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A history of spine biomechanics

Focus on 20th century progress

Introduction

The human spine serves as an important structural component of the human body. It bears the weight of the head, torso, and arms as well as externally applied loads. It moves to facilitate the varied activities of daily living. Finally, it protects the spinal cord and nerve roots such that they can carry on their vital functions [189]. Therefore, it is no surprise that throughout history, clinicians treating patients with spinal problems often turned to mechanics to assist them in developing appropriate strategies for treatment.

> » Mechanical principles of the spine have assisted physicians throughout history to develop appropriate treatment strategies

There exists ample evidence that ancient Egyptian, Indian, Chinese, Greek, and Roman physicians, most notably Hippocrates (460–377 BC) and Galen (130–200 AD), used mechanical principles and interventions for the treatment of various pathologies. These included traction for spinal deformity (◘ **Fig. 1**) and spinal manipulation for the reduction of vertebral fractures and dislocations [48, 112, 160]. Their writings include considerable commentary on these spine problems as well as disc herniation and the first anatomic descriptions of the spine [112, 160, 176]. Paul of Aegina (625–690 AD) was the first physician to advocate surgery as a means to decompress the injured spinal cord [48, 106]. More detailed descriptions of the contributions of these physicians from the ancient world and others during the Middle Ages can be found in the excellent review articles of Sanan and Rengachary [160] and Naderi et al. [112].

It was not until the Renaissance that the mechanics of the human body, or biomechanics, became a focus of study. Given the scientific nature of the discipline, this work was often performed by non-clinical scientists and engineers. The esteemed artist and engineer, Leonardo da Vinci (1452–1519), conducted detailed dissections of the human body and his drawings of the musculature surrounding the human spine demonstrate clearly their critical role in maintaining spinal stability (◘ **Fig. 2**). The scientific exploration of the spine continued with the pioneer of modern anatomy, Andreas Vesalius (1514–1564), who provided details on the spinal column anatomy from dissections of cadavers. Galileo Galilei (1564–1642) was a founder of science and also provided commentary on the strength of tubular bones [112]. The first analysis of loading of the human body was performed by Giovanni Borelli (1608–1679), leading him to be often called the "Father of Biomechanics" [145]. His equilibrium analysis of the loads on the spinal column were amazingly insightful as they highlighted the relative moment arms of the external loads and muscle forces on the different spinal levels (◘ **Fig. 3**). Further details on the contributions of Borelli can be gleaned from the thorough review articles by Provencher and Abdu [147] and by Pope [145].

The next 200 years after Borelli until the mid-19th century saw a series of important scientific developments related to mechanics that proved to be of great importance to the spine. These included the work of Isaac Newton (1642–1727) on the laws of motion, Leonard Euler (1707–1783) on the concept of mechanical stability of structures, and Robert Hooke (1635–1703) and Thomas Young (1773–1829) on the elasticity of materials. During this same time period in 1741, the field of orthopaedics was named by French physician, Nicolas Andry, and the spine was clearly central to this new entity as its name literally meant "straight-child", with scoliosis being one major pathology to be considered.

The 19th century saw several important developments that could be labelled

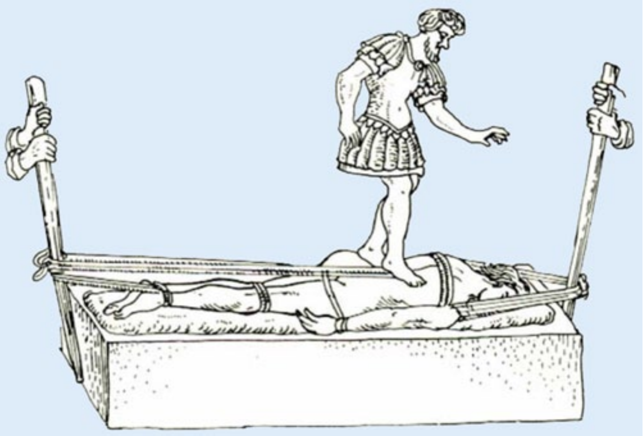

Fig. 1 ◂ A sketch of a spinal deformity patient being subjected to traction and external pressure in the time of Hippocrates. (From [162])

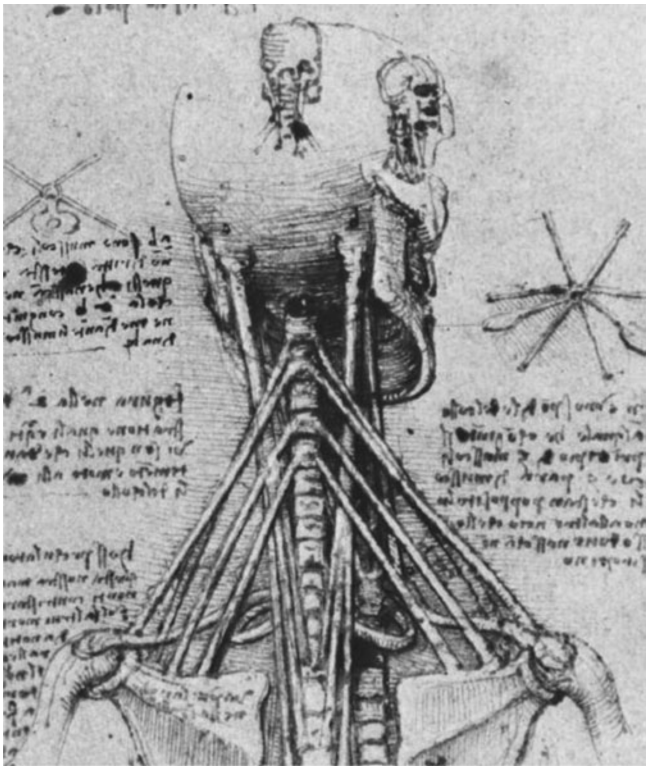

Fig. 2 ▲ Classical sketch of the neck musculature by Leonardo da Vinci. (From [76])

