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REVIEW OF THE LITERATURE

Sitting Biomechanics Part I: Review of the Literature

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ABSTRACT

Objective: To develop a new sitting spinal model and an optimal driver's seat by using review of the literature of seated positions of the head, spine, pelvis, and lower extremities.

Data Selection: Searches included MEDLINE for scientific journals, engineering standards, and textbooks. Key terms included sitting ergonomics, sitting posture, spine model, seat design, sitting lordosis, sitting electromyography, seated vibration, and sitting and biomechanics.

Data Synthesis: In part I, papers were selected if (1) they contained a first occurrence of a sitting topic, (2) were reviews of the literature, (3) corrected errors in previous studies, or (4) had improved study designs compared with previous papers. In part II, we separated information pertaining to sitting dynamics and drivers of automobiles from part I.

Results: Sitting causes the pelvis to rotate backward and causes reduction in lumbar lordosis, trunk-thigh angle, and knee angle and an increase in muscle effort and disc pressure. Seated posture is affected by seat-back angle, seat-bottom angle and foam density, height above floor, and presence of armrests.

Conclusion: The configuration of the spine, postural position, and weight transfer is different in the 3 types of sitting: anterior, middle, and posterior. Lumbar lordosis is affected by the trunk-thigh angle and the knee angle. Subjects in seats with backrest inclinations of 110 to 130 degrees, with concomitant lumbar support, have the lowest disc pressures and lowest electromyography recordings from spinal muscles. A seat-bottom posterior inclination of 5 degrees and armrests can further reduce lumbar disc pressures and electromyography readings while seated. To reduce forward translated head postures, a seat-back inclination of 110 degrees is preferable over higher inclinations. Work objects, such as video monitors, are optimum at eye level. Forward-tilting, seat-bottom inclines can increase lordosis, but subjects give high comfort ratings to adjustable chairs, which allow changes in position. (J Manipulative Physiol Ther 1999;22:594-609)

Key Indexing Terms: Sitting; Biomechanics; Lordosis; Ergonomics; Spine; Model; Vibration; Posture; Chair Design

INTRODUCTION

Because of a void in the literature, an automotive engineering corporation requested that the authors determine an optimal sitting spinal model of a driver and an optimal driver's seat. To complete these two objectives, the state of the current knowledge concerning chair design and sitting ergonomics in the work place (office and factory) and in automobiles was reviewed. Part I of this review concentrates on sitting in the work place. Sitting dynamics (vibration) and sitting of drivers will be discussed in part II.

Because few studies exist for sitting in the driver's seat of an automobile compared with sitting in the work place, the purpose of part I is to review sitting ergonomic principles that will be applied to automobile seats presented in part II. Key words used in MEDLINE searches were sitting ergonomics, sitting posture, spine model, seat design, sitting lordosis, sitting electromyography, vibration, and sitting and biomechanics.

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Discussion

The concepts of ideal sitting posture have a long history in the literature, especially in the German literature. In 1884, Staffel[1] wrote the standard for the sitting position that was quoted later by Fick,[2] Strasser,[3] and Schede.[4] By 1929, Drescher[5] had already designed seats for Siemens factories that had adjustable backrests and seat bottoms with rounded front edges to reduce pressure on the under-thigh region. In 1948, Akerbloom[6] provided a review of sitting principles from the period 1853-1947.

Keegan, in 1953[7] and again in 1962,[8] wrote a comprehensive evaluation of seats and sitting while discussing degeneration and herniation of lower lumbar discs. He[7] obtained lateral radiographs of the lumbar spine of his subjects in a variety of positions, including standing, squatting, bending, and sitting in different chairs. In 1966, Knutsson et al[9] had an interesting review in the first part of their article on electromyographic evaluation of the sacrospinal muscles during sitting. In 1971, Kroemer[10] reviewed the footrests, office equipment, consoles, work benches, and machine stands in factories and office settings.

Seated posture has also been of interest in Sweden. In 1970, Nachemson and Elfstrom[11] inserted pressure sensors into the discs of live subjects (4 subjects) and showed that sitting posture caused a higher disc pressure than standing or lying. Andersson et al[12-16] wrote a series of articles on electromyographic measurements and disc pressure during seated postures, including office chairs, wheel chairs, and driver's seats.

In 1980, the Society of Automobile Engineers[17] wrote a manual covering all aspects of car seats, both front and rear. Williams et al[18] presented a more recent review of sitting and pain and reported that lordosis is preferred over kyphosis. In a review done especially for automobile seats, Fubini[19] wrote a synopsis of safety, comfort, adaptability, practicality, solidity, and suitability.

In the late 1800s and early 1900s, several design items were identified. Very early, Parow[20] and von Meyer[21] concluded that the ischial tuberosities were the chief points of support in the sitting position because of posterior pelvic rotation. Von Meyer[21,22] stated that spinal ligaments were not in tension while sitting and that a support is required to give lumbar relaxation. He noted that straight-back chairs did not give support to the spinal column. In 1884, Staffel's designed chair[1] had a lumbar support and a space under this support for the buttocks to slide backward to effect some forward rotation of the pelvis.

The debate about what constitutes a normal position of the lumbar spine during sitting (kyphosis or lordosis) occurred as early as 1911. Fick[2] thought that the spine should be "ventriflexed," whereas Staffel[1] suggested that the lumbar curve in sitting should be as close as possible to its form in the standing position.

Some of the issues (or variables) studied before 1950 included the following: (1) seat-bottom height, (2) seat-bottom incline, (3) seat-bottom contour, (4) seat-bottom width, (5) seat-bottom length, (6) seat-back tilt inclination, (7) seat-back lumbar support, (8) seat-back height, (9) table and desk height, (10) the correct sitting posture, (11) muscle activity while seated, (12) thigh angle to trunk, (13) knee angle, and (14) footrest position.

Fig 1 illustrates some of these ideas, which Keegan[8] suggested for seat design, and these are numbered from most important to least important.

Before Snijders et al,[23] Fick[2] and von Meyer[22] discussed sitting with crossed legs. Before Marumoto et al,[24] Spitzy[25] and Schede[4] discussed table height and near sightedness while sitting. Before Lord et al[26] and Keegan,[8] von Meyer[22] and Staffel[1] had written about loss of lumbar lordosis from standing to sitting. Before Coleman et al[27] and Keegan,[8] Staffel[1] had incorporated lumbar supports on his designed chairs. Before Hooton[28] and Floyd and Roberts,[29] Staffel[1] discussed table heights for adults and children while sitting. Before Reinecke et al[30] presented lumbar support motion as a "new" strategy, Hertzberg[31] had designed a pulsating seat cushion and lumbar support for the US Air Force.

Let us next examine normal standing posture. Because humans are the only species on earth with an upright stance, all dynamics (after rising from a lying position) are changes from an upright posture. Thus such movements as walking, squatting, climbing, and sitting can be described as changes from the upright position. Therefore normal upright posture must be defined before sitting changes are described.

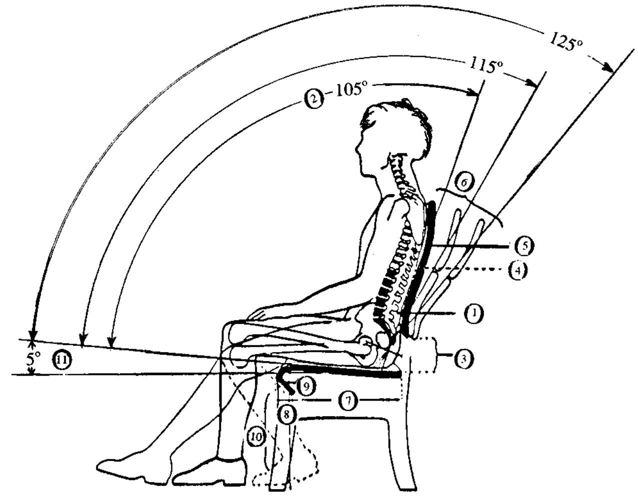

Fig 1. *Keegan's[7] 1953 list of important aspects of seat design:* 1, *lumbar support;* 2, *minimum 105-degree tilt angle of backrest;* 3, *open space for posteriorly projecting sacrum and buttocks;* 4, *convex thoracic support with height to lower scapulae;* 5, *shoulder support at 105 degrees;* 6, *any adjustable tilt of seat back pivoted on a point in line with the hip joints;* 7, *maximum length of seat bottom (16 in);* 8, *seat-bottom height above floor (16 in);* 9, *seat bottom curved down under back of knees;* 10, *free space for feet under seat bottom; and* 11, *upward tilt of seat bottom of 5 degrees for maintenance of back against back support.*

Normal Standing Procedure

The details of sitting posture require more than just a definition of upright human posture. Although posture alignment is of vital importance, posture provides few details of the inside spinal alignment. Because the positions of individual vertebrae are desired for a sitting spinal model, a normal upright spinal model is required to discuss spinal changes occurring in the sitting posture. Thus after discussing normal upright posture, a normal spinal model will be reviewed.

