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Development of test methodologies for determining the safety of wheelchair headrest systems during vehicle transport

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Abstract—For wheelchair users unable to transfer to a vehicle seat, the wheelchair serves as a means of mobility and postural support during activities of daily living and as a seating support in a vehicle. The performance of commercially available adaptive seating components in a dynamic or impact situation, as well as their effect on the safety of the user, is unknown and should be determined. The main objective of the project was to develop a test methodology to statically determine the crashworthiness of wheelchair headrest systems and show the efficacy of that methodology by applying it to several commercially available headrest systems. The methodology was based on Federal Motor Vehicle Safety Standard (FMVSS) test conditions, which use static test procedures to ensure that vehicle head restraints will perform adequately during actual crash conditions.

The procedure developed to evaluate the headrests gave informative and repeatable results. The tests performed calculated the energy associated with a critical deformation of the headrest under quasi-static conditions. The results were used to determine the level of safety provided by the devices and to recommend design improvements. The headrests tested exhibited similar modes of deformation due to bending of a vertical adjustment bar, and several devices were determined to be capable of providing adequate restraint in an impact situation.

Key words: *physical disability, postural support, vehicle transport, wheelchair.*

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INTRODUCTION

For several reasons, wheelchair users are being transported more frequently than in past years while seated in their wheelchairs. Of an estimated 1.1 million wheelchair users, approximately two-thirds require special transportation services (1). The Department of Transportation (DOT) has estimated that approximately 72,000 children are transported in their wheelchairs to and from school (2). A better understanding of the safety characteristics of devices involved in the transportation of wheelchair users is needed to ensure an acceptable level of safety for everyone.

Individuals transported in their wheelchairs are often supported by pads, cushions, and restraints designed for postural support, not transportation safety. Headrests are one type of device used by some wheelchair users to support and align the head and neck in a stable, functional position. An integral part of the seating system, headrests are typically utilized throughout the day and, therefore, remain on the wheelchair while the user rides in or drives a vehicle. New and proposed regulations mandate that wheelchair users be transported in a forward or rear facing direction (3–5). These orientations increase the importance of headrests to prevent whiplash and other neck injuries.

Schneider recommended provision of a head restraint for wheelchair occupants in a vehicle, suggesting that without head support the individual is more susceptible to whiplash or head injury (6). Seeger et al. specified the use of a padded head restraint as a crashworthiness design principle for transporting per-

sons in their wheelchairs in buses (7). The authors reported that head restraints are not provided during transport as a rule, and that a removable restraint of sufficient strength is needed. These researchers were advocating that an add-on headrest be designed to attach to those wheelchairs without headrests; however, individuals who need head support throughout the day must rely on the integrity of their current headrest during transportation in a vehicle.

The National Highway Traffic Safety Administration (NHTSA) regulates head restraints that are part of standard vehicle seating systems (8). The regulation does not apply to headrests attached to wheelchairs or other mobility devices. However, it can serve as an adequate benchmark when assessing the transportation safety of adaptive seating components.

Objective

The objective of this project was to develop a test methodology to aid in determining the transportation safety of the wheelchair-seated vehicle occupant using a current headrest system, as well as for testing future headrest designs. The goal was to evaluate the headrests according to current clinical use and practice.

The first goal was to develop static testing procedures to evaluate the headrests' strength and usefulness in the prevention of whiplash injury. A static testing protocol is necessitated by the vast number of commercially available devices and the high cost of dynamic test procedures. At minimum, the level of safety should be equal to that intended for the occupant in a vehicle seat that has complied with Federal Motor Vehicle Safety Standards (FMVSS). FMVSS are enforced for all occupants seated in an original equipment manufacturer (OEM) seat, whether the individual has a disability or not. The intent of this study is to assess the headrest systems for their ability to provide an equivalent level of safety to the individual transported while seated in his or her mobility aid. The second goal was then to subject commercially available headrests to the developed procedures to evaluate the efficacy of the procedures applied, as well as the performance of the devices.

METHOD

Review of Standards and Research

To determine the level of risk or safety provided by the devices, a standard method of evaluation is required. FMVSS 202, which specifies safety requirements for head restraints, was studied along with other pertinent research, and the test procedures were modified and performance criteria established to evaluate wheelchair-mounted headrests (8).