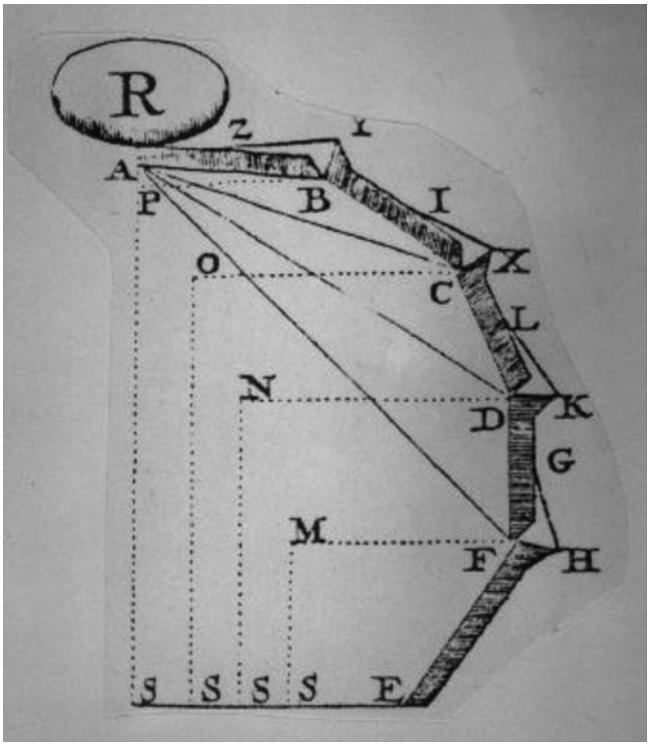

Fig. 3 ▲ Classical sketch of the spine geometry by Andreas Borelli showing the diagonal lever arms and lines of posterior muscle action. (From [24])

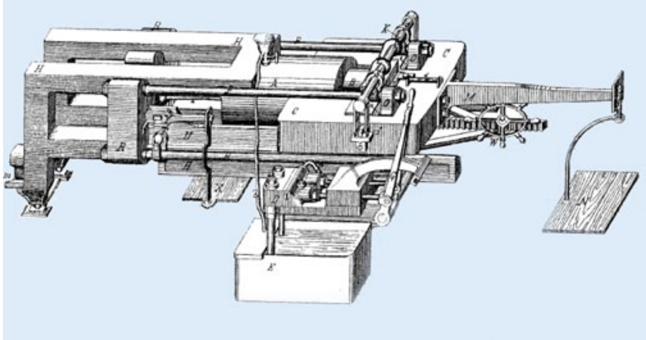

Fig. 4 ◀ Schematic diagram of the hydraulic press used by Messerer [104] to determine the compressive strength of vertebral bodies

as classical biomechanical studies. The Weber brothers, followed by Braune and Fischer conducted fundamental studies on human motion and established the important roles of the musculature on the performance of human gait [25, 183]. The earliest studies on the properties of human bones were conducted by Rauber [150] and Messerer [104], with mechanical testing machines that are most impressive for the time period (**Fig. 4**). Messerer's data on the strength of spinal vertebral bodies remain important to this day [189].

The last portion of the 19th century was the beginning of the age of mechanobiology, where the basic premise of relating mechanical stresses and strains to tissue response was discussed. Culminating in the classic publication by German orthopaedic surgeon Julius Wolff, *Das Gesetz der Transformation der Knochen* (The Law of Bone Remodelling) [193], Wolff's Law has become a common term in modern orthopaedics and biomechanics. The years preceding the 1892 publication were most interesting, in that a vigorous discussion was clearly taking place between Wolff and colleagues Karl Culmann, Engineering Professor at ETH Zurich, and Wilhelm Roux, Biology Professor in Innsbruck and Halle [20]. It seems that each of these individuals can lay claim to certain concepts behind Wolff's Law. This may be the first clear example of the interdisciplinary collaboration that is so important to a field such as spine biomechanics.

» Mechanobiology, which relates mechanical stresses and strains to tissue response, began in the late 19th century

Clearly, the field of spine biomechanics has a rich history, beginning with these ancient physicians, Renaissance, and post-Renaissance scholars. Contemporary biomechanics related to the spine experienced enormous progress throughout the 20th century towards our current state of understanding in 2015. The purpose of this article is to provide a historical overview of spine biomechanics with a focus on the developments in the 20th century. I will briefly summarize our current knowledge in key areas of spine biomechanics, with a goal to highlight the classical works that enabled us to achieve our current understanding. In doing so, I hope to acknowledge the seminal contributions of the pioneers in the field. The material is organized in five main areas—spine loading, spinal posture and stability, spinal kinematics, spinal injury, and surgical strategies.

Spine loading

The loads that occur along the length of the spine has been a topic of interest since the very early days of spinal investigation, as it seems clear that clinical conditions such as spinal trauma, disc herniation, and spinal deformity are caused by excessive forces and moments.

> Important information on compressive loading in the thoracolumbar spine available for a range of daily activities

Indirect methods of estimating spinal loads were used by determining the strength of various components in the spine, such as the spinal vertebrae and discs. This included the pioneering work of Rauber [150], Messerer [104], and others. This approach produced important baseline data, but did not provide good estimates of spinal loads due to the high variability in the component strengths.

