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The progression of human posture concept and advances in postural assessment techniques

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Summary

This narrative review delves into the historical and evolutionary aspects of human bipedal upright posture, tracing its development from anthropological perspectives to modern postural analysis methods. It examines the multifaceted factors influencing the evolution of upright posture in human ancestors, challenging the notion of a singular cause. The review highlights various environmental and social hypotheses, such as the need for gathering food, self-defense, or tool use, which may have contributed to this significant evolutionary shift. The concept of posture has been interpreted differently across historical periods, reflecting the prevailing cultural and scientific understanding. From Aristotle's view of upright posture as a divine gift to Johann Gottfried Herder's perspective of it as a distinguishing human characteristic from animals, and to the more contemporary views of Henry and Florence Kendall, the evolution of the concept mirrors the changing paradigms in human thought. The development of methods for evaluating posture is also a key focus. The review traces the journey from the introduction of the plumb line in the 1850s, a simple yet effective tool for assessing spinal asymmetries, to the advent of the Adams test and the scoliometer, which revolutionized scoliosis

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diagnosis. Today, advanced techniques like rasterstereography and AI-based methods offer sophisticated, non-invasive means for detailed posture analysis, minimizing errors and maximizing efficiency. The review emphasizes the ongoing importance of posture in the context of overall health, underscoring the adage of a healthy mind in a healthy body. It illustrates how the study of posture, from its evolutionary roots to modern analytical tools, remains a vital aspect of understanding human health and well-being.

Keywords: *Posture, Evolution, Spine, Plumb line, Rasterstereography, Machine learning, Artificial intelligence, Healthcare.*

Riassunto

L'evoluzione del concetto di postura umana e progressi nelle tecniche di valutazione posturale

Questo lavoro approfondisce gli aspetti storici ed evolutivi della postura eretta bipede umana, tracciandone lo sviluppo da prospettive antropologiche ai moderni metodi di analisi posturale. Esamina i molteplici fattori che influenzano l'evoluzione della postura eretta negli antenati umani, sfidando la nozione di una causa singolare. La revisione evidenzia varie ipotesi ambientali e sociali, come la necessità di raccogliere cibo, l'autodifesa o l'uso di strumenti, che potrebbero aver contribuito a questo significativo cambiamento evolutivo. Il concetto di postura è stato interpretato in modo diverso nei periodi storici, riflettendo la comprensione culturale e scientifica prevalente. Dalla visione di Aristotele della postura eretta come dono divino alla prospettiva di Johann Gottfried Herder che la considera una caratteristica umana che distingue gli animali, fino alle visioni più contemporanee di Henry e Florence Kendall, l'evoluzione del concetto rispecchia i paradigmi mutevoli nel pensiero umano. Un altro obiettivo chiave è lo sviluppo di metodi per la valutazione della postura. La revisione traccia il viaggio dall'introduzione del filo a piombo nel 1850, uno strumento semplice ma efficace per valutare le asimmetrie spinali, all'avvento del test di Adams e dello scoliometro, che hanno rivoluzionato la diagnosi della scoliosi. Oggi, tecniche avanzate come la rasterstereografia e i metodi basati sull'intelligenza artificiale offrono mezzi sofisticati e non invasivi per un'analisi dettagliata della postura, riducendo al minimo gli errori e massimizzando l'efficienza. La revisione sottolinea l'importanza continua della postura nel contesto della salute generale, sottolineando il detto di una mente sana in un corpo sano. Illustra come lo studio della postura, dalle sue radici evolutive ai moderni strumenti analitici, rimanga un aspetto vitale per comprendere la salute e il benessere umano.

Parole chiave: *Postura, Evoluzione, Colonna vertebrale, Filo a piombo, Rasterstereografia, Apprendimento automatico, Intelligenza artificiale, Sanità.*

1 Introduction

Posture has always been considered a topic closely related to studying human body development and its internal and external processes tied to the environment. It represents the "calling card" of each of us, it gives general information to those who observe us. It is so much argued as it continues to be an expression of good health, or not, psychological and musculoskeletal. A widely used description is that good posture is a state of musculoskeletal balance that protects important body structures from trauma or deformity [1]. From a purely anatomical point of view, posture can be understood as an organ with a specific task, protecting important structures and supporting the body throughout life; meanwhile, from a psychological point of view, posture is the expression of a person's internal experience. The posture bent forward in standing, and sitting is one of the main physical aspects of patients with depressive syndrome major. Classically, one who is slumped is identified as a sad person, while a person who remains with an erect trunk manifests a more confident state [2]. In addition, it is a shared belief in some studies that adopting an upright posture rather than a slumped posture leads to fewer negative and more positive thoughts. Regardless of the different research fields, relegating postural response to a specific internal interaction is undoubtedly reductive. Posture should be considered a mixed entity that conveys psychological and musculoskeletal interactions together, not compartmentalized. This consideration stems from what determined the transition from a quadrupedal to a bipedal posture. For a long time, research has been more concerned with understanding the clinical implications of posture and walking in the context of surgery while providing little information concerning how posture evolved [3]. Understanding this provides a unique perspective that would be limited if only current anatomy were considered. This issue emerges along the historical development of posture analysis techniques, which have seen significant advancements over time. Initially, posture assessment was predominantly qualitative, largely based on visual observations by healthcare professionals. As the understanding of posture's importance in both health and psychology deepened, there arose a clear need for more accurate and objective methods. This evolution saw the introduction of various technologies for precise posture analysis, from early photographic techniques to modern motion capture systems and AI-enhanced tools. Therefore, this narrative review aims to traverse the path of posture study, encompassing physiological aspects, historical conceptions, and the development of diverse tools for its analysis.

