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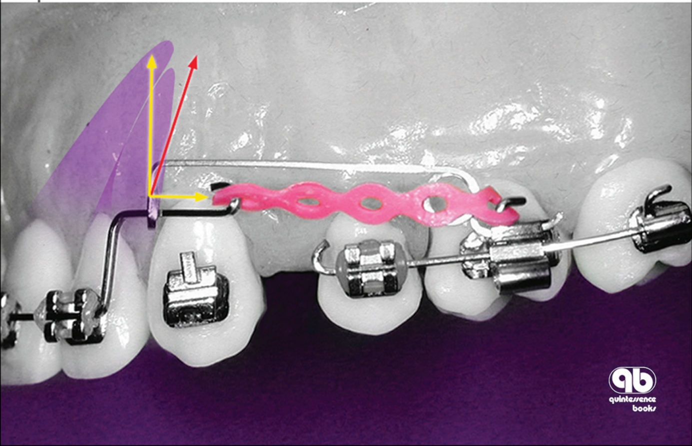
The Biomechanical Foundation of Clinical Orthodontics



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Quintessence Publishing Co, Inc

Chicago, Berlin, Tokyo, London, Paris, Milan, Barcelona, Istanbul,
Moscow, New Delhi, Prague, São Paulo, Seoul, and Warsaw

Library of Congress Cataloging-in-Publication Data

Burstone, Charles J., 1928- , author.
The biomechanical foundation of clinical orthodontics / Charles J. Burstone and Kwangchul Choy.
p. ; cm.
Includes bibliographical references and index.
ISBN 978-0-86715-651-5
I. Choy, Kwangchul, author. II. Title.
[DNLM: 1. Biomechanical Phenomena. 2. Orthodontic Appliances. 3. Malocclusion--therapy. 4. Orthodontic Appliance Design. WU 426]
RK521
617.6'43--dc23

2014043660

Quintessence Publishing Co, Inc
4350 Chandler Drive
Hanover Park, IL 60133
www.quintpub.com

5 4 3 2 1

Editor: Leah Huffman
Design: Ted Pereda
Production: Sue Robinson

Printed in China

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Preface

Historically, the mainstay of orthodontic treatment has been the appliance. Orthodontists have been trained to fabricate and use appliances and sequences of appliance shapes called *techniques*. However, appliances are only the instrument to produce force systems, which are the basis of tooth position and bone modification. And yet a thorough understanding of scientific biomechanics has not been a central part of orthodontic training and practice. Both undergraduate and graduate courses in most dental schools lack sound courses in mechanics and physics. What makes this problem worse is that there are few textbooks that describe biomechanics in a way that is suitable for the clinician. The authors hope this text will fill this void.

This book was motivated by the request of orthodontists at all levels—from graduate students to experienced clinicians—to learn, understand, and apply scientific orthodontics and, in particular, efficiently manipulate forces in their everyday practices. This is particularly relevant at this time, when orthodontics is undergoing a wide expansion in scope. Twenty-first-century orthodontics has introduced substantial changes in the goals and procedures: bone modification by orthognathic surgery and distraction osteogenesis, airway considerations, temporary anchorage devices, plates and implants, brackets with controlled ligation forces, new wire materials, and nonbracket systems such as aligners. No longer can clinicians depend entirely on their technical skills in the fabrication and selection of appliance hardware to adequately treat their patients. The establishment of treatment goals and the force systems to achieve them has become the paramount characteristic of contemporary orthodontics.

Different orthodontic audiences can benefit in special ways from a force-driven approach to treatment. The clinician is aided in the selection of appliances, creative appliance design, and treatment simulation. Simulation is the most valuable because it allows the clinician to plan different strategies using force systems and then select the best. It enables more predictive appliance shapes that approach optimal forces. Unlike an older approach of trying out new procedures directly in the mouth, it is also cost-effective. Particularly in orthodontics, clinical evaluation requires long-term observation. With sound theory, many appliances can be evaluated so that long-term studies or trials can be avoided.

While commercial orthodontic companies may not initially welcome clinical orthodontists who are knowledgeable in biomechanics, it is to their advantage when new important products are introduced to be able to discuss the innovations with scientifically trained clinicians. Researchers in orthodontic physics and material science also need this background. Biologic research at all levels also needs to control force variables. Studies on experimental animals where forces or stresses are delivered must control the force system to have valid results. Many times biologists do not understand the forces in their research and, hence, erroneous or insignificant results are obtained.

Because most orthodontists do not have a strong background in physics and mathematics, the goal of this book is simplicity and accuracy in developing a scientific foundation for orthodontic treatment. In an orderly, step-by-step approach, important concepts are developed from chapter to chapter, with most chapters building on the previous one. From the most elementary to the most advanced concepts, examples from orthodontic appliances are used to demonstrate the biomechanical principles; thus, the book reads like an orthodontic text and not a physics treatise. Yet the principles, solutions, and terminology are scientifically rigorous and accurate.

The biomechanics described in the book are ideal for teachers and students. The simplest way to teach clinical orthodontics is to describe the force systems that are used. Clear force diagrams are far better than vague descriptions. The teaching of the past, such as “I make a tip-back bend here” or “I put a reverse curve of Spee in the arch” is obviously lacking.

What is the best way to learn biomechanics? The simplest approach is to carefully read each chapter and to understand the fundamental principles. Then solve each of the problems at the end of the chapter. It will be quickly apparent if one genuinely understands the material. Over time, introduce biomechanics into your practice. When undesirable side effects are observed, use what has been learned to explain the problem. How could the side effect be avoided with an altered force system and appliance? Critically listening to lectures and reading articles can also be good training for developing a high level of biomechanical competence. One learns to bond a bracket quickly, but development of creative-thinking skills using biomechanics will take time.

It was the intent of the authors to write a basic book on orthodontic biomechanics that would be simple and readable. Clear diagrams and clinical cases throughout ensure that it is neither dull nor pedantic. Our philosophy is that the creative thinking involved in manipulating forces and appliance design should be fun.

Note on the metric system

The authors have adopted the metric system as their unit system of choice. However, the long shadow of American orthodontics has influenced the terminology in this book. Because the United States is the only major country not to fully adopt the metric system and is a major contributor to the literature, some units used throughout the book are not metric. Tradition and familiarity require some inconsistencies: inches are used for wire and bracket slot sizes, and a nonstandard unit—the "gram force"—is the force unit. It is our hope that the specialty of orthodontics will adhere fully to the International System of Units in the future; therefore, future editions of this book will most likely use only metric units.

Acknowledgments

This book would not have been possible without the input of many graduate students and colleagues. One of the authors (CJB) has been teaching graduate students for over 62 years. Long-term teaching has guided us both in how to most effectively present material and where most difficulties lie in acquiring biomechanical skills in a group of biologically trained orthodontists. This book could not have been developed in this manner without their intriguing questions and interaction.

Special thanks are given to the staff at Quintessence Publishing for their valuable contribution in the development of this book: Lisa Bywaters, Director of Publications; Sue Robinson, Production Manager, Book Division; and particularly Leah Huffman, our editor, who worked so hard on a difficult book combining biology, physics, and clinical practice complicated by specialized dental and physics terminologies and equations.

Dr Choy wishes to acknowledge the help he received from his wife Annie and his daughter Christa in the preparation of the manuscript. He is also grateful to his student Dr Sung Jin Kim for taking the time out of his busy schedule to review the questions and answers.

Sadly for us, after finishing this book, a giant fell.

Most of the contents of this book are based on Dr Burstone's energetic and rigorous research for more than 200 research articles. The format of this book was adapted from the lectures on biomechanics that we gave at the University of Connecticut and Yonsei University for many years. Over the last 3 years, my work with Dr Burstone to convert those lectures and ideas into this book was one of the most challenging, most exciting, and the happiest moments in my life. As one of his students, an old friend, and a colleague, I have to confess that all of the concepts in this book are his.

In the beginning, Force was created with the Big Bang. Fifteen billion years later, Newton discovered the Law of Force in the universe. However, the knowledge of how to control orthodontic force remained an occult practice that was only revealed through years of orthodontic apprenticeship. It was Dr Burstone who uncovered the magic and found the principles governing this treatment method that was once thought to be mysterious. There is no doubt that the Law of Orthodontic Force was his discovery.

I would like to share Dr Burstone's words from his last lecture with me on February 11, 2015, in Seoul: "Don't believe blindly in experience, but believe in theory, and think creatively."

My father shaped my body; you shaped my thoughts. Charles, our dearest friend, may you rest in peace.

Kwangchul Choy

In Memoriam

Dr Charles J. Burstone
(1928–2015)

Dr Charles J. Burstone, orthodontist, educator, researcher, and friend to many, passed away February 11, 2015, of an apparent heart attack in Seoul, Korea. He died doing what he loved to do and in a place where he loved to be.

Dr Burstone is well known for the development of the field of scientific biomechanics. He was a master teacher in orthodontics who could bridge the gap between understanding key engineering concepts and applying them to clinical practice. He made biomechanics understandable by showing how to use simple engineering principles to solve most orthodontic problems. He developed the Segmented Arch Technique through the use of sound engineering principles.

Dr Burstone was unwavering in his enthusiasm for student learning and was dedicated to ensuring clinical excellence in his students. When I was a student, I can remember reviewing a patient's treatment plan and him asking me, "What do you want to do with the lower incisors and why?" He emphasized the importance of having clear, specific, and defensible treatment objectives and then designing mechanical plans that would achieve those treatment objectives, step by step.

Over his lifetime, Dr Burstone trained hundreds of orthodontists, first at Indiana University and then later at the University of Connecticut. He served as Department Chairman while at each institution. He was a recipient of many awards and honors and remained active in organized dentistry throughout his life, serving in many positions and lecturing around the world.

Dr Burstone also had a deep connection to Korea. He served there during the Korean War, and his photographs and movies from this period depicted everyday Korean life in a time of conflict. The National Folk Museum in Seoul developed an exhibit around his images entitled "Korea, 1952," and his images were also used in a Korean documentary about the Korean War. He was devoted to Korea, and it is indeed fitting that his last lecture was delivered in Seoul.

He truly loved his profession and was a beloved mentor and colleague to many. He leaves the worldwide orthodontic community to mourn his passing.

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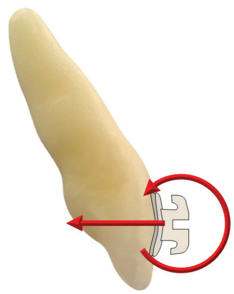
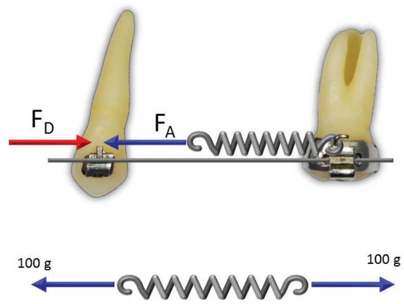
A Color Code Convention for Forces

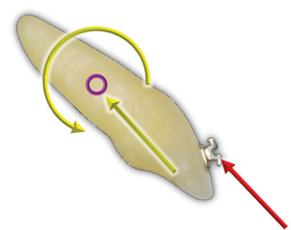
This book has several force illustrations that are used for different applications; there are activation and deactivation forces, equivalent forces, and resultant and component forces. To make it easier for the reader to understand the logical development of important concepts, a color code convention is utilized in this book.



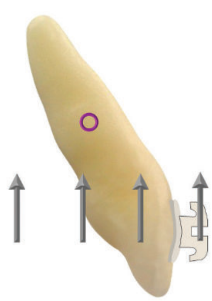
Solid straight arrows and *solid curved arrows* represent forces and moments, respectively. *Red arrows* are forces that act on the teeth. Newton's Third Law tells us that there are equal and opposite forces acting on the wire or an appliance.



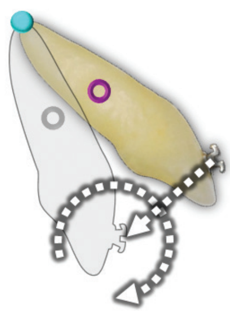
Forces acting on a wire are drawn in *blue*. In special situations, forces can act both on a wire and on the teeth; in this book, therefore, depending on the point of view, the function being considered determines the color of the arrow.