Postural control is a fundamental but complex motor function, which is involved in nearly every motor task. Different theories have been developed to explain the neural organization required for sitting, standing, breathing, and movement.[32] Electromyographic studies have been performed on infants to follow the evolution of sitting to standing posture.[33]

All authors of postural studies represent the anteroposterior view of upright stance as a true vertical alignment of centers of mass (Fig 2, *A*). However, in the lateral view, there is debate about which anatomic structures are aligned to a vertical gravity line (Fig 2, *B-D*). Normal standing posture has been defined as perfect alignment of the ear, shoulder, hip, knee, and ankle (Fig 2, *B*).[34] In 1985, Woodhull et al[35] stated that good standing posture is often idealized[36] and that studies[37-41] reporting the average standing posture indicate that the body center of gravity lies slightly anterior to the talus of the ankle (Fig 2, *C*). For different ideal posture, Kapandji[42] stated that the posterior parts of the head, back, and buttocks

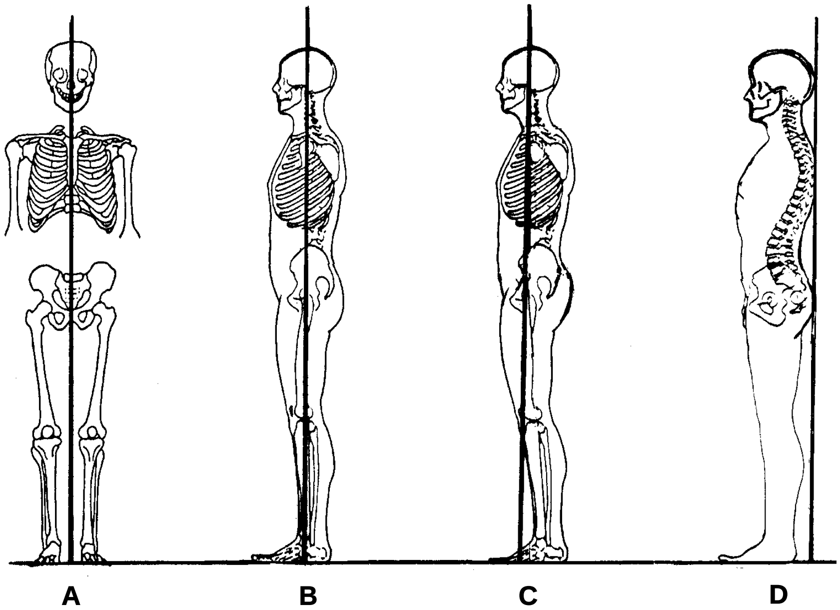

Fig 2. *Standing postural alignment. The anteroposterior view depicts the vertical alignment of the body centers of mass and vertebrae in* ***A****. The literature agrees on this anteroposterior view alignment. There is disagreement among the idealized alignments in the lateral view (****B*** *and* ***D****) and the averages of measured human alignment in the lateral view* ***(C)****. Compared with the ideal posture* ***(B)****, the average posture* ***(C)*** *has anterior head translation and anterior pelvic translation.*

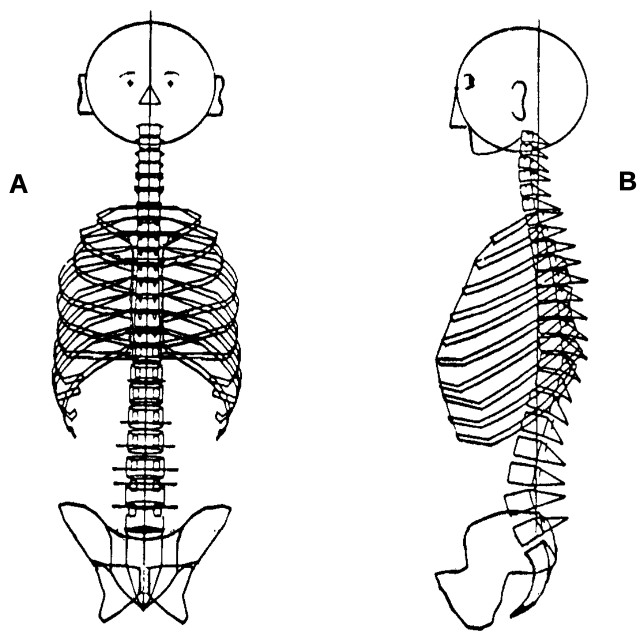

Fig 3. *Belytschko and Privitzer's[55] sitting spinal model developed for the Air Force. Note that the pelvis is rotated posteriorly, but the head and rib cage remain in the alignment found in the ideal standing position.*

should be vertically aligned (Fig 2, *D*). Thus, as in spinal modeling, there is debate concerning the use of an ideal normal position versus an average normal position.

The validity of restoring normal posture as a clinical outcome[43,44] and reliability of measuring posture has been established.[45-47] Even though ideal posture has been described in the literature for more than a hundred years, the alignment of the vertebrae in the lateral view cannot be determined from posture.[48-50]

Average spinal alignment in the sagittal view has been determined from numerous radiographic studies. Spinal modeling, although determining some guidelines of alignment during impact simulations, has often used the alignment determined from one human subject instead of using equilibrium equations or an average from a large population of subjects. To develop normal alignment of the cervical lordosis, thoracic kyphosis, lumbar lordosis, and pelvic tilt, spinal modeling and lateral radiographic studies will be reviewed.

Spinal Modeling and Spinal Alignment

Spinal modeling began in the 1950s to explain spinal injuries to ejected Air Force pilots.[51] In 1984, King[52] reviewed the use of biomechanical models for studying musculoskeletal biomechanics. In 1987, Yoganandan et al[53] reviewed the types of spinal models in the biomechanics literature, including the following: (1) anthropometric, (2) discrete parameter, (3) continuous elastic, and (4) finite element (FEM). After the description of locations of centers of mass for various body parts by Clauser et al,[54] Belytschiko and Privitzer[55] published a complete 3-dimensional spinal model with in vivo and in vitro validation. Theirs was a seated model with posterior pelvic rotation to simulate the forces on pilots who were subjected to seat pyrotechnic ejections. Fig 3 illustrates this model. They concluded that the spinal alignment must be a true vertical in the anteroposterior view, have lordotic cervical and lumbar curvatures in the lateral view, and be without any anterior head translation or posterior thoracic translation.

Another early spinal model was described by Schultz and Galante.[56] For the anteroposterior spinal alignment, Schultz and Miller[57,58] stated that "the spine is approximately straight when viewed frontally because each vertebra and disc is approximately symmetric about the sagittal plane." In 1991, Schultz[59] stated that "one advantage of using a mathematical rather than a physical model is that changes are easy to make in a mathematical model." In the lateral view for the cervical spine, such changes could be the inclusion of specific angles for average cervical lordosis. For example, a mean of 23 degrees was reported for Ruth Jackson's stress lines on C2 compared with C7.[60] Ruth Jackson's stress lines are examples of posterior tangents at C2 and C7. The angle formed by these tangents at C2 and C7 is termed an absolute rotation angle (ARA).

In 1996, Yoganandan et al[61] reviewed the use of FEM models of the cervical spine. They state that "the finite element method is an invaluable application tool that can supplement experimental research in understanding the clinical biomechanics of the spine." An FEM can be described as dividing an object of interest into small geometric shapes (eg, tetrahedrons), thereby creating a 3-dimensional mesh. Each of these geometric shapes (elements) can be assigned appropriate mechanical (material) properties, which have been established from experiments. These models can then be subjected to nearly limitless experimental conditions by means of software interface and can closely approximate stresses, strains, deflections, bending moments, and shears. For example, at the Iowa Spine Institute, Goel et al[62,63] now have a complete spine FEM with pelvis and ribs.