2 Physiological and neurological aspects of the posture

Maintaining proper posture requires the musculoskeletal system to generate mechanical forces that counteract the effects of gravity and external loads [4]. This involves sustained muscle contractions over long periods of time, which can lead to fatigue, soreness, and injury. The muscle fibers involved in posture maintenance are predominantly slow-twitch fibers, which possess a high oxidative capacity due to their high content of myoglobin and mitochondria. The development of slow-twitch muscle fibers, which are highly resistant to fatigue, involves the increased expression of proteins such as myosin heavy chain isoform I, which is characteristic of slow-twitch fibers [5]. The increased expression of these proteins is thought to be driven by changes in gene expression in response to the demands of posture maintenance and locomotion [6]. This allows them to generate energy through oxidative metabolism, thereby producing sustained contractions without the accumulation of metabolic byproducts that lead to muscle fatigue [7].

Also the bones have been subjected to changes during the evolution. Maintaining proper posture requires a strong and stable skeletal system, which is achieved through the continuous process of bone remodeling. This process involves the coordinated activity of bone-forming osteoblasts and bone-resorbing osteoclasts, which are regulated by a complex network of signaling molecules and transcription factors [8]. The expression of these molecules is thought to be influenced by the mechanical forces generated by posture maintenance and locomotion, leading to changes in bone remodeling and adaptation [9; 10]. Finally, also the tendons play a crucial role in posture maintenance, as they are highly elastic and can store and release mechanical energy during postural adjustments [11]. This reduces the amount of work required by the muscles to maintain posture, leading to increased efficiency and decreased fatigue.

The neurophysiological aspects of posture involve the integration of multiple brain regions, neurotransmitters, and the peripheral nervous system. The motor cortex, located in the frontal lobe of the brain, is responsible for the initiation and execution of voluntary movements [12]. The primary motor cortex is organized in a somatotopic map, with specific regions dedicated to the control of specific body parts, including those involved in posture maintenance. The premotor cortex, located anterior to the motor cortex, is involved in the planning and preparation of movements. It receives input from multiple sensory and motor areas of the brain, allowing it to integrate information from different sources to generate motor commands necessary for posture control. The cerebellum is another key area of the brain involved in posture control. It receives input from sensory receptors in the joints, muscles, and vestibular system, allowing it to generate motor commands that adjust posture in response to changes in the environment [13]. The cerebellum is particularly important for maintaining balance during standing and walking, and damage to this area of the brain can lead to significant deficits in postural control [14].

Neurotransmitters play an important role in the neurophysiological response to posture. The release of acetylcholine, dopamine, and norepinephrine can modulate the activity of neurons involved in postural control, leading to changes in muscle tone and posture [15; 16]. For example, the release of acetylcholine can increase the activity of motor neurons, leading to increased muscle tone and posture adjustments. Conversely, the release of dopamine and norepinephrine can decrease the activity of motor neurons, leading to decreased muscle tone and posture adjustments.

3 The evolution of the posture

To date, understanding the evolutionary changes in primate anatomy, especially in spine morphology, has been crucial for comprehending the development of bipedal locomotion, postural changes, and their implications for human evolution [17]. Researchers have extensively studied vertebral column adaptations in primates to uncover these evolutionary patterns [18]. In an insightful analysis of hominoid spine characteristics, Lovejoy C.O. [19] highlighted key evolutionary aspects of the human spine and pelvis by recalling a publication of the mid 1990s which distinguished between "long back" and "short back" primates [20], characterizing the latter group by adaptations that facilitate lower limb locomotion. These adaptations include changes in the shape of the scapulae and thorax, as well as a reduction in the number of lumbar vertebrae, culminating in the locking of the last two vertebrae between the iliac crests. Thompson et al. [21] in 2017 found from hominins and ape fossils that the hypothesis of a long-backed scenario is not supported, conversely to the short-back one. Moreover, the reconstruction of the last common ancestor between humans and chimpanzees possessed a vertebral structure with 13 thoracic vertebrae and only 4 lumbar vertebrae [21]. This condition would appear to have caused a reduction in lower back mobility, fostering habitual upright posture. This change resulted in walking with flexed hips and knees, less visible in humans but still present in chimpanzees and bipedal gorillas [22; 23]. This postural stance would have been due essentially to the need to drop the body's center of gravity within the support polygon [19] (Fig. 1). However, walking with flexed hips and knees increases fatigue, reducing the musculoskeletal system's ability to protect the joints from trauma during long walks. This condition, therefore, would appear to have been one of the first adjustments in favor of bipedal posture. The modern lumbar spine is very mobile compared to our ancestors because several anatomical changes have occurred such as widening the ilium and sacrum, thus eliminating the conflict between the iliac crests and the last lumbar vertebrae [19].