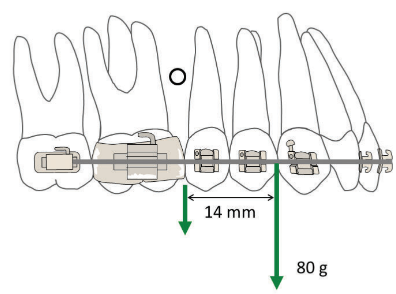
Equivalent forces such as a force and a couple or components are identified with *yellow arrows*.



Gray arrows denote unknown or incorrect forces.



Body motion including tooth motion is shown by a *dotted straight or curved arrow*. Motion arrows that describe linear and angular displacement are purposely different so that they are not confused with forces or moments.



The diagrams for the "Problems" in each chapter and their solutions at the end of the book are kept simple, so the standard code above is not used. Problem figures for emphasis show known and unknown forces as *green arrows*. Solutions are shown in *red arrows*. Equilibrium diagrams (forces acting on a wire, for example) can show force arrows in *blue* in the solution section.

In situations where multiple forces must be shown, other colors may be utilized.

PART

I

The Basics and Single-Force Appliances

CHAPTER

1 Why We Need Biomechanics

"We build too many walls and not enough bridges."

— Isaac Newton

OVERVIEW

Dentofacial changes are primarily achieved by the orthodontist applying forces to teeth, the periodontium, and bone. Hence, the scientific basis of orthodontics is physics and Newtonian mechanics applied to a biologic system. The modern clinician can no longer practice or learn orthodontics as a trade or a technique. He or she must understand forces and how to manipulate them to optimize active tooth movement and anchorage. Communication with fellow clinicians and other colleagues in other fields requires a common scientific terminology and not a narrow "jargon." There is no such thing as a unique "orthodontics physics" divorced from the rest of the scientific community. New appliances and treatment modalities will need a sound biomechanical foundation for their development and most efficient use.

Every profession has its trade tools. The carpenter uses a hammer and a saw. The medical doctor may prescribe medication and is therefore a student of proper drug selection and dosage. Traditionally, the orthodontist is identified with brackets, wires, and other appliances. Such hardware is only a means to an end point: tooth alignment, bone remodeling, and growth modification. The orthodontist achieves these goals by manipulating forces. This force control within dentofacial orthopedics is analogous to the doctor's dosages. An "orthodontic dosage" includes such quantities as *force magnitude*, *force direction*, *point of force application* (moment-to-force ratios), and *force continuity*.

Historically, because the end point for treatment is the proper force system, one might expect the development and usage of orthodontic appliances to be based on concepts and principles from physics and engineering. On the contrary, however, most appliances have been developed empirically and by trial and error. For that reason, treatment may not be efficient. Many times undesirable side effects are produced. If appliances "work," at a basic minimum the forces must be correct, which is independent of the appliance, wires, or brackets. Conversely, when bad things happen, there is a good possibility that the force system is incorrect.

These empirically developed appliances rarely discuss or consider forces. Forces are not measured or included in the treatment plan. How is it possible to use such mechanisms for individualized treatment? The answer is that they are *shape driven* rather than *force driven*. Different shapes and configurations are taught and used to produce the desired tooth movement. This approach is not unreasonable because controlled shapes can lead to defined wire deflections that relate to the produced forces. Unfortunately, there is so much anatomical variation among different patients that using a standard shape for a bracket or a wire or even modifying that shape will not always produce the desired results predictably.

An example of a shape-driven orthodontic appliance is what E. H. Angle called the *ideal arch*. In a typical application of this ideal arch, an archwire is formed with a shape so that if crooked teeth (brackets) are tied into the arch, the deflected wire will return to its original shape and will correctly align the teeth. Today, wires have been improved to deflect greater distances without permanent deformation, and brackets may have compensations to correct anatomical variation in crown morphology. The principle is the same as Angle's ideal arch, but this approach is now called *straight wire*. Straight-wire appliances can efficiently align teeth but can also lead to adverse effects in other situations. The final tooth alignment may be correct, but the occlusal plane may be canted or the arch widths disturbed. Intermediate secondary malocclusions can also occur. An understanding of biomechanical principles can improve orthodontic treatment even with shape-driven appliances by identifying possible undesirable side effects before any hardware is placed. Aligners also use the shape-driven principle of an ideal shape.

All orthodontic treatment modalities, including different brackets, wires, and techniques, can be improved by applying sound biomechanics, yet much of clinical orthodontics today is delivered without consideration of forces or force systems. This suggests that many clinicians believe that a fundamental knowledge and application of biomechanics has little relevance for daily patient care.

Scientific Biomechanics

There are many principles and definitions used in physics that are universally accepted by the scientific community. At one extreme, there is classical physics—concepts developed by giants like Newton, Galileo, and Hooke. There are also other scientific disciplines, such as quantum mechanics. What the authors find disturbing is the hubris of what they call *pseudo-biomechanics*—new physical principles developed by orthodontists that are separate and at odds with classical mechanics. Orthodontists' journal articles and lecture presentations are filled with figures and calculations that do not follow the principles of classical mechanics. Orthodontists may be intelligent, but we should not think we can compete with the likes of Newton.

There is another major advantage in adopting scientific or classical mechanics. The methodology, terminology, and guiding principles allow us to communicate with our scientific colleagues and set the stage for collaborative research. Imprecise words can confuse. We speak of "power arms," but *power* has a different meaning to an engineer than it does to a politician or a clinician. Force diagrams in orthodontic journals are difficult to decipher and may not be in equilibrium. The concepts, symbols, and terminology presented in this book are not trade jargon but will be widely recognized in all scientific disciplines.

Note that the theme of this book is orthodontic biomechanics. The "bio" implies the union of biologic concepts with scientific mechanics principles. Let us now consider some specific reasons why the modern orthodontist needs a solid background in biomechanics and the practical ways in which this background will enhance treatment efficacy.

Optimization of Tooth Movement and Anchorage

The application of correct forces and moments is necessary for full control during tooth movement, influencing the rates of movement, potential tissue damage, and pain response. Furthermore, different axes of rotation are required that are determined by moment-to-force ratios applied at the bracket. For example, if an incisor is to be tipped lingually around an axis of rotation near the center of the root, a lingual force is applied at the bracket. If the axis of rotation is at the incisor apex, the force system must change. A lingual force and lingual root torque with a proper ratio must then be applied. These biomechanical principles are relevant to all orthodontic therapy and appliances—headgears, functional appliances, sliding mechanics, loops, continuous arches, segments, and maxillomandibular elastics (also sometimes referred to as *intermaxillary elastics*). The hardware is only the means to produce the desired force system.

Equally important as active tooth movement is the control over other teeth so that they do not exhibit undesirable movements. This is usually referred to as *anchorage* and depends in part on optimally combining and selecting forces. Some orthodontists might think that anchorage is determined by factors independent of forces. For instance, the idea that more teeth means greater anchorage is very limiting. Working with forces can be more effective in enhancing anchorage, such as in pitting tipping movement against translation. All archwires produce multiple effects. Many of these effects are undesirable, which should also be considered anchorage loss. In a sense, a new malocclusion is created, resulting in an increased treatment time. Let us assume that translation of teeth could be accomplished at the rate of 1 mm per month. In a typical orthodontic patient, rarely does tooth movement exceed 5 mm. Not considering any waiting for growth, total treatment time should be no longer than 5 months. So why is treatment longer? Usually, more time is required to correct side effects. The use of temporary anchorage devices (TADs) may eliminate side effects. As will be shown in chapter 18, a good biomechanical understanding is required to successfully use TADs; otherwise, adverse effects can still occur.

Selecting or Designing a New Appliance

New appliances and variations of older existing appliances are continually presented in journal articles or at meetings. What is the best way to evaluate these appliances? One approach is to try them in your clinical practice. This evaluation will be quite limited because there is a lot of variation in a small sample of malocclusions. Moreover, it is time-consuming and unfair to the patient. Because treatment is so long term, it may take many years to arrive at a conclusion on the efficacy of a new appliance. A better approach would be an evaluation based on sound and fundamental biomechanical principles. Drawing some force diagrams is much easier than protracted treatment. This is particularly valid when considering that most new appliances and techniques do not stand the test of time.

Orthodontists have always been very creative. Not all great research has come from university research laboratories. Whether in their own offices or on typodonts in the lab, clinicians have made significant achievements in bracket design, various wire configurations, and treatment sequences (techniques). It is much more efficient to work with a pencil and a sheet of paper (or a computer) than it is to go through the demanding trial and error approach. The best appliances of the future will require rigorous engineering and sound biomechanical methodology.

Let us assume for now that we have selected the best appliance for our individual patient. There are still many variables that require a sound biomechanical decision. For example, what size wire should we use? A 0.014-inch nickel-titanium (Ni-Ti) superelastic wire is not the same as a 0.014-inch Nitinol wire. The choice between a 0.016- and a 0.018-inch stainless steel (SS) archwire is significant. The larger wire gives almost twice the force.

Research and Evaluation of Treatment Results

The clinician can be surprised at the progress of a patient. When the patient arrives for an appointment, mysterious changes are sometimes observed. Why is there now an open bite or a new reverse articulation (also referred to as *crossbite*), or why is the malocclusion not improving? These unexpected events may be attributed to biologic variation. Or it may be the wrong appliance (or manufacturer). In reality, most of the clinical problems that develop can be explained by deviation from sound biomechanical principles. Thus, an understanding of applied biomechanics allows the orthodontist to determine both why a puzzling and problematic treatment change occurred and also what to do to correct it. Sometimes the force system is almost totally incorrect; other times, a small alteration of the force system can produce a dramatic improvement.

The prediction of treatment outcomes requires precise control and understanding of the applied force system as well as the usual cephalometric and statistical techniques. Good clinical research must control all of the known variables if the efficacy of one appliance is to be compared to another. Let us consider a study that is designed to compare the different outcomes between a functional appliance and an occipital headgear. It is insufficient to simply specify headgear or even occipital headgear. Headgears can significantly vary not only in force magnitude but also in direction and point of force application. It is little wonder that some research studies lead to ambiguous and confusing conclusions.

A biomechanical approach to clinical studies opens up new avenues for research to help predict patient outcomes. The relationship between forces and tooth movement and orthopedics requires more thorough investigation. Relationships to be studied include force magnitudes, force constancy, moment-to-force ratios at the bracket, and stress-strain in bone and the periodontal ligament.

Force systems and "dosage" determine not only tooth or bone displacement with its accompanying remodeling; unwanted pathologic changes involving tissue destruction can also occur. Root resorption, alveolar bone loss, and pain are common undesirable events during treatment. Some histologic and molecular studies suggest a relationship between force or stress and tissue destruction. Although other variables may be involved, a promising direction for research is between stress-strain and the mechanisms of unwanted tissue changes. To control pain and deleterious tissue destruction, it is likely that future research will validate that "dosage" does count.

How Scientific Terminology Helps

As previously discussed, orthodontic appliances work by the delivery of force systems. In this book, the methods and terminology of the field of physics are adopted. Tooth movement is only part of a subset of a broader field of physics. This allows orthodontic scientists and clinicians to communicate with the full scientific community outside of dentistry, setting the stage for collaborative research. Many of the specialized orthodontic terms produce a jargon that is imprecise and certainly unintelligible to individuals in other disciplines. The orthodontist speaks of "torque." Sometimes it means a moment (eg, the force system). At other times, however, it means tooth inclination (eg, "the maxillary incisor needs more torque"). Imprecision leads to faulty appliance use, which will be discussed later.

A universal biomechanical and scientific language is the simplest way to describe an appliance and how it works. It not only allows for efficient communication with other disciplines for joint research but also offers the best way to teach clinical orthodontics to residents or other students. The old approach was primarily to teach appliance fabrication. Treating patients was just following a technique. An adjustment was how you shaped an arch: "Watch how I make a tip-back bend, and duplicate it." Emphasis was on shape, and therefore we can call it *shape-driven orthodontics*. The biomechanical approach emphasizes principles and force systems. This approach, *force-driven orthodontics*, is the theme of this book.

With clear terminology and sound scientific principles, the learner can better understand how to fabricate and use any appliance or configuration. It shortens the time and confusion in teaching students. It is said that a number of years of experience is required to complete the education of an orthodontist. Some say as many as 10 years. Why? It is the time needed to make and learn from your mistakes. If the student understands the biomechanical basis of an appliance, many common mistakes will never be made.

