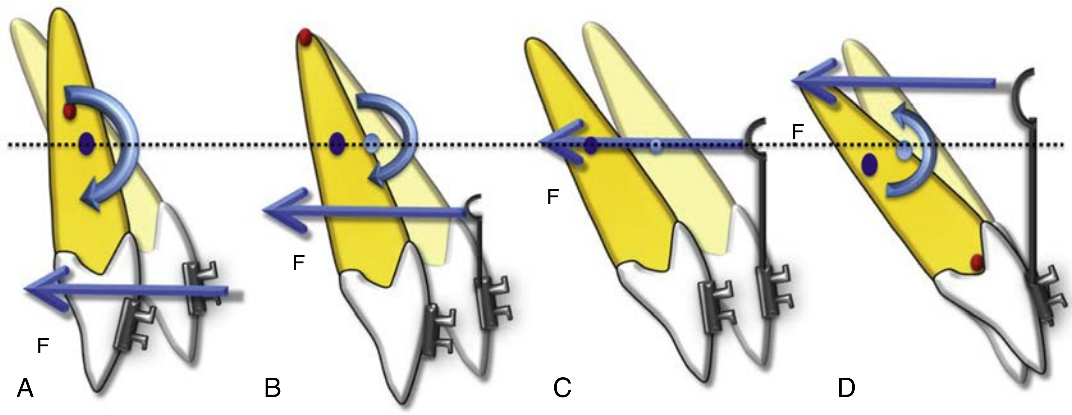
• **Fig. 1.13** Types of tooth movement: (A) Uncontrolled tipping, (B) controlled tipping, (C) root movement (torqueing), (D) translation or bodily movement. The center of rotation (C_{ROT}) in every case is depicted by a *red dot*. Note that during translation, the C_{ROT} is at infinity or, in other words, does not exist.

Estimating the Center of Rotation

The C_{ROT} can be easily estimated as shown in Fig. 1.12. Take any two points on the tooth and connect the before and after positions of each point with a line. The intersection of the perpendicular bisectors of these lines is the C_{ROT}.[6]

Types of Tooth Movement (Fig. 1.13)

As we saw in the preceding section, the C_{ROT} is key in defining the nature of tooth movement. Controlling the C_{ROT} automatically gives precise control over the type (extent) of tooth movement. When a single force is applied on a tooth, the tooth will move in the direction of the force applied. In addition, depending on the distance of the force from the C_{RES}, the tooth will experience a moment (M_F) around the C_{RES}. This combination of a force and a moment will cause the tooth to rotate as it moves, placing its C_{ROT} slightly apical to the C_{RES}.[5,6] This type of tooth movement is called ***simple tipping*** or ***uncontrolled tipping***. It is easy to visualize here that both the crown and the root will move in the opposite direction. Tipping can happen in many different ways depending



• **Fig. 1.14** The application of a power arm to create different types of tooth movement. Note, the force has been kept constant through A–D. (A) Uncontrolled tipping, no power arm. (B) Controlled tipping produced by a power arm below the C_{RES} of the tooth. (C) Translation as the force is now being applied through the C_{RES} made possible by increasing the length of the power arm. (D) Root movement with minimal crown movement; here the power arm extends beyond the center of resistance (C_{RES}) (the *red dot* is the C_{ROT} while the *blue dot* is the C_{RES}). Note how the M_F is increasing or decreasing with an increase or decrease in the distance of force application from the C_{RES}.

on where the C_{ROT} is along the tooth. But for ease of classification they can be bunched up into two other groups:

Controlled Tipping

During such a movement the C_{ROT} is located at the root apex. The tooth moves similar to a pendulum on the clock, with its apex fixed at a particular point and the crown moving from one side to the other.

Root Movement

Here the C_{ROT} is located at the crown tip while the root is free to move in the direction of the force. Traditionally, in the orthodontic literature, this is not characterized as a tipping movement, but mechanically the movement is similar to controlled tipping. Almost the entire universe of tooth movement primarily consists of tipping the crown, the root (rare), or a combination (most common). However, there is one tooth movement that is extremely rare and very difficult to achieve in its strictest sense (i.e., **translation**, sometimes also known as ***bodily movement)***. Here, both the crown and the root move in equal amounts and in the same direction with no rotation. In this case, the C_{ROT} is nonexistent, or in mathematical terms approaches infinity.

Moment-to-Force (M/F) Ratios

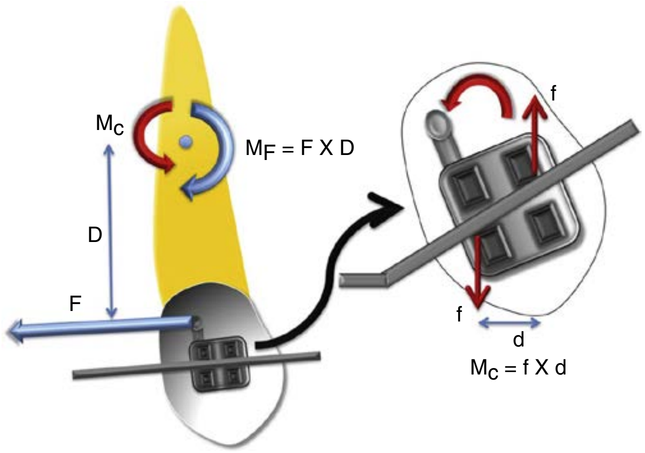
Tipping (uncontrolled) is the most common tooth movement in everyday orthodontics, but not always the preferred one. To modify this pattern of tooth movement and create a new one, the force system acting on the tooth needs to be altered. There are primarily two ways to do this based on the mechanics involved:

1. Altering the Point of Force Application (Fig. 1.14)

A simple way of doing this is by applying a force closer to the C_{RES} of the tooth. A rigid attachment, often called a *power arm*, can be attached to the bracket on the crown of the tooth. Then the force can be applied to this power arm. In this way, the line of force can be moved to a different location, thereby altering its distance from the C_{RES}. This causes a change in the moment of the force too. For example, if the power arm can be made long and rigid to extend till the C_{RES} of the tooth, the moment arm (M_F) can be entirely eliminated, as the applied force will now pass through the C_{RES}. This method works beautifully for altering the tipping movement of the crown; however, for movements requiring higher levels of control, like translation and root movement, this method possesses certain problems. The "long" arms can be a source of irritation to the patient, by extending into the vestibule and/or impinging on the gingiva and cheeks. In addition, the arms are sometimes not rigid enough and can undergo some degree of flexion under the applied load/force.