The transition from quadrupedalism to bipedalism involves crucial trade-offs in limb posture and weight support. While nonhuman primates maintain hind limb flexion to reduce forelimb loading, extended-limb bipedalism in humans offers reduced energy costs, enhanced endurance, and the ability to forage over longer distances [24]. This shift likely facilitated hominin success by enabling both increased limb extension and the preservation of arboreal adaptations. The hamstrings control deceleration during walking and the gluteal muscles stabilize the lower limb and trunk, controlling its forward rotation; the quadriceps muscle, on the other hand, performs its propulsion function in walking. Bipedal posture, therefore, represents the fulcrum around which structural changes have occurred and determined the evolution of the species. However, the question that research is still trying to answer is why our ancestors needed to change from quadrupedal to bipedal posture. In the dissertation of the German anatomist Carsten Niemitz, "The evolution of the upright posture and gait-a review and a new synthesis", he analyzed what research has posited as basic assumptions

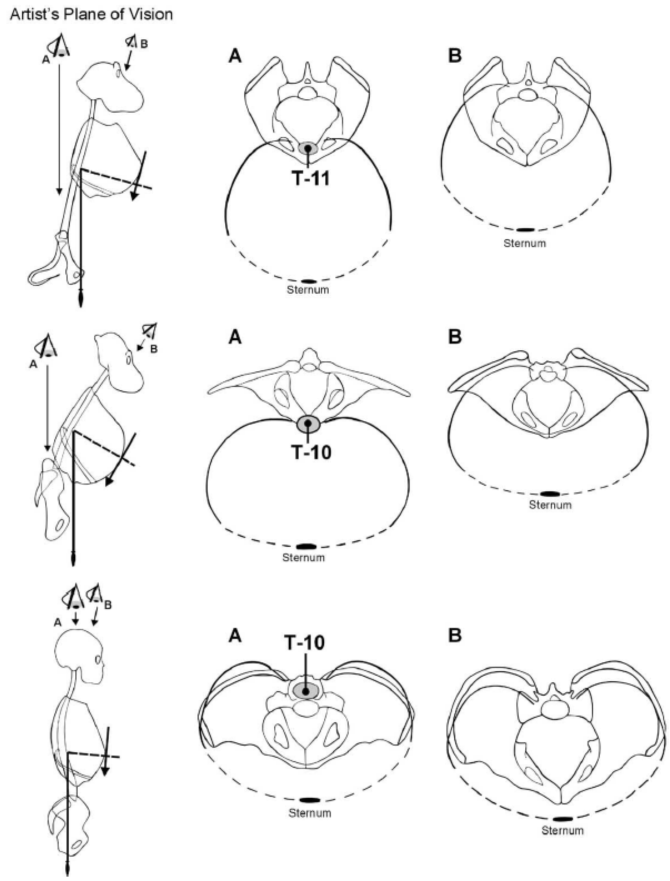

Figure 1: Center of Mass projection changes between a baboon (top), an African ape middle), and a modern human (bottom). Source of the image: Lovejoy C.O., 2005 [19].

for the evolution from quadrupedal to bipedal posture by arguing each of the theories published so far [25]. The whole argument starts from a simple postulate "Whatever one may think of it, the upright posture does not offer sufficient advantages for it to have persisted according to the classic criteria of natural selection" [26]. This sentence, therefore, supports an important judgment: favoring the survival of the bipedal species were several evolutionary and environmental factors that resulted in overcoming natural selection. Several hypotheses have been proposed during the last century, ranging from the hypothesis of the upright station to control the environment from the presence of predators [27] to the need to transport infants [28]. One of the earliest hypotheses is that of Charles Darwin, who in his work "Descent of Man" points to the need for free hands to gather food, self-defense or use of tools as a hypothesis to erect posture [29]. Although it has been well accepted as a hypothesis, it is believed that manipulation could not have been a promoter of upright posture [30]. Nevertheless, the hands-free hypothesis has been strongly argued by presenting different versions in later years. Both the hypothesis of the upright station to reach higher food and carry supplies were strongly supported because they were indicative of parental care and thus support of species survival [30; 31]. An interesting hypothesis is that proposed by Jablonski and Chaplin, who identify the transition to upright posture as a response to intergroup conflict resolution, thus emphasizing the need for the transition to bipedal posture as a necessity for the social rather than purely musculoskeletal sphere [32]. As already reiterated, many hypotheses have been proposed; however, it is believed that the choice of upright posture should be considered a necessity arising from multiple factors rather than from one precisely [33].