Direct measurement of the loading in the spine began in earnest in the 1950s with the seminal investigations of Hirsch and Nachemson, who pioneered the measurement of pressures inside the lumbar intervertebral disc. Their work began with in vitro studies in human cadaveric discs to understand the relationship between disc pressure and the applied force [70, 109]. These initial studies were followed by the classical in vivo measurements in people [110, 111] that provided the first estimates of spinal loads in the lumbar spine across a range of postures. Subsequent studies were conducted in humans in seated postures by Andersson et al. [7, 8]. These classical studies were replicated in the late 1990s by Wilke and Sato with modern transducer technology and these investigators essentially verified the earlier findings, with some subtle differences [161, 191]. Since then, intradiscal pressures were measured in the thoracic spine [144] while there remains only one report for the cervical spine [67]. Overall, these studies have provided us with a good understanding of the compressive loading in the thoracolumbar spine for a range of daily activities (■ **Fig. 5**).

Insight into other loads such as shear forces have come from in vivo measurements of spinal loading using novel, telemetrized implants. In a series of exceptionally important studies, Rohlmann et al. [154–157] monitored the forces and moments in anterior and posterior spinal implants in many patients across a range of activities. These measures are vitally important data for implant designers. However, the loads measured in these studies do not represent the total load across an intervertebral level and thus other approaches are needed.

Mathematical models have been utilized to predict the loads in the spine, using the concept of mechanical equilibrium (i.e., force balance). The early models provided good estimates of both compression and shear loads in the lumbar spine [32, 165, 166]. However, Panjabi noted in 1971 [126] that the lack of physical property data for the spinal components limited the general applicability of the models. Considerable effort has been devoted to filling this gap of spinal properties over the past several decades and some of this progress is reported in the Spine Kinematics section of this article.

> Finite element models allow estimation of stresses and strains within spinal tissues

A powerful engineering approach to modelling the spine, termed the finite element (FE) method, was first applied to the spine by Schultz et al. [18] and Hakim and King [63], and then further developed and popularized by Shirazi-Adl et al. [168] and Goel et al. [58], amongst others. These models provide a unique means to estimate three-dimensional stresses and strains within spinal tissues. FE models have become very sophisticated over the past 30 years and this subject has been reviewed recently [163]. Current mathematical models include those that use the FE method, but there are also rigid body dynamic models, and both of these types of models can use EMG-assisted, optimization, and other approaches [12, 34, 35, 64, 77, 81, 94, 99, 169]. A constant challenge with these models is the need for exper-

Abstract · Zusammenfassung

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A history of spine biomechanics. Focus on 20th century progress

Abstract

The application of mechanical principles to problems of the spine dates to antiquity. Significant developments related to spinal anatomy and biomechanical behaviour made by Renaissance and post-Renaissance scholars through the end of the 19th century laid a strong foundation for the developments since that time. The objective of this article is to provide a historical overview of spine biomechanics with a focus on the developments in the 20th century. The topics of spine loading, spinal posture and stability, spinal kinematics, spinal injury, and surgical strategies were reviewed.

Keywords

Posture · Stability · Kinematics · Functional spinal unit · Surgery

Historisches zur Biomechanik der Wirbelsäule. Fortschritte des 20. Jahrhunderts im Fokus

Zusammenfassung

Die Anwendung mechanischer Prinzipien im Rahmen der Behandlung von Problemen an der Wirbelsäule geht bis in die Antike zurück. Wesentliche Entwicklungen bezogen auf die Wirbelsäulenanatomie und das biomechanische Verhalten durch Gelehrte der Renaissance und Postrenaissance gegen Ende des 19. Jahrhunderts bildeten eine solide Grundlage für die Fortschritte seit dieser Zeit. Ziel dieses Beitrags ist es, einen historischen Überblick über die Biomechanik der Wirbelsäule zu geben, fokussiert wurde dabei auf die Entwicklungen im 20. Jahrhundert. Die Themen Wirbelsäulenbelastung, Wirbelsäulenhaltung und -stabilität, Wirbelsäulenkinematik, Rückenmarksverletzung und chirurgische Strategien wurden überprüft.

Schlüsselwörter

Körperhaltung · Stabilität · Kinematik · Funktionelle Einheit der Wirbelsäule · Chirurgie

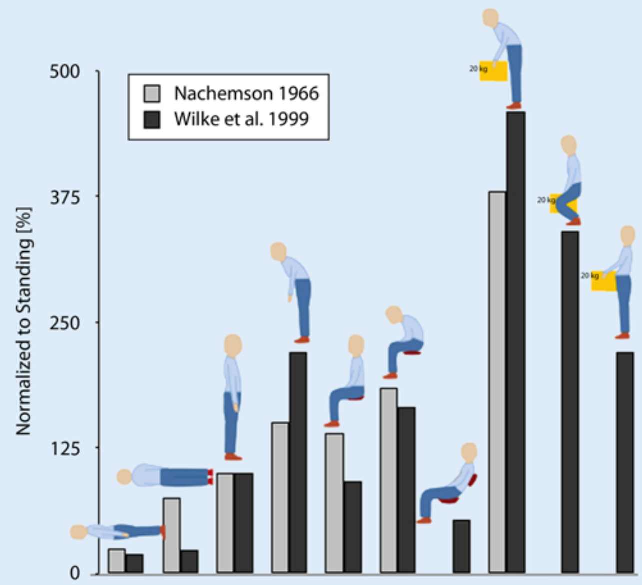

Fig. 5 ◀ Plot of the normalized lumbar spine compressive forces across a range of activities of daily living from the research by Nachemson [110] and Wilke et al. [191]. (adapted from [191]; courtesy of Wolters Kluwer Health, Inc.)