2. Altering the Moment-to-Force Ratio (Fig. 1.15)

An alternative method to alter the tooth movement is to play with the rotational component of the applied force (i.e., the M_F). This is done by adding a counterbalancing moment (i.e., a moment in the opposite direction to that of the M_F) to the system. This new moment can be created in two ways. First is the traditional way of applying a force (this would be a different force than the one generating the M_F). However, with a bracket fixed on the tooth, it is usually difficult to apply a force at some other point. Therefore this approach is usually not practical or efficient. The second approach involves creating a couple in the bracket. A rectangular archwire fitting into a rectangular bracket slot on the tooth is most widely used. This new moment (Mc) together with the applied force determines the nature of tooth movement. This combination is popularly known as the ***moment-to-force*** *(M/F) ratio.* By varying this moment-to-force ratio, the quality of tooth movement can be changed among tipping, translation and root movement (i.e., different centers



• **Fig. 1.15** A schematic diagram depicting the generation of a moment caused by a couple (M_C). It is the ratio of the M_C to the force applied (F) that determines the nature of tooth movement (M/F ratio). The higher the ratio, the greater will be the control over the tooth movement.

of rotation along the long axis of the tooth are created by changing the magnitude of the couple and the applied force). In terms of the direction, the moment of the couple is almost always going to be in the direction opposite the moment of the force about the C_{RES}.

Note that in orthodontics, moments are measured in gram-millimeters and forces in grams, so that a ratio of the two has units of millimeters. This ratio is also indicative of the distance away from the bracket that single force will produce the same effect (i.e., through a power arm as discussed earlier).

Space Closure Mechanics With Mini-Implants

The extraction of premolars and anterior teeth retraction is generally indicated when there is obvious protrusion of teeth and there is a strong esthetic need. While retracting anterior teeth in a full unit Class II malocclusion or in a Class I bialveolar dental protrusion case, anchorage control assumes profound importance because maintaining the posterior segment in place is critical. A loss in molar anchorage not only compromises correction of the anterior-posterior discrepancy but also affects the overall vertical dimension of the face.[7–9] The application of mini-implant (MI) supported anchorage can circumvent the anchorage issues in such situations and maintain a Class II molar or Class I relationship, while establishing a Class I canine relationship for esthetics and functional guidance. In this chapter, we will use space closure as a basis for understanding the nuances of MI-assisted biomechanics in clinical practice.

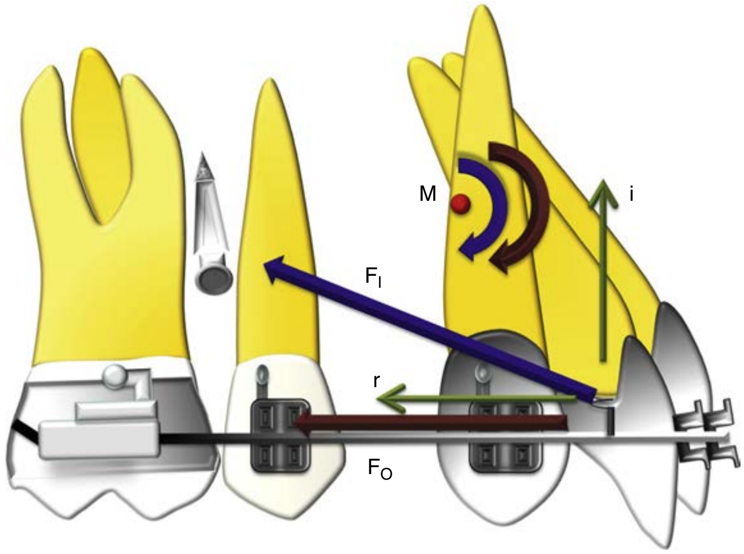
Mechanical differences in incisor retraction between MIs and conventional techniques

Using MIs for retraction of anterior teeth presents a paradigm shift from the conventional method of space closure. The shift is seen not only in the anchorage demand between the two techniques but also in the mechanics involved in space closure. Some of these differences are:

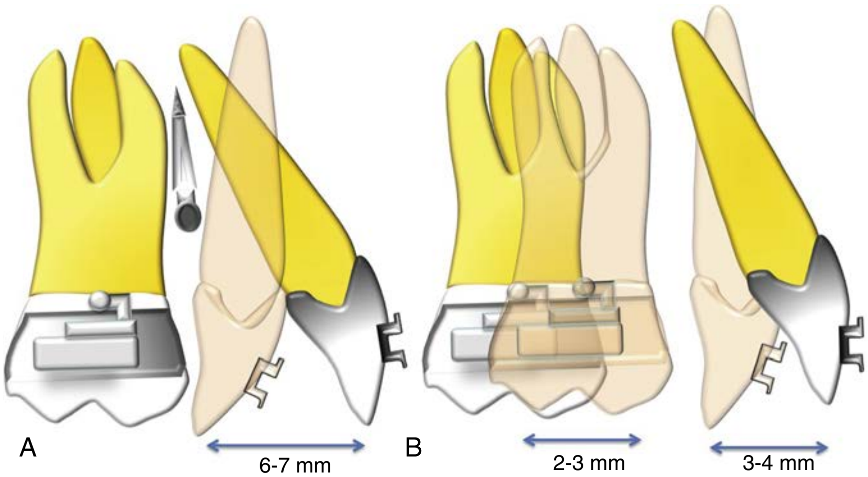
1. When using conventional mechanics, force application is usually parallel to the occlusal plane, and hence we are required to analyze the force only in one plane. However, because MIs are usually placed apical to the occlusal plane into the bone between the roots of teeth, force applied is always at an angle. (Note: the preferred location for MI placement is between the roots of the second premolars and first molars close to the mucogingival junction. Care should be taken that the MIs are not inserted too far apically in the movable mucosa, since this can lead to implant failure because of persistent inflammation around the MI site.) This angulated force lends itself to be broken into two components by the law of vector resolution[10]: a horizontal retraction force (r) and a vertical intrusive force (i). The force applied with MIs in such a setup is also closer to the C_{RES} of the anterior unit. Therefore the M_F (moment caused by the force) is significantly less compared to that generated in conventional mechanics.[7–9,11,12] Clinically, it translates to a decreased tendency for the teeth to tip (Fig. 1.16).
2. With conventional mechanics, the posterior segment usually serves as the passive unit (anchor unit), while the anterior teeth as the active unit. The force system is therefore differentially expressed in the active unit and the anchorage or passive unit within the same arch. In contrast, when MIs are incorporated as the third counterpart, precise movement of the anterior and posterior segments is possible. Accurate planning for the amount of the desired tooth movement is thus a prerequisite before active treatment can be initiated.
3. The clinical observation of the amount of tipping will depend on the amount of space closure. A greater amount of space closure will yield greater degrees of side effects or in this case tipping. With conventional techniques part of the space is taken up by molar mesialization. Previous research has shown that in contrast to MI-supported anchorage, conventional methods show 2 to 3 mm of anchor loss in a typical extraction case.[7–11] Therefore the anterior teeth during space closure with MIs are automatically predisposed to more tipping and "dumping," as they have to be distalized a greater distance to close the extraction space (Fig. 1.17). Therefore greater degrees of torque control might be warranted for space closure using skeletal anchorage. These and other differences have led to a gradual evolution of implant-based mechanics in orthodontics. However, before exploring this further, the mechanics of space closure will be discussed.

Basic Model for Space Closure

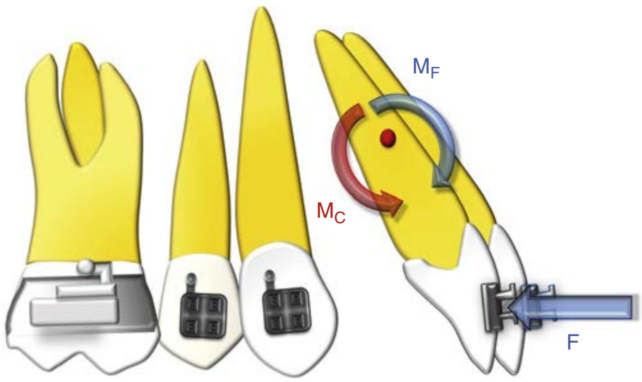
In incisor retraction, the objective is to apply a force between the incisor and the posterior segment to close the space that exists between them. This force is usually applied on the bracket attached to the crown of the teeth (Fig. 1.18) and is



• **Fig. 1.16** Biomechanical design of the force system involved during ‘en masse retraction of anterior teeth. The vector of force varies between conventional mechanics (F_O) and implant-based mechanics (F_I) for space closure. Here, $F_I >> r > i$, (F = total force, i = intrusive component and r = retractive component). Also the moment created by the implant will be significantly less than that created by conventional mechanics (force application with implants is closer to the center of resistance (C_{RES}) and M = F × distance to the C_{RES}). Note: with the conventional approach, there is no intrusive force generated.



• **Fig. 1.17** Anterior teeth that have to be distalized a greater distance (A) and will be automatically predisposed to greater degrees of tipping than those requiring less distalization (B). Note: the molar represents the posterior segment while the incisor represents the anterior teeth.



• **Fig. 1.18** Basic mechanics of tooth movement. Here, F = retraction force, M_F = moment caused by the force, M_C = counterbalancing moment.

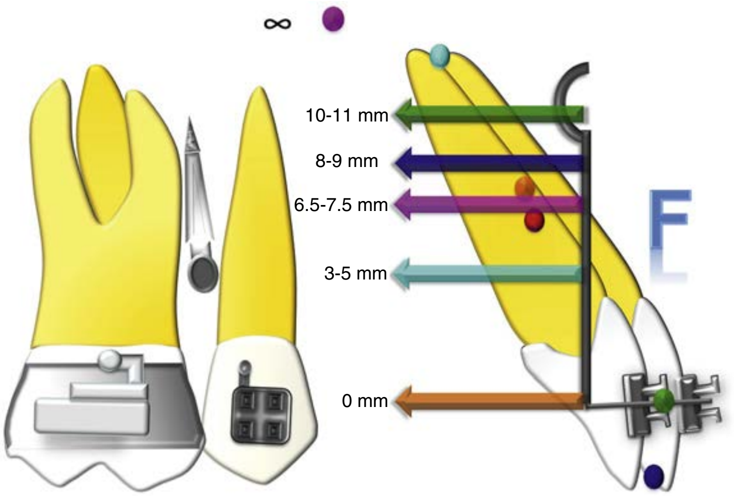
occlusal and buccal to the C_{RES} of the units experiencing the force. This generates moments (moment caused by force, or M_F as described previously), which cause tipping and rotation of the teeth in the direction of the applied force.[13,14]

Here, it is easy to see that by simply controlling the M_F, different types of tooth movement can be achieved (e.g., tipping, translation, etc.). But how can we manipulate the M_F?