In 1996, while presenting a simple geometric cervical spine model as a normal standard and as an initial starting position, Harrison et al[64] noted that "considering all these models, a rigorously defined normal, static position is encountered rarely." Using the posterior tangent line analysis at C2 and C7, Harrison et al[64-67] presented validation of a circular sagittal cervical model with an average ARA of 34 degrees and an ideal ARA of 42 degrees. They also presented average relative rotation values for each pair of cervical vertebrae from a large population of 400 subjects.[64] For the thoracic kyphosis, nearly identical means were reported for all the segmental angles (relative rotation angles [RRAs]), and an overall thoracic kyphosis mean value was reported as an ARA of 40 degrees from T1 to T12.[68,69]

For the lumbar lordosis in a 1997 study, Troyanovich et al[70] compared results from 7 separate standing lateral lumbar studies (n = 552). They found that a fundamental lumbar lordosis existed across a large range of age groups. Average segmental RRAs, ARAs, Cobb angles, Ferguson angles, arcuate angles, and Z-axis translations for T12 to S1 were determined for the lumbar spine.[70] While refining the Harrison spinal model, the sagittal lumbar lordosis was successfully modeled with an 85-degree portion of an ellipse with an L1 to L5 ARA of 40 degrees and a T12 to S1 Cobb angle of 65 degrees.[71,72]

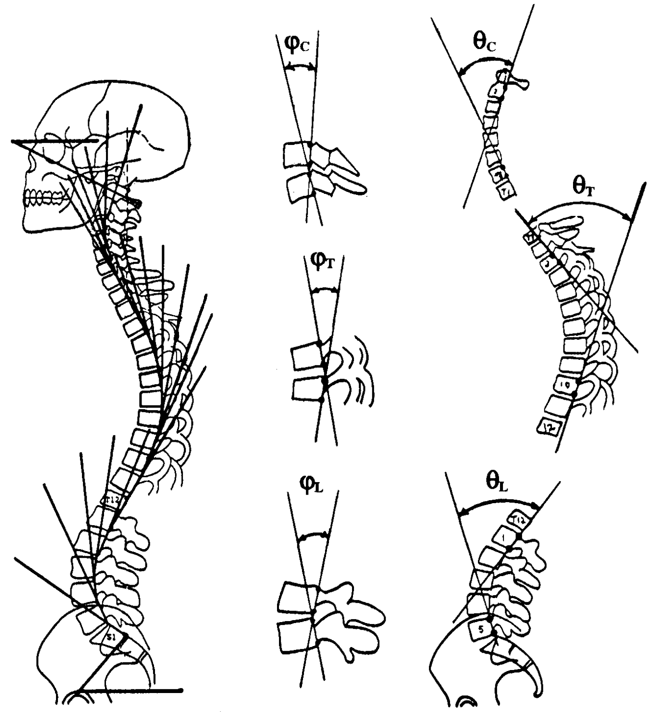

Fig 4. *Harrison geometric model with circular arcs for the cervical and thoracic curvatures and an elliptic arc for the lumbar spine. Normal average and normal ideal values for these angles can be found in Harrison et al.[73]*

The Harrison spinal model provides qualitative normals (geometric shapes are cervical circular arc, thoracic circular arc, and lumbar elliptical arc) and tables of quantitative normal sets of values for the cervical lordosis and lumbar lordosis.[73] With these normals, diagnosis of spinal displacement on radiographs is possible. Fig 4 illustrates this Harrison geometric model with end-of-curve measurements on the base of the posterior tangent radiographic method at C2 to C7, T3 to T10, and L1 to L5.

The elliptical shape of the lumbar lordosis might lead one to design an elliptical-shaped lumbar support. However, Mosner et al[74] failed to find any significant differences in lordotic radiographic appearance between black and white persons, even though there are entirely different lateral low back skin contours present during physical examination. With normal qualitative and quantitative values for standing posture, we are now able to describe what happens to a human in the seated posture, which are described as changes from standing.

Biomechanics of Seated Postures

Previously, a list of design aspects affecting seated posture was given. These items affect seated posture in different ways. Before determining how a sitting human's posture will be changed, it is convenient to categorize seated posture by location of the center of gravity.

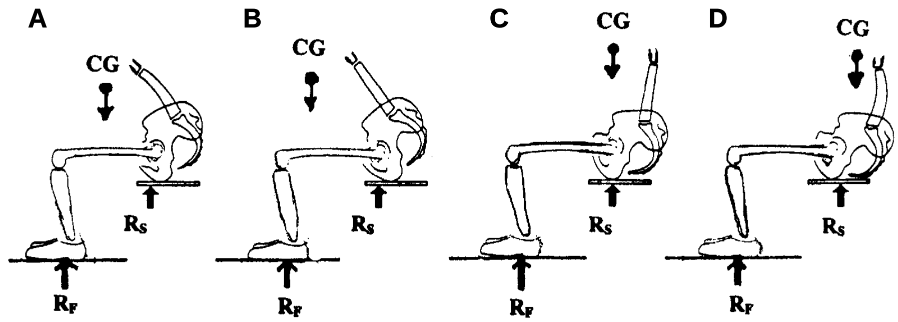

Fig 5. *Schoberth's three sitting categories on the basis of center of gravity location. The vector* R_S *represents the reaction force through the seat bottom.* R_F *is the reaction force from the ground at the feet.* CG, *Center of gravity of the body mass above the pelvis.*

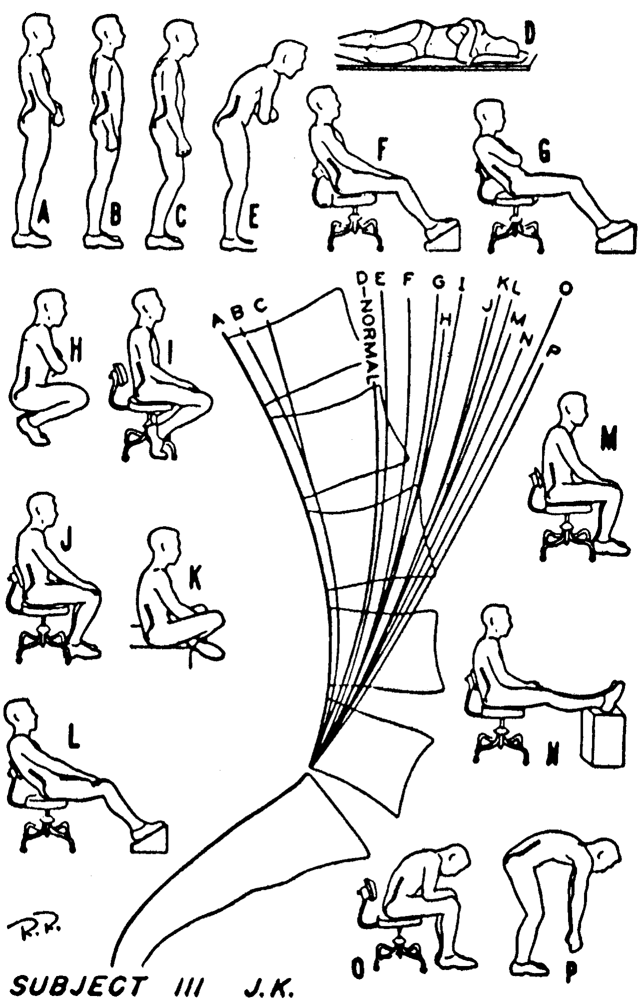

Fig 6. *In 1953, Keegan radiographed subjects in different sitting, standing, and lying postures. Reprinted with permission: Keegan JJ. Alterations of the lumbar curve related to posture and seating. Reprinted with permission from* J Bone Joint Surg *1953;35-A:589-603.*

In 1962, Schoberth[75] defined 3 different sitting postures on the basis of the location of the center of gravity of the body and the proportion of body weight transmitted to the floor by the feet. Schoberth termed these 3 sitting postures as anterior, middle, and posterior. He noted that these 3 postures also differed with respect to the shape of the lumbar spine. He showed radiographically that his subjects posteriorly rotated their pelvises 40 degrees on average during transition of standing to sitting.

In the middle position (Fig 5, *C*), the center of gravity is above the ischial tuberosities, and the feet transmit about 25% of the body weight to the floor. In sitting in a relaxed middle position, the lumbar spine is either straight or in slight kyphosis. The anterior position can be obtained from the middle position either by a forward rotation of the pelvis (Fig 5, *B*) or by creating a kyphosis of the spine by flexing without much rotation of the pelvis (Fig 5, *A*). In this anterior position the center of gravity is in front of the ischial tuberosities, and the feet transmit more than 25% of the body weight to the floor. In the posterior position (Fig 5, *D*) the center of gravity is above or behind the ischial tuberosities, and less than 25% of the body weight is transmitted by the feet. This position is obtained by extension rotation of the pelvis and simultaneous kyphosis of the spine.

Before Schoberth's[75] sitting categories were published, Keegan[7] radiographed a small number of subjects (only 4) in various standing and sitting postures to determine changes in the lumbar spine in the lateral view. He traced the posterior vertebral bodies on each radiograph and then superimposed the sacrums of all tracings to create a composite template. Fig 6, *A-P*, shows the positions radiographed and resulting variations in the lumbar spine. Note that Fig 6, *F, G, L,* and *N*, are types of posterior sitting; Figs 6, *I, J,* and *M*, are examples of middle sitting; and Fig 6, *O*, is a type of anterior sitting.

