SPINE BIOMECHANICS PROVIDE the foundation for the disciplines of spine medicine and spine surgery. Although modern spine biomechanics emerged during the second half of the last century, it has many ancient, medieval, and post-Renaissance roots. In Part I of this series, the ancient and medieval roots of spine biomechanics were reviewed. In Part II, the effects of post-Renaissance scientists on the development of modern spine biomechanics, as well as the studies on gait, bone, and muscles performed before the 20th century, are reviewed. Subsequently, war-related studies performed in the 20th century contributed to the formation of modern biomechanics. The first biomechanics-related organizations and scientific publications did not emerge until the second half of the 20th century. These events provided the final bricks in the foundation that facilitated the emergence of modern spine biomechanics research.

KEY WORDS: Biomechanics, History, Spine


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The most important findings and advancements regarding spine biomechanics were defined during the second half of the 20th century. The progress enjoyed during the latter half of the 20th century had its roots in the ancient age, the Renaissance, and the post-Renaissance era. This is particularly true of the latter part of the 17th century, also known as the Century of Scientific Revolution, and the 19th and 20th centuries. As noted in Part I of this series, the eras and periods have been arbitrarily chosen and are depicted as overlapping. The significant contributors are portrayed for reference purposes in Figure 1.

The most significant contributions of ancient and medieval scientists to the discipline of biomechanics included an awareness of the normal and pathological anatomy of the human spine, a heightened knowledge base regarding traumatic and non-traumatic spine deformities, and an understanding of the gait patterns of mammals (46). It is notable that the majority of these aforementioned contributions were derived from the physicians and philosophers of the ancient age. The contributions by medieval scientists were of less importance and, importantly, they often represented the reintroduction of concepts and knowledge drawn from ancient manuscripts. Translations of ancient manuscripts from Arabic to Western languages opened the door for the rest of the world to the works of the ancient civilizations. These manuscripts encouraged the study of pre-Renaissance works. This, in turn, encouraged and facilitated the efforts of the Renaissance scientists. This ultimately led to a scientific revolution during the Renaissance.

The scientists of the 17th century studied mathematics, mechanics, and occasionally biomechanics. The 18th century was the century in which gait was predominantly studied. Many studies on muscles were performed as well (9, 27). Many more studies on bone mechanics were performed in the 19th century. The scientists of the 19th century sought to relate bone trabecular architecture to its mechanical, load-bearing attributes. During this era, it was commonly thought that bony architecture responded anatomically to stress (10, 48, 50, 61, 73, 74, 80). This process resulted in the definition of Wolff’s law. These studies and subsequent studies in the 20th century contributed to the development of biomechanics as a new discipline.

THE RENAISSANCE

It is commonly thought that modern scientific thought was born in the Renaissance, a period during which religious influence diminished. Scientists began to probe and discover the wonders of the human body and other sci-
entific phenomena, rather than focusing on religious issues. It is notable that the Renaissance initially provided few significant, direct contributions to the sciences, compared with the substantial contributions to the arts made during this era.

There were essentially two relatively distinct periods of scientific development before and during the Renaissance. The first period began during the second half of the 11th century and peaked in the 13th century. The second period began in the 16th century. Whereas the first period was characterized by the translation of ancient manuscripts from Latin or Arabic languages, the second period was characterized by studies in the arts (27).

The only major scientific contributions during the beginning of the Renaissance were those of Leonardo da Vinci. The main topic of discussion during the 16th century was that of methodology. Sir Francis Bacon (1561–1626) was the first scientist to criticize scholarly traditions. Rene Descartes (1596–1650) presented and introduced very valuable mathematical data and theory. At the beginning of the 17th century, there were no important advances in physics other than the development of the magnet. After this timeframe, however, the combination of mathematics and scientific experiments led to progress in physics. The first half of the 18th century was, for the most part, non-productive. During the second half of this century, however, many studies were performed by Leonard Euler (1707–1783), Joseph Lagrange (1736–1813), and Pier Simon Laplace (1749–1827). They set the stage for modern scientific and biomechanical thought. A discussion of the major scientists and contributors during this era is in order.

Leonardo Da Vinci (1452–1519)

Leonardo da Vinci (Fig. 2) was an artist, engineer, and scientist who contributed substantially to the understanding of biomechanics. Born in 1452, da Vinci became famous as an artist, but worked and functioned predominantly as an engineer. He made major contributions to the study of mechanics in the course of pursuing his numerous engineering projects and innovations. He had an understanding of the components of force vectors, friction coefficients, and the acceleration of falling objects. da Vinci also demonstrated an understanding of Newton’s third law (27, 68).

