REVIEW OF THE LITERATURE

Sitting Biomechanics, Part II: Optimal Car Driver's Seat and Optimal Driver's Spinal Model

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ABSTRACT

Background: Driving has been associated with signs and symptoms caused by vibrations. Sitting causes the pelvis to rotate backwards and the lumbar lordosis to reduce. Lumbar support and armrests reduce disc pressure and electromyographically recorded values. However, the ideal driver's seat and an optimal seated spinal model have not been described.

Objective: To determine an optimal automobile seat and an ideal spinal model of a driver.

Data Sources: Information was obtained from peer-reviewed scientific journals and texts, automotive engineering reports, and the National Library of Medicine.

Conclusion: Driving predisposes vehicle operators to low-back pain and degeneration. The optimal seat would have an adjustable seat back incline of 100° from horizontal, a changeable depth of seat back to front edge of seat bottom, adjustable height, an adjustable seat bottom incline, firm (dense) foam in the seat bottom cushion, horizontally and vertically adjustable lumbar support, adjustable bilateral arm rests, adjustable head restraint with lordosis pad, seat shock absorbers to dampen frequencies in the 1 to 20 Hz range, and linear front-back travel of the seat enabling drivers of all sizes to reach the pedals. The lumbar support should be pulsating in depth to reduce static load. The seat back should be damped to reduce rebounding of the torso in rear-end impacts. The optimal driver's spinal model would be the average Harrison model in a 10° posterior inclining seat back angle. (J Manipulative Physiol Ther 2000;23:37-47)

Key Indexing Terms: Sitting; Biomechanics; Lordosis; Ergonomics; Spinal Model; Motor Vehicles; Whiplash Injury; Chiropractic

INTRODUCTION

Although the ergonomics of sitting in a factory or office have been studied extensively, the biomechanics of automobile drivers and passengers have received less attention. Recently, because of a complete void in the literature for a seated driver's spinal position, an automotive engineering firm requested that the authors determine an optimal driver's spinal model. Because the design of a driver's seat directly affects the driver's spinal biomechanics and extremity ergonomics, the design of an optimal car seat is also of interest.

To accomplish these 2 goals—optimal driver's seated spinal model and optimal car seat design—we searched automotive engineering American National Standards, automotive engineering reports, Index Medicus at the National Library of Medicine (1949 to 1998), and relevant texts.

DISCUSSION

Epidemiology

Patients with low-back pain frequently report an intolerance to sitting; their severity of pain is inversely related to the ability to change posture if seated.1 2 People without history of low-back pain still have neck pain, back pain, and sciatica after prolonged static sitting.3 Drivers have little room to change posture because of being confined to a small space by the constraints of control positions, pedals, and vision requirements. Drivers are in a high-risk group for spinal disorders, including back pain, neck pain, sciatica, spondyloarthrosis, degeneration, and herniated discs.4 12 Kelsey2 and Kelsey and Hardy6 found that truck drivers were 4 times more likely to develop a herniated lumbar disc. Professional driving frequently involves known risk factors such as prolonged sitting, ergonomic factors, whole-body vibration, twisting and bending, and heavy lifting. Rosegger and Rosegger11 reported that 70% of tractor drivers had premature degenerative changes in their spines as evidenced by radiography.

Anderson et al13 studied muscle activity (electromyography [EMG]), intradisc pressure, and optimal positions for car seats. Although sitting has been indirectly blamed for a multitude of health problems, vibration of drivers has been directly linked to pain and degenerative diseases of the spine. It is thought that dense foam in the seat bottom will reduce vibration to the occupant from the car.

Recently, Jurgens14 presented a review of seat pressure distribution and seat bottom contour. In 1996, Brienza et al15 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. Fig 1 illustrates the seat-pressure distribution in a soft seat without lumbar cushion compared with a firm seat with lumbar support. However, more must be done than incorporating denser foam to dampen vibrations.

**Vibrational Effects**

Many studies have shown that low-back pain and degenerative diseases of the spine occur more frequently in drivers than in the general population. In 1987, Heliovaara discovered that vibration was the greatest occupational risk factor among many types of workers. Investigators have pinpointed specific vibrational frequencies and vibrational magnitudes that cause resonance in the upright spine. At certain natural frequencies, the spinal system will absorb and transmit motion in excess of the input. This mechanic behavior is characteristic of a resonating system. In 1982, Wilder et al identified 3 frequencies that cause the spine to resonate: 4.75 Hz, 9.5 Hz, and 12.7 Hz. Fig 2 illustrates a typical subject’s response to vibration at frequencies from 0 to 20 Hz. In the Wilder et al study, resonance meant that the spine vibrated vertically more than would be expected for applied loads.