From other lateral tracings, Keegan derived a relationship between lordosis and thigh-trunk angle. He radiographed his subjects in the lateral recumbent position while varying only the thigh-trunk angle. Fig 7 shows that as the thigh-trunk angle is reduced from 200 to 50 degrees, the pelvis rotates posteriorly, and the lumbar lordosis becomes kyphotic. Keegan discovered that the length (he hypothesized tension) in the anterior and posterior thigh muscles accounted for the effects of thigh-trunk flexion and extension. In Fig 7 the anterior and posterior thigh muscles are darkened to show their attachments. Fig 7 also shows how tension in these muscles will pull on the pelvis. He determined that the 135-

degree thigh-trunk angle was a neutral position for tension in the thigh muscles. He believed that tension in the anterior thigh muscles (and psoas) in standing accentuated the lumbar curve. He thought that, beside the lever arm for posterior pelvic rotation caused by sitting on the ischial tuberosities, the tension in the posterior thigh muscles played a large role in posterior rotation of the pelvis and reduction of the lumbar lordosis.

In a recent study with 109 subjects, Lord et al[76] measured the changes in lumbar lordosis between standing and sitting posture. The sitting posture was upright middle posture with 90-degree thigh-trunk angle and 90-degree knee angle; the feet were made to rest on the floor by adjusting the height of the seat. By using a Cobb angle from the top of L1 to the top of S1, the mean standing lordosis of 49 degrees was reduced to 34 degrees in the seated posture.

In another recent study, Yasukouchi and Isayama[77] measured lumbar lordosis and pelvic rotation of 20 male subjects in standing and 3 different middle sitting postures. The 3 sitting postures were based on thigh-trunk angles of 120, 90, and 60 degrees, which were obtained by changing the height of the seat bottom above the floor. To obtain the 120-degree thigh-trunk angle, they also had to incline the seat bottom forward. Additionally, they varied the knee angle at 60, 90, and 120 degrees in the two thigh-trunk postures of 60 and 90 degrees. Instead of radiographs, an inclinometer was used for lumbar lordosis. Taped skin markers were used on the armpits, iliocristale, trochanter major, and lateral epicondyle for thigh-trunk angle. Also, instead of radiographs for pelvic tilt, skin markers on the trochanter major and iliocristale were photographed and compared with a vertical line. They concluded that pelvic tilt was caused by different hip extensors to an extent dependent on changing the thigh-trunk and knee angles. Because skin markers are somewhat inaccurate because of elasticity of the stretching skin, their results may be less valid than radiographic studies. However, several investigators[77-79] have reported that lumbar lordosis was affected by the knee flexion angle.

In another recent study without radiographic measurements, Black et al[80] used a Metrecom, a 3-dimensional computerized digitizer, to mark the palpated points of the (1) anterior nasal spine, (2) mastoid process, (3) spinous process of T1, (4) palpation-derived body of T4, (5) suprasternal notch, (6) spinous process of L1, (7) spinous process of S2, and (8) anterior-superior iliac spine. They studied 3 different sitting postures: (1) middle sitting slumped, (2) middle sitting erect, and (3) anterior sitting with only pelvic rotation. Although trying to separate upper and lower cervical spine movements, they modeled the cervical spine as 3 rigid bodies: head, neck, and base of the cervical spine. The degree of lumbar lordosis was assessed by using a Cybex 320 electronic digital inclinometer. They used intraclass coefficients with repeated measures to show their method was repeatable; all intraclass coefficients were greater than 0.65 except head inclination, which was 0.48. Because of elasticity of the stretching skin and the use of palpation, their results are not as valid as those obtained in radiographic studies, but they claimed that flexion in the lumbar spine was accompanied by extension in the cervical spine, while the head orientation remained fairly constant.

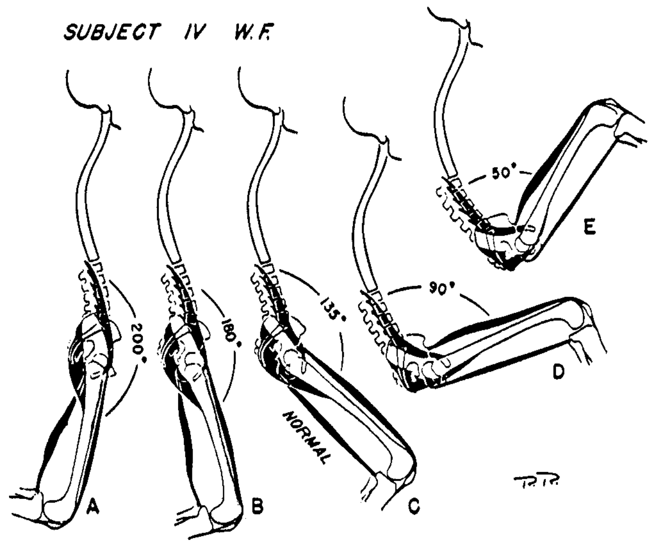

Fig 7. *Effects of altering the thigh-trunk angle in the lateral recumbent posture. Reprinted with permission: Keegan JJ. Alterations of the lumbar curve related to posture and seating. Reprinted with permission from* J Bone Joint Surg *1953;35-A:589-603.*

Effects of Seat Design

Bendix and Biering-Sorensen[81] studied the effects of seat-bottom inclination on 10 subjects. They studied 4 positions of the seat bottom: (1) level, (2) 5-degree forward inclination, (3) 10-degree forward inclination, and (4) 15-degree forward inclination. They used an inclinometer to measure the distances between 4 points marked with a Speed marker: (1) a sacral point near the spinous process of S2, (2) a lumbar point near the L1 spinous process, (3) a thoracic point near the spinous process of T4, and (4) the external occipital protuberance. The height of the chair was adjusted to keep the subjects' thighs horizontal and lower legs vertical. They observed their subjects for 1 hour of sitting in "a comfortable position with elbows placed on the table," which was provided. They noted an increase in lumbar lordosis with a forward increase in seat incline, and they hypothesized 3 possible ways of adapting the body to a forward-tilting seat bottom. Fig 8 illustrates these positions. Because their subjects' lumbar angles showed a 4-degree increase, these authors suggested that the position in Fig 8, *B*, occurred. Subjects rated the 0- and 5-degree inclines as most comfortable after 1 hour of sitting while reading. This study and other studies examining longer sitting periods confirm frequent leg crossing in seated subjects.[81-83]

The incline or slope of seat bottoms has been a subject of debate for more than 100 years. In 1884, Staffel[1] recommended a forward slope. Other profiles, such as level and backward slopes, have been suggested.[84-86] In Akerbloom's classic text,[6] he suggested 3 to 5 degrees of backward incline, which was actually proposed by Schulthess[87] in 1905. By

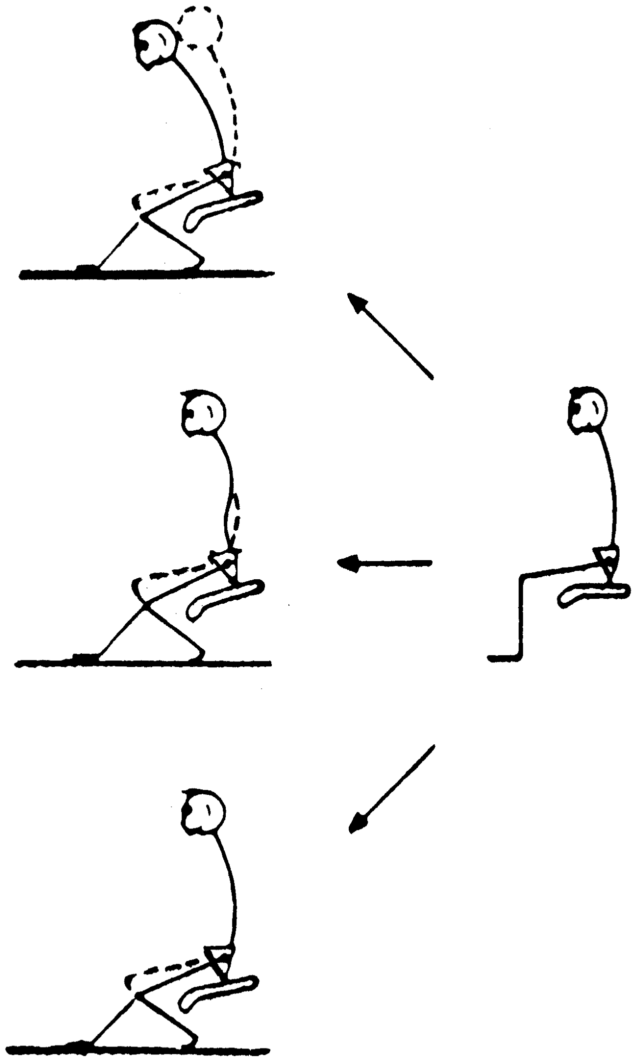

Fig 8. *Hypothesized 3 possible ways to sit on inclined seats. Bendix and Biering-Sorensen[81] determined that position A could not occur from their data and that position B was how their subjects adapted to forward-inclining seat bottoms.*

1958, Floyd and Roberts[29] suggested that the slope of the seat bottom should be changed to fit the job requirements. The horizontal seat allows freedom of movement, while the backward slope tends to move the subject against the backrest and lumbar support.