He studied muscles because he wanted to understand how the human physical specimens that he portrayed in his paintings actually functioned. da Vinci completed more than 750 drawings on the basis of his anatomic dissections on 10 cadavers (Figs. 3–5). In these meticulous drawings, he applied his knowledge of mechanical principles to the study of human anatomy by concentrating on dynamic illustrations of joints, muscles, bones, ligaments, tendons, and cartilage.

Leonardo da Vinci was the first to accurately describe the human adult S-shape spinal posture with its curvatures, articulations, and vertebrae (notably, with the number of vertebrae portrayed accurately). He emphasized the contribution of muscles to cervical spine stability and described a method by which the spine provided stability to the human body. He wrote

“You will first make the spine of the neck with its tendons like the mast of a ship with its side-rigging (transverse or spinous processes), this being without the head. Then make the head with its tendons (muscles that can provide active force of effort) which (attached to the side rigging) gives it (the head) its movement on its fulcrum (spinal joints)” (68, p 660).

He stated “nature cannot give the power of movement to animals without mechanical means” (68, p 660). He seems be the first to understand the principles of lever systems, as applied to human motion. da Vinci analyzed the mechanics of walking, both up- and downhill, as well as rising from the seated position. However, delightful as his notebooks are to explore, they were personal works and remained unpublished for centuries. As a result, the brilliant recordings of his daydreams had little
scientific impact. Hence, his studies and observations had little effect on the scientific literature during his lifetime (51).

Andreas Vesalius (1514–1564)

The development of the study of anatomy contributed to the understanding of spine biomechanics. Andreas Vesalius produced an entire series of anatomic drawings (or plates) in “De Humani Corporis Fabrica” (Fig. 6). Many consider this work, published in 1543, to have heralded the era of modern medicine.
A review of this book reveals that, like da Vinci, he also accurately described the nuances of spine anatomy in great detail (5).

Vesalius (Fig. 7) described the intervertebral disc, he termed the spine the “dorsum” (backbone) (Fig. 8), and he observed that the spine provides the route of passage for the spinal cord, as did Galen and Avicenna. According to Vesalius, the spine was defined as the “keel of the body, composed of 34 bones (vertebrae). The neck has seven bones…by means of the first of these bones, we move the head directly forward and backward. By the use of the second vertebra (to which a prominent process resembling a canine tooth is attached) we turn the head...” (5). Although such statements regarding the biomechanics of the upper cervical spine were not new and had been recorded by Avicenna in the 11th century, Vesalius described partitions of the spinal column and foramina in detail.

It is notable that Vesalius did not address the cervical and the lumbar curves of the spine. As was the case with many scientific discoveries in the past, Andreas Vesalius built upon the rediscovery of the work of Galen. The studies of da Vinci and Vesalius are indicative of the importance of a methodological dissection by specialists in scientific studies. The notion that human anatomy was an objective discipline based on observation and well-defined scientific principles began to emanate within the scientific community. da Vinci and Vesalius, both men of modern science, were instrumental in bringing about these changes. Their focus on revealing anatomic secrets through the investigation of human cadavers was, henceforth, brought to the forefront of the scientific community.

Galileo Galilei (1564–1642)

According to the eminent scientific writer Gribbin, Galileo Galilei is the person who most deserves the title of “first scientist” (27). He not only applied what is essentially modern scientific methodology to his work, but he also confidently laid down the ground rules for others to follow. Galileo Galilei was born 21 years after the death of Copernicus. The strength of his powerful, irascible personality dominated the scientific world of his time. Thus, he became the great animating spirit of the scientific revolution that followed the Renaissance. Galileo Galilei was a student of medicine before he became famous as a physicist. Galileo’s fame was so great and his lectures in Padua were so popular that his influence on biomechanics went far beyond his personal contributions. He was particularly aware of the mechanical aspects of bone structure (51). In Discourses on Two New Sciences (1638), Galileo noted the following:

“The mass of animals increase disproportionately to their size, and their bones must consequently also disproportionately increase in girth, adapting to load-bearing rather than mere size” (51).

“The bending strength of a tubular structure, such as a bone, is increased relative to its weight by making it hollow and increasing its diameter” (51). “Marine animals can be larger than terrestrial animals because the water’s buoyancy relieves their bones of weight bearing responsibilities” (51).

He also stated that to preserve the strength of a tubular bone while increasing its length three times, it is necessary to increase its thickness nine times. His work gave impetus to the study of mechanical events in mathematical terms, which, in turn, provided a basis for the emergence of kinesiology as a science. Galileo showed that mathematics was the essential key to science, without which nature could not be properly under-
stood. This outlook inspired Descartes, a great mathematician, to pursue the discipline of physiology.