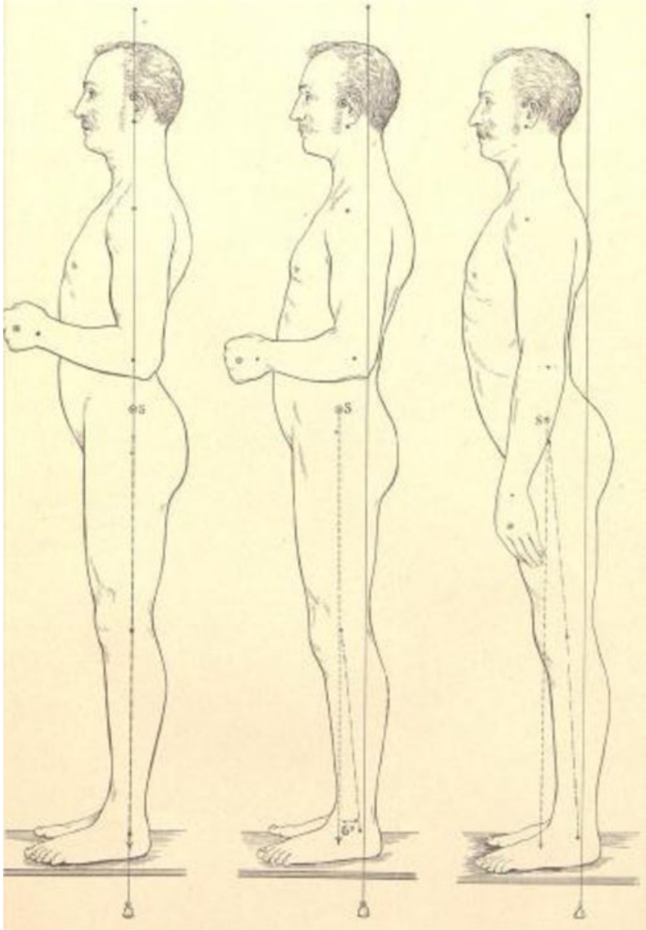

Fig. 6 ◀ Sketches of three subjects with different sagittal plane postures, due partially to varied pelvic geometries. (From [52], courtesy of Elsevier)

imental validation, but they have proven insightful in the past and they have great potential for future clinical application.

A final important aspect of spinal loading is the distribution of the load across the different components of the intervertebral joint. A common "rule-of-thumb" is that 80 % of the applied compressive load passes through the anterior column (i.e., intervertebral disc) with 20 % passing through the neural arch. These percentages were determined in cadaveric tests, first by Adams and Hutton [2] and shortly thereafter by others [88, 194]. Of note is that the 80 % of compression passing through the anterior column is highly dependent upon spinal posture.

Spinal posture and stability

The overall geometry of the pelvis and spine has been of long-standing interest as evidenced by the name given to the field of orthopaedics (i.e., straight-child). The ability of the body to maintain an erect posture is tied directly to maintaining stability; thus, these two topics are included together in this section.

There is a strong impression today that the geometrical relationships between the hip joints, the pelvis, and the spine are fundamentally important for the proper functioning of the spine. The modern concept of "sagittal balance", introduced by Duval-Beaupère in 1992, has its roots in clinical observations at the beginning of that century. In his classic work, *Handbuch der Anatomie und Mechanik der Gelenke*, Fick [52] noted the varying external postures of individual people (■ **Fig. 6**) and he linked this with the different shapes of the spine and pelvis. A series of anatomists in the ensuing 70 years contributed to our understanding of overall spinal shape, including the works of Appleton [11], Asmussen and Klausen [14], and Bonne [23]. Currently, the parameters of pelvic incidence, sacral slope, and sagittal balance provide a means to describe the position of the pelvis as it relates to the hip joints and to the sacrum [41, 75, 85, 158] and they have been shown to correlate with clinical symptoms [54, 83].

Stability of the spine is an oft-used, but ill-defined term. In the context of this article, stability means "mechanical stability", not "clinical stability". Mechanical stability is a precise engineering concept, defined as whether a structure returns to its original state after a perturbation. The early research on this topic for the spine was by Lucas and Bresler [90], who demonstrated that the thoracolumbar spine was mechanically unstable without the activation of the paraspinal muscles. Important biomechanical studies

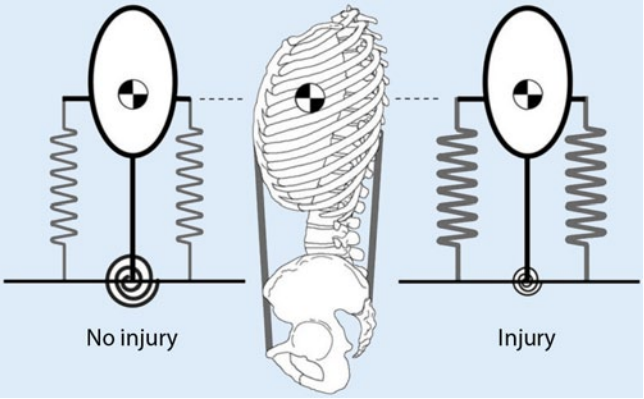

Fig. 7 ◂ Schematic diagram of the muscle co-activation necessary to maintain mechanical stability of the spine: *left* modest level with normal intervertebral joint, and *right* increased level with an injured intervertebral joint. (From [152], courtesy of Elsevier)