In 1953, Keegan[7] noted that seat-bottom height, when too high above the floor, could cause shorter people to have dangling legs. This position causes compression stresses on the soft tissues of the posterior thigh and becomes uncomfortable in a short period of time. Thus a short person sitting on a chair that is too high for him or her will soon sit on the edge of the chair and negate any seat-bottom incline or any lumbar support.

This situation can occur when the seat-bottom length is too long (seat depth).[29,84,88] The shorter person will not slide back against the backrest because of pressure at the posterior knee area. The minimum width is from trochanter to trochanter to allow support for the ischial tuberosities.[29,89]

Table 1. *Summary of seat-back inclination before 1972*

Author	Year	Suggested seat-back angle
Schulthess[87]	1905	100-105 degrees
Schede[4]	1935	Individual minimum*
Lay and Fisher[85]	1940	111-117 degrees
Morant[96]	1947	110 degrees for alert pilots, 110-125 degrees for rest position
Kroemer[90]	1971	90-120 degree range in review article

*When subject began to rest against the back support.

The maximum width would be to accommodate overweight subjects. The range of seat width and length in most references were between 35 and 40 cm for both dimensions.[90]

Seat-bottom contour has also been discussed in the literature. Various contour shapes have been proposed, including saddle-shape, molded to fit the buttocks, and sloping valley posteriorly. Attempts to conform the seat to the thighs have proved unsuccessful, and a flat surface has been suggested as optimal.[84] The pressure zones on flat seats were determined by viewing a naked person sitting on a glass plane or by using powder on a naked person to check for sitting impression.[91] Others[92-94] have studied the pressures under the ischial tuberosities and thighs in sitting. Brienza et al[94] presented their seating system structure, which has a support surface of vertical elements arranged in an 11 × 12 array. These elements depress linearly by the amount of pressure applied, thus forming a pressure distribution with measured values.

In 1962, Swearingen et al[95] studied the supporting structures for 104 subjects. The body weight is supported by 8% of the seat area under the ischia, which carries 64.8% of the weight. They observed that the remaining 35.2% is borne by the combination of footrests (18.4%), armrests (12.4%), and a backrest (4.4%) at 105 degrees. They believed that the small amount of weight carried by the backrest indicated that stability was achieved here, although not necessarily relaxation of the muscles.

The classic texts and review article by Akerbloom,[6] Keegan,[7,8] and Kroemer[90] presented reviews of the topic of seat-back design. Table 1[4,85,87,90,96] summarizes the recommended setback inclinations from 90 to 125 degrees. Seat-back height ranged from the inferior of the shoulder blades to the top of the shoulders. In Keegan's 1962 text,[8] he presented a rating system for evaluating 36 seats ranging from church benches to car and truck seats. He stated that manufacturers were ignoring ergonomic research on seat designs, and that seat-back incline research and lumbar support research were not being applied for the public comfort.

Kroemer[90] also discussed use of a lumbar support pad. Most references recommended a lumbar support in the range (3-5 cm) suggested by Akerbloom in 1948.[6] Majeske and Buchanan[97] investigated changes in the angular positions of the forearm, upper arm, pelvis, trunk, neck, and head in middle relaxed sitting with and without a lumbar support. Photographs of data markers placed on the subjects' skin were measured with a protractor. They claimed the various joint angles were more normal in sitting with a lumbar support. They also noted a reduction in anterior head carriage with a lumbar support. In 1991, Williams et al[18] studied 210 subjects with pain while sitting randomly assigned to kyphotic sitting or sitting with a lumbar support. When sitting with a lumbar support, their subjects reported significantly reduced low back pain and reduced referred leg pain. An increase in pain for kyphotic sitting subjects was found.

In 1971, Kroemer[90] also suggested armrests depending on the ergonomic requirements of the sitter. If free mobility of the trunk, shoulders, and arms was required, then armrests might be a hindrance. Otherwise, adjustable armrests are helpful in changing positions and for decreasing the load on the spinal column.

Before 1970, head restraints are not discussed. Especially in automobile impact research, head restraints were designed to reduce extension strains during whiplash. Recently, posterior head translation strains were considered a major factor in whiplash.[98]

The reader may have noticed that we have presented a history of seat design up to about 1970, with only a few references that are recent, and thus we have not yet presented the advancements in the past 30 years. In the later 1960s and early 1970s, a shift in research methods took place. Before 1970, most sitting "research" was (1) theoretical and based on the mechanical ideas of the particular authors, (2) based on the comments of comfort of the subjects, (3) based on the observed reactions of the subjects studied, (4) based on anthropometric averages of populations,[99] and/or (5) based on radiographic studies. Around 1970, 3 types of methods began to help the researcher sift through the multitude of personal opinions about sitting.

In the later 1960s, ergonomists began to develop comfort rating methods, which were made better with reliability and validity studies. In the 1960s, electromyographic studies of muscle activity in different postures began to appear. In 1970, Nachemson and Elfstrom[11] published their famous study on internal pressures in the intervertebral disc in various sitting and standing postures. They inserted needle electrodes into the lumbar discs (usually L3-L4) of live subjects. Many people believe that Nachemson and Elfstrom only studied disc pressure in lying, standing, and sitting, and that sitting caused the greatest disc pressure. However, they studied 17 body positions, including some in lifting weights. Fig 9 is from their study and illustrates loads on the discs in various positions.

In the cervical and lumbar areas, the annulus of the disc is wedge shaped, being thicker and higher anteriorly than posteriorly.[100-102] Measurements of disc pressure in vivo and in vitro have established lordosis in the cervical and lumbar areas as the normal configuration.[103,104] On the basis of in vitro studies, the pressure in the nucleus has been determined to be approximately 50% higher than that found during any externally applied vertical load when two adjacent vertebral bodies are parallel and much less than that found when in the normal, slightly extended position.[11,103,104] Any shift in load from vertical creates a concomitant myoelectric activity, which increases the load on the disc.[11] When standing erect, the normal vertebral column is straight in the anteroposterior aspect and curved in the lateral aspect; there is a cervical lordosis, a thoracic kyphosis, and a lumbar lordosis.[12] Thus some additional scientific information became available for later studies (1970-1998) to determine optimal seat designs and optimal seated positions for different ergonomic requirements.

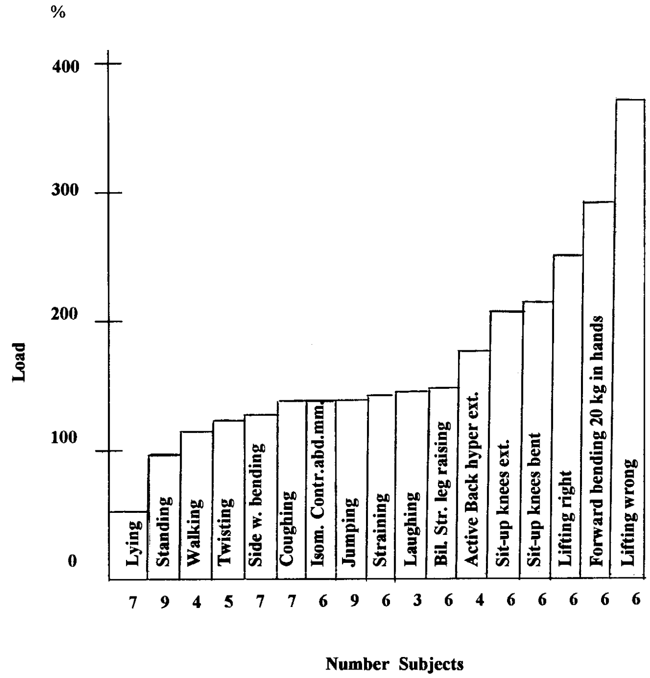

Fig 9. *Results of Nachemson and Elfstrom's 1970 study.[11] Mean change in load (%) compared with standing values.*

Optimal Seated Posture

Akerbloom[6] used electromyography to demonstrate that the support of the lumbar spine in seated posture is sufficient to rest the back muscles. In other early studies with electromyography in sitting, Lundervold studied typists in 1951[105] and 1958.[106]

In 1954, Basmajian and Bentzon,[107] and in 1958, Basmajian[108] studied muscles of the thigh, leg, foot, and the iliopsoas during standing posture. In 1955, Floyd and Silver[109] studied the myoelectric patterns of the erector spinae in standing posture. In a series of myoelectric studies in standing, Joseph and Nightingale,[110-112] Joseph et al,[113] and Joseph and Williams[114] investigated hip, thigh, and leg muscles.