It is not only the beginning student who benefits from sound biomechanical teaching. As new appliances are developed, the experienced orthodontist can better learn the "hows" and "whys" so that the

Fig 1-1 Jacques Carelman painting of a pitcher. Although the pitcher looks reasonable, it will not actually pour coffee, much like some orthodontic appliances seem reasonable but do not actually work.

Fig 1-2 A wine bottle in a curved wine rack. Although it would seem that the bottle would fall over, it is in a state of static equilibrium so that it does not move. Similarly, some orthodontic principles that seem illogical are actually quite effective because they are based on sound biomechanics.

learning interval is shortened. More important, fewer errors will be made. Lectures at meetings will be shorter and easier to understand.

Knowledge Transfer Among Appliances

The orthodontist may feel comfortable treating with a given appliance because routine treatment has become satisfactory and predictable. However, if he or she wants to change appliances (eg, moving from facial to lingual orthodontics), the mechanics may not be the same. When lingual orthodontic appliances were introduced a few years ago, some orthodontists were troubled that their mechanics (wire configurations and elastics) did not do the same on the lingual that they did on the buccal. Biomechanical principles that determine the equivalent force system on the lingual are simple to apply. Clinicians could have saved much "learning time" spent doing trial and error experimentation. A few simple calculations covered in chapter 3 could have helped the clinician avoid any aggravation.

Advantages of Biomechanical Knowledge

Historically, there have been many exaggerated claims made by clinicians and orthodontic companies about the superiority of appliances or techniques. Hyperbole is used with such terms as *controlled*, *hyper*, *biologic*, and *frictionless*. Journals and orthodontic associations are now doing a better job of monitoring possible conflicts of interest. The best defense against unwanted salesmanship is to stay vigilant and always apply scientific biomechanics. What may look possible becomes clearly impossible when the underlying principles are understood. The pitcher in Jacques Carelman's painting looks reasonable, but it will not pour coffee (Fig 1-1). On the other hand, a sound biomechanical background can make possible what appears impossible. A filled wine bottle is placed in a curved wine rack. The rack is not glued to the table, so one might think that the bottle will tip over, but it does not (Fig 1-2). As will be discussed later, the bottle is in static equilibrium and, hence, the impossible becomes possible. Figure 1-3a shows an auxiliary root spring on an edgewise arch designed to move the maxillary incisor roots to the lingual. Is this possible or impossible? If the spring is bent to push lingually on the crown, the edgewise wire will twist to produce labial root torque (Figs 1-3b). This is an example of an impossible appliance. Placing the auxiliary on a round wire makes the mechanism possible (Fig 1-3c).

The many advantages of a biomechanical knowledge for the clinician, including better and more efficient treatment, have been mentioned here. But what about for the patient? Obviously, one benefit is better and shorter treatment. Another significant advantage is the elimination of undesirable side effects. Side effects might require more patient cooperation. To correct problems, new elastics, headgear, surgery, or TADs may be prescribed. With better me-

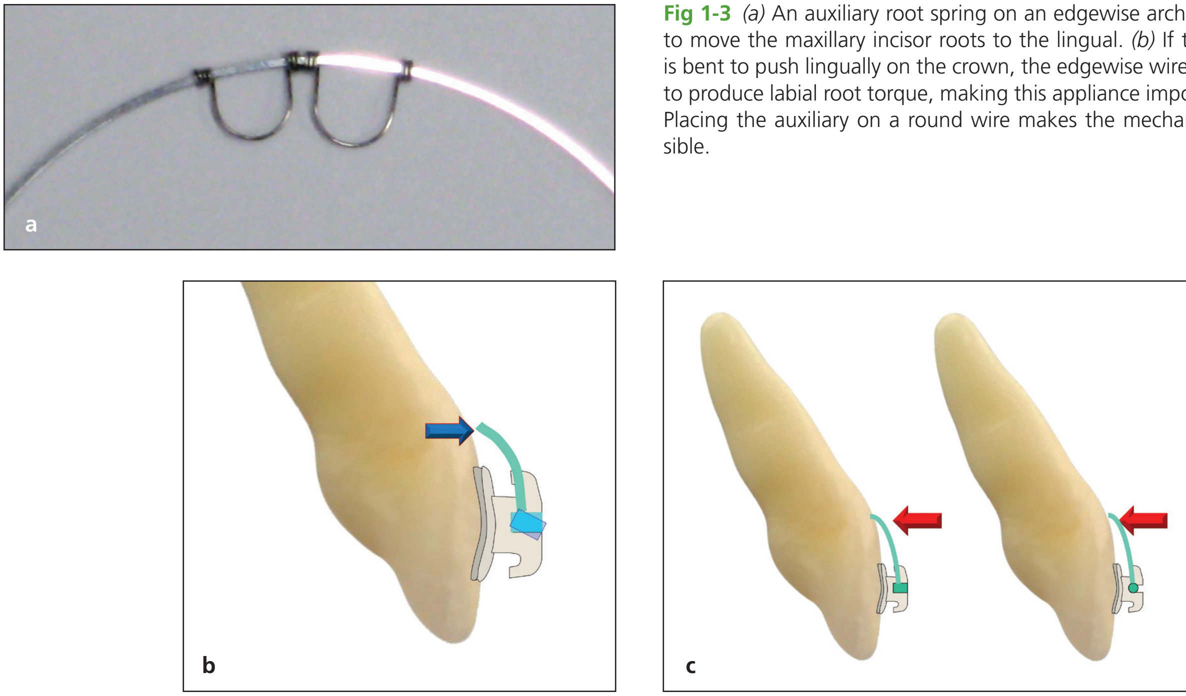


Fig 1-3 *(a)* An auxiliary root spring on an edgewise arch designed to move the maxillary incisor roots to the lingual. *(b)* If the spring is bent to push lingually on the crown, the edgewise wire will twist to produce labial root torque, making this appliance impossible. *(c)* Placing the auxiliary on a round wire makes the mechanism possible.

chanics, such anchorage loss would not have happened. It is not fair to ask our patients to cover up our mistakes with added treatment time or added therapy requiring considerable appliance wear, such as headgear.

The future of the profession will be determined by how well we train our residents. Currently, not all graduate students are being trained in scientific biomechanics in any depth. Ideally, when a student graduates from a program, an understanding of biomechanics should be second nature. Otherwise, he or she will not be able to apply it clinically. Lectures and problem-solving sessions are very useful; however, biomechanical principles must be applied during chairside treatment. Carefully supervised patients and knowledgeable faculty are the key ingredients to teaching biomechanics.

Conventional wisdom in orthodontics has emphasized the appliance. Graduate students and orthodontists were taught to fabricate appliances or make bends or adjustments in these appliances. Perhaps some lip service was given to biomechanics or biology, but basically the clinician was a fabricator and user of appliances. Treatment procedures were organized into a technique sequence. This empirical approach to clinical practice led to the development of different schools of thought, sometimes identified with the name of a leading clinician. Shape-driven orthodontics (where forces are not considered) is usually a standard sequence or cookbook approach that does not adequately consider the individual variation among patients.

The new wisdom is not appliance oriented. It involves a thinking process in which the clinician identifies treatment goals, establishes a sequence of treatment, and then develops the force systems needed for reaching those goals. Only after the force systems have been carefully established are the appliances selected to obtain those force systems. This is quite a contrast to the older process in which the orthodontist considered only wire shape, bracket formulas, tying mechanisms, friction, play, etc, without any consideration whatsoever of the forces produced.

It is easy for the clinician to harbor negative feelings about orthodontic biomechanics. Some may believe that treatment mechanics are only common sense and that intuition and everyday knowledge are sufficient. Others may regard biomechanics as too sophisticated, demanding, and complicated for daily practice. Indeed, many of us became dentists and orthodontists because, as students, we disliked mathematics and physics and preferred the biologic disciplines. Fortunately, the physics used in orthodontics is not complicated, and many simple principles and concepts can be broadly and practically applied. Orthodontics is not nuclear physics. Scientific biomechanical thinking is actually easier than vague and disorderly thought processes and simplifies our overall treatment.

The genius of pioneers such as Newton is that their principles are anything but common sense. Aristotle reasoned that if a heavy weight and a light weight were dropped from the same height, the heavy weight would hit the ground first. This seems like common sense. Galileo, on the other hand, thought that both weights would hit the ground at the same time. He supposedly dropped two different weights from the Leaning Tower of Pisa to prove his point. Many common-sense ideas are false. Common sense would tell you that the earth is flat and that the sun rotates around the earth, and yet the earth is round, and it rotates around the sun. As will be shown in this text, many of our conventional and accepted orthodontic ideas from the past are invalid.

There are many textbooks and articles that describe techniques involving different types of brackets, sequences of wire change, and slot formulas, much like a recipe in a cookbook. Many malocclusions might be successfully treated following such cookbook procedures. However, surprises can occur as unpredicted problems develop during treatment. One or more recipes will not always work because malocclusions vary so much. Therefore, the clinician must seek sound biomechanical principles rather than a technique to correct the problem. Thus, bioengineering is needed not only for the challenging situation but also for the routine patient who may show an unexpected response to an appliance. Even if we typically treat by a certain technique, we must have biomechanical knowledge and skill in reserve, which will be required when unfortunate surprises strike. If that knowledge is not readily available because we do not continually apply it, we limit our ability to get out of trouble. By way of analogy: One of the authors recently tried to do some simple plumbing. When the house became flooded, an experienced plumber was called, and his backup knowledge and expertise solved the problem. Unfortunately, when the orthodontist gets into trouble, he or she traditionally does not seek the advice of others, leading to either a poorer result or a lengthier treatment time.

What about the “easy” case we may routinely treat successfully? It could be argued that applying creative biomechanics could also improve our treatment result or allow us to treat more efficiently. We might treat a Class II patient without extraction with some leveling arches and Class II elastics. A certain technique might work, negating any biomechanical thinking. However, the end point might be different than our treatment goals. Perhaps the mandibular incisors are undesirably flared or the occlusal plane angle steepened too much. The goals and quality of treatment can vary so much that it is difficult to define what a routine or “easy” case entails. It takes a very knowledgeable orthodontist to identify what an “easy” case really is.

Technical competence is developed by fabricating and inserting appliances, but understanding principles involves thinking. Admittedly, technical skill is important in daily practice. But performing techniques without understanding the fundamental principles behind them is risky. At the same time, principles without technique lack depth. This book therefore explains the “hows” and “whys” of orthodontic treatment, which are inseparable.

Orthodontic biomechanics is not just a theoretical subject for academics and graduate students. It is the core of clinical practice; orthodontists are biophysicists in that daily bread-and-butter orthodontics is the creative application of forces. The 21st century will be characterized by a major shift from shape-driven orthodontic techniques to a biomechanical approach to treatment, and with this shift will come rapid advancements in treatment and concepts.

CHAPTER

2 Concurrent Force Systems

"Goodbye, old friend. May the Force be with you."

— Obi-Wan Kenobi, From *Star Wars Episode IV: A New Hope*

OVERVIEW

The branch of physics dealing with forces is called *mechanics*. The most relevant Laws of Newton are the First and Third Laws. Many orthodontic questions and their solutions can be considered equilibrium situations, so Newton's Second Law, which relates forces to bodies that accelerate, is less important. The division of mechanics describing bodies in equilibrium is called *statics* and for bodies that accelerate, *kinetics*. The simplest force system is force acting on a point; it is fully defined by force magnitude, force direction, and sense. Manipulating a force system includes adding a number of forces to obtain a resultant or breaking up a resultant into separate components. Forces are vectors that must be added geometrically and cannot be added algebraically. Simple orthodontic appliances that act on a point are maxillomandibular elastics (also known as *intermaxillary elastics*), finger springs, and cantilevers.