FMVSS 202, ''Head Restraints,'' specifies requirements for head restraints to reduce the frequency and severity of neck injuries in rear-end and other collisions. The head restraint may satisfy the regulation with a dynamic or static test procedure applied to the restraint in its fully extended position. If the static test procedure is used for compliance, the restraint must also meet size requirements.

Dynamic Test Procedure

The head restraint must limit rearward angular displacement of the head to 45° with respect to the torso during an 8 g forward acceleration applied to the seat supporting structure.

Static Test Procedure

This procedure is designed for headrests integrated into vehicle seats. A headform is used to apply a rearward load 6.35 cm below the top of the head restraint perpendicular to the torso centerline. The load is such that it will produce a 373 N-m torque about a seating reference point defined in the standard. This corresponds to an approximate headrest load of 587 N. The head restraint must limit horizontal (anterior-posterior) displacement of the headform to 10 cm from the torso centerline and must withstand increasing this load to 890 N or until seat failure.

Size Requirements

The top of the head restraint must not be less than 70 cm above the seating reference point, measured parallel to the torso centerline. When measured at a point either 6.35 cm below the top of the head restraint or 63.5 cm above the seating reference point, the width of the head restraint must be 25.4 cm for a bench seat and 17 cm for bucket seats.

A search for references supporting FMVSS 202 resulted in minimal documentation on the development of the standard. However, extensive research has been done on injuries associated with rear-end collisions and the effectiveness of head restraints in preventing these injuries. A few studies have identified safe anatomical neck loads and strength criteria for head restraints. These studies, however, do not indicate that any of the subjects had a disability and no data were found on persons with disabilities.

Mertz and Patrick investigated the kinematics and kinetics of whiplash, determining the mechanics of whiplash injury mechanisms and the effectiveness of head support in reducing whiplash injury (9). The kinematics of actual car-to-car rear-end collisions were reproduced on a crash simulator using anthropomorphic dummies, human cadavers, and a volunteer. An index was developed based on voluntary limits of human tolerance to statically applied head loads and was used to define the severity of the simulations in cases involving an unsupported head. The index was based on the maximum tolerable static limits determined from maximum resistive forces and moments to static loading of the volunteer's head. The tests showed that head torque at the occipital condyles, rather than neck shear or axial forces at the base of the skull, is the major factor causing whiplash injury. The severity of the whiplash simulation and the effectiveness of the safety devices were evaluated by determination of neck reactions and head restraint loads. With the head initially supported by a flat, padded head restraint and a rigid seat back, the volunteer withstood a simulation of a 70.4 km/h rear-end collision with only slight discomfort. The maximum head restraint load seen at a 10 g, 36.8 km/h simulation was approximately 667 N.

In a subsequent study, Mertz and Patrick presented data relative to the static strength of the neck in flexion and extension (10). They also presented dynamic response and strength data for the human neck in flexion and extension. Finally, they recommended noninjurious tolerance values for hyperextension and flexion of the neck. In their study, human volunteers were subjected to static and dynamic environments which produced noninjurious responses of the neck. Cadavers were then used to extend the data into the injury region. The data revealed that the equivalent moment at the occipital condyles is the critical injury parameter in flexion and extension. Resultant shear and axial forces at the base of the skull were well below tolerable levels and were not considered critical parameters by the authors. A maximum dynamic value of 47.5 N-m in extension was reached without injury in a 50th percentile male cadaver. This torque level occurred at a rotation of the neck of approximately 80°. The authors concluded that neck extension should be limited to 80°, and preferably 60°, to avoid injury.

More current research by Foret-Bruno et al. studied the effects of seat stiffness on the effectiveness of head and torso restraints (11). An accidentology study was performed on the frequency and severity of injuries to occupants in rear impact accidents. The laboratory analyzed data involving 8,000 vehicles for impact severity, occupants' conditions, and types of injury. A conclusion from this study was that head restraints are effective in reducing the risk of cervical injury by 30 percent for men and women.