In 1980, Pope et al reported that many vehicles, including light trucks, jeeps, motorcycles, vans, and buses, vibrate in the 3.0 to 6.0 Hz range, a range that includes the largest amplitude found for human spine resonance, approximately 4.75 Hz. In 1986, Panjabi et al showed that spinal resonance was much more involved than just the vertical resonance previously measured. They measured vertical, horizontal, and rotational vibrational resonance of the spine at specific frequencies. They determined 4.4 Hz as the largest amplitude of resonate spinal frequencies and determined that the resonance of the sacrum and pelvis were significantly higher (9% to 18%) than in the lumbar vertebrae. They hypothesized that the lumbar lordosis’ flexibility caused a decrease in the resonate frequency of the vertebrae.

Dieckmann in 1957 and Coermann in 1962 compared the movement of the head with the input at the seat to measure spinal resonate frequencies in the 4.0 to 8.0 Hz range. In 1966, Christ and Dupuis determined 4.0 Hz as a resonate spinal frequency in the vertical and horizontal directions.

Bovenzi and Zadini discussed the mechanisms of low-back injury from vehicle vibrations and spinal resonance. They stated that EMG measurements obtained during vibration (based on Seide and Seroussi et al) are not protective. In fact, the enhanced muscle tension increases the load on the vertebral bodies and discs. This causes fatigue and pain and results in an increased susceptibility of the spine to injury. From Brinckmann et al and Hansson et al, cyclic compression loading on the spine in vitro caused degenerative changes, such as end-plate defects and fractures in subchondral trabeculae. The rotational and translational resonance found by Panjabi et al indicates that the combination of torsional stresses with axial loading are likely to cause anular ruptures or spondylolytic fractures, as hypothesized by Froom et al in 1984. Although it might
seem a large step to apply experimental results in the laboratory to real-work environments, the autopsy evidence of increased occurrence of ruptures of the anulus fibrosus in driving occupations\textsuperscript{45} seems to unite both experimental and epidemiologic studies.

Magnusson et al\textsuperscript{34} used a uniaxial accelerometer between truck drivers' seats and buttocks to record vertical accelerations of the truck seat during normal working conditions. A typical vertical vibrational spectrum from a truck ride is illustrated in Fig 3. Note that only 2 of the 3 human spine resonate frequencies (4.74 Hz, 9.7 Hz, 12.7 Hz) are directly being affected by the truck vibrations.

In Sweden, truck seats are damped between 4.0 and 6.0 Hz to reduce the human spine natural frequency with the largest amplitude during vibrations (ie, 4.75 Hz). Magnusson et al\textsuperscript{34} have reported a significant difference in reported injury complaints between US truck drivers (no dampening) and Swedish truck drivers (with seat dampening at 4.0 to 6.0 Hz). The spectrum in Fig 3 clearly shows the dampening of the Swedish truck seat at 4 to 6 Hz.

A voluminous amount of material has been reviewed from the literature on the biomechanics of seated posture, effects of seat design, and ergonomics of sitting.\textsuperscript{46} Our focus is on car driver's seats. With these ideas from the literature, it is possible to discuss specific aspects of an optimal driver's spinal model and an optimal design for an automobile seat.

**Automobile Drivers**

A review of the extensive literature on sitting biomechanics reveals only a few papers in which with automobile drivers are the subjects.\textsuperscript{13,47-49} In 1974, Andersson et al\textsuperscript{13} studied 4 adult subjects in a Volvo seat adapted for adjustion. Fig 4 illustrates this car seat. They studied 3 support parameters: seat back inclination, seat bottom inclination, and lumbar support. They determined that the lowest level of myoelectric activity was at 120° backrest inclination, horizontal lumbar support of 5 cm, and seat bottom inclination of 14°.