In the entire orthodontic spectrum, there are only two broad mechanical pathways to achieve this:

1. Changing the line of force application (or reducing the magnitude of M_F)
2. Counterbalancing the M_F (adding another moment in the opposite direction).

Let us consider each of these options.



• **Fig. 1.19** Altering the line of force application can change the center of rotation and/or the type of tooth movement. *Orange*: uncontrolled tipping, *Blue*: controlled tipping, *Pink*: translation, *Purple*: root movement, *Green*: root movement with crown moving forward. *Red dot*: center of resistance, *other dots*: center of rotations corresponding with the line of force.

1. Changing the Line of Force Application

A simple way of accomplishing this is to apply the force closer to the C_{RES} of the anterior teeth. A rigid attachment, often called a *power arm*, can be attached to the bracket on the crown of the tooth or on the wire itself. Force can then be applied to this power arm. In this way, the line of force is moved to a different location, thereby altering its distance from the C_{RES}. This also causes a change in the moment of the force. For example, if the power arm can be made long and rigid to extend to the C_{RES} of the tooth, the moment arm (M_F) can be entirely eliminated, as the applied force will pass through the C_{RES} (moment = applied force × distance from the C_{RES}).

Based on theoretical calculations, in vitro and in vivo experiments, and with certain assumptions, we have come up with a model (Fig. 1.19) describing various types of tooth movement depending on the line of force application,[15,16–20] and by the location of the tooth's C_{ROT} as a rotation axis. The figure shows the C_{ROT} for every level of force. This model only applies for maxillary incisors and measures only the initial tooth movement.

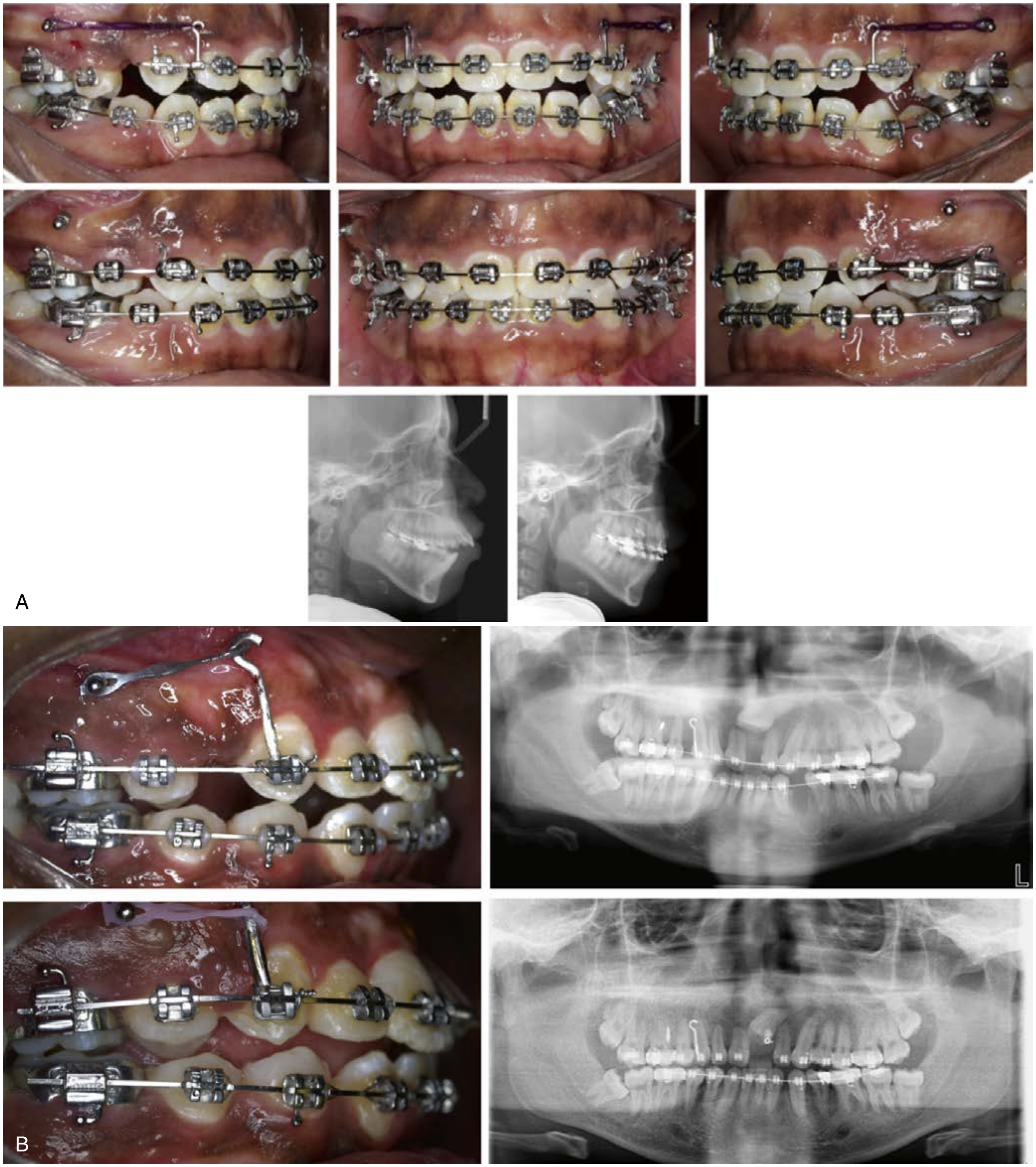
This approach is easier to execute with skeletal anchorage because MIs are usually placed between the roots of the molar and premolar. Here, the height of both the power arm and MI can be varied depending on the line of force required. It works well for both large segments of teeth or individual teeth (Fig. 1.20). However, for movements requiring greater degrees of control, such as translation or root movement, this method possesses certain problems. The "long" arms can be a source of irritation to the patient, by extending high into the vestibule and/or impinging on the gingiva and cheeks. In addition, the arms are sometimes not rigid enough and can undergo some degree of flexion under the applied force. Therefore retraction of incisors is often performed without the use of a power arm. However, without the power arm, the ability to reduce the M_F is also lost. In this situation, how do we control the tooth movement? How do we bring about the desired tooth movement, which can be so easily achieved with "power arms?"