The Foret-Bruno research also included a dynamic study. Using Hybrid III dummies, testing manipulated horizontal head-to-restraint distance, head restraint stiffness, seat back elasticity, and impact speed to study their influence on neck load measurements. The tests supported the observed effectiveness of head restraints in actual rear impacts, and also indicated that in order for the restraint to be as effective as possible, it should stay in contact with the head and not deflect easily under the force of the head. As the distance between the restraint and the head increases, the shearing force at vertebra C1, and the rotation of the head in relation to the thorax, also increases. These investigators concluded that the head restraint, when placed in contact with the back of the head, should be able to withstand the following loads "without any change in position:" longitudinal force of 750 N, a vertical force of 250 N, and a torque of 70 N-m.

Performance Criteria

To evaluate wheelchair headrest effectiveness, performance criteria were established. In general, headrests should be designed to limit displacement of the head to within a noninjurious range and to withstand the loads applied.

The dynamic test of FMVSS 202 requires that the head be limited to a 45° angular displacement with respect to the torso. As mentioned earlier, Mertz and Patrick reported the maximum extension that could be reached without injury was 80°; therefore, the rotation of the head should be limited to 80 and preferably 60° (9). Due to the lower tolerance levels that may occur for an individual with disabilities and the desire to provide the same level of safety as FMVSS 202, a more conservative limit of 45° was chosen as our criterion.

A critical linear displacement of the head was defined for testing by calculation of the linear displacement that would correspond to a 45° angular displacement. This measurement was based on anatomical and anthropomorphic data. The center of rotation for the neck of a Hybrid II 50th percentile male Anthropomorphic Test Device was used to calculate the chordal displacement of the center of gravity of the head for a 45° rotation of the head relative to the thorax (**Figure**

1). The chord displacement was calculated to be approximately 9.0 cm and is close to the 10 cm limit of the horizontal displacement of the headform specified in the static procedure of FMVSS 202.

A restraint must also sustain loads applied by the head during an acceleration. Based on crash test results, FMVSS 202 established that the restraint must limit the displacement of the head to 10 cm when a load of approximately 587 N is applied and maintain its integrity up to a 890 N load. Mertz and Patrick found a maximum headrest load of 667 N during a 10 g, 36.8 km/h simulation, supporting the load values of FMVSS (9). We used the FMVSS 202 load requirement of 587 N and the displacement of 10 cm to calculate the work required to deform the restraint assuming an elastic deformation. Therefore, a critical energy of 29.8 J was defined as the criterion used to determine whether the restraint would prevent neck injury. Thus, the criteria set to determine whether a restraint system was suitable to provide protection during vehicle transportation were that within a 9.0 cm displacement of the head, the applied load must reach a minimum of 587 N and the associated energy must be greater than 29.8 J. In addition, the restraint must withstand loads up to 890 N.

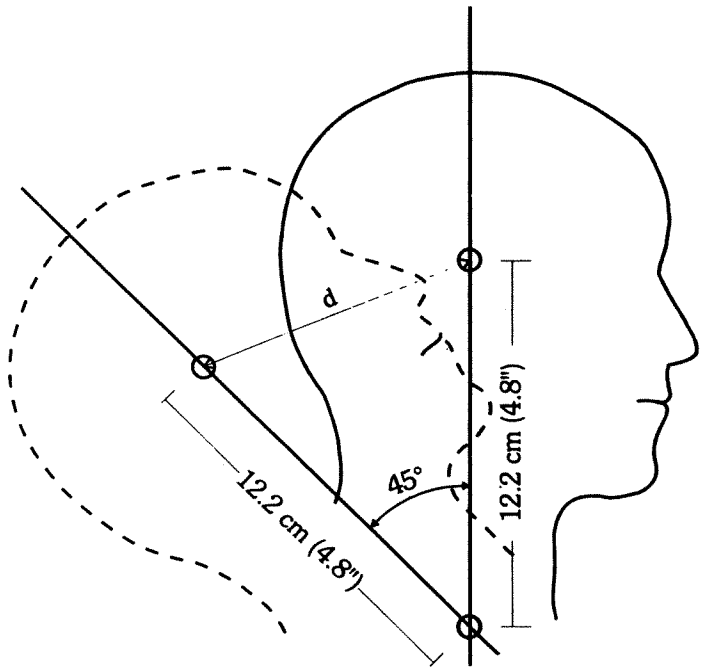

Figure 1.
Calculation of critical displacement of the head; d = chordal displacement for 45° rotation.