In 1986, Hosea et al\textsuperscript{49} studied the myoelectric activity of 12 men who were driving automobiles. They claimed that the Andersson et al\textsuperscript{59} study was limited by the small number of subjects (4), small time period studied (12 seconds), fixed position of subjects (arms on steering wheel, head forward, eyes fixed straight ahead), and use of a car simulator. The Hosea et al\textsuperscript{49} EMG recordings were obtained for 12 back muscle groups, including the lumbar, thoracic, cervical, and trapezius areas. Over a 3.5-hour period, they varied the backrest inclination at 100°, 110°, 120°, and 130°; seat bottom inclination was varied at 14.5° and 18.5°; and lumbar support was varied at 3 cm, 5 cm, and 7 cm of horizontal movement. All EMG readings were small and decreased with increasing seat back inclination and increasing lumbar support except (1) a slight increase in EMG readings in the lumbar area at 130° compared with 120°, (2) an increase in thoracic and lumbar EMG values for the 7-cm lumbar support, and (3) a slight increase in EMG values for the seat bottom inclination at 18.5° compared with 13.5° in the thoracic and lumbar regions.

In 1997 Fubini\textsuperscript{47} presented a review of the technical requirements versus the comfort in automobile seats. He stressed safety and comfort. He suggested that it was possible to extend to car seat design the validity of some basic ergonomic requirements that Occhipinti et al\textsuperscript{50} have applied to the design of office seats. The seat with seat belts must restrain driver and passengers, provide comfort, and protect occupants from injury such as whiplash. The seat structure should absorb energy with deformation such as front, rear, and side impacts. The seat adjustment switches and safety belt attachments must not conflict. A number of international regulations and standards are set forth in the Society of Automotive Engineer's (SAE) Motor Vehicle Seating Manual.\textsuperscript{51}

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**Fig 4.** 1974 car seat simulator. Five items are adjustable when measuring disc pressure and EMG recordings: 1, seat back inclination, 2, lumbar support height and depth, 3, seat bottom height above the floor, 4, seat distance to dash, and 5, depth of brake pedal displacement.

**Fig 5.** Physiological effects at different frequencies. Besides the vibrational resonance found in humans in the 0 to 20 Hz range, there are a multitude of other vibrational side effects.
The goal of increasing comfort aims to reduce driver fatigue and avoid musculoskeletal disorders. To do so, the seat shape, upholstery characteristics (contour, firmness, etc) and covering materials, seat bottom height, seat bottom tilt, seat back angle and contour, lumbar support, head rest support, and arm rests must be as important as the ergonomics for office chairs. These factors contribute to dynamic comfort, which is very important. However, there are many more effects than just the resonant frequencies. Cole discussed 13 human disorders caused by frequencies between 0 and 105 Hz; these are illustrated in Fig 5.

The majority of physiologic effects from vibration occur below 20 Hz (Fig 5). To reduce these vibrations in car seats, the trend has been to reduce the use of seat springs and use a thick, firm foam. However, the best method is the additional use of shock absorbers to eliminate certain frequencies, such as is done in Sweden (Fig 3). In Sweden it has been the accepted practice to use such shocks only on truck seats, in which much driving is done during the workday. Why isn’t this practiced more widely?

The optimal sitting spinal model will be suggested to accommodate an ideal sitting spinal model and human posture. The beginning standing position will be the Harrison normal spinal model, which is the only standing model in the literature with precise segmental spinal angles and pelvic position. This position will be altered as changes are made to the car seat and supports.

It is reasonable to suggest that all automobile seats be damped with shock absorbers, at least in the 3 resonate frequencies of the human spine. The evidence suggests there are benefits from dampening all frequencies from 0 to 20 Hz. Fiat marketing research found that during the workweek, 90% of cars have only the driver’s seat occupied. During holidays, 64% of vehicles have only the driver and one passenger. Only medium-sized cars have a third passenger, who 77% of the time sits behind the passenger. Thus it would appear that at least the front seats and perhaps the rear seat behind the front passenger should have shock absorbers. Because the space below the front seats must be sufficient to accommodate the feet of the rear passengers, the extra height needed to fit shock absorbers to the front seats is not a problem, except possibly for the 95th percentile male driver’s head room.

**Fig 6.** SAE automobile seat mannequin. This mannequin is known as the H-Point machine. It is used to check for the size of the driver’s space, fit of the seat, and ability of seat foam to resist the load applied as weights.