**Rene Descartes (1596–1650)**

Rene Descartes was not a major contributor in the field of biomechanics; his thoughts, however, had an indirect impact on the field. Descartes was one of the founders of mechanical philosophy. He was the mastermind behind the creation of the Cartesian coordinate system. This philosophy suggested that changes observed in the natural world should be explained only in terms of motion and rearrangements of the parts of matter. Descartes’ mathematical theory of mechanics provided the basis for the maturation of the science of mechanics in the 18th century. In 1624, Descartes published the first paper devoted to physiology, *L’homme*. This treatise emphasized the theory that movement was coordinated through the nervous system. Descartes’ application of mechanics to humans included the belief that humans were soul-containing organic machines running on auto pilot (27).

In 1675, Descartes stated in “Tractus de Homine et de Formatione Fœtus” (“A Treatise on Humans and the Formation of the Foetus”) that “all of animal physiology could be explained by mechanics.” His following statement is well-known: “the body is a machine (lever is machine) made by the hand of God!” (68, p 661).

**Giovanni Alfonso Borelli (1608–1679)**

Giovanni Alfonso Borelli (Fig. 9) was the founder of the concept of iatrophysics (i.e., medical physics). Born in Naples, Italy, on January 28, 1608, he studied mathematics in Rome and was a student of Benedetto Castelli, who was a student of Galilei. Castelli arranged for Borelli to teach a lectureship on mathematics in Messina. In a short time, he was recognized throughout Italy in the fields of mathematics, physiology, physics, and astronomy (63). He then became professor of mathematics in Pisa where he met Marcello Malpighi (Fig. 10). Both were founding members of the short lived “Accademia del Cimento.” Around this time, Borelli also studied anatomy. The association between Malpighi and Borelli resulted in many new works. Malpighi stimulated Borelli’s interest in living beings, whereas Borelli stimulated Malpighi to investigate the manner in which living systems work (51, 52).

Borelli recalled, “What progress I made in philosophizing stems from Borelli.” Borelli states this about Malpighi: “I worked hard dissecting living animals at his home and observing their parts to satisfy his keen curiosity” (50).

Borelli applied the principles of “Equilibrium of Rotation” and “Equilibrium of Translation” to spinal biomechanical analysis. One of the most important mechanical features of animal (and human) motility observed by Borelli was that muscles act via short lever arms. Therefore, a joint transmit of force that is “n” order of magnitude greater than the weight of the load applied (or lifted). Borelli essentially, and appropriately, discredited older concepts of muscle action that implied that long lever arms were required to allow weak muscles to move heavy objects.

His book, *De Motu Animalium*, or *On the Movements of Animals*, published in 1680 shortly after his death, was the first in the field of biomechanics (Fig. 11). The first part of this book contained studies of external motions of the musculoskeletal system, whereas the second part contained studies on internal motions, such as muscle physiology and blood circulation. He defined his purpose in an introductory statement as follows:

“Animals are bodies and their vital operations are either movements or actions which require movements. But bodies and movements are the subject of mathematics. Such a scientific approach is exactly geometry. Similarly, the operations of animals are carried out using instruments and mechanical means such as sales, levers, pulleys, winding-drums, nails, spirals, etc.” (7).

This book provided many calculations regarding spine biomechanics, such as Borelli’s calculation of forces on spine musculature and intervertebral discs (Fig. 12). He noted that the spine had to be “stable, much like the hull of a ship” (6), and also noted that the vertebrae were flat and wide to prevent dislocations and to provide stability.
Borelli calculated the effect of a load borne in the neck. For example, he noted, “If the spine of a stevedore is bent and supports a load of 120 pounds carried on the neck, the force exerted by nature in the intervertebral discs and in the extensor muscles of the spine is equal to 25,585 pounds. The muscular forces are equal to 413 pounds and the forces exerted by the disc are equal to 1239 pounds” (7). These calculations revealed that Borelli was aware of the load-sharing concept in spine biomechanics (Fig. 13).

Borelli knew that for adequate flexibility of any animal, the spine must be divided into multiple segments by articulations. He noted that the intervertebral discs play an important role in spine biomechanics. According to Borelli, the intervertebral disc is a viscoelastic substance and functions as a cushion preventing attrition of the bone. He also noted that fibers comprising the intervertebral disc are much stronger than those in muscle. Therefore, he reported that the majority of the spinal load is borne by the intervertebral discs, with a much smaller portion borne by the spinal musculature.

Borelli was the first to experimentally determine the position of the human center of gravity (50). He used a wooden plank and trihedral pyramidal system to precisely balance a person (Fig. 14), observing a point located between the pelvis and the buttocks. The validity of this technique was confirmed approximately 200 years later by Braune and Fisher (11) in frozen cadavers.

After Borelli, there is little sign of biomechanical study in the literature until the latter half of the 19th century. Due to his early and substantial contributions, Borelli is widely recognized as the father of biomechanics (62, 63).