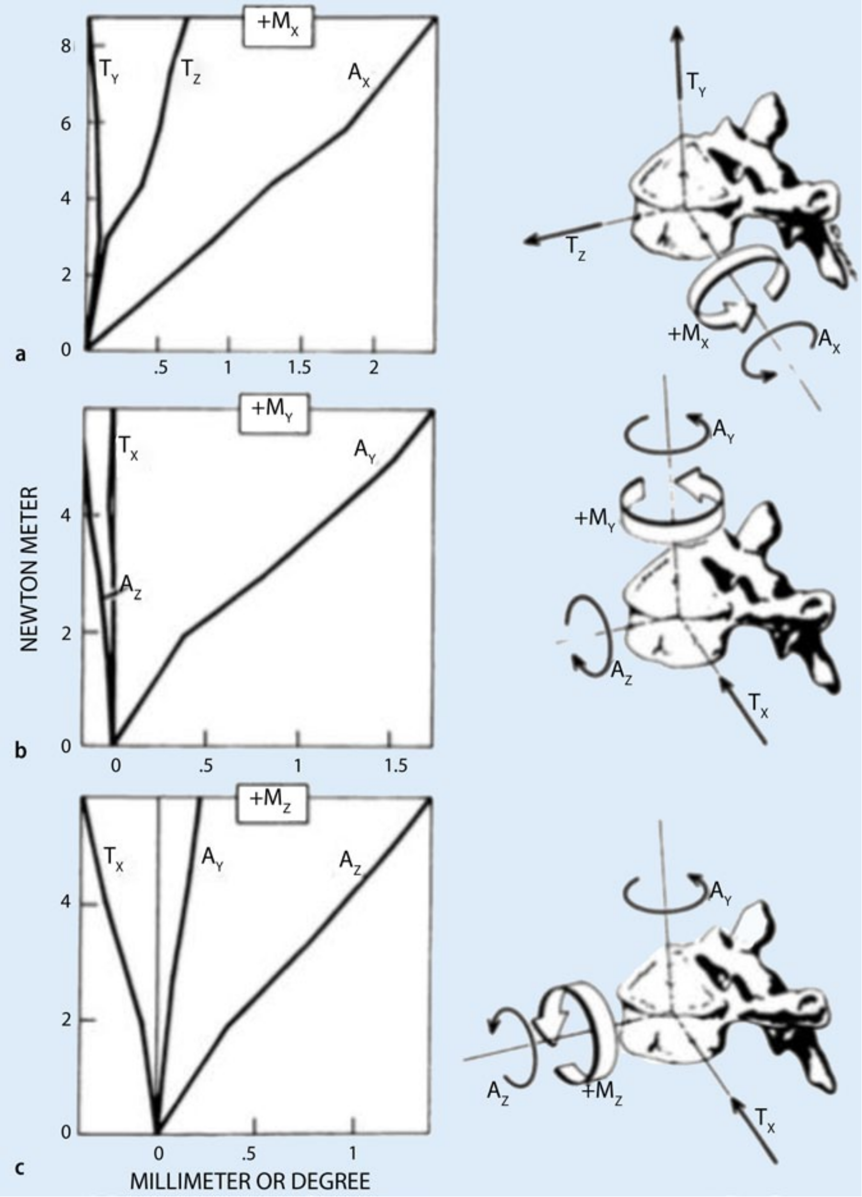

Fig. 8 ▴ Three-dimensional load displacement curves for thoracic functional spinal units under flexion–extension (**a**), axial torsion (**b**), and lateral bending (**c**) moments. (From [128], courtesy of The Journal of Bone and Joint Surgery, Inc.)

supporting this early finding were conducted by Bergmark [21], Crisco [37, 39], Shirazi-Adl and Parniapour [167], Cholewicki and McGill [33], and Kiefer et al. [78]. The clinical application of this work has been addressed by Hodges and Richardson [71] and Radebold et al. [148], amongst others. McGill [98, 100] has emphasized the importance of core muscle fitness for spinal rehabilitation.

» Core muscle fitness important for spinal stability and rehabilitation

The mathematical models referred to in the previous section use an equilibrium approach (i.e., force balance) to solve for the loads in the spine and the muscle forces. This approach will not predict muscle co-activation, which we know occurs in people and is needed for mechanical stability of the spine. The absence of a "stability criterion" in the models is one reason for this improper response, and this deficiency has been overcome in more recent models [46, 169].

The concept of mechanical stability was central to the Spine Stabilizing Hypothesis of Panjabi [123, 124]. This hypothesis states that the stability of the spine is maintained by the paraspinal musculature under the continuous monitoring of a neuromuscular control system. The effects of tissue injury and dysfunction on the performance of this Stabilizing System were described in these papers, along with Professor Panjabi's thoughts on how such a theory applies to low back pain [125]. More recent commentary on this topic make for insightful reading as they suggest tangible, clinically relevant effects such as increased muscle co-activation in the presence of injury to the intervertebral joint, (◘ **Fig. 7**; [151, 152]).

Spinal kinematics

The mobility of the spine is fundamental to its proper functioning. Some early studies in the 19th century documented vertebral movement, measured from pins inserted into the spinous processes of cadaveric specimens [183]. This methodology was employed by several subsequent investi-

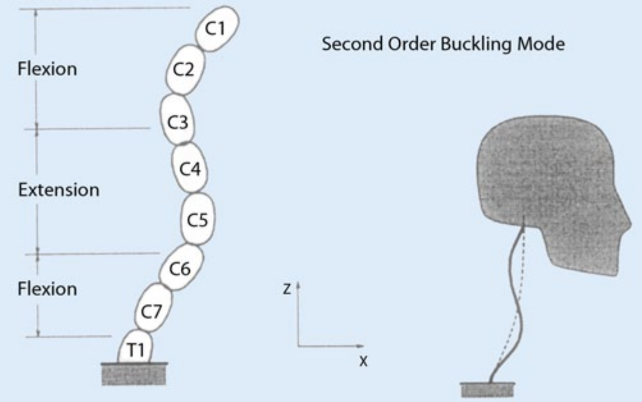

Fig. 9 ▲ A schematic diagram depicting one possible buckling mode of the cervical spine during a head-first impact from Nightingale et al. [117]. This concept shows that the local pattern of injury at an intervertebral level is not necessarily the same as the direction of the head motion. (Courtesy of The Journal of Bone and Joint Surgery, Inc.)

gators throughout the next 100 years, including Volkmann [181], Meyer [105], and Lovett [89]. The use of pins to measure vertebral movement was used throughout the 20th century, but with the advent of X-ray technology at the end of the 19th century, there was now a possibility to look inside the body. The feasibility of this approach was demonstrated by Virchow [178], who obtained flexion and extension views of the cervical vertebrae in one living subject, thereby heralding the technique of *functional radiography* for the investigation of spinal kinematics.