4 Historical perspectives of posture

The term posture has undergone multiple changes from a simple noun to a medical approach describing the individual's general health status. In "De Partibus Animalium" Aristotle refers to man as the only being capable of standing upright, adding that the acquisition of upright posture is such because man's nature is divine [34]. The divine nature determines the possibility of being intelligent, and he adds that it is not easy to be intelligent if the body is squashed downward or slouched. He, therefore, links posture to intellect for the first time, a precursor to the general idea that the is linked in some way to cognitive development. Also Plato in Timaeus discusses man maintaining an upright posture by identifying the acquisition of the upright posture as what distinguishes man from beast [35]. More contemporary is the thought of the philosopher Herder, who in "Ideas for the Philosophy of History of Humanity" describes the anatomical aspects of what determines man's upright posture compared to beasts, good-naturedly identifying the fundamental traits of upright posture [36]. However, he also refers to upright posture as a gift from God, an idea that contrasts with Immanuel Kant's thought that man does not have a perfect posture but can become one only through effort, only through rigorous self-improvement [37]. In the same historical period, a branch of medicine emerged that defined health status and disease of the body based on good posture [38]. In addition to the description of good posture, pathological postures such as hyperkyphosis, hyperlordosis, flat back, or sway-back posture come into play, as opposed to the correct posture, which would be the military one. From this moment, good and bad postures are discussed and various methods to correct poor posture begin to develop [39]. Therefore, various orthopedic tools emerge to mechanically correct poor posture problems, such as for children with rickets [39]. Posture then becomes a clear status of health. The 20th century indeed represents the magnifying glass on attention to posture as reported by Jessie Hubbell Bancroft, one of the founders of the American Posture League, who in her book "The Posture of School Children" urges teachers not to ignore the pupils' bodies by providing them with guidelines on correcting poor posture in the classroom and preventing postural alterations [40]. This was certainly pioneering thinking for the time that would result in increasing attention to the topic. A few years later Henry Otis with his wife Florence Peterson Kendall in the second half of

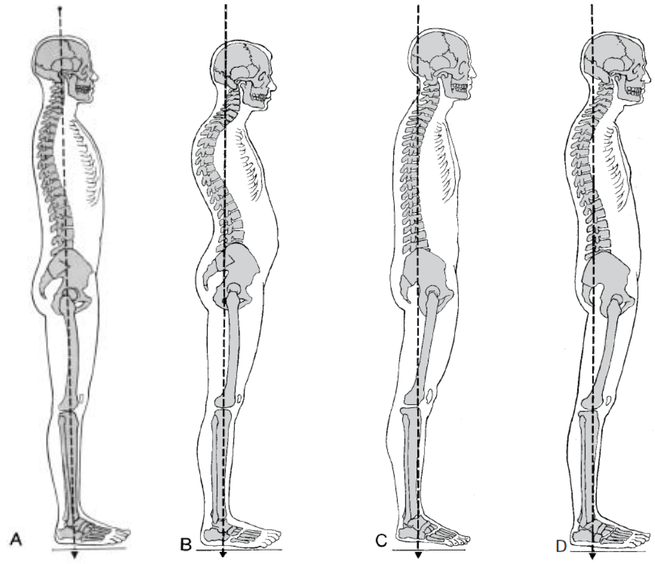

Figure 2: Four different sagittal representations of postures, according to Kendall. (A) healthy posture, (B) kypho-lordotic, (C) flat back, and (D) sway-back. Source of the image: Kendall F.P. et al., 2005 [43].

the 20th century laid the foundation for today's postural assessment. Indeed, their work defines in every detail the aspects of healthy and diseased posture. Given the profession of physical therapists, their concept is based purely on an orthopedic point of view. In fact, they refer to the American Academy of Orthopedic Surgeon's definition of posture, which describes as posture that state of muscular and skeletal balance that protects the supporting structures of the body from injury or deformity [1]. With this recall, the broad outlines of today's conception of posture from the anatomical point of view are finally drawn. In "Posture and Pain" published in 1952 all their work on the field of posture is collected [41] defining in detail both the parameters of healthy posture and of the various pathological postures such as kypho-lordotic posture, flat back and sway-back (Fig. 2). They state that good posture contributes to a person's physical well-being, but more importantly they say that poor posture can lead to pain and disability causing chronic problems. This assumption traces represents the idea that nowadays underlies the study of posture, to study the human body in order to reduce the occurrence of chronic pain and disability, thus avoiding the reduction of quality of life [42].

5 Structural and postural spinal alterations

Spinal deformities, critical areas of concern in orthopedic and rehabilitative medicine, encompass a spectrum of conditions that can be broadly categorized into two distinct groups: permanent structural deformities and nonstructural, or postural, deformities [44]. Structural deformities, characterized by irreversible changes in the spine's anatomy, pose significant challenges in medical management and patient quality of life. Among the notable structural deformities is scoliosis, a lateral curvature of the spine often accompanied by vertebral rotation [45]. The existing literature indicate its frequency between 0.47% and 5.2%, with a ratio of females to males affected by this disease typically spanning from 1.5:1 to 3:1 [46]. The etiology of scoliosis includes both genetic and environmental factors, with research indicating a multifactorial origin [47]. Scheuermann's disease, another structural deformity, is defined by structural hyperkyphosis of the spine [48]. This condition typically manifests during the growth spurt of adolescence. Patients with Scheuermann's disease often present with a rigid thoracic kyphosis, and in severe cases, this can lead to chronic pain and functional limitations. The exact cause of Scheuermann's disease remains unclear, but genetic predispositions have been suggested [49]. Isthmic spondylolisthesis involves the anterior displacement of a vertebra relative to the segment below it [50]. It is often the result of a defect or fracture in the pars interarticularis and is more prevalent in certain sports that place repetitive stress on the lumbar spine. This condition can lead to chronic low back pain, and in severe cases, neurological deficits may occur due to nerve root compression [51]. Spondylolysis, a fracture in the pars interarticularis of a vertebra, is often associated with isthmic spondylolisthesis [50]. This condition is frequently asymptomatic but can lead to lower back pain, particularly in athletes involved in sports requiring hyperextension of the spine. The diagnosis of spondylolysis is often confirmed through imaging studies, such as X-ray or MRI, and treatment typically involves a combination of physical therapy and activity programs specific to support the patient towards the correct execution of common movement in order to reduce the stress on the spine [52].