2. Counterbalancing the M_F (Sliding Mechanics With Mini-Implants)

Force system through time. The en masse retraction described at the beginning of the chapter outlined the forces and moment during the initial stages of space closure, i.e., it represented only the beginning phase of retraction. What happens later? We are well aware of the fact that space closure is a dynamic process, and things change as teeth move. Considerable research in this area has provided us with a more detailed representation of the incisor movement and its effect on the entire dentition.[11–18] Based on the evidence gathered from this pool of research, we have further refined the mechanic model of incisor retraction with MIs. Essentially, incisor retraction can be divided into four phases (please refer to Fig. 1.6 for each phase).

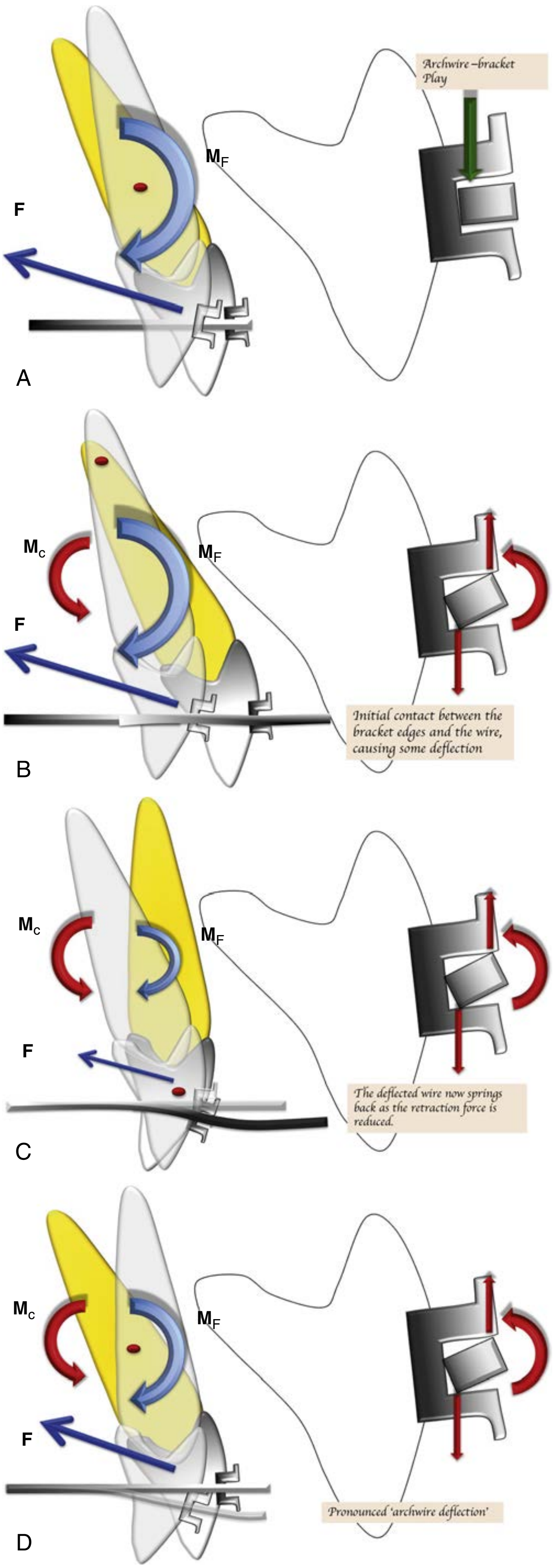
Phase I. This is the initiation of incisor retraction. A single force (F) is applied in an upward and backward/distal direction (Fig. 1.21A). This force produces a moment (M_F) acting at the C_{RES} of the incisor segment, causing it to tip as it is being distalized. Since there is some degree of play between the archwire and the bracket slot at this stage, the tooth is free to tip in the mesiodistal direction in an uncontrolled manner, creating a C_{ROT} slightly apical to the C_{RES}[13,14] (see Fig. 1.19). This can also be referred to as the *unsteady state* of incisor retraction, characterized by uncontrolled tipping. Here, it is easy to see that the greater the play, the more will be the tipping, or in other words, the smaller the size of the archwire, the greater will be the tipping.

Phase II. The incisor is now tipped to the extent that the aforementioned clearance (or play) between the bracket



• **Fig. 1.20** Power arm–based space closure. (A) En masse retraction of anterior teeth shows controlled tipping. (B) Translation of canine.

slot and the wire is eliminated. The sketch in Fig. 1.21B depicts the incisors somewhat later in time relative to Fig. 1.21A. Archwire–bracket slot contact now exists. This two-point contact by the archwire creates a moment (M_C) in the opposite direction of M_F resulting in less tipping of the incisors when compared to phase I. This is the "counterbalancing moment" or "moment caused by a couple" (M_C). As the wire further deflects, M_C continues to increase (force a deflection, as we will see later), and the C_{ROT} moves apically, creating controlled tipping of the incisors. This can also be called the *controlled state* of incisor retraction. From this point onward, the movement of the teeth will depend on the nature of the retraction force (i.e., a steady continuous force or a force



• **Fig. 1.21** Mechanics of incisor retraction with mini-implants (*red dot*: center of rotation). (A) Phase I (the unsteady state/uncontrolled tipping). The archwire–bracket play allows for uncontrolled tipping of the incisor. Note; because of the play there is no M_C (moment caused by a couple) generated. (B) Phase II (the controlled state/controlled tipping). The archwire–bracket play does not exist anymore. There are signs of initial contact between the archwire and the bracket edges giving rise to M_C. However still $M_F >> M_C$. (C) Phase III (restorative phase/root uprighting because of decreasing force). There is a decrease in the force levels causing a decrease in M_F. Here $M_F << M_C$. Note the deflected wire now springs back as the retraction force is reduced causing a reduction in the moment. (D) Phase IV (continuous/heavy force). Permanent deflection of the archwire caused by the continuous/heavy F making the M_C ineffective in creating any root correction. Here again $M_F >> M_C$.