In 1961, Carlsoo[115] examined muscles of the lower leg, thigh, hip, abdominal region, and neck in the standing posture with electromyography and then compared these readings with a multitude of abnormal postures and working positions.

One of the earliest studies of sitting posture with electromyography to determine an optimal seat-back incline and size of lumbar support pad was by Knutsson et al[9] in 1966. They studied 4 groups of subjects: normal subjects (n = 20), subjects with back pain without radiographic findings (n = 10), subjects with back pain with minor radiographic changes (n = 10), and subjects with back pain with severe

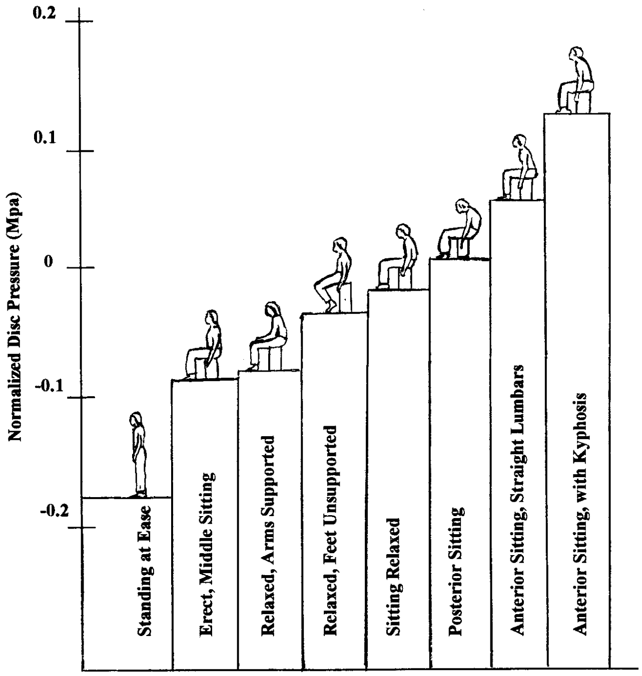

Fig 10. *Andersson et al's 1974 disc-pressure findings in unsupported sitting.[12-15]*

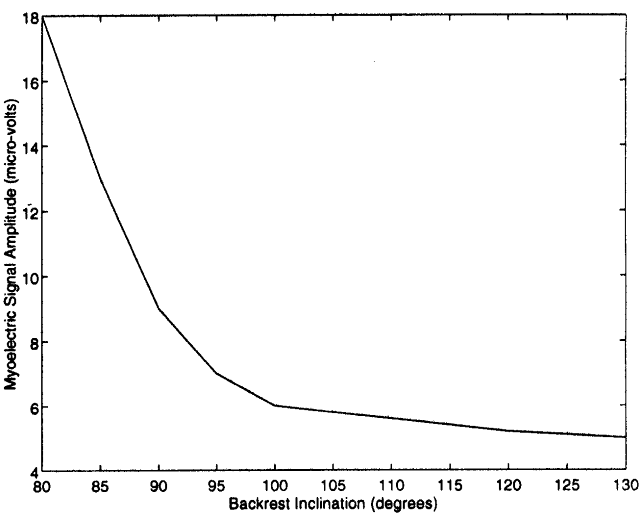

Fig 11. *Myoelectric amplitude reduces with increase in seat-back incline.*

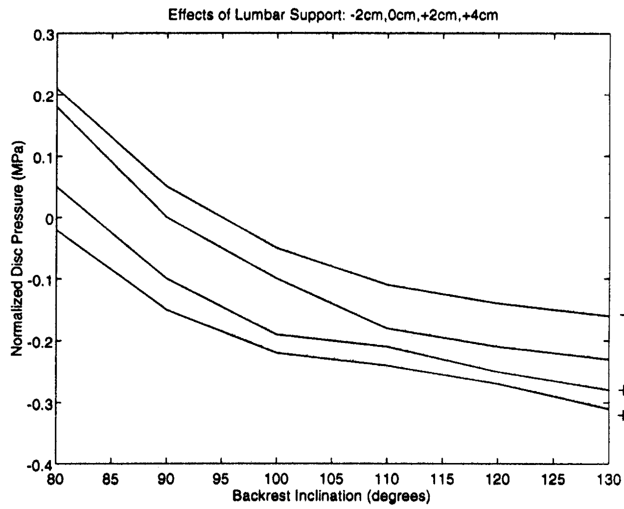

Fig 12. *Average values of normalized disc pressure (at 0.51 mPa) reduces with seat back incline and increasing horizontal lumbar support.*

radiographic findings of disc degeneration and spondylosis (n = 10). They studied middle sitting with two seat-back inclines of 100 and 110 degrees while varying the lumbar support pad at 0, 1, 2, and 3 cm. Patients sat against the seat back with knees at a 90-degree angle and hands resting on thighs. The electromyography readings favored a 110-degree seat-back incline and 1 to 2 cm of lumbar support, except for the severely degenerated patients who favored the 100-degree incline and 1 to 2 cm of support.

Many of the later studies of electromyography in sitting combined disc internal pressure and muscle activity. In a series of articles in 1974 combining disc internal pressure and muscle activity, Andersson et al[12-15] studied sitting in an experimental chair, sitting at a work table, sitting in a wheelchair, and sitting in an automobile seat. The 4 parameters studied were backrest inclination, seat-bottom inclination, lumbar support (height and amount of horizontal travel), and (upper) thoracic support. Andersson et al studied standing, 7 unsupported sitting positions, and supported sitting postures. They found that internal disc pressure was considerably higher in unsupported sitting than in standing. Increase in backrest inclination and increase in lumbar support was associated with a decrease in disc pressure in supported sitting. Myoelectrical activity was approximately the same for standing and relaxed unsupported sitting. For electromyographic readings, the highest level of activity occurred in anterior sitting, and the lowest occurred in posterior sitting. To obtain low values of both electromyographic readings and disc pressure, the authors stated that the backrest should be inclined to at least 100 degrees. Fig 10 shows disc pressure in the standing position and in their 7 unsupported sitting positions. Fig 11 shows their results of decreasing myoelectric activity with backrest inclination, whereas Figs 12 and 13 show decreasing disc pressure with seat-back inclination and the effects of support (lumbar support, thoracic support, and seat-bottom backward incline), respectively.

In 1974, Andersson et al[14] studied the effect of armrests on disc pressure and myoelectric activity. They found that the use of armrests further reduced the disc pressure and the myoelectric activity in the trapezius muscles. If armrests are too high, the subject must elevate the shoulders and abduct the arms.[116] If the armrests are too low, the subject must slide the buttocks forward or lean forward to use them. If the armrests are too far laterally, increased abduction of the arms and increased inward rotation of the humerus occurs. Fig 14 illustrates lower disc pressure, with changes in seat-back inclination, when using armrests compared with arms hanging.