In contrast to structural deformities, nonstructural spinal deformities, while resulting in abnormal spinal curvature, are typically reversible and fall under the category of postural alterations. This distinction is crucial in both diagnostic and therapeutic approaches, as these conditions often stem from reversible causes and can be managed with non-surgical interventions. One such condition is scoliotic paramorphism or false scoliosis, characterized by the absence of spinal rotation. Unlike true scoliosis, scoliotic paramorphism often arises from disparities in lower limb length or other postural disorders [53]. This can lead to a compensatory curvature of the spine, mimicking scoliosis, but without the structural vertebral anomalies. The diagnosis of scoliotic paramorphism requires careful clinical evaluation and radiographic imaging to differentiate it from true scoliosis, especially since treatment approaches differ significantly. Lordotic posture, another nonstructural change, is distinguished from a healthy spine by an exaggerated pelvic anteversion and increased lumbar lordosis [54]. This posture can be commonly observed in populations with sedentary lifestyles or in individuals engaged in activities that promote anterior pelvic tilt [55]. The exaggerated curvature can lead to lower back pain and muscle imbalances. Intervention often includes strengthening and stretching exercises targeting the abdominal and lower back muscles, alongside postural reeducation to alleviate symptoms and restore normal lumbar curvature. Similarly, kyphotic posture, characterized by increased thoracic kyphosis, forward-rounded shoulders, and altered cervical lordosis, is another postural deformity [56]. Often associated with prolonged sitting and poor ergonomic practices, this posture can lead to neck and shoulder pain, reduced respiratory function, and aesthetic concerns [55]. Management strategies for kyphotic posture involve a combination of stretching exercises for tight chest muscles, strengthening exercises for weak upper back muscles, and ergonomic adjustments to reduce strain on the thoracic spine.

Generally, the importance of early detection and intervention cannot be overstated. Nonstructural deformities, while reversible, can lead to chronic pain and functional limitations if not properly managed. While nonstructural spinal deformities are less severe than their structural counterparts, their impact on quality of life and the potential for progression to more chronic conditions necessitates a proactive and holistic approach to management. Advances in our understanding of biomechanics and ergonomics continue to refine treatment strategies, offering hope for improved outcomes for individuals affected by these conditions [57].

6 Evaluation of the posture

Whether it was for fording a river [58], escaping danger [59], or environmental habitat pressures [60], still today, human posture is a rich subject to study and investigate. Although knowledge of posture alterations is quite comprehensive, today's research focuses on finding the most effective methods to monitor changes in posture and its alterations.

The various instruments available in the market make it possible to perform a reliable postural assessment digitally, circumventing the error due to the clinical hand [61]; however, in the mid-1990s, few instruments were present to assess posture. The Egyptians more than 4000 years ago, invented one of the tools still used today, the plumb line, to locate a vertical point during building construction [62]. The nature of the plumb line has remained alike, coming into our hands as a tool for identifying a straight line perpendicular to the ground. In 1855 the anatomist Christian Wilhelm Braune employed the plumb line in measuring a subject's back, attracting the attention of physicians [63]. From that moment, the quantification of posture concerning a "straight line inside the body" was born, becoming a standard parameter in the field of orthopedics [64], as Kendall would later show [41]; however, it would enter scientific research many years later. One of the earliest papers we find on its application is from 1982, and it is employed for the assessment of natural head posture where markers were placed on one side of the head and compared with the plumb line as a vertical reference [65]. A few years later, a study employed plumb line assessment to monitor the reduction in anterior head displacement following manual treatments. The researchers observed by plumb line a statistical reduction in anterior head displacement [66]. A study conducted by an Italian research group in 1989 used the plumb line for early diagnosis of scoliosis in a population of adolescents, show-