**Fig 7.** Changes in the angle of pelvic tilt when standing (50°), when rotated 40° posterior in middle sitting, and in driver’s seat with 120° seat backrest incline. A, The standing average angle of pelvic tilt, measured as incline of postero-inferior S1 to a horizontal at the top of the femur head, is 50°. B, The pelvis rotates 40° posteriorly on the x-axis (extension) in the middle sitting position, whereas the lumbar lordosis is flattened. C, The lumbar support increases pelvic rotation and lumbar lordosis. The ideal pelvic rotated position is 35° on a firm seat with lumbar support, with 10° seat bottom incline, 5° depression into the seat bottom, and 120° seat backrest incline.
Fig 8. Ideal backrest angle of 120° causes abnormal 30° head flexion of the driver.

can be established and the amount of lumbar support determined. Harrison et al55 have defined the normal pelvic rotation (arcuate line compared with horizontal) while standing at 50° between posterior-inferior S1 to top margin of the acetabulum on the lateral radiograph (Fig 7, A). In the middle sitting position (Fig 7, B), Schoberth56 reported that the mean posterior rotation of the pelvis was 40° when changing from standing to relaxed middle sitting. Thus this Harrison et al55 arcuate line would be 10° from horizontal before addition of a lumbar support. Fig 7, C illustrates this pelvic position in a slightly depressed position as a result of firm foam on a typical car seat. The apparent angle of seat bottom to floor and seat bottom to seat back angle are altered as a result of the pelvic depression into the seat bottom and seat back.

Use of a 4- or 5-cm (adjustable) lumbar support will rotate the pelvis forward and increase lumbar lordosis. Keegan57 showed that sitting with a lumbar support resulted in a lumbar curve value between the values for standing and erect middle sitting. However, without exact values, it can only be determined that erect middle sitting has a larger arcuate pelvic angle than relaxed middle sitting. The needed size of the lumbar support will depend on the size of the person. However, taking a conservative 35° angle for the arcuate line to be horizontal with a 5-cm lumbar support, the result would be a lumbar curve with a Cobb angle larger than 34° between L1 and S1.58

To preserve a trunk-thigh angle of at least 105°, an angle necessary to preserve lumbar lordosis,59 the seat back angle to seat bottom must be at least 110° as a result of pelvic depression into the foam. If the seat bottom is 10° to the floor, then the seat back will be 120° to the floor (adjustable). These ideas are illustrated in Fig 7, C.

The seat back angle of 120° has been reported as the optimum.59-61 Because the knee flexion angle62-64 has affected lumbar lordosis and because drivers sit with a small knee flexion angle (approximately slightly less than 45°), then one might believe that the seat backrest angle should be greater than 120° to preserve lordosis. However, this does not reduce the head flexion necessary for proper vision through the windshield. Fig 8 illustrates that the head would be flexed an abnormal amount (30°) in the seat position suggested in Fig 7, C.

Williams and Lissner65 demonstrated that neck muscle forces needed to keep the head in a balanced position increased proportionally with the sine of the angle of forward inclination of the head. In an effort to determine neutral resting head posture and direction of view angle, Snijders et al66 hypothesized that a 15° gaze angle below the horizontal was a neutral position. With a computer program, they calculated that a retroflexed (extension) angle of 30° from this neutral position is where the neck muscle effort was at a minimum. To check this theoretical head position, de Wall et al67 calculated the expected and actual head positions of 10 subjects connected to electronic goniometers when their computer screens were 15° inferior to horizontal and 15° above horizontal over an 8-hour period. They found that subjects preferred the computer screens to be at eye level and adjusted their gaze position instead of their head position when the computer screen was high or low. However, they noted that the subjects' whole body postures were more normal when using the horizontal or high position of the computer screen.67 This suggested that the inferior 15° head flexion position was not normal. This negates the theoretical 30° inferior flexed head position suggested by Vital and Senegas.68

In consideration of the large head-flexion angle caused by the ideal backrest angle of 120° from horizontal suggested by Andersson et al,59-61 it becomes apparent that this backrest angle must be reduced to lessen the loss of cervical lordosis caused by such a large flexion of the head to thoracic cage (30°). As shown on the Andersson et al13 graphs, there is not much difference in EMG readings between a backrest
angle of 100° and 120°. Also there is not a large change in disc pressure from a backrest angle of 100° to 120°. The seat bottom inclination did not affect the disc pressure in a significant manner, and the use of arm rests made a significant difference in disc pressure (lower).