Products Tested

The headrest systems tested were commercially available and included:

- Adaptive Engineering Lab's (AEL) Adjustable Bracket
- Dan Mar Mini
- Dan Mar Sweep
- Miller's Fixed Occipital
- Miller's Swingaway Occipital
- Otto Bock Single-Axis Offset
- Otto Bock Multi-Axis Offset
- Techni Seat Contoured Assembly.

Most systems included: attachment hardware, vertical adjuster, anterior/posterior or horizontal adjuster, and a headrest pad (**Figure 2**). The attachment hardware for all the headrests tested was designed to mount on a solid seat back and usually consisted of a receptacle secured with bolts and T-nuts. The vertical adjuster allows the user to raise and lower the pad to the appropriate height. The horizontal adjuster also allows the restraint to be adjusted based on the needs of the user. This allows the headrest pad to be placed at various distances anterior to the seat back. The pad usually attaches to the end of the horizontal adjuster and may include additional adjustability by allowing various angles of tilt. The pads contain an inner structure of metal or plastic surrounded by foam padding contained in a cover. The specific characteristics of the headrests tested are described in **Table 1.**

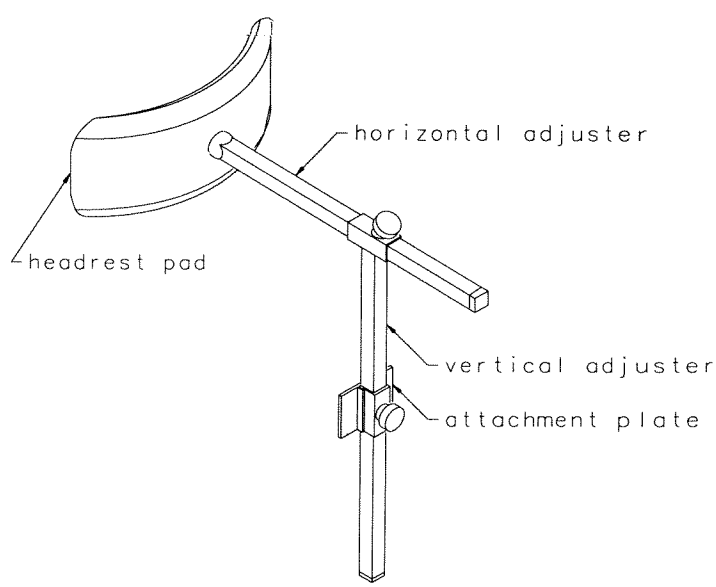

Figure 2.
Example of a typical headrest and components.

Table 1.
Headrest characteristics.

Headrest	Vertical Adjuster	Horizontal Adjuster	Pad, Width & Height	Attachment Receptacle
AEL	Aluminum Solid Square 1.5	Aluminum 0.5 x 2.5	Curved 17.8 x 7.6	Steel
Dan Mar Mini	Mild Steel 0.3 x 3.2	None	Curved 30.5 x 12.7	None*
Dan Mar Sweep	T5052 Aluminum 0.6 x 2.5	None	Soft Foam Occipital Support 35.6 x 20.3	None*
Miller's	Mild Steel Solid Round 1 cm Diameter	Same as Vertical Adjuster	5 cm high Occipital	"Fixed"-Steel "Swingaway:" Wood/Steel
Otto Bock (All Types)	Mild Steel Square Tubing 1.3 cm O.D.	Same as Vertical Adjuster	Curved 24.8 x 9	Aluminum
Techni Seat	Stainless Steel 0.3 x 3.8	Same as Vertical Adjuster	32.4 x 12.7 Lateral Support	Stainless Steel

All measurements in cm. *Vertical adjuster(s) bolted directly to seat back.