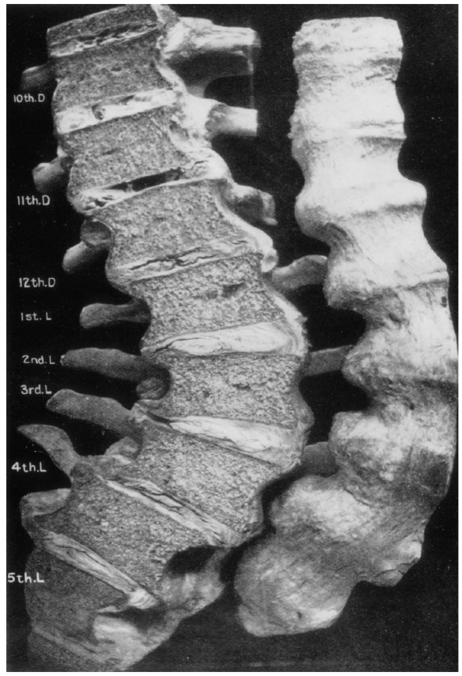

Figure 3: Photo of the postmortem spine of a subject with scoliosis. Source of the image: Fairbank J., 2004 [68].

ing that the plumb line can easily show postural changes due to scoliosis [67]. In the field of scoliosis during that historical period, other essential tests were introduced that are still used today. The forward bending test, or Adams test, was first described in 1865 by orthopedist William Adams following a postmortem observation of the back of a subject with scoliosis (Fig. 3) [68]. He noticed that the scoliotic back during anterior flexion tended to be more prominent on one side due to the rotation of the vertebral bodies. From that time, the Adams Test became a pivotal test in diagnosing scoliosis. About a hundred years later, an innovative, noninvasive instrument capable of estimating vertebral rotation is introduced. William P. Bunnell first introduced the inclinometer, or scoliometer, to measure the trunk asymmetry seen in scoliosis [69]. The appearance of this instrument is a cross between a ruler and a spirit level with a ball inside a hollow slot. When placed on the back in anterior flexion, the ball will move to the left or right if the rotation of the vertebrae is present. This instrument, with a false-negative rate of 0.1 percent, will become the key tool in scoliosis screening precisely because of its ease of use. Because of these two methods, a more recent study in pediatric orthopedics uses the forward bending test and scoliometer for scoliosis screening in the school setting [70]. Although school screening is widely accepted, shared, and still necessary [71], at the time, this approach was innovative and important; for that reason, the idea of prevention of postural alterations spread to schools.

The utility of the combination of plumb line, scoliometer, and Adams' test is still confirmed today for the screening of postural alterations. In 2021 Scaturro et al. [72] examined 428 adolescents equally distributed between males and females using the ISICO (Istituto Scientifico Italiano Colonna Vertebrale) screening protocol and found that the combination between the three methods was highly specific for the early diagnosis of adolescent idiopathic scoliosis. Table 1 shows the results of the study of Scaturro et al. [72].

Concerning its applicability as supportive in the pathologies management, Zhang et al. (2020) demonstrated its use in predicting postoperative coronal imbalance in patients with degenerative lumbar scoliosis, emphasizing its role in ensuring successful surgical outcomes by predicting post-surgical complications. Similarly, Berlin et al. [73] explored the prevention of postoperative shoulder imbalance in adolescent idiopathic scoliosis, where the plumb line aids in assessing shoulder balance, a factor critical for cosmetic outcomes and patient satisfaction. Additionally, Walker et al. [74] discussed its significance in evaluating coronal balance in minimally invasive spinal surgery for degenerative scoliosis, underlining its utility in correcting spinal deformities with minimal disruption. Lastly, Higuchi et al. [75] investigated the impact of postoperative residual coronal decompensation on self-image in adolescent scoliosis patients, where the plumb line is key in assessing residual decompensation, which significantly affects patients' body image and satisfaction with surgery. Collectively, these studies underscore the plumb line's indispensable role in spinal surgeries, particularly in conditions like degenerative lumbar scoliosis and adolescent idiopathic scoliosis, for precision and effectiveness.

In 1977 Adair, Wijk, and Armstrong presented Moiré Topography for screening scoliosis to the scientific community [76]. This approach involves projecting a light beam through a particular screen crossed by nylon threads onto the subject's back. This particular screen determines an interference to the light that, based on the shape of the back, allows the body's overall shape and symmetries to be assessed. The authors employed this method in school-based screening programs obtaining promising results as this approach highlighted the presence of shoulder asymmetry, winged scapulae, and scoliosis. This method was compared with radiography and the forward bending test, finding a 94% match of correct diagnosis of scoliosis when compared with radiography versus a 46% match of the forward bending test. It was a very valid method; however, current research does not show any particular validity in the diagnostic field, especially compared with radiography [77]. A few years later, Frobin and Hierholzer introduced rasterstereography, nothing more than the union of Moiré topography and stereophotography, thus obtaining a three-dimensional evaluation of the back [78]. Rasterstereography overcomes a significant limitation placed on Moiré topography, the need to observe changes in posture three-dimensionally, thus assessing not only its lateral displacements but also those of depth and rotation. Based on the geometry and mathematical calculations, this approach was documented in subsequent publications by the same [79; 80; 81] and later supported by researcher Burkhard Drerup showing its applicability in the field of posture assessment, especially in the analysis of scoliosis (Fig. 4) [82; 83; 84]. Modern rasterstereography is a spreading technique that determines the vertebral position and normal or abnormal posture using light detection and ranging technol-