Robert Hooke (1635–1703)

According to Hooke’s law, it is estimated that no solid is perfectly rigid. When several external forces act on a solid at rest...
and the resultant net force is zero, the solid remains at rest. Hooke’s law expresses that for small displacements, the size of the deformation is proportional to the deforming force. This law is of significant importance when one considers the forces applied to the spine by a spine instrumentation construct (as well as the response of the construct to these forces). For larger displacements, however, the neutral zone is exceeded and the elastic limit is reached. Exceeding the elastic limit causes the solid to acquire a permanent set; if the external forces are removed, the solid does not spring back to its undeformed configuration. The solid will ultimately fail if further forces are applied. This point is termed the point of failure (27). Apart from the definition of Hooke’s law, Hooke studied gravity and was the first scientist to use the term “cell.”

**Isaac Newton (1642–1727)**

Isaac Newton (Fig. 15) made many significant scientific contributions, but did not write specifically about biomechanics. His findings regarding calculus, laws of motion, and analytical portrayals of the hydraulic characteristics of viscous fluids, however, were critical regarding the emergence of biomechanics as a field of study. His publication of Philosophiae Naturalis Principia Mathematica in 1686 presented laws of motion that are used today to describe and define motion. These laws express the relationship between the forces and their effects (27, 64).

**Newton’s First Law of Motion (Law of Inertia)**

Every body continues in its state of rest, or of uniform motion, in a right line, unless it is compelled to change that state by forces impressed upon it.

**Newton’s Second Law of Motion (Law of Momentum)**

The change of motion is proportional to the motive force impressed and made in the direction of the right line in which that force is impressed.

**Newton’s Third Law of Motion (Law of Interaction)**

To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal and directed to the contrary parts.

Newton is also credited with the first observations regarding the parallelogram of force, based on his observation that a moving body affected by two independent forces acting simultaneously moved along a diagonal equal to the vector sum of the forces acting independently (63). Newton’s laws of motion, along with his idea of the parallelogram of force, can be readily applied to spine biomechanics.

**Leonard Euler (1707–1783)**

Leonard Euler is another important individual who studied mathematics, astronomy, physics, and biomechanics. In 1736, Euler published a systematic introduction to mechanics in Mechanica sive motus scientia analytice exposita, or Mechanics or motion explained with analytical science. He stated that the human spine carries compressive loads like a column and that such loads may lead to instability or failure. He studied mathematical models to derive these findings (27, 68).

**Thomas Young (1773–1829)**

Thomas Young studied the formation of the human voice and identified it as resulting from vibrations. He connected this process with the elasticity of materials. He improved on Hooke’s law by providing a measure, Young’s modulus. Young’s modulus defines a proportionality between force and stretch or compression for different substances. This modulus is a measure of the elastic properties of stretchable and compressible bodies. It is defined as the limit, for small strains, of...
the rate of change of stress with strain. Young’s modulus can be determined experimentally from the slope of a stress-strain curve created during tensile or compressive tests conducted on a sample of the material. Young’s modulus is extensively used in spine biomechanics today (27).

THE 19TH CENTURY

A variety of scientific studies were performed during the 19th century; however, a limited number of studies were published on muscle, nerve, and bone physiology. The majority of the publications resulted from the collaboration between engineers and physicians. The Weber brothers, Christian Wilhelm Braune, Otto Fischer, and Julius Wolff were among the scientists contributing to the field of biomechanics during this era.

The Weber Brothers

Ernst Heinrich Weber (1795–1878), Wilhelm Eduard Weber (1804–1891), and Eduard Friedrich Wilhelm Weber (1806–1871) espoused the idea that the human torso was maintained in the erect position primarily via tension of the ligaments, with little or no muscular exertion. The Webers were the first to investigate the reduction in the length of an individual muscle during contraction and devoted much study to the role of bones as mechanical levers (75). They were also the first to describe, in chronological detail, the movement of the center of gravity. The modern concept of locomotion originated with the studies of Borelli (7). Very little was accomplished in this field before the Webers’ publication of Die Mechanik Der Menschlichen Gehwerkzeuge (Mechanics of the Human Gait) in 1836 (76). Their treatise, which still stands as a classical work in the field, was based solely on observations. Nevertheless, it firmly established the mechanism of muscular action on a scientific basis.

Christian Wilhelm Braune (1831–1892) and Otto Fischer (1861–1917)

In 1891, the first three-dimensional mathematic analysis of human gait was conducted by Wilhelm Braune and his student Otto Fischer. It was published in their book Der Gang des Menschen (Human Gait) (10). Their major premise was that knowledge of the position of the center of gravity of the human torso and of the body’s component parts was fundamental to an understanding of the resistive forces that the muscles must overcome during movement. Braune and Fischer (11) performed a very careful study of mass, volume, and the center of mass of three adult male cadavers and their body segments. The cadavers, each of which had committed suicide, were close to the average build of German soldiers of that period. To avoid fluid loss, the cadavers were kept frozen throughout the study. The center of mass of each body segment was not estimated by using the use of balance plates, as in the previously described studies, but rather by driving thin rods into the tissue and hanging the body segment from three axes. The intersection of three externally fixed planes, e.g., vertically through each of the axes formed on the segment, corresponded to the center of mass. After these preliminary studies, they were able to provide a thorough analysis of gait from photographs taken simultaneously by four cameras (10).