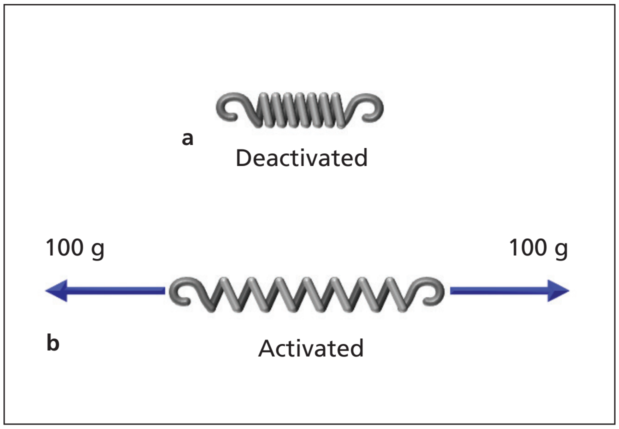


Fig 2-1 Simple coil spring demonstrating Newton's First Law. *(a)* Deactivated. *(b)* Activated. The spring is in equilibrium in both *a* and *b*.

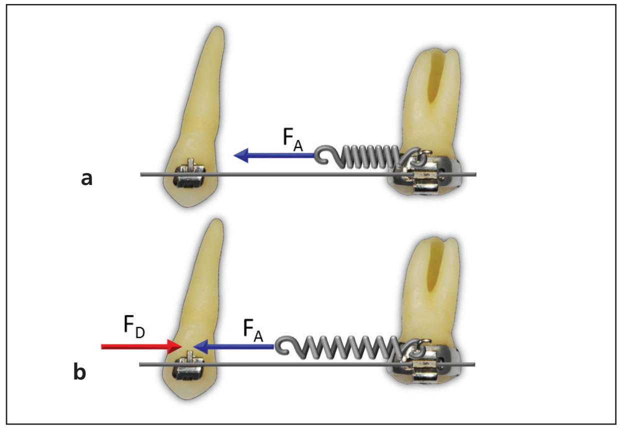


Fig 2-2 *(a and b)* Newton's Third Law. Equal and opposite forces act at the canine. F_A *(blue arrow)*, activation force on the coil spring; F_D *(red arrow)*, deactivation force on the canine.

Medical doctors may use thousands of medicines to treat their patients, but orthodontists use only one treatment modality: force. No matter what kinds of wires, springs, and brackets or appliances used, the hardware serves only as an intermediate tool to deliver a force or a series of forces. With proper force positioning and dosage, all kinds of tooth movement can be achieved. Therefore, knowledge of force is essential for understanding tooth movement. Because the word *force* has different meanings in common language and in physics, important definitions and concepts required for the application of force analysis to the field of orthodontics are developed in this chapter.

The Field of Mechanics

Mechanics is the field of physics dealing with the study of forces. Mechanics can be subcategorized into *statics, kinetics,* and *material science*. *Statics* deals with a force on a body with constant velocity, including a state of rest. *Kinetics* deals with a force on a body with acceleration. Finally, *material science* deals with the effect of forces on materials.

The classic laws explaining the relationship between force and bodies were presented by Newton in 1686. Newton's First Law (law of inertia) describes bodies at rest or bodies with uniform velocity (no acceleration): An object at rest tends to stay at rest, and an object in motion tends to stay in motion with the same velocity and in the same direction unless acted upon by an unbalanced force. This is the most important law for orthodontics, because it is the basis of all equilibrium applications. Activated appliances and restrained teeth within the bone and periodontium are examples of the first law. A simple orthodontic appliance component, a coil spring, is shown in Fig 2-1. The deactivated spring in Fig 2-1a is at rest; there are no forces acting on it. (This free-body diagram purposely ignores gravity and other nonrelevant forces.) The application of two forces in Fig 2-1b extends the spring, which can now be placed in the mouth between the anterior and posterior teeth for space closure. The forces are equal (100 g) and opposite, allowing the spring to remain in equilibrium. The spring deforms but does not accelerate, demonstrating the First Law.

Newton's Second Law (law of acceleration) states that when force is applied to an object, it accelerates proportional to the amount of force applied. The famous Newtonian formula is

$$F = ma$$

where m is mass, a is acceleration, and F is force.

This formula defines the nature of force—an ability to accelerate an object. One would think that Newton's Second Law would have important applications in orthodontics. Are teeth not moving? Although they move, they are not accelerating. Teeth are restrained objects and hence are bodies in equilibrium and at rest. Imagine a simple model in which a tooth is suspended by coil springs on all sides. Similar to the spring in Fig 2-1, the tooth is still in equilibrium after a force is applied to the crown. Therefore, this book does not cover applications in the field of kinetics.

Newton's Third Law (law of action and reaction) states that for every action there is always an equal and opposite reaction (ie, for every force there is an equal and opposite force). The commonly used example of this law is a rifle shot where the bullet feels the force and one's shoulder feels the equal and opposite force. In Fig 2-2a, a coil spring is activated by a mesial force to allow its placement on the canine hook. Because this force (F_A) produces an elongation of the elastic, it is called the *activation force* (Fig 2-2b). This force extends the elastic during the act of placement by the orthodontist, and later the canine hook maintains the mesial activation force, holding the elastic in place. At the canine hook, one observes the two equal and opposite forces of Newton's Third Law (see Fig 2-2b). The blue force (F_A) is the activation force (the force on the appliance), and the red force (F_D) is the equal and opposite force on the tooth or the hook. This equal and opposite force *(red arrow)* is called the *deactivation force* and is in the direction of the tooth movement. In other words, the hook pulls on the elastic, and the elastic pushes on the hook. These action and reaction forces occur at the hook. In this example, it is also true that the canine and the molar feel equal and opposite forces, but this is not an expression of Newton's Third Law. Why? The elastic is in equilibrium; hence, the forces on the elastic are equal and opposite. The explanation lies in Newton's First Law, which covers equilibrium on bodies at rest (the elastic is not accelerating). Newton's Third Law is properly used when both activation and deactivation forces are showing on the canine (see Fig 2-2b).

This chapter introduces how to manipulate or handle orthodontic forces. First, concurrent forces (ie, forces acting on a point) are considered. In the next chapter, this will be developed further to consider forces in three dimensions on a body.

Characteristics of a Force

A force has three attributes: magnitude, direction and sense, and point of force application. Figure 2-3 shows three forces acting on a point *(red dot)*, a hook on the maxillary arch. Because the hook defines the point of force application, only force magnitude and direction require further description. From where do the forces originate? Their source could be maxillomandibular elastics* or intra-arch elastics. Forces are vector quantities that cannot be added algebraically but are rather added geometrically. Note that the elastics have different angles to each other, representing different lines of force application and denoting their vector properties.

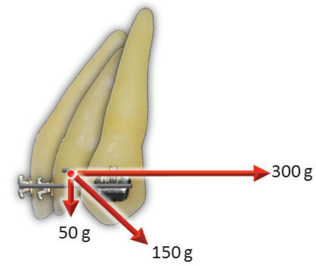


Fig 2-3 Elastic forces acting at a point. The hook *(red dot)* defines the point of force application. Different force magnitudes are represented by the length of the *red arrows*. The direction of the forces can be measured by the force angle to the occlusal plane.

Force magnitude

The force magnitude is given in grams (g). The force magnitudes in Fig 2-3 are represented by arrows; the length of the arrow is proportional to the magnitude of the force. Note that the 150-g maxillomandibular elastic arrow is three times as long as the 50-g vertical elastic arrow and half the length of the 300-g intra-arch elastic arrow.

Why are grams the unit of force in this example? This unit is technically incorrect, as shown below. Historically in America, ounces were used, and spring measuring scales were calibrated in ounces. More universal metric force gauges then became available, and the units were in grams. Generally, scales used by the layman for measuring body weight can be calibrated in pounds or kilograms. For the physicist, these are not force (weight) units but rather units for measuring mass. So let us briefly consider the relationship between *mass* and *force*. Again, the classic Newtonian formula is *force equals mass times acceleration* ($F = m \times a$). The force is the product of mass (kilograms) and acceleration (m/s^2). The unit of this magnitude of force is therefore kg•m/s^2, and 1 kg•m/s^2 equals 1 Newton (N). The terms *gram weight* and *kilogram weight* are therefore incorrect.

Traditionally, orthodontists use the gram as the unit of force. In the strict sense as explained above, this is incorrect because grams are a unit of mass and not force. For example, gravity (a force) at sea level attracts a 100-g mass (the amount of material). The calculated acceleration of gravity is 9.8 m/s^2. Let us now calculate how much force is acting on the 100-g mass at sea level using Newton's Second Law.

$$F = m \times a$$
$$F = 100\ g \times 9.8\ m/s^2$$
$$F = 0.98\ kg{\bullet}m/s^2 = 0.98\ N = 98\ cN$$

*Traditionally, orthodontists have used the term *intermaxillary elastics* to denote elastics placed between the maxillary and mandibular arches, because both jaws used to be referred to as maxillae. However, because the mandible is no longer considered a maxilla, the term *intermaxillary* makes no sense, hence the new term: *maxillomandibular elastics*.

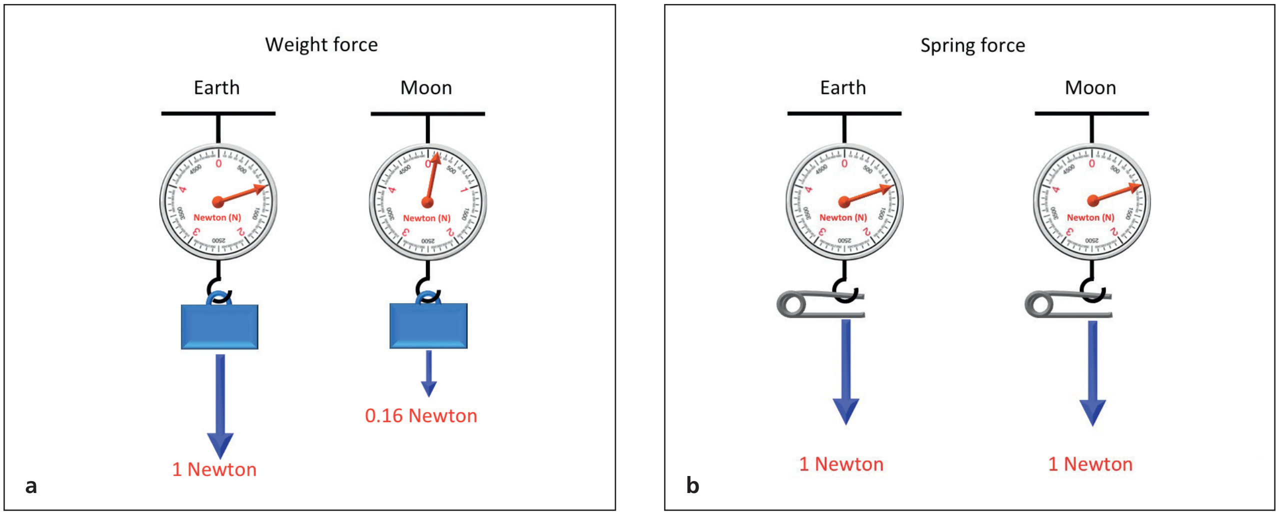


Fig 2-4 *(a)* Force depends on gravitational acceleration, so people weigh less on the moon than on earth. *(b)* However, the same activation of an orthodontic appliance would produce the same force on the moon as on earth.

Scientifically, a centi-Newton (cN) is the correct unit for force, but in this book, grams will be used as the unit of force because of its tradition in orthodontics; perhaps this unit will be easier to understand for the clinician. However, the authors recommend that scientific publications and presentations use Newtons or centi-Newtons as the unit of choice. For purposes of practical conversion, 1 g equals 1 cN.*

Perhaps in the not-so-distant future, an orthodontist might have a satellite office on the moon. If we attach a 100-g mass to a force gauge, as shown in Fig 2-4a, the measured gravitational force will be about 1 N on the earth but only 0.16 N on the moon. This is why people can jump with less effort on the moon, because they actually weigh less there. Let us now use this same force gauge to measure the force from an orthodontic appliance (Fig 2-4b). This type of force gauge uses a calibrated spring and has nothing to do with gravity. A spring gauge is based on Hooke's law, where force is proportional to wire deflection. If the same appliance is used on the moon as on earth, there would be no difference in the forces, provided the activation is the same (see Fig 2-4b). Our imaginary orthodontist could therefore use the same appliances and activations used on earth, provided that there were no biologic differences required in outer space.