	Sensitivity (%)	Specificity (%)	Positive predictive value (%)	Negative predictive value (%)	LR+ (n)	LR- (n)
Adam's test	50.8	94.4	79.0	82.1	9.02	0.52
Axial trunk rotation	46.0	93.4	74.4	80.6	6.95	0.58
Plumb line	61.1	86.8	65.8	84.2	4.61	0.45
Adam's test or axial trunk rotation	56.3	92.7	76.3	83.6	7.74	0.47
Axial trunk rotation or plumb line	91.3	80.8	66.5	95.7	4.75	0.11
Adam's test or plumb line	95.2	81.5	68.2	97.6	5.14	0.06
Adam's test + axial trunk rotation	40.5	95.0	77.3	79.3	8.15	0.63
Axial trunk rotation + plumb line	15.9	99.3	90.9	73.9	23.97	0.85
Adam's test + plumb line	16.7	99.7	95.5	74.1	50.33	0.84
Positive to at least one examination	100.0	80.1	67.7	100.0	5.03	—
Positive to all three examinations	15.1	99.7	95.0	73.8	45.54	0.85

Table 1: Results data from Scaturro et al. [72] demonstrate the usefulness of the screening with plumb line Adams' test and scoliometer in school settings.

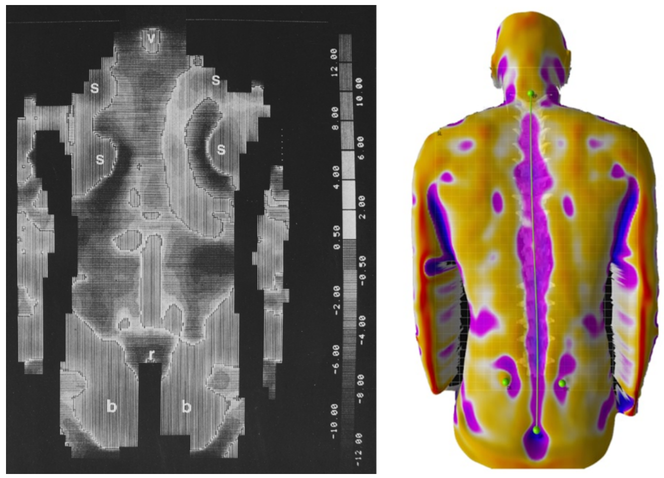

Figure 4: On the left is the first representation of rasterstereography on a scoliotic patient, on the right is the modern rasterstereography measurement. Source of the image: Drerup P., 1985 [87].

ogy. Specific algorithms use these measures to reconstruct a three-dimensional spine analysis in the sagittal, coronal and transverse planes. Because of its excellent intra- and inter reliability [85], rasterstereography can deal with many users; however, it cannot yet be considered as a replacement for x-rays, so cases requiring more in-depth investigation should be analyzed with x-rays. [86].

Mohokum et al. [88] collected all the articles investigating the applicability of rasterstereography for screening various spinal pathologies, including scoliosis, thoracic hyperkyphosis, and Scheuermann's disease. The authors highlighted the validity and reliability of this method compared to X-ray measurements, suggesting that it could serve as an alternative for assessing spinal deformities, potentially reducing reliance on radiographs in clinical practice. Although we support this notion, we hesitate to fully endorse the idea that it can replace X-rays. To date, diagnostic methods such as X-rays or magnetic resonance imaging offer high precision in detecting the presence or absence of specific pathologies. Rasterstereography, while highly precise in analyzing the back surface, cannot be equated with X-ray analysis because it does not provide sufficiently accurate information for diagnosing a pathology.

Another direction followed by researchers recently in the assessment of posture is the photogrammetry evaluation through smartphone devices, which is low cost, valid, and easy to perform (Fig. 5). Although recent, one of the first studies involving the use of mobile application for the analysis of posture is the study of Boland and colleagues [89]. The study aimed to assess the inter- and intra-rater agreement of one of the first mobile application for the analysis of posture, PostureScreen Mobile® for the evaluation of static posture. With different mobile applications is possible to obtain a rapid analysis of human posture [89; 90]. The photogrammetry through a smartphone device may be suitable for population screening due to its characteristics. This method can spot differences in posture between healthy young males and females [89], suggesting that it may

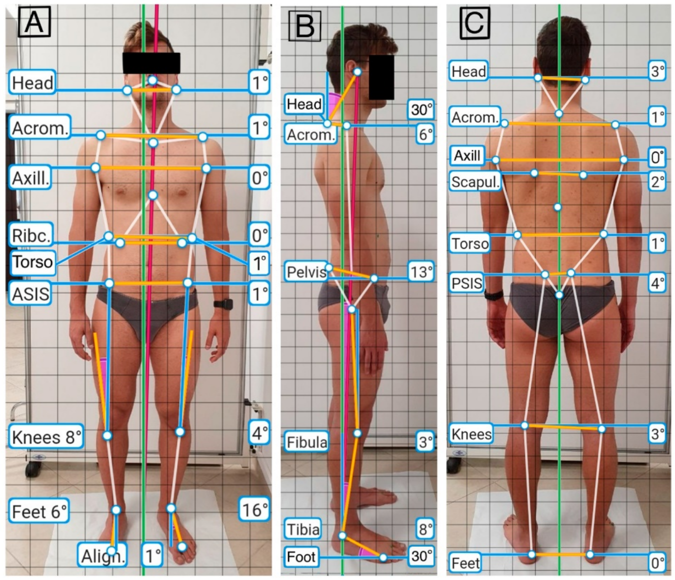

Figure 5: Example of a postural evaluation performed with photogrammetry through a smartphone device. Source of the image: Trovato B. et al., 2022 [89].