Julius Wolff (1836–1902) and Wolff’s Law

The definition of Wolff’s law may be one of the most important events defining the field of biomechanics. Julius Wolff established this law on the basis of his own work and the studies of earlier scientists. Therefore, it is necessary to address the studies supporting his work.

In 1832, Marc Jean Bougery (1797–1849), Claude Bernard (1813–1878), and Nicolas Henri Jacob (1782–1871) raised the question of the relationship between the architecture and the mechanical function of bones and assumed that, in the neck of the human femur, there was a line of compression along which the trabeculae seemed to be particularly dense and strong (8).

In 1838, F.O. Ward, a London anatomist, compared the architecture of the femoral neck with that of a street lamp in a triangular wall-bracket in Outlines of Human Osteology. He reported that the horizontal trabeculae in the bone were responding to stress and the oblique trabeculae were responding to pressure (74). This was a unique study that addressed stresses on bone. During this era, engineers were studying and analyzing stresses associated with railways, bridges, cranes, etc. Ward applied the findings of engineers of his time to biological systems, specifically bone.

In 1867, Hermann von Meyer (1801–1869), an anatomist from Zürich and author of The Architecture of the Spongiosa, and Karl Culmann (1821–1881), an engineer from Germany, compared the stresses on the femoral neck and on a crane. They showed that the structure of the femoral neck, which supports the torso, was mathematically equivalent to a crane (48). They discovered a remarkable similarity between the trabecular architecture of the proximal femur and the patterns of stress trajectories, calculated using “Graphical Statics,” a new methodology developed by Culmann (73). It is said that Culmann, on seeing a longitudinal section through the proximal end of the femur prepared by von Meyer, exclaimed: “This is my crane!” (50). In 1881, Wilhelm Roux suggested that the formation and functional adaptation of trabecular architecture in bone is regulated locally by cells that are governed by mechanical stimuli (66). In 1883, Hugh Owen Thomas (1834–1891) mentioned, “Eccentric forms, that cannot be altered in the dead body without rupture or fracture can, during life, be altered by mechanical influence, as time and physiological action will command the part to the direction of the employed force” (70).

In 1890, a university clinic for orthopaedic surgery was opened in Berlin, Germany with Julius Wolff (Fig. 16), an orthopaedic surgeon, as its first director. Before beginning to work as director of this department, Wolff was a pupil of Langenbeck, who suggested that Wolff’s doctoral thesis should be on the experimental production of bone in animals. Apart from the aforementioned studies, he reviewed the works of Belchior, Hunter, Duhamel, and Flourens, all of whom had published on osteogenesis (48). Roentgenography was not yet available. To analyze trabecular architecture, Wolff made thin sections from bone. In 1892 he wrote his book, “Das Gesetz de
Transformation de Knochen,” or The Law of Bone Remodeling, which was the culmination of the knowledge gained from the aforementioned project. Wolff thought that bones were formed by satisfying a mathematical optimization rule. Apparently, Culmann’s findings provided a blueprint for a design of bone for Wolff who described a trabecular orientation in healthy and deformed bones. He attributed this orientation to the assumed capacity of bone to form and adapt its architecture in accordance with externally applied loads. He determined that bony deformation led to changes in internal structure and secondary adaptive microarchitectural changes. He stated that “every change in the form and function of a bone, or function alone, is followed by specific definite changes in the internal architecture and equally definite secondary changes in its external configuration, in accordance with mathematical laws” (80). From this work, Wolff concluded that trabecular morphology matches the stress trajectories. This conclusion is known as his “trajectorial hypothesis” and forms the basis of Wolff’s law. Wolff’s law has become one of most important elements of spine biomechanics.

The law formally states that “Every change in the form and function of a bone, or function alone, is followed by specific definite change in its internal architecture and equally definite secondary changes in its external configuration, in accordance with mathematical laws.” Elsewhere, the law states that “Structure is nothing else than the physical expression of function...under pathological conditions the structure and form of the parts change according to the abnormal conditions of force transmission” (80).