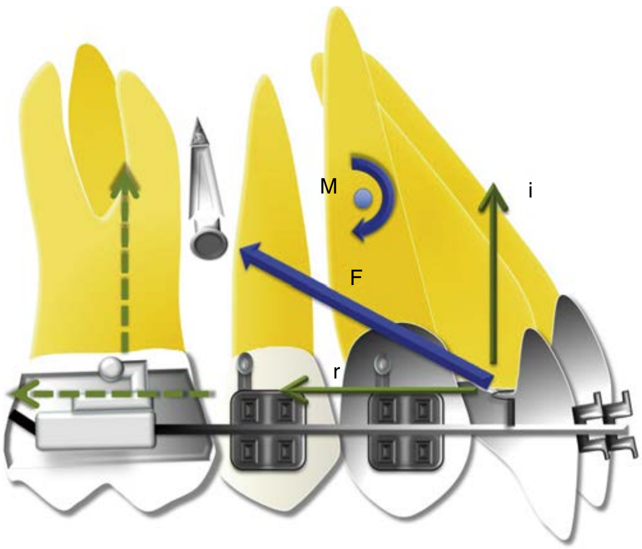
decreasing with time). This at the clinical level is a very relevant supposition.

Phase III (decreasing force). For the space closure to enter this phase, it must be assumed that the distal driving force is undergoing a constant decay through the retraction process. This is often seen with an elastomeric chain or active tiebacks.[21–23] As the force decreases, so does the M_F; however, because of the angulated bracket and the local bending of the archwire, the M_C remains constant. Therefore here $M_C >> M_F$ (Fig. 1.21C). This results in restoration of the axial inclination of the incisors (uprighting or root correction). This can be called the *restorative phase* of incisor retraction and can be clinically referred to as the third-order torqueing of the incisors. With the reactivation of the elastomeric chain, the process resumes from Phase I.

Phase IV (continuous force or heavy force). Incisor retraction enters this phase if the retraction force is either constant or heavy to begin with. Examples can be: nickel titanium closed coil springs, heavy elastomeric chain, etc. Here, because of the heavy retraction force, M_F is always >> M_C, therefore there is anterior bending or deflection of the archwire and the tipping of incisors continues (Fig. 1.21D). Clinically, the incisors might appear as "dumped" or retroclined (loss of torque) with deep bite and sometimes accompanied with a lateral open bite with the molars tipped forward because of a similar wire deformation. This deformation is accompanied with an increase in friction and/or binding at the wire bracket interface making tooth movement slow. (Note: It is important to mention here that at any point if $M_C = M_F$ the incisors would theoretically undergo translation. But this almost never happens, as it is very difficult to maintain such a balance between the moments for any measurable period of time).

Sequela of Phase IV: Distalization Effect of Mini-Implant Assisted Retraction

It has been widely reported that MI-assisted retraction of incisors has the potential to distalize the whole arch en masse.[7–9,11,12] This can occur primarily in two situations



• **Fig. 1.22** Biomechanical design for the force system involved after space closure. Retraction of the upper anterior teeth still in progress. Note the increase in the angulation of the total force relative to the occlusal plane. (Here, F >> r ≈ i). Such a mechanical configuration has important implications for vertical control and Class II correction.

that are not necessarily mutually exclusive. At the end of phase IV, as we saw in the previous section, there is increased binding and interlocking of the wire to the bracket. This causes the upward and backward retraction force to be transmitted to the posterior segment through the archwire. The stiffer and thicker the archwire, the more pronounced will be this effect. A similar effect is also seen when the space between the anterior and posterior teeth is completely closed but the retraction force is continued for closing residual anterior spaces. This results in transmission of the total force to the posterior segments through the interdental contacts, producing a distal and intrusive force on the posterior teeth and a moment (M) on the entire arch (Fig. 1.22). These mechanics have often been used to correct Class II molar relationships without extractions.[24,25]

Distalization with MIs also helps in efficient control of the vertical dimension by preventing the extrusion of the molars (see Fig. 1.22), thereby maintaining the mandibular plane angle and in some situations even resulting in intrusion of the posterior teeth and consequent upward and forward rotation of the mandibular plane.[7–9,25]

Mechanical Factors Affecting Incisor Retraction

It is evident from the previous discussion that the archwire bracket clearance is a very important factor in determining the type of anterior tooth movement in sliding mechanics. The greater the degree of play between the archwire and the bracket, the greater will be the tipping, as the incisor brackets can rotate in that space, causing the roots to move labially.[20] In other words the incisors will undergo a prolonged phase I space closure. Table 1.1 shows the approximate values of play between archwires and a 0.022 × 0.028–sq. inch bracket.[26–29] Needless to say that a 0.016 × 0.022–sq. inch wire will show more tipping than a 019 × 025–sq. inch wire (Fig. 1.23).