Functional radiography provided insight into movement characteristics of the spine, including flexion–extension and rotation

Functional radiography in living subjects has shed considerable light on the movement characteristics of all regions of the spine, most notably the cervical and lumbar regions. The basic movement characteristics of the upper cervical spine were shown by Werne [186] to consist of flexion–extension toggling at both C0–C1 and C1–C2 with large axial rotation almost exclusively at C1–C2. We have learned that flexion–extension motions of the middle cervical spine (i.e., C4–C6) are largest of the levels in the neck, while axial rotation and lateral bending motions at all levels in this region are rather small (i.e., less than 5°) [42, 44, 142]. In the lumbar region, functional radiographic studies have shown that the lower lumbar spine (i.e., L4–S1) moves more in flexion–extension than the upper lumbar levels [43, 45, 91]. Axial rotation motion at all lumbar levels is small (i.e., 3° or less) while lateral bending motions are similar in magnitude to the sagittal rotations. In the lumbar spine, these two-dimensional studies were backed up by pioneering three-dimensional studies by Pearcy et al. [140, 141]. It is exciting that the past 10–15 years has seen the publication of more data on in vivo spinal kinematics, which is a trend that must continue [9, 10, 73, 74].

Our understanding of spinal kinematics has been formed also by extensive studies in human cadaveric tissue. These experiments have the advantage of being able to precisely monitor vertebral kinematics under well-controlled applied loads, thereby enabling one to quantify the structural properties of the intervertebral joint, or so-called functional spinal unit (FSU). Obviously, these cadaveric studies have the main limitation that the musculature is no longer able to actively apply loading and thus they are reliant on simulated forces and moment. Furthermore, the tissues in these studies are no longer living, but this has been shown to not be a significant issue in characterizing the mechanical properties of the spine [170].

While many investigators studied the motion characteristics of cadaveric spines and shed considerable light on their behaviour, including classic work of Fick [52], it was the group under the supervision of Professor Carl Hirsch in Gothenburg Sweden that performed some of the earliest precise biomechanical studies on the motion patterns of human cadaveric spine segments. Classic studies that were written as doctoral theses by Lysell in the cervical spine [93] and White in the thoracic spine [187] were foundational in their respective regions of the spine. More detailed three-dimensional characterizations of the motion characteristics of the upper cervical [59, 134], cervical [107, 133, 137, 185] and thoracic [128, 130, 188] regions were conducted in the following decades. These studies quantified the natural coupling that occurs between rotations of axial rotation and lateral bending in all spinal regions, as shown in ■ **Fig. 8** for the thoracic spine. While considerable early testing of the lumbar cadaveric spine was conducted in compression [3070, 179], shear [87], and torsion [51], the detailed three-dimensional motion characteristics of the lumbar FSU were described in the late 1970s and early 1980s [22, 86, 136, 146, 173].

The 3D characterization of flexion–extension, axial torsion and lateral bending quantified natural couplings in the spine

Subsequent studies on the mechanical behaviour of the FSU have demonstrated some of its important features. Its nonlinear load-displacement response has been described, leading to the description of the neutral zone parameter [131], which has been shown to be particularly sensitive to spinal injury [120, 123]. The important role of the spinal musculature in applying a physiological compressive preload on the spine was first studied by Panjabi et al. [129, 135] and subsequently shown to substantially stiffen the FSU in all directions of loading [172, 190, 192], due partially to artifact loads [38]. This research led to the development of the follower load concept for in vitro testing [138, 139].

Many other classic studies on the biomechanical properties of individual tis-

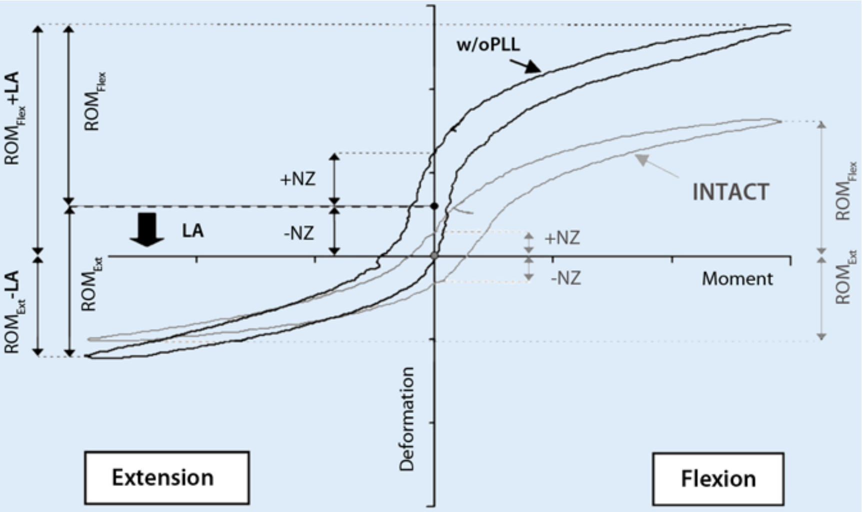

Fig. 10 ▲ Typical rotation–moment curves for the normal lumbar FSU in flexion–extension, depicting nonlinear behaviour and the effect of posterior ligament transection. (From [69], courtesy of Elsevier)

sues within the FSU have shed light on its overall behaviour. Important, early examples include the work of Galante [53] on the annulus fibrosis and of Tkaczuk [175] on the longitudinal ligaments of the lumbar spine. A complete chronology of such biomechanics testing is outside the scope of this review.

Spinal injury

An important function of the human spine is to maintain its structural integrity and thereby protect the spinal cord and nerve roots. Excessive loads can be applied to the spine during high-speed situations such as a motor vehicle accident or during certain vulnerable daily activities such as lifting a heavy object. If the applied load results in stresses that exceed the strength of any component of the spine, injury will occur. This section provides an overview of some classical studies on spinal injury, including those for the FSU, vertebrae, and intervertebral disc.