Thus the seat back angle can be reduced to 100°, the seat bottom incline to 5°, and arm rests added while maintaining low EMG readings for the postural muscles, and low disc pressure values while driving. This will cause only a small, well-tolerated, 10° head flexion angle, but a reduced knee flexion angle will occur unless the seat is raised (Fig 9).

Because the seat bottom cushion depresses more than the seat back in near upright sitting, the trunk-thigh angle is close to 95°. To reduce the disc pressure and EMG recorded values, armrests are needed, but at what height and lateral distance? To discover an upper arm position that reduced sick leave, employee turnover, and rehabilitation costs at a telephone factory in Norway, Aaras determined that the arm flexion (humerus) should be less than 15° and arm abduction less than 10°. Of course, many drivers will grip the upper half of the steering wheel so the arms are in a state of relaxed hanging. One could argue that humerus angles need to be directly studied in drivers.

However, if the armrests, when used, are adjusted to allow the normals determined by Aaras, then static trapezius load is at a minimum and disc pressure is reduced (Fig 9). With arms bent and elbows on armrests, the steering wheel must be adjustable.

From the preceding information, several recommendations can be made for different-sized adults to accommodate the position depicted in Fig 9. Before doing so, it should be mentioned that shorter persons would have the back of the knees in contact with the front edge of the seat bottom when the 95th percentile of human weight is used for seat design, according to anthropometric studies. Therefore, one of our recommendations will be that the seat back be able to move forward-backward in relation to the seat bottom to alter the front-back depth of the seat bottom. In addition, adjustable armrests bilaterally are needed on most vehicles. If present, usually only the right armrest is attached to the driver's seat, and it is not adjustable. An armrest is often considered to be present on the driver's door where the window and door lock switches are located. However, this is not a suitable armrest. It is never adjustable and is usually too low to be used.

**Head Restraint**

One of the final recommendations in this paper concerns the headrest, which is missing from the optimal car seat and optimal seated position of an automobile driver in Fig 9. The headrest should be adjustable, not only vertically, but horizontally. It is uncomfortable to sit in a car seat with a headrest that pushes the head forward into an anterior translated position. The headrest should have a convex surface similar to the lumbar support. Whereas the lumbar lordosis has been modeled with an ellipse with deeper curve at L3-S1, the cervical lordosis has been modeled successfully with an arc of a circle. Thus the contour of the cervical support on the head rest will be smaller and more uniform in shape compared with the lumbar support. It must still be composed...
of a soft enough foam density to be comfortable when fully leaning the head backward for rest.

The human body has a vertical vector component of force during whiplash. Thus the head tends to translate above the height of a low headrest and then be left behind, as a result of inertia, as the car seat system moves forward. This causes the head to extend around the headrest and be more vulnerable to traction and shear forces. From the tractioned posterior, extended position the head has higher acceleration, and the anterior compression, as the head flexes, is greater as the chin strikes the chest or the head hits the steering wheel or dashboard. To avoid this situation, the headrest must extend above the driver’s head. Fig 10 illustrates the necessary headrest height and adjustable circular horizontal support for the cervical lordosis.

As shown in Fig 9, the change in the seat backrest angle from 120° to 100° and the change in seat bottom incline by 5° has caused a change in the pelvic angle of tilt (arcuate) from 35° to 50°. This angle is the normal pelvic tilt found in standing posture.55,70 If the lumbar support is somewhat elliptical in shape and is applied approximately 5 cm at the top of posteroinferior iliac spine area of the pelvis, then the driver’s sitting lumbar curve will be close to the normal curve while standing. If the head rest is circular in shape and applied at mid neck with a concave identification for the back of the head, then the sitting spinal model in an ideal driver’s seat will be nearly identical to the standing spinal model determined by several other studies.70–73 The average cervical, thoracic, and lumbar posterior tangents at C2–C7, T3–10, and L1–L5 measure 34°, 35°, and 40°, respectively. Fig 11 illustrates the normal sitting spinal model in an ideal driver’s seat with adjustable lumbar and cervical supports. The head nods 10° on the top vertebra to bring the line of eyesight to horizontal without flexing the neck. This is also a comfortable position, which a person should be able to maintain for long periods without fatigue.

Seat Design Aspects to Protect the Occupant During

The term “whiplash” was coined in the 1920s to describe the resulting injury from violent head and neck retraction, and over the years our understanding of this commonly maligned and misunderstood condition has continued to evolve.