TABLE 1.1 Archwire-Bracket Clearance Angle (Play) for Various Archwires When Placed in a 0.022 × 0.028–Sq. Inch Bracket

Wire Size (in inches)	Amount of Play (degrees)
0.016 × 0.022	16–18
0.017 × 0.025	12–14
0.019 × 0.025	6–8
0.021 × 0.025	2–3

Another important mechanical aspect to consider is the flexural rigidity of the archwire, which is critical in regulating the wire deformation. Flexural rigidity (D) is denoted by EI, where E is Young's modulus of the archwire material, and I is the moment of inertia of the cross-sectional area. Once the tipping of incisors has occurred and there is no wire bracket clearance, the flexural rigidity of the archwire or the archwire deformation under the applied load (retraction force) will largely determine the type of tooth movement.[20,30] If the wire undergoes elastic deformation, the incisors will keep on tipping in spite of the "zero" clearance between the archwire and bracket. The amount of archwire deformation can be estimated depending on both the flexural rigidity of the archwire and net force acting on the incisors. As a rule, smaller-size wires and less stiff wires show increased flexion when subjected to retraction forces.[25] Therefore it is advisable to carry out "en masse" space closure with rigid stainless steel archwires as opposed to the more flexible nickel-titanium based archwires.

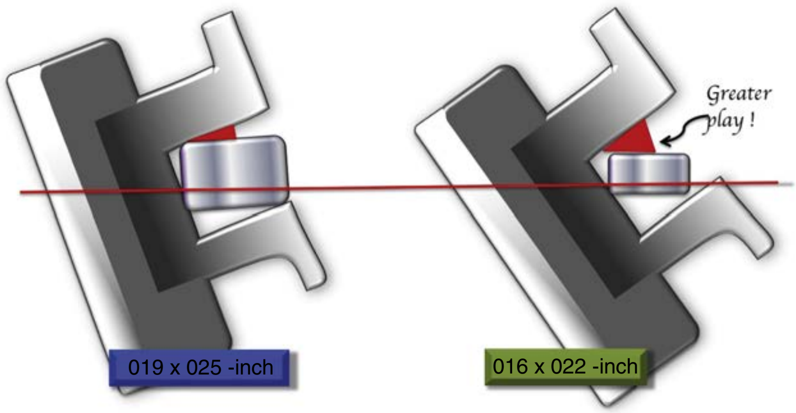
The mechanical factors explained in the preceding section can be elegantly described by an equation from beam mechanics[30–32]:

$$\Delta = \frac{FL^3}{K.D}$$

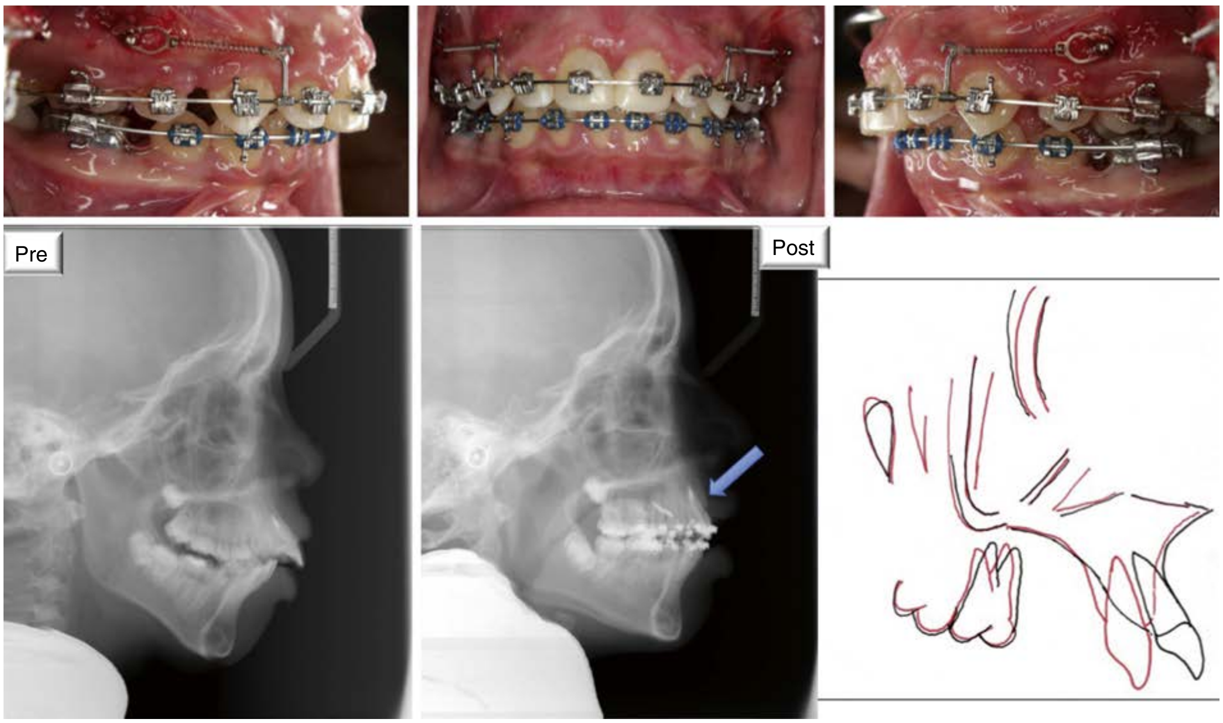
Here, Δ is the amount of deflection of the archwire under the applied load F from its original position (as shown in Fig. 1.21C–D), L is the length of the archwire between the two attachments (here it can be assumed between the molar and the incisors), D is the flexural rigidity described earlier, and K is a constant that reflects the stiffness of the beam and is dependent on the brackets supporting it. Please note, this equation will be more suitable to describe tooth movement that mimics a "three-point bending test" or a cantilever beam with the load concentrated at the free end.