Force direction and sense

Force also has sense and direction. The direction of the force is defined by its line of action. This direction is referred to as the *sense*. The arrows shown in Fig 2-3 demonstrate direction, sense, and the line of action of three elastics. The origin of each arrow is the point of force application (hook, *red dot*), the line (of action) indicates direction, and the arrowhead indicates the sense. The direction of the force in Fig 2-5 is demonstrated by the dotted line, and the arrowhead shows the sense. The two red forces have the same direction but different senses.

To specify the direction of a force vector, a proper coordinate system is required; the direction of the force can be represented by the angle between a given axis of the coordinate system and line of action. There are several coordinate systems, but rectilinear Cartesian coordinates are most frequently used. Figure 2-6a shows the three axes of a Cartesian coordinate system and a sign convention in three dimensions. In this book, two-dimensional diagrams, such as those in Fig 2-6b, are used for simplicity's sake. Any coordinate system and sign convention is acceptable, provided that it is clearly specified.

The orientation of a coordinate system can be set arbitrarily, depending on the problem to be studied. In an orthodontic analysis, frequently used axes include the occlusal plane, the Frankfort horizontal, the midsagittal plane, and the long axis of a tooth. The direction of an orthodontic force is specified in accordance with a given established coordinate axis. For example, in Fig 2-7, a crisscross elastic *(red arrow)* is applied at 90 degrees to the mandibular right first molar relative to the midsagittal plane. What is the best coordinate system to evaluate the molar movement? Of the three shown *(dotted lines)*, the authors would most likely select the system based on the mesiodistal or buccolingual axes of the tooth. Resolving the force into rectilinear

*More accurately, 1 g equals 0.98 cN, and 1 cN equals 1.02 g.

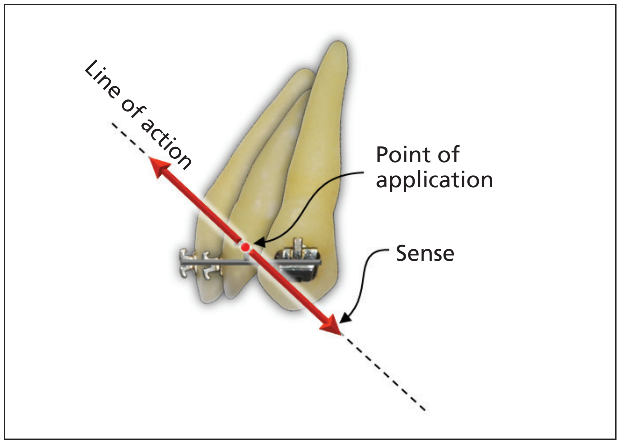
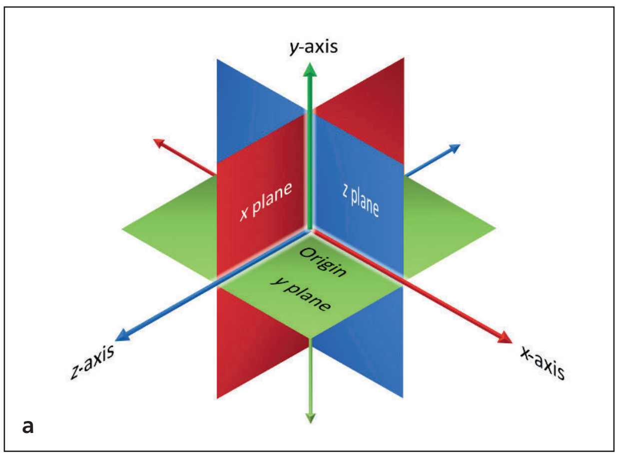


Fig 2-5 Force sense and direction. The line of action *(dotted line)* demonstrates the direction, and the arrowheads denote the sense of the force.



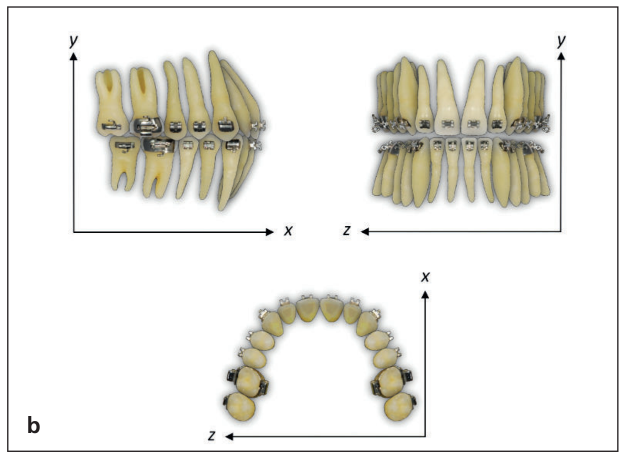


Fig 2-6 Cartesian coordinates in three dimensions. *(a)* Three mutually perpendicular axes with a sign convention specified on each axis. *(b)* Two-dimensional diagrams with the same coordinates as those shown in *a*. For simplicity's sake, most diagrams in this text show only two dimensions.

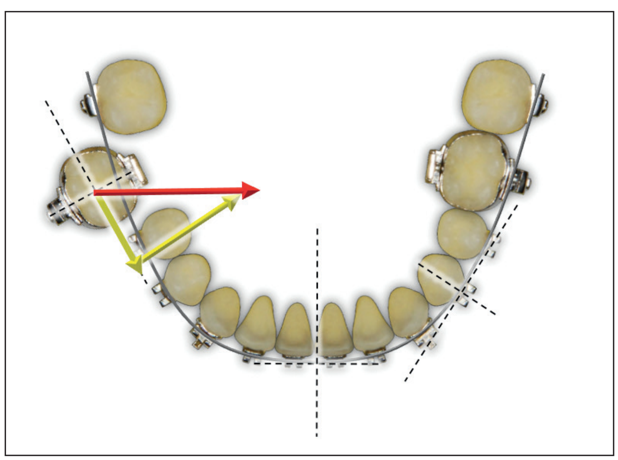


Fig 2-7 A crisscross elastic is attached at the buccal of the mandibular right molar. A coordinate system is selected that gives the information that is most useful. Here the mesiodistal crown axis system was selected. The elastic force *(red arrow)* has both lingual and mesial components of the force *(yellow arrows)*.

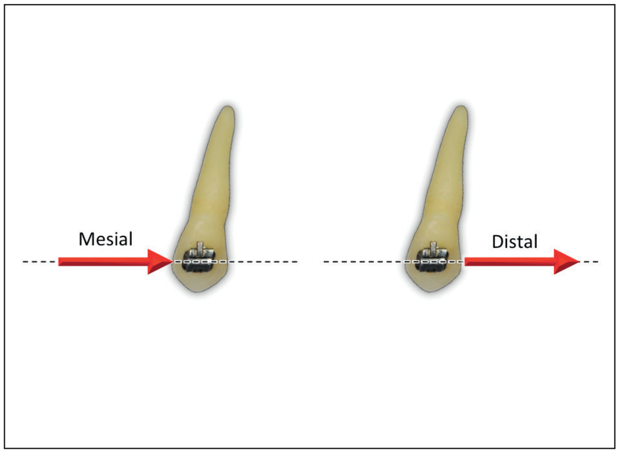


Fig 2-8 Law of transmissibility of force. The effect is the same whether the force is applied at the mesial or the distal of a canine as long as the force is along the same line of action *(dotted line)*.

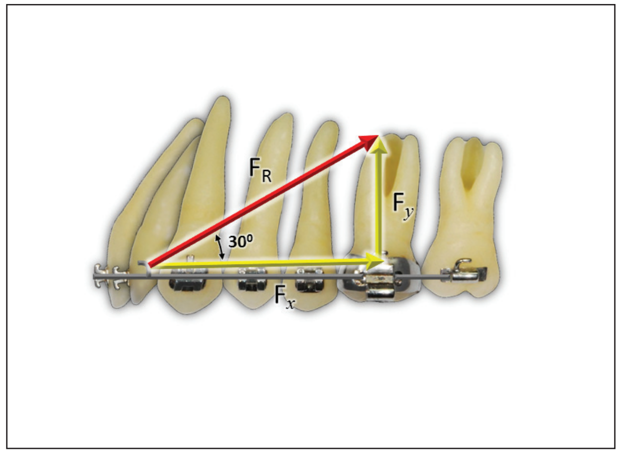


Fig 2-9 A force from an occipital headgear (F_R, *red arrow)* can be resolved graphically into two rectilinear horizontal (F_x) and vertical (F_y) components *(yellow arrows)*.

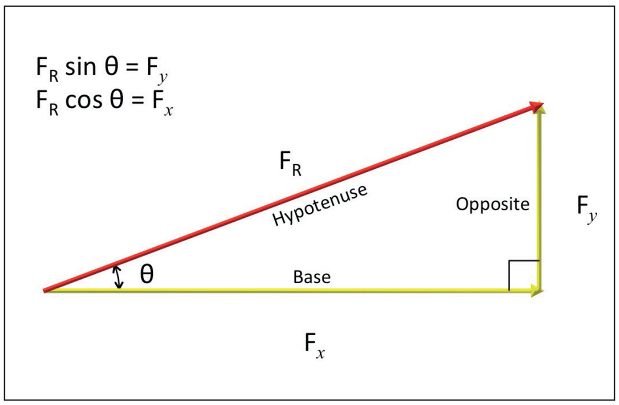


Fig 2-10 The same force from an occipital headgear (F_R) shown in Fig 2-9 is resolved into F_x and F_y components mathematically using simple trigonometric functions.

components tells us that there are both mesial and lingual forces *(yellow arrows)*. It has been argued at some orthodontic meetings that there are advantages to canine retraction achieved by either pushing from the mesial or pulling from the distal. As observed in Fig 2-8, however, there is no difference in the line of action if the force is applied at the mesial or the distal. A force acting anywhere along this line of action has the same effect. In other words, a force can be moved along its line of action without changing its effect. This principle is called the *law of transmissibility of force*. The appliance may differ with either an open or closed coil spring, but if the force is along the same line of action, the response should be the same (assuming no other variables). A locomotion engine can either push or pull a train car with the same effect.

Manipulating Forces

Components

It is convenient to resolve a force into rectilinear components (ie, two forces at 90 degrees to each other). Another clinical way to look at direction is to ask how much force is parallel to the occlusal plane and how much is vertically directed. If distances are accurately drawn to represent the forces, the solution can be obtained graphically. A force from an occipital headgear is shown in Fig 2-9. The direction is clearly shown as 30 degrees to the occlusal plane. Note that the headgear force (F_R, *red)* can be achieved by mentally walking from the hook (application point) at 30 degrees upward and backward. However, we can resolve this force into rectilinear components graphically by drawing two perpendicular lines: Force X (F_x) and Force Y (F_y), with F_x parallel and F_y perpendicular to the occlusal plane. Now let us take our imaginary walk using these lines. Starting at the hook, we walk along the occlusal plane (F_x) to the right and then walk upward at 90 degrees to the occlusal plane (F_y). This route may take longer, but we still end up at the apex of the original red arrow. Forces are vectors, so we can establish components using geometric addition. If measured, the two component force lengths *(yellow)* tell us the magnitude and sense of the vertical and horizontal rectilinear components of the original force. Although the F_y component is depicted at the arrowhead of F_x for analysis, F_y acts at the hook.

During clinical visits, many times a diagram may be good enough to evaluate the rectilinear com-

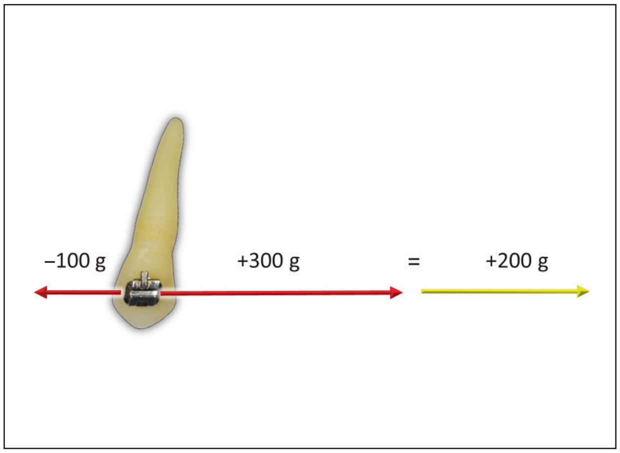


Fig 2-11 The two forces *(red arrows)* applied at the canine bracket can be added arithmetically to give a resultant *(yellow arrow)* because they act along the same line of action.