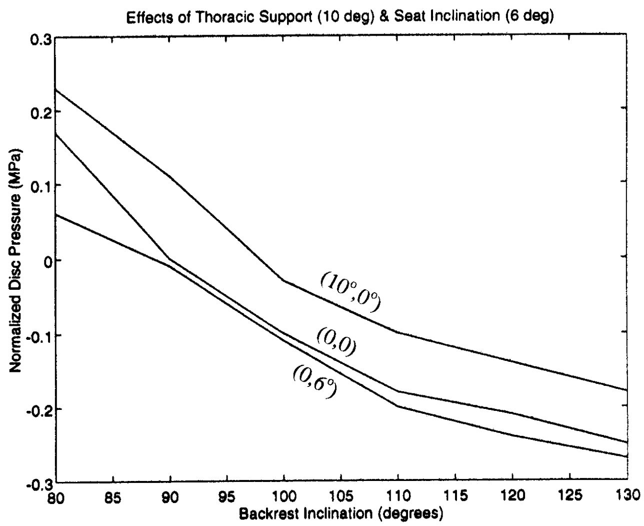

Fig 13. *Normalized (at 0.51 mPa) disc pressure decreases with seat-back inclination and seat-bottom posterior tilt but increases with use of thoracic support. Inside the parentheses, the first value is either 10 or 0 degrees for a support under the upper thoracic vertebrae, and the second value, 0 or 6 degrees, is for seat-bottom posterior tilt.*

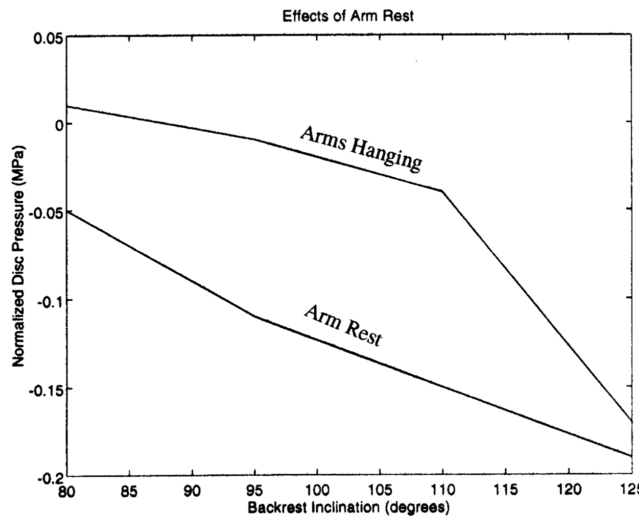

Fig 14. *Disc pressure (normalized at 0.51 mPa) is lower for the same seat-back incline when using armrests.*

Lumbar Lordosis versus Kyhosis in Seated Posture

The vast majority of authors have favored a lordotic lumbar spine, whereas a few[117-119] have advocated a flexed posture when sitting. The electromyographic studies and disc pressure studies just reviewed proved that flexion of the lumbar spine while seated caused an increase in load on the muscles and discs, whereas a lordotic posture greatly reduced these pressures. Still, in 1983, the flexed position while seated was promoted by Adams and Hutton.[117]

Adams and Hutton[117] loaded cadaveric lumbar motion segments for 4 hours, with some segments in flexion and some in extension. Flexed discs lost more fluid, especially in the nucleus pulposus. They concluded that fluid flow in flexed postures can aid the nutrition of the lumbar discs. Adams and Hutton seemed to discount the fact that it might be disadvantageous to lose fluid rapidly from the disc in a prolonged flexed posture.

In 1988, Dolan et al[118] studied 11 subjects in different postures, including standing and sitting, with surface electromyography. They measured the lumbar lordosis with electronic inclinometers. Their results confirmed data from previous studies that all sitting postures reduced the lumbar lordosis and increased electromyographic readings. They also noted that compressive forces on the apophyseal joints are reduced in flexed postures. They claimed that "people want to reduce the lumbar lordosis whenever possible, even at the expense of increasing back muscle activity." They appear to be influenced by a 1965 study on primitive peoples by Fahrni and Trueman.[119]

In 1965, Fahrni and Trueman[119] claimed that the incidence of lumbar disc disease was very low in people who habitually sit or squat in positions that greatly flex the lumbar spine. Although Fahrni and Trueman promoted squatting with feet flat on the ground, Keegan (Fig 6, *H*) had shown that squatting on the toes was associated with very good lordosis compared with most sitting positions. Fahrni and Trueman also neglected the idea that primitive peoples are generally more active, not overweight, in better physical condition, nonsmokers, and do not sit for prolonged periods as do modern people.

Finally, in the 1990s, Adams and colleagues began to reverse their minority-held opinion about sitting flexed postures being desirable in their published works in 1995[120] and 1996.[121] In a 1995 review of lumbar spine mechanics, they stated that the only known loading condition to cause posterior disc prolapse involved prolonged forward bending (flexion) with compression and lateral bending. In 1996, they noted in their review of the literature that the ability of the disc to act as a hydrostatic cushion depends on the high water content of these tissues, especially the nucleus pulposus.

The discerning reader realized that Adams and Hutton's 1983 study[117] had shown high water content loss in flexed postures and that they[121] may be about to reverse their minority position on flexion. They also noted that stress concentrations in the posterior annulus caused by prolonged flexion might be a common cause of pain from the disc. They noted that as the disc creeped under sustained loading, a small loss of fluid led to a large drop in pressure, and the compression load was transferred to the middle to outer annulus instead of the nucleus and inner annulus. They noted that the posterior annulus is affected most because it is the narrowest part of the disc and least able to sustain large compressive strains. This situation would occur on rising after prolonged flexion. They also note that these stress concentration peaks in the outer annulus can account for the observed collapse of the inner annulus into the nucleus and that this is caused by creep-related water loss from the nucleus.

In 1996, they wrote the following: "Pain originating from either of these mechanisms would be expected to increase

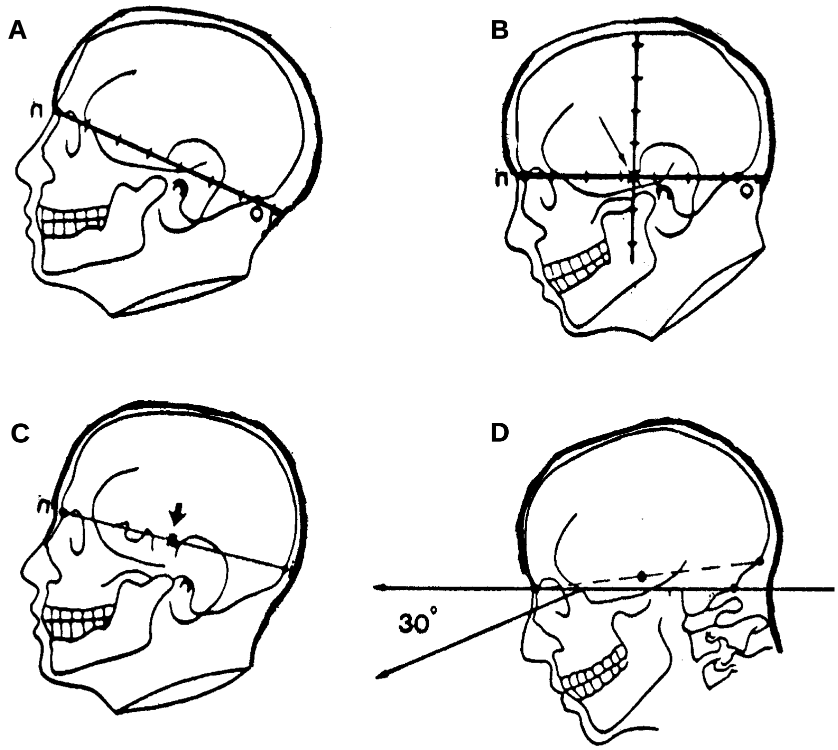

Fig 15. *Center of mass and neutral resting head posture. Vital and Senegas[128] found that suspension will result in the nasion-opisthion reference line becoming horizontal (**A** and **B**). Vital and Senegas located the center of gravity of the head at the midpoint of the nasion-inion line, just posterior to the sella turcica **(C)**. Vital and Senegas claim a comfortable gaze angle is declined 30 degrees to the nasion-opisthion reference line, when it is horizontal **(D)**.*

during the course of a day, especially in an individual who had spent a considerable amount of time with his lumbar spine flexed, so that disc creep would have been unchecked by the apophyseal joints. This would explain why prolonged automobile driving is so closely associated with back pain and disc prolapse".[121]

In 1997, Hedman and Fernie[122] studied anterior column forces and articular facet forces in the lumbar spine during sitting. They attempted to determine the relationship between seated forces and the mechanical responses in lumbar tissues. They loaded whole lumbar spines (L1-S1) in two postures, flexed and extended. Their results suggested a mechanism of force balancing in lordotic postures under static loads, whereas flexed postures produced large increases in the tensile forces in the posterior annulus.

Thus after 1996 the literature agrees that sitting with a lordotic lumbar spine is the preferred position. We now focus our attention on head and neck position.

Forward Head Position

From biomechanical[123] and epidemiologic studies,[124,125] strains on the cervical spine in the sitting position appeared to be related to increased forward inclination of the head. A forward position of the head can occur from anterior translation, forward flexion (x-axis rotation), or a combination of both. To understand forces on the cervical spine in sitting, it is necessary to review the cervical coupling patterns for anterior head translation and forward flexion. Also, the position of the center of gravity of the head will be important for discussing forces on the cervical spine in various sitting positions.