THE EMERGENCE OF MODERN BIOMECHANICS IN THE 20TH CENTURY

Although, there were a limited number of studies published in the field of biomechanics (21), the collaboration between engineers and physicians contributed to the understanding of biomechanical principles and the publication of high quality, meaningful works. The biomechanical studies from the first half of the 20th century focused predominantly on acquiring information regarding gymnastics education and sports activities in schools, gait and musculoskeletal analyses performed for general health problems, World War I- and II-related injuries, and analysis of craniospinal trauma from motor vehicle accidents. Wilbur Bowen, Tuth Glassow, William Skarstrom, Gladys Scoth, Louise Alley, Arthur Steindler, Katharine Welles, Marion Broer, and John Cooper were among the scientists who focused on biomechanics in the late 19th and early 20th centuries, with the aim of reorganizing gymnastics in the United States (17, 42).

World Wars I and II resulted in many casualties and many disabled veterans requiring long-term care. Many war-related injuries occurred among airplane pilots. Both patient populations presented significant opportunity for biomechanical analysis. Jules Amar (1879–1935), using force and motion measurement techniques, was one of the first researchers to provide a biomechanical evaluation of the gait and task performance of thousands of disabled veterans in France. His book, The Human Motor, was published in France in 1914 and was translated into English in 1920 (4, 17).

World War II paralleled the introduction of high performance aircraft, which led to an interest in spine biomechanical testing. At that time, ejection seats of airplanes could not be handled manually and complications were evident because of the lack of extraction of German pilots from airplanes during an emergency. A multitude of spinal column injuries resulted, leading Siegfried Ruff to perform spine biomechanics studies on this subject (67).

Similar studies were performed to test the strength of the spinal column. To achieve good spinal posture at the moment of ejection, Olof Perey tested ejection seats from Swedish J-21 fighters in 1945, and the Martin-Baker aircraft company performed tests in England in 1944 (15).

The United States Air Force initiated similar studies to design ejection seats for aircraft in 1945. Contemporary researchers at Wayne State University performed studies on the biomechanical aspects of the spinal column, while teams at Massachusetts General Hospital and Massachusetts Institute of Technology studied the properties of the intervertebral disc (15).

Contemporary clinical studies were performed as well. Friedrich Pauwels (1885–1980) (Fig. 17) and Nikolai A. Bernshtein (1896–1966) were among the scientists who systematically studied musculoskeletal biomechanics in the first half of the 20th century (50, 61).

In addition to the aforementioned studies performed in Europe, some were performed in the United States. A “myodynamics laboratory” was established within the Department of Surgery of the University of Rochester School of Medicine and Dentistry in 1926 by Russell Plato Schwartz (1894–1965). Dr. Schwartz’s intention was to devise mechanisms for the accurate recording of human locomotion to establish norms for both normal and abnormal gait. Beginning in the mid-1930s, research in the myodynamics laboratory was focused increasingly on
the development of the “functional” principles of shoe design, with a continued perfection of gait recording instruments and the development of such surgical tools as the microsurgery. The laboratory maintained its interest in the pure mechanics of human locomotion and the application of these studies to the diagnosis and management of gait abnormalities, whether caused by injury or congenital conditions. The establishment of this rudimentary biomechanics laboratory provided a vision and a direction for studies on spine biomechanics (3).

Similarly, in the biomechanics laboratory at Wayne State University in Detroit, Michigan, Professor Herbert Richard Lissner (1908–1965), an engineer, and Professor E. Stephen Gurdjian (1900-1985), a neurosurgeon, initiated studies on head injury and cranial fracture mechanisms in 1939 (King A, personal communication). Professor Lissner studied spine biomechanics in the early 1950s (20, 28, 29, 31). Together Lissner and Gurdjian attempted to determine the effects of axial compression and transverse bending on lumbar disc herniation. This represents one of the first true modern spine biomechanics experiments.

They also sought to determine the reason for thoracolumbar wedge fractures in pilots ejecting from disabled military aircraft. Lissner built a vertical accelerator in an elevator shaft at the school of medicine to duplicate this injury in cadavers (King A, personal communication).

These preliminary studies were followed by other studies in the 1950s, including those of Virgin (72), Hirsch (35, 37), Hirsch and Schajowicz (41), Hirsch and Nachemson (40), Evans (18, 19), Evans and Lissner (20), Higgins (34), Friberg and Hirsch (22), Sylven et al. (69), and Werne (77). These works led to the performance of the first studies of bending moment in the spine with the load-deflection, energy-absorption, and bending-moment studies of Evans and Lissner (20).

One of the pioneers in this era was Carl Hirsch (1913–1973), an orthopaedic surgeon from Sweden (Fig. 18) who performed biomechanical studies on the knee, hip, and spine in the 1940s (35). Hirsch’s studies captured the imagination of many scientists, and many surgeons and engineers visited his center in the 1950s and 60s (2). Victor Frankel, George Galante, Augustus White, Wilson C. Hayes, and Albert B. Scultz were among the American scientists who visited Hirsch’s laboratory during this era (Panjabi MM, personal communication).