“Whiplash” describes the mechanism more than the clinical nature of the problem, but the search for a more accurate term was hampered by early theories about occupant kinematics that were simplistic and incomplete. This led to a number of cumbersome and inaccurate terms, such as “hyperextension/hyperflexion injury.” More recently, “cervical acceleration/deceleration injury” has been suggested.77

Pioneered by early crash test researchers,78–80 head restraints made a late entrance into federal motor vehicle safety standard law in 1969 in the United States. However, they varied widely in design from one manufacturer to another and were developed in a near vacuum of biomechanic and clinical understanding. Consequently, large epidemiologic studies consistently reported only marginal (11% to 14%) success in reducing injuries to occupants in rear impact crashes.81–84 Several factors account for this dismal result. Chief among them is the failure of 83% of drivers and passengers to properly adjust the head restraint.85 Another is the inherent difficulty in designing seats for the majority of occupant statures. The male driver whose stature is in the 50th percentile is usually chosen as a compromise, leaving drivers in the 95th percentile (more than 6 feet 2 inches in height) grossly unprotected even with the restraints in the optimal position. Yet another variable is occupant posture and position.

When the driver slouches, as studies have shown many do, the backset—the distance between the head and the restraint—increases markedly. Backset also increases as seat back inclination increases. Moreover, on rear impact the occupant’s torso will impact the seat back and ramp up a variable distance depending on numerous factors, including the frictional interactions between seat material and occupant clothing, occupant weight, the use or nonuse of lap belts, and the inclination and stiffness of the seat back. Forward-slouching occupants will interact more violently with the seat back and have more even ramping.86–91

Full-scale crash tests with human volunteers have demonstrated that the overall vertical motion of the lap-belted occupant’s head in rear impacts as low as 8 km can be as much as 3.5°.92 Part of this rise is thought to be the result of a straightening of the lumbar, thoracic, and cervical curves caused by the rearward thrusting of the seat back. Thus a head restraint height that appears adequate in the resting position may be too low when ramping occurs. This was, in fact, observed by McConnell et al93: the heads of the volunteers ramped above the restraints, striking them on their tops and driving them into the lowered position. Thus analysis of the restraint, once adjusted, is another important design feature currently lacking in many passenger vehicles.

As recently as 1997, the Insurance Institute for Highway Safety evaluated the geometry (ie, height and backset) of the head restraints of 167 modern passenger cars, light trucks, and minivans and rated only 5 as “good,” whereas 117 received “poor” ratings even when adjusted to optimal positions.93 However, geometry is only one of the considerations in the design of head restraints. Because the head can strike the restraint with considerable force, the head may rebound with sufficient force to aggravate the injury kinematics.86–93

Indeed, as a result of the interactions between occupant and vehicle, significant occupant overspeeds of up to 70% are possible: the occupant’s speed change is usually significantly higher than that of the vehicle, while the head linear acceleration is usually 2 to 3 times that of the vehicle.78–80,92,94–96 Ideally, the mechanic properties of both head restraint and seat back should be tuned so that the energy imparted (vis-à-vis coefficient of restitution) from this head restraint/seat back system will be uniform.

For many years, authors have debated the relative merits of stiff versus flexible seat backs as they concern the potential for injury in low-speed, rear-impact crashes.97–99 Recent human volunteer crash tests at low speeds (4 to 8 km/h) have
demonstrated that seat back stiffness plays an important role in injury mechanics,95 with stiffer seat backs resulting in greater compressive forces in the cervical spine and more flexible seat backs resulting in greater shear stress in the cervical spine. Based on our current knowledge, it would appear that the trade-off would favor a stiffer seat because the neck is more resilient to compressive forces than to shear forces.

However, innovative designs have been suggested in which a fluid damped seat system would allow controlled rearward motion in the event of rear impact.100 Such a design has recently been incorporated into the Volvo S80. Saab has also developed an integrated seat in which a cam device is actuated in the seat back by rearward torso displacement. The head restraint is moved into opposition to the head by the cam to prevent rearward head motion. Neither seat, however, has been extensively tested in human volunteer crash tests.

Many current head restraint designs consist of a simple cylinder of foam wrapped around a metal framework. When the rear of the head—anywhere from the lambda to the inion—strikes the restraint, the inertia of the neck will carry the head into flexion, imparting a strong bending moment through the upper cervical spine. Thus it is important to design a restraint that achieves support of both the head and the neck simultaneously.