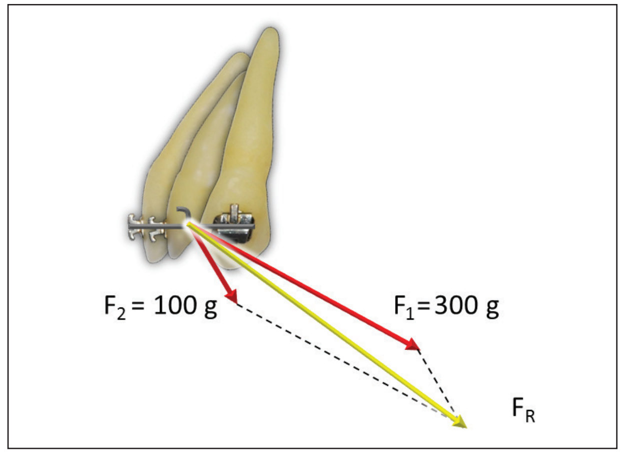


Fig 2-12 Two elastics *(red arrows)* applied at the canine hook. The resultant, F_R *(yellow arrow)*, is determined using the parallelogram method. The arrow (F_R) connects the origin at the hook with the opposite corner of the parallelogram.

ponents of a force (graphic method). However, we might prefer to use an analytical method, employing some simple trigonometry. Figure 2-10 is the same diagram as Fig 2-9, where the angle of the headgear force can be any angle (θ). F_x and F_y can be determined using the following trigonometric relationships:

$$F_y = F_R \sin\theta$$
$$F_x = F_R \cos\theta$$

Resultants

Often clinical situations require that we add a number of forces. The canine shown in Fig 2-11 has two forces acting at the bracket from two chain elastics *(red arrows)*. Because both elastics act along the same line of action, we can find the sum of forces by simple arithmetic (addition), remembering that a force vector has a sense (direction), and therefore sign (+ or –) must be considered.

$$(-100\ g) + (+300\ g) = +200\ g$$

The principle that forces along the same line of action can be simply added together is important for orthodontists. The two elastics on the canine in Fig 2-11 produce a total of +200 g *(yellow arrow)*. This sum of all the forces is called the *resultant*.

In Fig 2-12, two forces from maxillomandibular elastics (F_1 = 300 g, F_2 = 100 g) are applied to the canine hook. The magnitudes of each force are the same as those in Fig 2-11, but they lie on different lines of action. What is the magnitude of the resultant? If you said 400 g, the arithmetic total, the answer is incorrect. Forces are vectors and must be added geometrically. Forces F_1 and F_2 do not lie along the same line of action. The addition must be done graphically.

Lines parallel to F_1 and F_2 are constructed, forming a parallelogram. A diagonal line (F_R, *yellow arrow)* is drawn from the force origin (the hook) to the opposite corner of the constructed parallelogram. This line represents the vector sum of F_1 and F_2 and is the *resultant force*. The length of the diagonal line proportionally represents the force magnitude, and the angle to any plane represents the sense and direction of the resultant. Note that the length of F_R (resultant) is not the arithmetic sum of the lengths of F_1 and F_2, and its direction is different than the applied individual elastics. The clinician might be advised to place a single elastic (the resultant) for simplicity rather than two, because the action on the arch will be the same.

Perhaps a more useful and universal graphic method for force addition is the *enclosed polygon method*. Figure 2-13 shows the same component forces acting on the hook as shown in Fig 2-12. Sequential forces will be geometrically added instead of forming a parallelogram. Starting with F_1, an arrow is drawn downward and to the distal. At the arrowhead of F_1, F_2 is drawn, keeping its angle and magnitude the same as the original F_2 in Fig 2-12. Connecting the origin (the hook) with the arrowhead of the new F_2 gives the resultant. In other words, we can walk the short way *(yellow arrow resultant)* or take the long way following the arrows of the F_1 and F_2 components *(red arrows)*, ending up in the same place.

The closed polygon method is particularly useful if more than two components are to be added. Four noncollinear forces are to be added in Fig 2-14. Each force is laid out in sequence, arrowhead to tail. The resultant force (F_R, *yellow)* is a line connecting the origin hook and the final component (F_4) arrowhead.

Graphic methods for finding a resultant are very practical for the clinician. Most of the time, they are accurate enough for patient care; more important, they do not require complicated calculations. During chairside treatment, we are able to visualize the forces and come to correct conclusions in our "mind's eye" visualization of force vectors and overall geometry. Nevertheless, an actual diagram is most helpful as a starting place for manipulating forces, either by graphic or analytical methods.

Analytical method for determining a resultant

Instead of the graphic method, resultants can be calculated by using trigonometric functions and the Pythagorean theorem. Figure 2-15a shows two forces *(red arrows)* acting on a hook mesial to the canine. F_1 is a long Class II elastic, and F_2 is a short and more vertical Class II elastic.

Step 1: Resolve all forces into components using a common coordinate system.

In order to add forces, common lines of action can be obtained by resolving F_1 and F_2 into *x* and *y* components. Figure 2-15a shows the forces F_1 and F_2 resolved into rectilinear components relative to an occlusal plane coordinate system. F_x is the horizontal component of force *F*, and F_y is the vertical component of force *F*.

Using trigonometry,

$$F_x = F \cos \theta$$
$$F_y = F \sin \theta$$

Step 2: Add all x forces and y forces.

All forces on the *x*-axis are added. All forces on the *y*-axis are added (Fig 2-15b).

$$F_{x1} + F_{x2} = F_x$$
$$F_{y1} + F_{y2} = F_y$$

Step 3: Draw a new right triangle using the summed F_x and F_y values.

A new right triangle is drawn based on F_x (the sum of F_{x1} and F_{x2}) and F_y (the sum of F_{y1} and F_{y2}) (Fig 2-15c).

Step 4: Calculate the magnitude and direction of the resultant.

The magnitude of the resultant is calculated using the Pythagorean theorem.

$$F_R = \sqrt{F_{R_x}^{\ 2} + F_{R_y}^{\ 2}}$$

And the tangent function is used to calculate the direction (angle).

$$\tan \theta = \frac{F_{R_y}}{F_{R_x}}$$

Below are some actual calculations using this method. Let us suppose that F_1 = 300 g and F_2 = 100 g, with the direction specified in Fig 2-15a.

Step 1: Find the components of each force.

$$F_{x1} = F_1 \cos \theta_1 = 300 \text{ g} \times \cos 30° = 300 \text{ g} \times 0.87 = 261 \text{ g}$$
$$F_{y1} = F_1 \sin \theta_1 = 300 \text{ g} \times \sin 30° = 300 \text{ g} \times 0.5 = 150 \text{ g}$$

$$F_{x2} = F_2 \cos \theta_2 = 100 \text{ g} \times \cos 60° = 100 \text{ g} \times 0.5 = 50 \text{ g}$$
$$F_{y2} = F_2 \sin \theta_2 = 100 \text{ g} \times \sin 60° = 100 \text{ g} \times 0.87 = 87 \text{ g}$$

Step 2: Add each component.

$$F_{R_x} = F_{x1} + F_{x2} = 261 \text{ g} + 50 \text{ g} = 311 \text{ g}$$
$$F_{R_y} = F_{y1} + F_{y2} = 150 \text{ g} + 87 \text{ g} = 237 \text{ g}$$

Step 3: Now we have the x and y coordinates of a resultant, and we can draw a new right triangle.

Step 4: Find the magnitude and direction of the resultant.

$$F_R = \sqrt{F_{R_x}^{\ 2} + F_{R_y}^{\ 2}} = \sqrt{311^2 + 237^2} = 391 \text{ (g)}$$

$$\tan \theta = \frac{F_{R_y}}{F_{R_x}} = \frac{237}{311} = 0.76$$

Therefore, $\theta = 37.3°$.

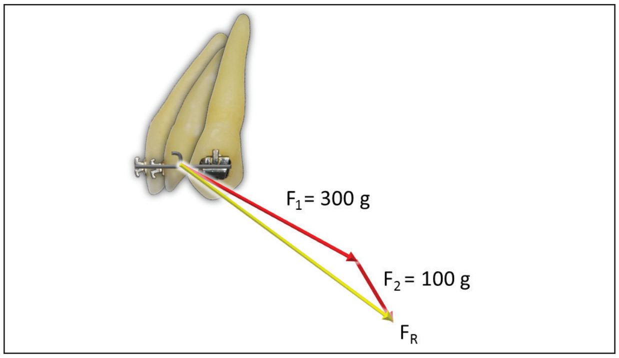


Fig 2-13 Enclosed polygon method for adding forces graphically. Starting at the hook, each force is laid out tail to arrow, maintaining the magnitude, direction, and sense *(red arrows).* Connecting the origin at the hook and the end point gives the resultant *(yellow arrow)*.

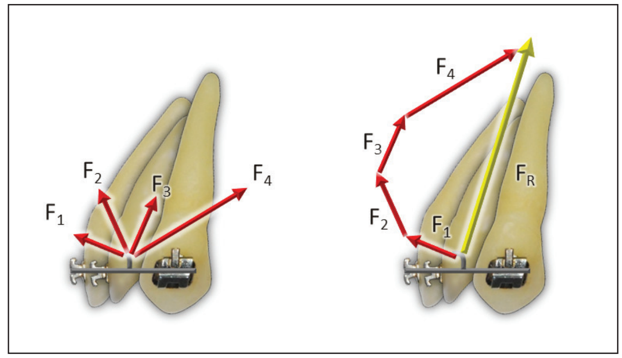


Fig 2-14 The enclosed polygon method is useful, especially when there are more than two components of force. F_R *(yellow arrow)* is the vector sum of all four components *(red arrows)*.

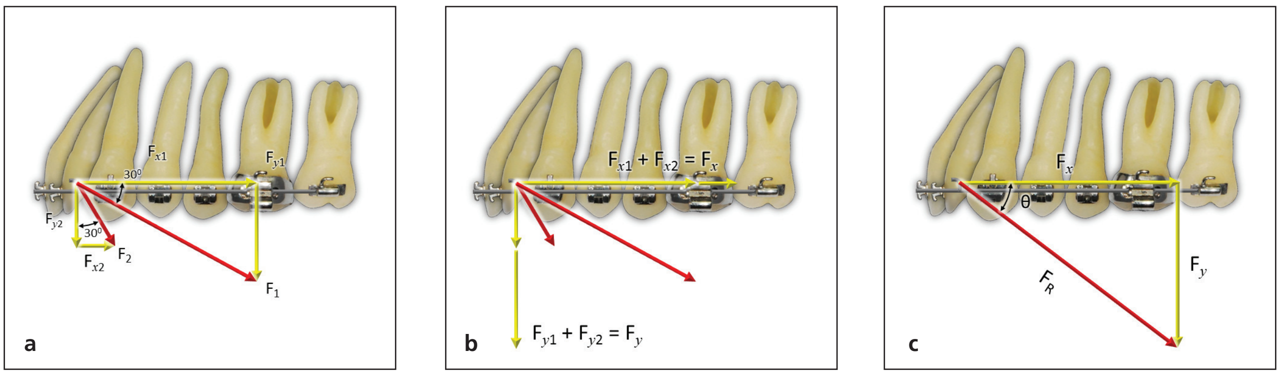


Fig 2-15 Analytical method for determining a resultant. *(a)* Resolve all forces into rectilinear components *(yellow arrows). (b)* Add all *x* and *y* forces. *(c)* Construct a new right triangle with the summed F_x and F_y *(yellow arrows)*. The hypotenuse *(red arrow)* is the resultant (F_R). The magnitude and angle are found using the Pythagorean theorem and the tangent of θ.

Clinical Applications

This chapter has discussed important concepts relating to a force or a group of forces acting on a point. A force on a point was selected in one plane because it offers a simple introduction to force manipulation. The same principles will operate with forces on a body in two or three dimensions. The major difference is the location of the point of force application, which will be considered in the next chapter. However, the clinician will be confronted with many challenges that will involve forces on a single point only, so let us now consider some of these clinical applications.