The earliest scientific studies on spinal injury were those by Haughton [68], Rauber [150] and Messerer [104]. The latter two authors studied the compressive strengths of vertebral bodies from various regions of the spine. They showed a clear strengthening of the vertebral body as one progressed caudally from the cervical to the lumbosacral spine. Later investigators documented this size effect, but also noted the significant effect of bone mineral density on the strength of the vertebral body [15, 17, 28, 65, 108]. The study by Haughton described the biomechanical principles surrounding judicial hanging, including calculations on the required parameters to fracture the human neck.

» Spinal injury biomechanics in the late 1940s and 1950s focussed on improving automotive and aircraft safety

Little research on spinal injury biomechanics occurred until the late 1940s and 1950s, when the post-war era brought intense interest into the safety of airplane ejection and also automobiles. A landmark study of the lumbar FSU under high-rate compressive loading was reported by Perey in 1957. He documented that the vertebral end-plate was the first component of the FSU to fail under high-rate, axial compressive loads, particularly in younger, non-degenerated specimens, due to high central loading from the nucleus pulposus. His data suggested that in degenerated discs, the loading was more peripheral through the annulus fibrosus and the end-plate fractures were less likely to occur. The susceptibility of the end-plate to injury in compression was also observed by Roaf [153] and these findings were consistent with the observations of central protrusions into the vertebral bodies in pathological specimens by Schmorl and Junghanns [164]. An important cadaveric study by McNally and Adams [102] supported these observations as they precisely described the loading distribution across the healthy and degenerated intervertebral disc.

In the same timeframe as Perey was conducting his experiments, others were also focussed on spinal injury [49, 50, 61, 66, 159], with much of focus on producing disc herniation. It became quite clear that this it was a rare occurrence under pure compression. The first study to reliably produce lumbar disc herniation was from Adams and Hutton [4], who needed to superimpose flexion and lateral bending moments on the applied compressive force in order to produce herniations in about 50 % of their specimens. Since that time, they also produced disc herniations under cyclic loading [3] and others have reproduced their findings [31, 60, 177, 182].

The motivation for better automotive and aircraft safety led to subsequent research on neck injury, much of it conducted at Wayne State University and reported through the Stapp Car Crash conferences. These studies led to volunteer experiments with the goal of determining the lower limits of human tolerance to neck injury [103]. Human cadaveric tests enhanced our understanding of cervical spine injury mechanisms [5, 16, 72, 79, 97, 119]. An important series of experiments by Nightingale et al. at Duke University identified the importance of boundary conditions during head-first impacts in affecting the types of injuries produced [117]. This group also showed clearly that the motion of the head during an impact does not relate to the pattern of cervical spine injury at the intervertebral level, due to local buckling (◘ **Fig. 9**). This research has developed to the point that a neck injury tolerance criterion, termed Nij, exists for the design of automobiles and other devices where a risk for neck injury exists [47].

A range of other spinal injuries have been produced in human cadaveric tissue but it is outside the scope of this review to document the entire list. Suffice to say that huge progress has been made in our understanding of how the spine is injured and the loads that cause these inju-

Table 1 Summary of the biomechanical studies that were included in the list of "Top 100 classic papers in lumbar spine surgery" by Steinberger et al. [171]. These manuscripts are listed under "Topics" that are used in this historical review. The number of citations are from the ISI Web of Science and are those listed in the Steinberger article

Topic	Authors	Reference	# Citations
Spinal loading	Wilke HJ, Neef P, Caimi M, Hoogland T, Claes LE	New in vivo measurements of pressures in the intervertebral disc in daily life (1999) Spine (Phila Pa 1976) 24(8):755–762	450
	Marras WS, Lavender SA, Leurgans SE, Rajulu SL, Allread WG, Fathallah FA, Ferguson SA	The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury (1993) Spine (Phila Pa 1976) 18(5):617–628	358
	Adams MA, McNally DS, Dolan P	"Stress" distributions inside intervertebral discs: the effects of age and degeneration (1996) J Bone Joint Surg Br78:965–972	256
	Schultz A, Andersson G, Ortengren R, Nordin M, Björk R	Loads on the lumbar spine. Validation of a biomechanical analysis by measurement of intradiscal pressures and myoelectric signals (1982) J Bone Joint Surg 64:713–720	226
	Shirazi-Adl SA, Shrivastava SC and Ahmed AM	Stress analysis of the lumbar disc-body unit in compression: a three-dimensional nonlinear finite element study (1984) Spine 9(2):120	208
	Schultz AB, Andersson GB	Analysis of loads on the lumbar spine (1981) Spine (Phila Pa 1976) 6(1):76–82	193
	Sato K, Kikuchi S, Yonezawa T	In vivo intradiscal pressure measurement in healthy individuals and in patients with ongoing back problems (1999) Spine (Phila Pa 1976) 24(23):2468–2474	177
Spinal posture and stability	Hodges PW, Richardson CA	Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis 1996) Spine (Phila Pa 1976) 21(22):2640–2650	574
	Cholewicki J, McGill SM	Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain (1996) Clin Biomech (Bristol, Avon) 11(1):1–15	424
	Cholewicki J, Panjabi MM, Khachatryn A	Stabilizing function of trunk flexor–extensor muscles around a neutral spine posture (1997) Spine 22:2207–2212	260
	Bergmark A	Stability of the lumbar spine. A study in mechanical engineering (1989) Acta Orthop Scand Suppl230:1–54	230
	Wilke HJ, Wolf S, Claes LE, Arand M, Wiesend A	Stability increase of the lumbar spine with different muscle groups A biomechanical in vitro study (1995) Spine (Phila Pa 1976) 20(2):192–198	221
	Radebold A, Cholewicki J, Polzhofer GK, Greene HS	Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain (2001) Spine (Phila Pa 1976) 26(7):724–730	197
Spinal kinematics	Panjabi MM, Oxland TR, Yamamoto I, Crisco JJ	Mechanical behavior of the human lumbar and lumbosacral spine as shown by three-dimensional load-displacement curves (1994) J Bone Joint Surg Am 76(3):413–424	217
	Yamamoto I, Panjabi MM, Crisco T, Oxland T	Three-dimensional movements of the whole lumbar spine and lumbosacral joint (1989) Spine (Phila Pa 1976)14:1256–1260	190
	Abumi K, Panjabi MM, Kramer KM, Duranceau J, Oxland T, Crisco JJ	Biomechanical evaluation of lumbar spinal stability after graded facetectomies (1990) Spine (Phila Pa 1976) 15(11):1142–1147	183
Surgical strategies	Belkoff SM, Mathis JM, Jasper LE, Deramond H	The biomechanics of vertebroplasty. The effect of cement volume on mechanical behavior (2001) *Spine (Phila Pa 1976)* 26:1537–1541	326
	Lee CK, Langrana NA	Lumbosacral spinal fusion. A biomechanical study (1984) Spine (Phila Pa 1976) 9(6):574–581	236
	Weinhoffer SL, Guyer RD, Herbert M, Griffith SL	Intradiscal pressure measurements above an instrumented fusion. A cadaveric study (1995) Spine (Phila Pa 1976) 20:526–531	176
Other	Panjabi MM, Goel V, Oxland T, Takata K, Duranceau J, Krag M, Price M	Human lumbar vertebrae. Quantitative three-dimensional anatomy (1992) Spine (Phila Pa 1976) 17:299–306	198