The seatpan should also be designed to deform under a vertical load to reduce the effect of ramping and consequent spinal compression. Such a design would not interfere with the ability of the seatpan to prevent submarining in frontal impacts and, in fact, may enhance this safety feature. Belt pretensioners have been designed and implemented in many newer passenger vehicles. Under crash level loads detected by sensor arrays arranged on the front of the vehicle, pyrotechnic devices cause cables to tighten lap and shoulder belts in an effort to snug the occupant into the seat. Although these systems can reduce occupant loads significantly,101 current units are designed to deploy only in frontal crashes.

Based on our current knowledge, it would seem highly probable that such systems would also reduce loads to the occupant if rear sensor arrays allowed deployment in injury-threshold rear crashes.

Several recent studies have provided a clear picture of occupant kinematics in rear impact crashes.92,95,96,102,103 On average, the head moves forward only after the torso begins to move forward, a lag resulting from the head's inertia. The net result is a retraction of the neck (shear), coupled with very high compression. Only then does the head begin to extend rearward. Contact with the head restraint occurs between 80 ms and 100 ms after hyperextension of the joints of the lower cervical spine has occurred. Thus it is likely that injury occurs in many cases within a tenth of a second and before head contact occurs. This underscores the need to minimize initial backset. Taking all the foregoing into consideration, the following recommendations are made. Optimal design of the seat for minimizing injury from rear impact crashes will require the following:

1. A seat back of mid-range stiffness.
2. A method of dampening such that a controlled rearward motion of the seat of up to 3 cm is possible, with a minimal rebound (ie, a coefficient of restitution approaching 0).
3. A head restraint that is tuned to the seat back (ie, one that possesses similar mechanical properties of restitution) and mutually supports both the head and the neck.
4. A head restraint with enough adjustability to allow for minimal backset over a broad range of occupant statures.
5. A mechanism for locking the head restraint in position once adjusted.
6. A seatpan designed to deform under loading conditions to reduce vertical occupant motion (ramping).
7. A belt and shoulder harness pretensioner system with rear array actuation.
8. A torso seat back element designed to deform under loading conditions to reduce straightening of the thoracic kyphosis which contributes to ramping and compression of the spine.

Pulsating Lumbar Support

From references presented in this review, we have shown that compared with unsupported sitting, the use of lumbar lordotic support pads reduces disc pressure and paraspinous myoelectric activity. Repetitive spinal motion improves metabolism and nutrient transfer in animal discs,104 and similar benefits are thought to occur for human discs.105 To determine if continuous passive motion could be incorporated into a car seat lumbar support in 1994, Reinecke et al106 studied 28 drivers who routinely drive more than 2 hours per workday. They reported that drivers were more comfortable and had less back pain and less stiffness after using a pressure controlled pulsating pneumatic lumbar support in their automobile seats. They thought they were the first to suggest such a device. However, Hetzberg had made one for air force pilots in 1949.106

CONCLUSION

It might be thought that some of these recommendations will be too costly. However, what price should be affixed to activities of daily living, quality of life, and possibly life itself?

In addition to the recommendations for safety of the seat design, it is recommended that:

1. All automobile front seats should be damped, at least in the 3 resonant frequencies of the human spine, with shock absorbers.
2. Dense foam be used in the seat bottom cushion.
3. The backrest must be adjustable in the incline angle.
4. Backrest must have an adjustable lumbar support (up-down translation and in-out translation).
5. Seat height must be adjustable.
6. Seat bottom incline must be adjustable.
7. Seat bottom linear translation for shorter persons to reach gas and break pedals.
8. Seat back be linearly adjustable (forward-backward) to the seat bottom (for shorter and taller persons).
9. Bilateral adjustable arm rests are needed.
10. Adjustable steering wheel (forward tilt rotation and forward-backward translation are needed).
11. Seat back incline is recommended to be maintained at a 100° angle to reduce the risk of rising up this ramp during cervical acceleration-deceleration injuries.
12. Seat backs must be damped to absorb some of the compression forces applied to the torso during rear-end impacts to reduce torso rebounding during rear-end impacts.
13. Pulsating lumbar supports should be made available on car seats to reduce static load, and therefore, perhaps low-back disorders.

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