be suitable to be implemented in preventing large scale screening for the early detection of postural imbalances. Trovato et al. [89] employed APECS, another mobile application, to reconstruct the posture from a photo. The authors observed a high reproducibility for most analyzed postural variables, highlighted specific gender-based postural differences and noted its validity in terms of cost-effective alternative to more expensive postural assessment tools. Moreira et al. in a recent literature review pointed out the key features of the mobile applications for the posture analysis [91] supporting their strengths in the clinical assessments. Although these applications cannot be considered as first chose for the diagnosis, they can support the clinician during the physical examination of scoliosis [92], cobb angle [93], thoracic kyphosis [94] and lumbar lordosis [95]. Recent research in postural assessment has increasingly turned towards smartphone-based photogrammetry, offering a low-cost, valid, and user-friendly option. This technological advancement in posture analysis signifies a step forward in accessible, efficient healthcare tools.

7 Future steps of the analysis of posture

Nowadays, the non-invasiveness of postural analysis instruments is a fundamental prerequisite as we seek to obtain the most reliable measurements without harming the person's health. In the field of research, several instruments fulfill this task, which is more or less expensive and has possible drawbacks, whose reliability still cannot be compared to imaging instruments [61]. However, research in the field of postural assessment is making huge strides; recent studies are implementing machine learning models in order to estimate static posture or human movement through stills or videos without the need for special tools, e.g., 3D cameras, wearable sensors, but simply by subjecting these machine learning models to well-defined data [96; 97; 98]. The magnifying glass placed on posture analysis reflects the need for the world population to be as attentive as possible to the postural dysfunctions that affect the population on a daily basis regardless of age or gender [99].

The integration of artificial intelligence, particularly machine learning (ML) and deep learning, has brought about significant advancements in the healthcare sector [100]. The evolution towards the application of these methods aims to make evaluations increasingly objective, trying to eliminate the error of interpretation. Of course, these technologies must always be seen as supporting the clinician and not as replacement; the task of ML models is to analyze data, not to draw conclusions. The support of these technologies can be indispensable to speed up medical examinations, give a more precise service and reach a large number of people in a short time given the speed of analysis.

In recent years, digital alternatives for human pose estimation have emerged as more accessible methods [101]. Several algorithms based on skeletal models have been developed for research purposes. The strength of these new approaches lies in their ability to perform fast analyses of posture or movement using simple videos or photographs, which can be achieved in any setting. This capability is particularly relevant in clinical settings, where assessments need to be timely, objective, and reproducible [98; 102].

The integration of AI and machine learning models in posture analysis reflects the broader trend of leveraging technology in healthcare. These developments are reshaping how posture and movement are assessed, making the process more efficient, accurate, and accessible. They have been instrumental in diagnosing gait disorders [103], Parkinson's disease [104], stroke [105], and osteoarthritis [106]. However, the application of ML in the evaluation of posture parameters is relatively novel and unexplored. As research continues to evolve in this field, the potential for innovative solutions to address postural dysfunctions and contribute to public health is significant.

8 Conclusions

The study of human posture, tracing back to the assumption of upright posture by our ancestors, has continually evolved, enriched by diverse hypotheses and influenced by a range of environmental and adaptive factors. Throughout history, human posture has not only mirrored our physical evolution but also reflected diverse cultural, political, and social paradigms. Today, this subject has transcended into a significant area of scientific inquiry, employing an array of tools for its study and evaluation. The journey from ancient tools like the plumb line to the sophisticated machine learning algorithms of today underscores a remarkable evolution in understanding and assessing human posture. The shift towards non-invasive, digital methods in posture analysis aligns with modern healthcare's dual goals of precision and patient safety. It also reflects a deeper understanding of the importance of comfort and non-intrusiveness in medical assessments. Looking to the future, the untapped potential of AI and machine learning in posture analysis presents a frontier replete with possibilities. Continued research and development in this area promise not only the refinement of diagnostic tools but also the broadening of access to effective postural assessments. This progress is crucial in a world where postural health increasingly impacts quality of life across diverse populations. A pressing question today is this: considering the path that has led to our current state, in which direction is human evolution heading? As the Italian newspaper "Corriere della Sera" reports, the man's posture in a thousand years will be with a hump, a claw hand, and a small brain [107]. If such predictions of drastic changes are to be believed, it prompts us to consider what interventions might be necessary now to influence the trajectory of human posture and cognitive health. In this endeavor, the role of technology, especially AI, is pivotal in forging a path towards improved health and well-being, steering us away from potential negative trajectories in physical and cognitive health. The responsibility, therefore, lies in strategically harnessing these technological advancements to positively shape the future of human health and posture.

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