The location of the center of gravity of the head has been debated. Dempster[126] used volumetry to study the center of gravity of the head in 1955. Using only two cadavers, Biraune and Fischer[127] located the center of gravity of the head behind the sella turcica. Clauser et al[54] presented a thorough review of the literature for various body part centers of mass in 1969, with center of mass of the head located at the sella turcica. In 1986, Vital and Senegas[128] used a suspension technique to locate the head center of gravity of 6 cadavers "behind the sella turcica, above and slightly in front of the external auditory meatus."

They claimed that the nasion-opisthion reference line is the true normal orientation of the head because suspension makes this line horizontal (Fig 15). They determined that the center of gravity is the midpoint of the nasion-inion line (Fig 15, *C*). They also claimed that when the nasion-opisthion line is horizontal, it causes a 30-degree declined gaze position, which is formed by a perpendicular line to the orbits (Fig 15, *D*) and that this 30-degree declined position is recommended by ergonomists as a good working position.

In 1952, Kendall et al[43] described forward head posture as the external auditory meatus positioned anterior to a vertical postural line through the center of the shoulder joint. Patients seen in pain clinics frequently have postural faults.[35] Anterior head translation is one of these common postural positions.[129,130]

Determination of anterior head translation is clinically reliable.[131,132] In 1995, Haughie et al[133] showed that computer-terminal workers, who had more pain than their coworkers, had more anterior head translation, less range of motion in extension, and more medical visits.

Many physical problems have been associated with forward head posture, including the following: (1) increase of upper cervical curvature (C1-C4); (2) decrease in lower cervical curvature (C5-T1); (3) alteration of the upper thoracic kyphosis; (4) protraction, elevation, and downward rotation of the scapulae; (5) internal rotation of the humeri; and (6) elevation of the first and second ribs.[134-137]

Penning, in 1978[138] and 1995,[139] was the first to describe changes in cervical lordosis with anterior-posterior head translation. He reported that the upper segments (C1-C4) extended while the lower cervical vertebrae (C5-T1) flexed in anterior head translation. Hanten et al[46] have measured resting head posture and total head excursion, which is forward and backward head movement in translation, in 218 adults. For men, the average head excursion was 11.4 cm, and for women, it was 10.0 cm.

Eklund et al[140] investigated head posture in drivers of fork lifts, trucks, forestry machines, and cranes. They determined that head axial rotation was a frequent cause of pain in these workers and that forward head postures and forward body positions occurred in bad lighting conditions.

Flexion of the cervical spine has been studied by many investigators and recently by Dvorak et al.[141] Loss of cervical lordosis occurs in flexion, which causes increased disc pressure and increased electromyographic readings in the cervical musculature. However, the most important effect is tension on the cervical spinal cord, brain stem, and nerve roots.[142] Flexion is often found in desk workers and typists.[143] Fig 16 illustrates attempts by ergonomists to reduce back and neck stress with tilting seat bottoms and tilting stands for reading materials. However, this position still results in neck flexion. It will be shown in a later section that this is a common problem for drivers of automobiles.

Consensus by Comfort Ratings

It is interesting to note that carefully designed ergonomic chairs are often rejected by subjects in the workplace. In 1997, Christiansen[144] stated that "sitting comfort, a state of physical well-being, is a personal sensation." The feeling of comfort cannot be measured directly, and often it has been deduced from 3 principles: (1) the fit of the chair to the subject's body type, (2) the subject's performance or behavior while seated, and (3) the subject's assessment of his or her state of comfort (or discomfort). Although the electromyographic, disc-pressure, and radiographic studies previously mentioned are examples of item 2, much research has gone into items 1 and 3.

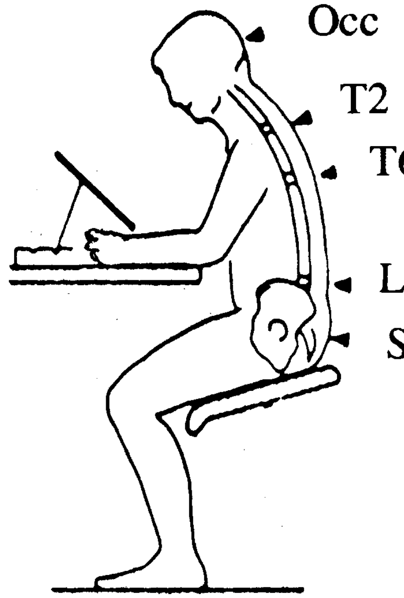

Fig 16. *Ergonomic chairs and reading material stands reduce but do not eliminate neck flexion.*

Body size and shape has been a topic of ergonomic research for 100 years. Before adjustable chairs, work chairs were made to fit the 50th percentile in body size. For an example of body dimensional research in 1997, Greil[145] studied 42,000 Germans, aged from birth to 70 years. Percentiles of trunk-cephalic height, trunk length, depth of lower trunk, maximum sitting breadth, vertical thigh diameter, lower leg and foot length, backrest-heel distance, and additive arm length were presented by sex, age, and type of body shape.

In each category (items 1-3) there are researchers who are adamant that their particular assessment for proper sitting posture is the best. For example, in 1969, Shackel et al[146] stated that "a further and conclusive reason for our concentrating upon subjective measures is inherent in the context of studying chair comfort in relation to individual users choosing for themselves, namely the ultimate criterion must be the subjective judgment of a representative sample of users."

Comfort ratings come in a variety of methods.[146-148] For a modern statistical analysis, Helander and Zhang[149] studied comfort and discomfort in sitting. Genaidy and Karwowski[150] presented a review of constrained body postures and deviations from the neutral posture over a long period while working. These postures have been associated with discomfort, pain, disc degeneration, high risk of arthritis, inflammation of tendon sheaths, muscle spasms, and general pain.

People generally avoid static positions for prolonged periods by frequently moving while standing and sitting. In 1967, Branton and Grayson[151] observed that people frequently change positions while waiting at train stations. They noted that certain postures (eg, leg crossing) occur significantly more often and for longer durations. In 1969, Branton[152] provided a review of 45,000 sitting observations, including time-lapse films, and concluded that chairs must allow for changes in position. Branton pointed out that this frequent movement of sitters is not just an "urge to move" but that certain postures occur more frequently for specific types of chairs and for tall versus short people. Branton noted that, by speeding up time-lapse films of sitters, certain sequences of postural changes occurred at least 12 to 16 times during 5-hour periods.

Branton[145] categorized sitting postures into 4 groups, which were described as follows: (1) minimal support derived from seat (3.3% of time, 3 minutes in duration); (2) full back support from seat and armrests (49.5% of time, 15 minutes in duration); (3) slumped. with some support from seat and armrests (23.4% of time, 11 minutes in duration); and (4) all other postures (23.8%, 5 minutes in duration). He noted that people often need to extend their legs and cross their ankles, which appeared to be a stabilizing position for the pelvis similar to crossing the knees. Change of position is thought to reduce ischemia of the tissues, but then the long duration of certain postures is unexplained.

In general, our cited references published before 1950* are opinion papers based on the best estimates of ergonomics, biomechanics, and observations. However, most of the references on posture[32-36,39-50] and spinal modeling[51-74] have reliability, validity, precise engineering measurements, and/or clinical data with statistics. The studies on sitting biomechanics,[75-81] seat design,[82-83,90-104] and optimal seated posture[105-116] are mostly recent articles with multiple subjects and clinical statistics with electromyographic data. The articles cited for lumbar lordosis versus kyphosis in the seated position[117,118,120-122] have biomechanical measurements in laboratories, whereas the citations on forward head posture[123-143] are large population clinical studies or randomized clinical trials. The studies on comfort ratings in sitting positions are based on patient questionnaires with statistical evaluations.

CONCLUSION

Sitting biomechanics has a long history in the literature. Posture and lower extremity positions have been reviewed here with the neglect of upper extremity positions, which can be found in the ergonomics literature. Since 1970, electromyography and disc-pressure studies have settled some debates about the ideal sitting position. Oftentimes, the theoretic ideal chair and sitting position are not preferred by subjects' comfort ratings.

Lumbar supports, armrests, seat-back inclination, freedom to move, freedom to cross the knees or ankles, adjustable heights of chairs, curved anterior seat bottom to reduce pressure on the popliteal area, and minimal anterior translation and/or flexion of the head have been shown to reduce sitting stress and to be associated with higher comfort ratings. By using electromyographic results and internal disc pressures, the optimum seat-back angle appears to be 120 degrees from horizontal, whereas the seat-bottom optimum appears to be approximately 0 to 10 degrees posteriorly inclined. The lumbar support optimum appears to be 5 cm of protrusion from the seat back. The seat height should be less than the distance from knee to feet to eliminate pressure on the posterior popliteal area. The special subject of optimal seating in a car seat will be the subject of part II of this review.

*References 1-6, 20-22, 25, 28, 37, 38, 84-89, 96.

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