Lysell was probably the first modern researcher to conduct a thorough in vitro study of cervical spine motion and patterns of motion. He also provided a comprehensive review of the literature in which he credits Weber (1827) with performing the first objective assessment of spinal motion. Lysell used fresh whole cadaveric cervical spine specimens (C2–T1). Using four 0.8-mm steel balls inserted into each vertebra and quantitative stereoradiography, he measured the three-dimensional relative motion between vertebrae. He studied a total of 28 specimens and found no effect of age or extent of degeneration on motion (49).

Hirsch and his contemporary researchers were, therefore, the pioneers of modern biomechanics (36). They carried out their studies in well established laboratories, and their fellows founded similar laboratories in their respective new institutions. This increased both the quantity and quality of biomechanics-related research in the 1950s and 60s (12, 36, 38, 39, 55–57, 65, 69). It also established the process of biomechanics education and the proliferation of qualified bona fide researchers and educators. This contribution of Hirsch, more than any other research endeavor, secured the future of the discipline of spine biomechanics.

Finite Element Analysis

A brief history of finite element analysis (FEA) was reported by Peter Widias (79). According to Widias, FEA was first developed in 1943 by Courant and Hilbert (14) who used the Ritz method of numerical analysis and minimization of variational calculus to obtain approximate solutions to vibration systems. In 1956, a study published by Turner et al. (71) established a broader definition of numerical analysis. The study focused on the stiffness and deflection of complex structures (79). In the late 1950s, the continuum model of the spine was first developed within the aviation industry to determine the relationship between emergency pilot ejection and the risk for spinal injury (33). This model evolved over the years.

By the early 1970s, FEA was limited to expensive mainframe computers, which were generally owned by aeronautics, automotive, defense, and nuclear industry companies. Since the rapid decline in the cost of computers and the phenomenal increase in computing power, FEA has attained incredible precision. FEA techniques have been used with increasing frequency, including use for spine biomechanics applications (25, 30, 32, 44, 59). Today, FEA is used for the biomechanical assessment of healthy and pathological spine states and for the testing of spine implants in many biomechanics laboratories.

Clinical Studies

Besides biomechanical laboratory research, many physicians applied the results of laboratory studies to the clinical arena. The term “stability” had been defined on many occasions by multiple authors (78). This led surgeons to develop scales and scoring systems, as well as to define column concepts. The two-column system for spine stability was defined in 1962 by Sir Frank Holdsworth (43) and the three-column system by Francis Denis (16). The definition of tumor-related instability required the definition of six columns (47). In this vein, Edward C. Benzal (6) described a cube system for determining stability that addressed the integrity of only the ventral column (vertebral body and intervertebral disc).

FIGURE 18. Carl Hirsch, orthopaedic surgeon and one of the pioneers of modern biomechanics.
Biomechanical Books, Journals, and Organizations

In the mid-1960s, the American Society of Mechanical Engineers published a collection of articles on spine biomechanics in a monograph edited by Y.C. Fung (23). In 1967, Byars, Contini, and Roberts edited an American Society of Mechanical Engineers monograph (13), including an introduction by Lissner with the provocative title “Biomechanics- What is it?” Many notable biomechanics books have been published since the 1960s. These books were followed by others (1, 6, 24, 26, 60).

The first biomechanics journal, Journal of Biomechanics, was established in 1967. Currently, many journals publish biomechanics-related manuscripts. In addition to the well-known neurosurgical and orthopedic journals, the following journals contain articles related to biomechanics:

- Bone
- Clinical Biomechanics
- Computer Methods and Programs in Biomechanics
- Electroencephalography and Clinical Neurophysiology
- Gait and Posture
- Injury
- Journal of Applied Biomechanics
- Journal of Back and Musculoskeletal Rehabilitation
- Journal of Biomechanical Engineering
- Journal of Biomechanics
- Journal of Electromyography and Kinesiology
- Journal of Human Movement Studies
- Journal of Sport Sciences
- Mathematical Biosciences
- Medical Engineering and Physics
- Medicine and Science in Sports and Exercise

The development of biomechanical laboratories and the focused study of biomechanics were energized by the organization of biomechanics-oriented conferences, the first of which was the First International Seminar on Biomechanics, which was organized by the Research Committee of the International Council of Sports and Physical Education in 1967 and held in Zurich. Subsequent meetings have been held biannually.