The "Hybrid Model" With Mini-Implant Anchorage

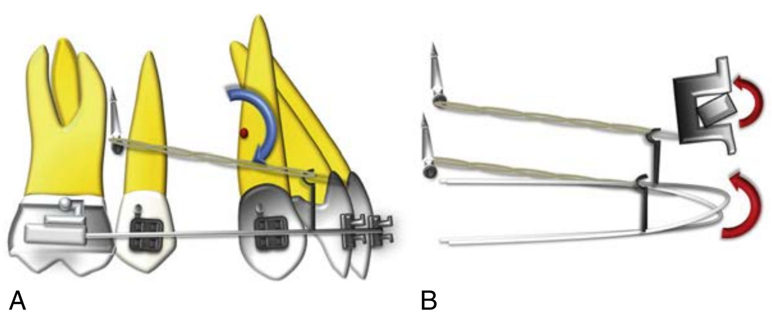
The hybrid approach combines the two methods of controlling anterior teeth retraction, that is, applying a



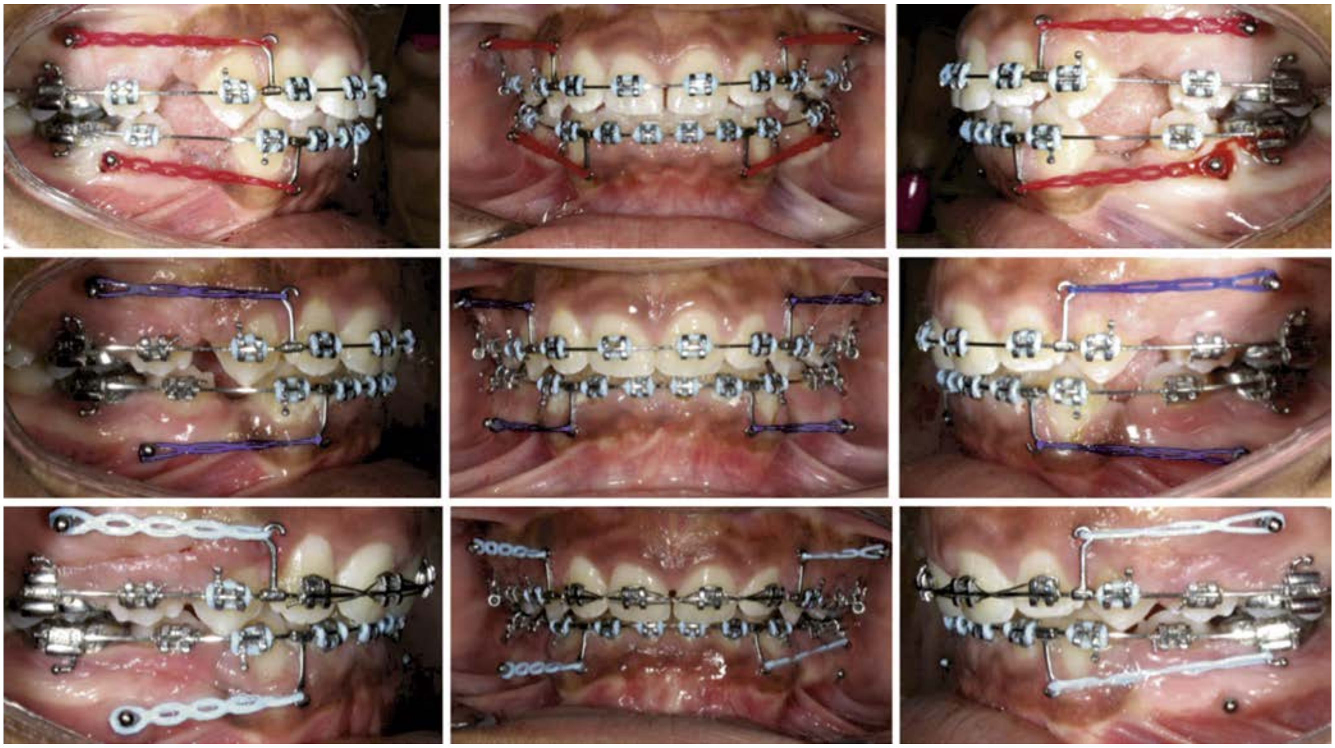
• **Fig. 1.23** The amount of play between the bracket and archwire depends on the size of the archwire.



• **Fig. 1.24** Clinical application of power arm soldered on 0.019 × 0.025 SS archwires for space closure. The *blue arrow* shows the root movement obtained.



• **Fig. 1.25** Sliding mechanics with power arm. (A) Moment *(blue)* caused by retraction force. (B) Moment *(red)* generated by the torsional effect of the archwire.



• **Fig. 1.26** A clinical example of power arm–based space closure.

counterbalancing moment and changing the line of force application (Fig. 1.24). In this approach, a power arm is soldered onto the archwire mesial to the canine, bilaterally. In this way, the clinician can choose the line of force application from the C_{RES} through the power arm to the MI. In addition, the retraction force from the power arm causes the upward deformation and the torsion of the anterior segment of the archwire. This torsion of the archwire produces a couple that works as anti-tipping moment to the anterior teeth (Figs. 1.25 and 1.26). In other words, this couple has a lingual root tipping effect on the incisors. Longer power arms are more effective in minimizing archwire deflection than are shorter ones, as the M_F is reduced. Also thicker wires will provide better torsional control than lighter wires will, as we saw in the preceding section.

Conclusions

MIs in the present day and age are one of the best modalities to maintain "absolute" anchorage. However, they by themselves do not guarantee a well-defined and controlled movement of teeth without side effects. Line of force application, amount of force, force decay/constancy, archwire–bracket play, and archwire deflection (regulated primarily by the archwire properties) are critical factors for controlling incisor retraction with MI-supported anchorage. It is imperative to regulate these factors to minimize archwire deflection for unwanted side effects like loss of torque control on the incisors, resulting deep bite and/or lateral open bite caused by tipping of the anterior and posterior teeth, increase in friction/binding forces leading to stagnant or slowing of tooth movement, etc.

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