Forces resolved into their rectilinear components are always useful in planning the force system for proper treatment. For example, we may want to know how large the distal force component is in comparison to the occlusal (vertical) component using the occlusal plane as our coordinate system.

Another clinical application is the simplification of the orthodontic appliance. In Fig 2-16a, two maxillomandibular elastics are used, a Class II elastic and a vertical elastic. These elastics could be replaced with a single elastic, the resultant *(yellow arrow)* in Fig

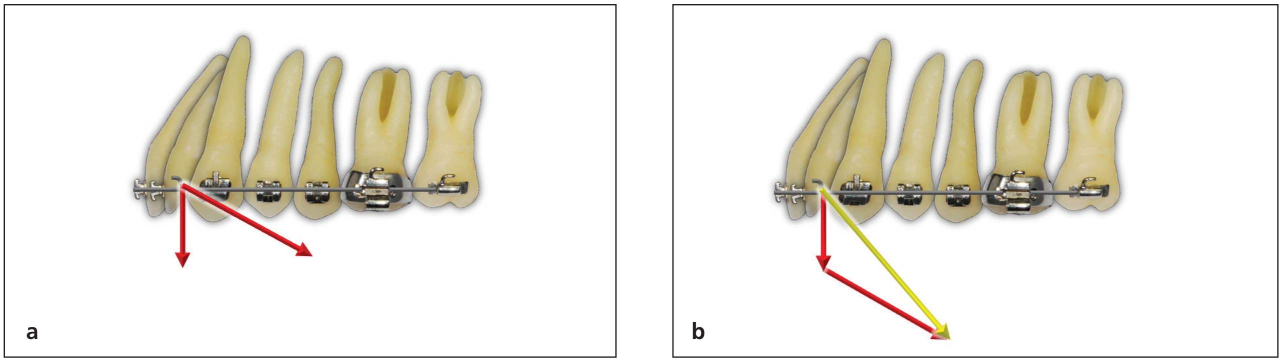


Fig 2-16 *(a)* A Class II elastic is applied. A vertical elastic is also used to close an open bite. *(b)* By using the enclosed polygon method, the two elastics can be replaced with one elastic *(yellow arrow)*, which is simpler for both the orthodontist and the patient.

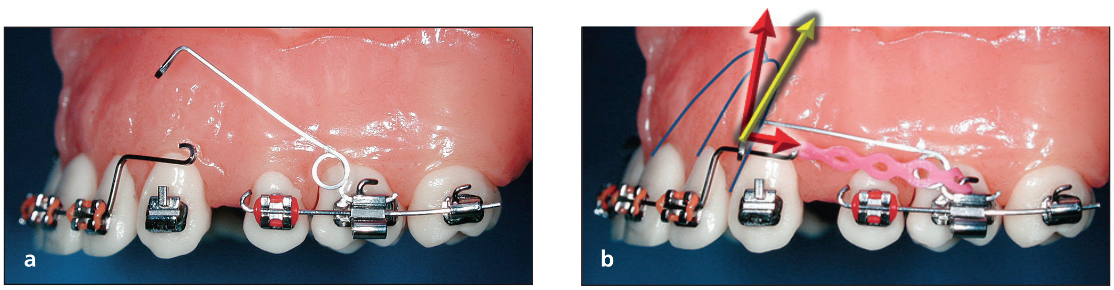


Fig 2-17 Intrusive force from a cantilever *(vertical red arrow)* and distal force from an elastic chain *(horizontal red arrow)* produce a resultant force *(yellow arrow)* acting parallel to the long axis of the incisors. *(a)* Deactivated spring. *(b)* Activated spring.

2-16b. The replacement makes it easier for the patient and is therefore more likely to ensure patient compliance. Conversely, sometimes it is better to use two or more elastics that will produce the same effect as a single elastic, because sometimes the direction of the force needs to be changed slightly. For example, the objective in Fig 2-17 is to deliver an intrusive force parallel to the long axis of the incisors. Two forces are used: *(1)* an intrusive force from an intrusive cantilever attached to the first molar auxiliary tube and *(2)* a chain elastic producing a distal force. Note that the resultant force *(yellow arrow)* is parallel to the mean of the root long axis. Moreover, multiple forces can replace a single force when a single force cannot be placed clinically because of anatomical limitations (eg, during canine retraction, three or more forces are applied at the bracket instead of one on the root).

Figure 2-18 shows an elastic chain engaged between brackets and a transpalatal arch. What would be the resultant force acting on the maxillary right second premolar and canine? Suppose the tension of the elastic is uniform; we could easily imagine a parallelogram and find the resultant graphically. The resultants *(yellow arrows)* on the premolar and canine are in the right directions to correct the malocclusion.

Suppose we want to apply lingual force on the canine. Figure 2-19a shows a single force directly acting on a canine using an auxiliary spring soldered to a passive lingual arch. What if there is no lingual arch present, and yet we need to apply a lingual force? The single lingual force can be resolved along the arch into two components (Fig 2-19b). Two simple elastics (component forces are *yellow arrows*) will produce the same effect on the canine as the auxiliary spring in Fig 2-19a. Anchorage, of course, will be different. Note that components are not always rectilinear.

Figure 2-20a seems to show the force system acting on the molar using a temporary anchorage device (TAD) and an elastic chain *(gray arrows).* But this diagram is incorrect. One might think that an intrusive force would be present because the elastic is wrapped above the entire crown. However, only a buccal force *(red arrow)* is produced from the elastic connecting the molar-bonded hook and the TAD (Fig 2-20b). Figure 2-20c demonstrates that although the chain elastic between the two hooks on the molar is stretched, part of the elastic produces no force on the molar.

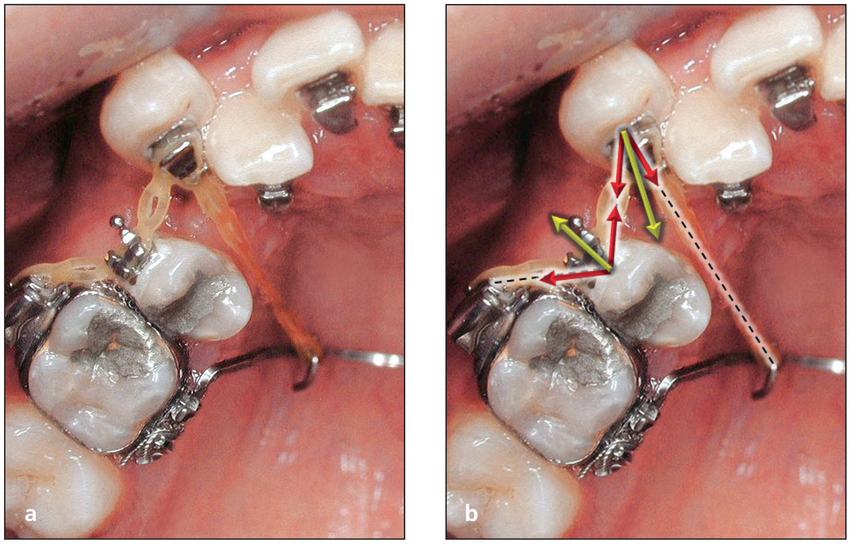


Fig 2-18 *(a and b)* One can easily imagine a parallelogram or enclosed polygon and estimate the magnitude and direction of the resultants *(yellow arrows)* graphically. The predicted direction of tooth movement is correct.

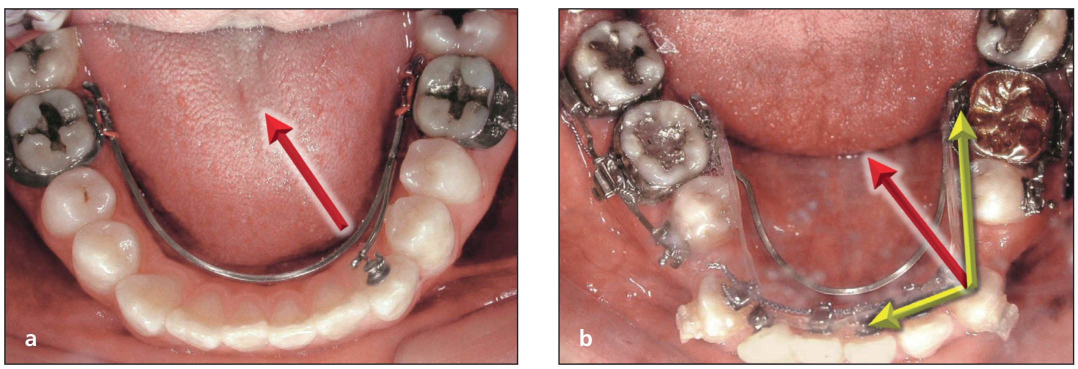


Fig 2-19 *(a)* A single force from a cantilever attached to a lingual arch gives a lingual force to the canine. *(b)* If no lingual arch is present, two components *(yellow arrows)* from an elastic chain could deliver a similar force.

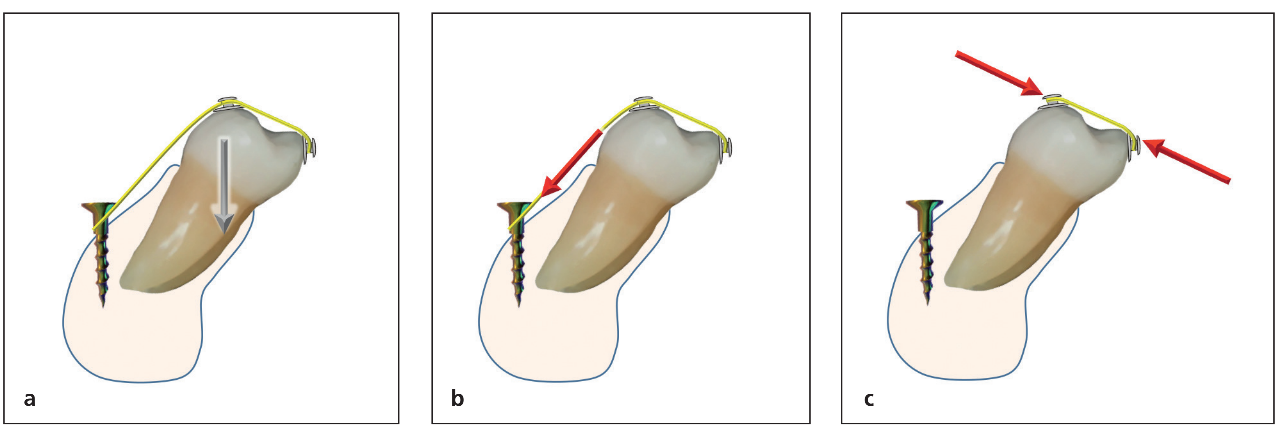


Fig 2-20 An elastic chain is attached from a buccal TAD to the molar. *(a)* The gray force does not exist. *(b)* Only the intrusive buccal force *(red arrow)* is produced. *(c)* The elastic stretched between the two buttons on the molar delivers no vertical force to the molar because both forces *(red arrows)* cancel to zero.

Summary

This chapter developed the key principles and methods for manipulating forces acting on a point. In most of orthodontic treatment, the clinician must plan for multiple point applications on three-dimensional bodies. The next chapter considers forces acting on more than one point in two and three dimensions—nonconcurrent forces. The principles and methods will be the same as for concurrent forces. Determining the point or points of force application will require consideration of an additional physical quantity—the moment.

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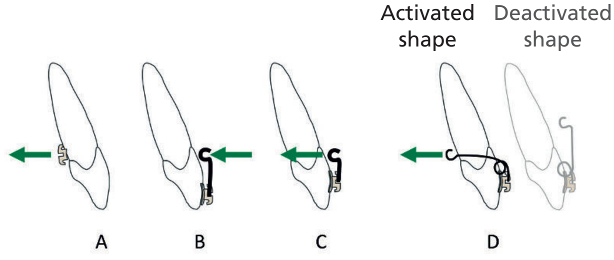
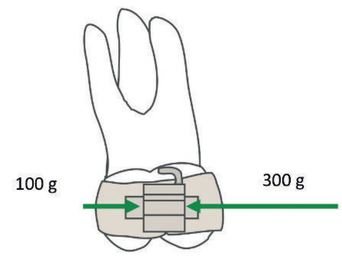
PROBLEMS

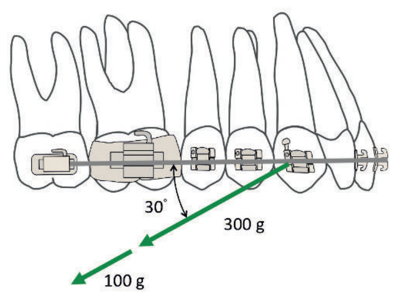
1. Compare A, B, C, and D. Is there a difference? The force is acting on a very rigid, nondeformable wire in B and C, and the force is applied on a very flexible wire in D.