The International Society of Biomechanics was formed in 1973, the European Society of Biomechanics in 1976, the Canadian Society of Biomechanics in 1973, the American Society of Biomechanics in 1977, and the Australia New Zealand Society of Biomechanics in 1996. Other biomechanics-related organizations include the following:

- British Association of Sport and Exercise Sciences, United Kingdom
- Bulgarian Society of Biomechanics, Bulgaria
- Chinese Society of Sports Biomechanics, China
- Comisia de Biomecanica Inginerie si Informatica, Romania
- Czech Society of Biomechanics, Czech Republic
- German Society of Biomechanics, Germany
- Japanese Society of Biomechanics, Japan
- Korean Society of Sport Biomechanics, Korea
- Polish Society of Biomechanics, Poland
- Russian Society of Biomechanics, Russia
- Societ de Biom, Canique, France

In summary, the progress and maturation of biomechanical studies in the past two centuries has, in part, led to an increase in the volume and quality of publications. War-related disabilities, general health problems, and automotive industry-related injuries created a demand for a myriad of innovative and clinically relevant works. In turn, this process helped craft the complex environment that the field of spine biomechanics enjoys today. The rapid emergence of a growing number of laboratories and organizations, along with the involvement of a large and growing number of scientists, has resulted in remarkable advancements in the field.

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COMMENTS

In the second part of this two-part series, the authors continued their exhaustive review of spine mechanics. Beginning with Leonardo da Vinci, the contributions of the Renaissance period are reviewed. da Vinci not only studied the anatomy of the spine, but also conducted important and relevant research on the subject of spine mechanics. The illustrations depicting this work nicely enhance this article. It was interesting to read about Andreas Vesalius, who fathered much of what we now call modern anatomy, but it seems that his understanding of the spine was not very advanced, particularly when compared with the earlier work of Leonardo da Vinci. I found the section on Giovanni Borelli to be particularly enlightening, particularly the discussion on the interrelationship to Malphighi. Borelli’s mathematical studies on the lever arm effect of muscles were particularly brilliant; his book De Motu Animalium is justifiably considered the first book on biomechanics. The illustrations added to the article are particularly helpful in explaining his views. The authors continue with reviews of the writings by Hooke, Newton, and the Weber brothers, among others, and nicely developed the historical theme of spinal biomechanics. There is a won-
The authors extensively review the history of biomechanics in this two-part series. For the most part, the authors have succeeded with this ambitious undertaking. The understanding of biomechanics of the spine plays a vital part in the management of spinal disorders. These two articles describing the history of biomechanics provide a good foundation for the overall understanding of spinal biomechanics.

Volker K.H. Sonntag
Phoenix, Arizona

As in the first part of this series, this article describing the post-Renaissance era summarizes an interesting period of invention and scientific progress. From Leonardo da Vinci to Julius Wolff, several significant scientific thinkers of this period contributed to many areas other than medicine or biomechanics, including astronomy, physics, mathematics, and art. By studying and theorizing on these various fields, some of the historical figures described in this article serendipitously laid down the foundation of the understanding of spine biomechanics as we know it today. These scientists include Sir Isaac Newton, the father of calculus and the laws of motion, and Thomas Young and Robert Hooke, who described how these forces interact with solid materials. Although these contributions did not primarily involve the spine, without them our ability to understand the effect of our surgical constructs on spine biomechanics would be greatly limited. During the past century, progress in spine biomechanics was remarkable. The experience of two World Wars has certainly accelerated our understanding in this field. The authors are to be commended for an excellent review of this time period.

Paul Khoueir
Michael Y. Wang
Los Angeles, California

The authors have provided a comprehensive overview of the history of spinal biomechanics. They have detailed numerous vignettes which allow the reader to recognize clinical problems present today that also had to be tackled in the past centuries. Furthermore, the authors discuss the basic methods available to the healthcare providers at that time. The lack of technological advancements of the current spinal treatments obviously made successful management of these afflictions much more difficult. Nonetheless, our predecessors managed to effectively care for their patients in the great majority of cases. The authors are to be lauded for tracking down these historic references and bringing them together to tell a cohesive story.

Robert F. Heary
Newark, New Jersey

In the current age of science, knowledge, and information, there is a great risk of our routinely using every new design as an important technological contribution to patient health. In this new age, the average life span has increased, which has brought with it an increase in problems of the spine and degeneration. There are so many great discussions in spine biomechanics. Very few scientists question the necessity of these systems. The real value of spine biomechanics could be better understood if evaluated in conjunction with human physiology and anatomy. These articles orient us regarding the value of anatomy in biomechanics by guiding us from the past to the future. Without a sound knowledge of the history of anatomy, we cannot understand the present or our future.

To my knowledge, da Vinci was a great artist and performed dissections on more than 30 cadavers. However, he was influenced by the works of another preeminent anatomist, Marc Antonio della Torre, as well as by Luca Pacioli, who was renowned for his knowledge of mathematics and geometry. Just after da Vinci’s contact with Pacioli, he was noted as saying, “There can be no certainty unless one can apply one of the mathematical sciences.”

Yucel Kanpolat
Ankara, Turkey

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