ries. These data are particularly important for the design of preventative devices. In fact, a 1995 review by King et al. [80] noted that 60 human lives have been saved through improved device design for each human cadaver tested. This is a most impressive statistic to support research in injury biomechanics.

Surgical strategies

The effects of surgical intervention on the biomechanical functioning of the spine has been a topic of investigation since the 1980s. Both surgical decompression procedures and spine stabilization procedures have been addressed in a wide range of experiments.

The effects of various decompressive procedures on spinal function have been evaluated, including disc annulotomy and nucleotomy [26, 27, 56, 57, 132], facetectomy of various degrees [1, 118, 195], and ligament resection [127, 130, 146, 173]. These studies typically monitor increases in motion, or conversely decrease in stiffness, with greater degrees of decompression (**Fig. 10**). As one would expect, the more material that is removed, the greater are the motion increases. However, it is the magnitude of the differences that is clinically important; thus, interpretation is required to apply the findings.

The effects of spinal instrumentation on biomechanical functioning of the spine have been studied often, beginning in the 1980s and increasing exponentially into the 21st century. These studies assess the index level of the surgery and/or the levels adjacent to the intervention. The biomechanics of motion-preserving devices will not be addressed herein.

The earliest studies on devices for spinal fusion followed the guidelines outlined by Panjabi [122], which include assessments for strength, fatigue, and stiffness. For the latter assessment at the index level, the goal for the device was substantial motion reduction such that the bony fusion would heal. An important animal study by Nagel et al. [114] showed that decreasing vertebral translations was important in this regard. Therefore, the studies on pedicle screw instrumentation [13, 55, 62, 82], anterior plate-screw devices [6, 40, 196], and interbody cages [29, 92, 116, 149, 174] were all focussed on measuring relative vertebral movements and assessing motion reduction compared to the intact spine. It is outside the scope of this review to summarize all of these studies.

> » Higher density bone results in more rigid bone-implant interfaces and thus stiffer and stronger constructs

A consistent biomechanical finding with the testing of spinal instrumentation is that performance of these devices is dependent upon the condition of the spinal tissues. For example, higher density bone will result in more rigid bone-implant interfaces and thus stiffer and stronger constructs [19, 36, 96, 101, 121]. Since it has been shown that soft tissue properties tend to be aligned with bone density [115, 175], this enhanced biomechanical performance is due to both hard and soft tissue.

Biomechanical changes adjacent to a spinal fusion has been studied often in in vitro human cadaveric models, beginning with the classic investigation by Lee and Langrana [84]. While generating much interest in the field via studies with similar methodology [184], these studies are fraught with a fundamental problem that we do not know how to properly simulate the postoperative condition adequately in the laboratory. A basic assumption of most such experiments is that postoperative lumbar spine motion is the same as what existed before the fusion. This creates obvious changes at the adjacent levels, as outlined in a recent review by Volkheimer et al. [180]. An exciting development in the field is the in vivo measurement of adjacent segment kinematics [10], and such studies will surely clarify a most controversial topic.

Overview

This review aimed to summarize the historical developments in spine biomechanics, particularly in the 20th century. There was been enormous progress over the past several decades, and this may be best illustrated by a recent review article that profiled the top 100 articles in lumbar spine surgery [171]. The selected articles, which were based on Web of Science citations, included 20 % that were biomechanical studies, which is a strong percentage from one subdiscipline. These most-cited articles are listed in **Table 1** and are distributed almost equally across the topics of this review. Some of these studies could be considered to be the “modern classics” of spine biomechanics. The methodology of the Steinberger review precluded some of the earlier true classic studies from being included (e.g., 7, 93, 110, 127, to name a few), so this needs to be acknowledged.

An appreciation for the history of spine biomechanics is important for engineers and scientists working on future research studies as well as for clinicians, both surgical and nonsurgical, who care for people with spinal problems. Hopefully, this review provides an appropriate context for both groups of people using the knowledge in the field of spine biomechanics.

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Compliance with ethical guidelines

Conflict of interest. T.R. Oxland states that there are no conflicts of interest.

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