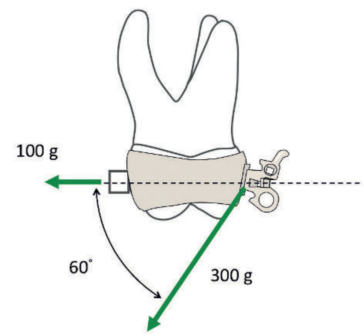
2. A 300-g force of headgear and a 100-g force of intra-arch elastic act on the first molar. Find the resultant.



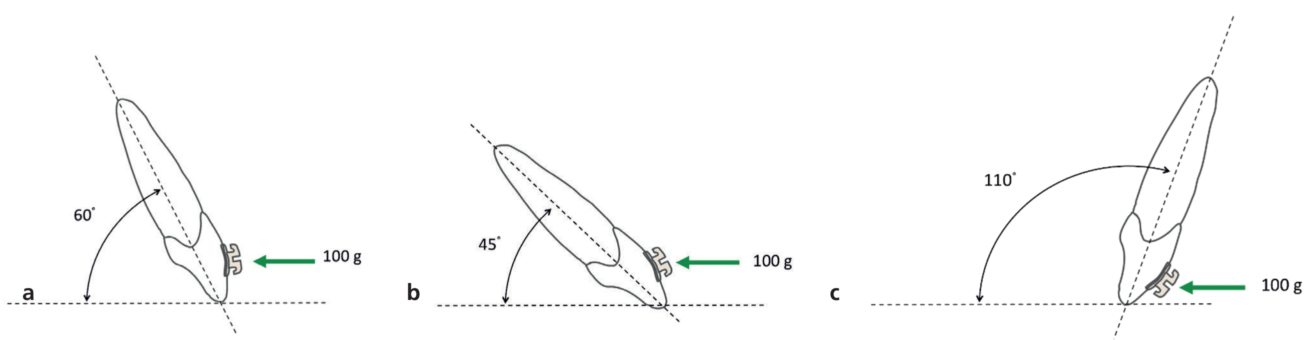
3. A headgear (300 g) and a Class II elastic (100 g) act at a hook on the archwire. Find the resultant.



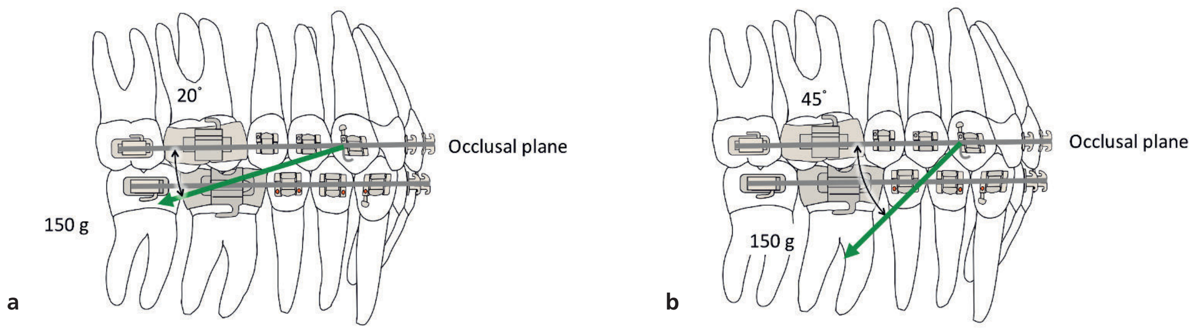
4. Find the resultant of the forces from the lingual arch and the crisscross elastic.



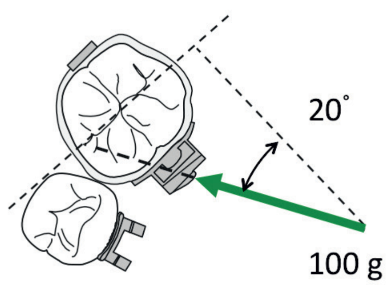
5. Resolve the 100-g force into two components parallel and perpendicular to the long axis of the tooth graphically and analytically when the angle is *(a)* 60 degrees, *(b)* 45 degrees, and *(c)* 110 degrees.



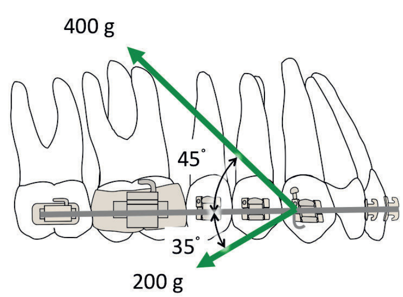
6. Resolve the 150-g force from a Class II elastic into two components parallel and perpendicular to the occlusal plane when the angle is *(a)* 20 degrees and *(b)* 45 degrees.



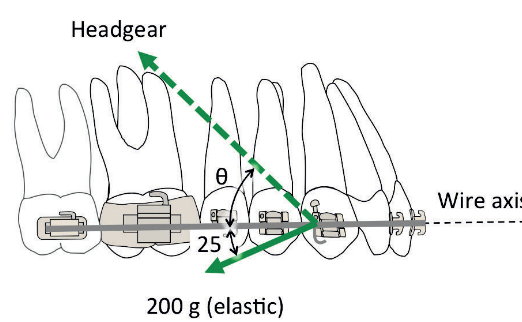
7. Resolve the 100-g crisscross elastic force attached at the buccal tube of the first molar into buccolingual and mesiodistal components.



8. Find the resultant of a 400-g headgear force and a 200-g Class II elastic force.



9. A Class II elastic and a headgear are simultaneously applied. The direction and magnitude of the elastic are kept constant. The resultant force must lie along the archwire axis. Find the angle when the headgear force is *(a)* 200 g, *(b)* 600 g, and *(c)* 1,000 g.



CHAPTER

3 Nonconcurrent Force Systems and Forces on a Free Body

"Everything should be made as simple as possible, but not simpler."

— Albert Einstein

OVERVIEW

Teeth, segments, and arches are three-dimensional, and all appliance forces may not act on a single point. Nonconcurrent forces and their manipulation are described in this chapter. The principle of vector addition or resolution is the same as with forces on a point. One new parameter must be found: the *point of force application*. The concepts of *moment* and *moment of force* are introduced in this chapter. The point of force application of a resultant can be found by summing all separate moments around an arbitrary point; the distance from that arbitrary point to the resultant gives an identical moment. The useful concept of *equivalence* is also introduced. Components and resultants are equivalent because their action is the same. Any force can be replaced with a force and a couple that is equivalent. Force and couple equivalents at the center of resistance of a tooth or an arch or at a bracket are a powerful tool for understanding and predicting tooth movement.

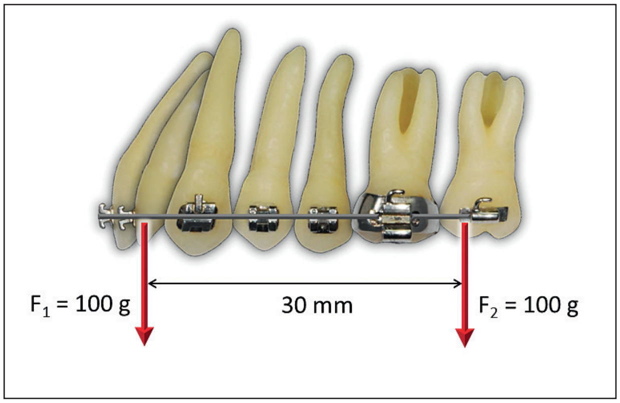


Fig 3-1 If forces are parallel, they can be added algebraically to establish a resultant.

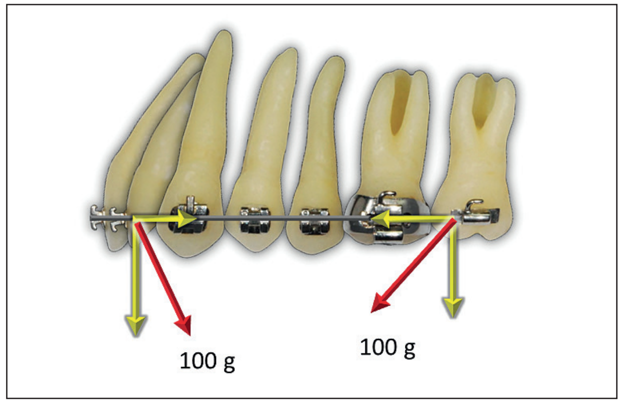


Fig 3-2 Nonparallel forces are resolved into components. Parallel components can then be added, and the magnitude and direction of the resultant can be determined.

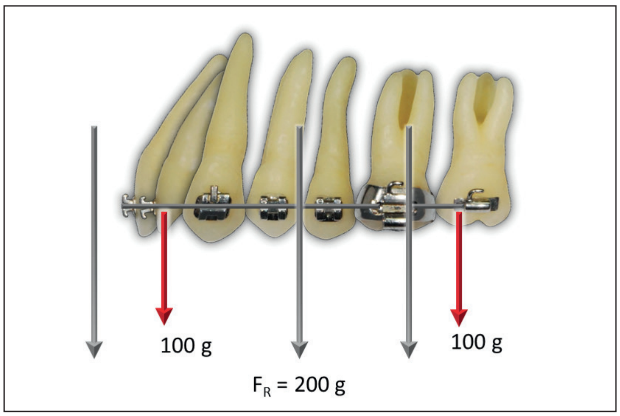


Fig 3-3 The point of force application of a resultant on a body must be determined among many *gray arrows*. The moment must be considered in order to determine the correct point of force application.

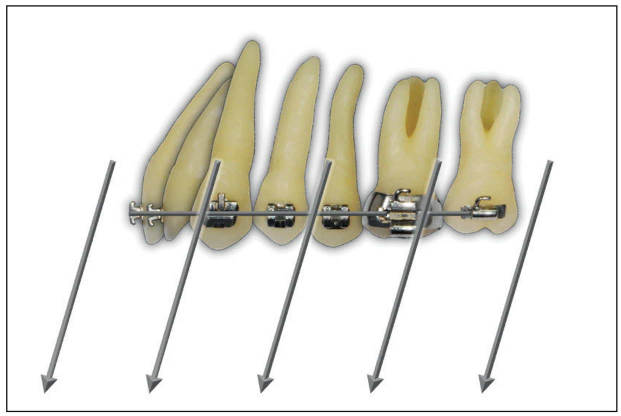


Fig 3-4 Resultants for angled elastics in Fig 3-3. The correct point of force application as in Fig 3-3 is determined by considering moments.

In chapter 2, we considered forces acting at one point and learned how to resolve a force into components and find a resultant. As mentioned in that chapter, however, most orthodontic treatment involves forces that act on anatomical structures in three dimensions. This chapter considers such three-dimensional (3D) force systems (eg, more than one force acting at different points on a full dental arch).

Determining the Magnitude and Direction of the Resultant

Figure 3-1 shows a lateral view of a maxillary arch with two vertical elastics applied at different points. Let us find a resultant—a single elastic that will do the same thing. A clarification is required before we start. For simplicity, in this text we will look at separate perpendicular projections while analyzing 3D clinical situations. This can be problematic if major asymmetries influence the location of the center of resistance (CR) of teeth (ie, if the CR varies from one plane to another).

A simpler approach allows us to study one plane at a time. Thus, in Fig 3-1, both forces are projected on the *xy* plane (also called the *z* plane). Our analysis for now is limited to just one plane. Both forces have the same direction (angle) and sense but lie on different lines of action. Because they are parallel to each other, they can be added algebraically, just like multiple forces on a point with a common line of action.

$$F_1 + F_2 = F_R$$
$$100\text{ g} + 100\text{ g} = 200\text{ g}$$
$$F_R = 200\text{ g}$$

The resultant is therefore 200 g.