Test Setup

For the modified procedure, a headform was used to load the headrests to simulate the loading from the occiput during a collision. The headform (**Figure 3**) used to load the restraint was a wooden half cylinder with a 16.5 cm diameter and a 15.25 cm profile. The headform is the same as that defined by FMVSS 202, and the dimensions represent those of a 50th percentile male. The headform was mounted by a ball joint to a load cell on the crosshead of an 1122 Instron Universal Testing Instrument (Instron Corporation, Canton, MA), the accuracy of which is ±0.5 percent of the indicated load (**Figure 4**). The system was configured in its compression mode to measure and record the displacement of the crosshead and the load applied to the headrest system. The linear displacement of the headform, along with the freedom of movement provided by the ball joint, was chosen to represent the translation and rotation of the head while allowing for a consistent method of calculating the energy associated with the displacement of the headrest being tested.

A support structure was designed for attaching a plywood mount unit to which headrest assemblies were secured (**Figure 4**). A stiff support structure was needed that permitted deflection of the headrest linkages during loading and permitted adjustment of the headrests into proper alignment with the headform for testing. The plywood unit was mounted on the top of the support structure so that the plywood, simulating the wheelchair seat back, was horizontal. The long axis of the half-cylinder headform was oriented along the vertical head axis. The curved side of the headform was lowered to meet the pad of the headrest mounted on the plywood. The amount of vertical clearance required for deformation of the restraint depends on the maximum linear displacement of the headform and the additional clearance for the headrest components. Horizontal clearance was determined based on the maximum width of the headrests tested. In addition, the support structure and the means used to secure the plywood to the structure must remain rigid relative to the test unit to isolate the behavior of the headrest during loading and to minimalize the movement of the plywood with respect to the support structure.

Testing Protocol

Each headrest was tested according to the following protocol:

1. The attachment hardware of all the headrests was mounted to 1.3 cm (half-inch) thick plywood, based on the manufacturer's directions and using all provided hardware. Plywood was chosen to simulate current clinical practice and manufacturer recommendations with regard to headrest and backrest attachment: foam-covered plywood of 1.3

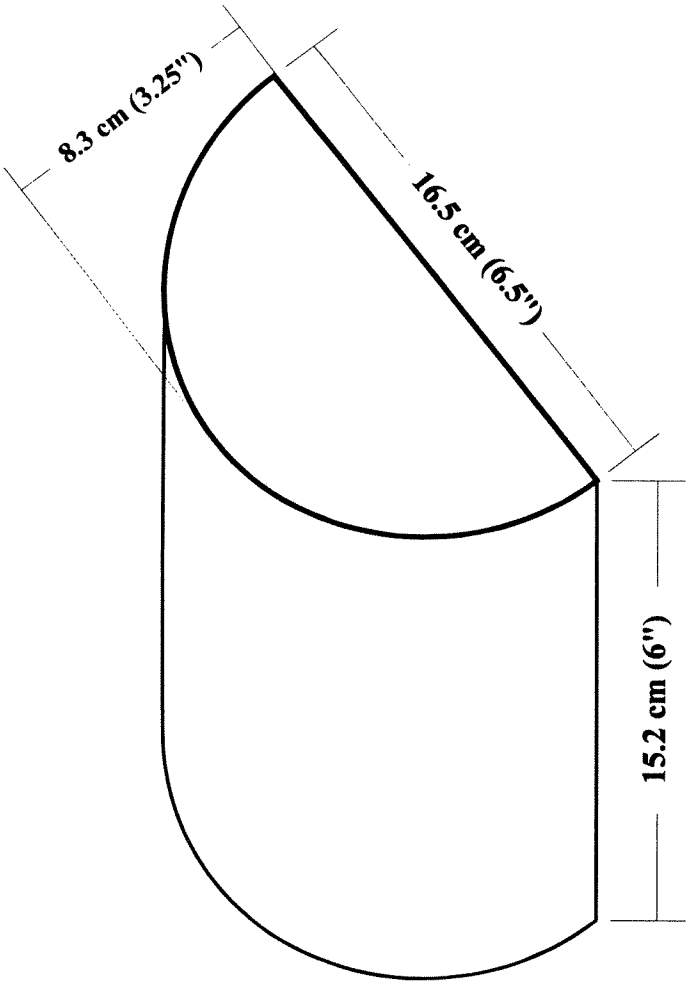

Figure 3.
Dimensions of headform used for loading restraint.

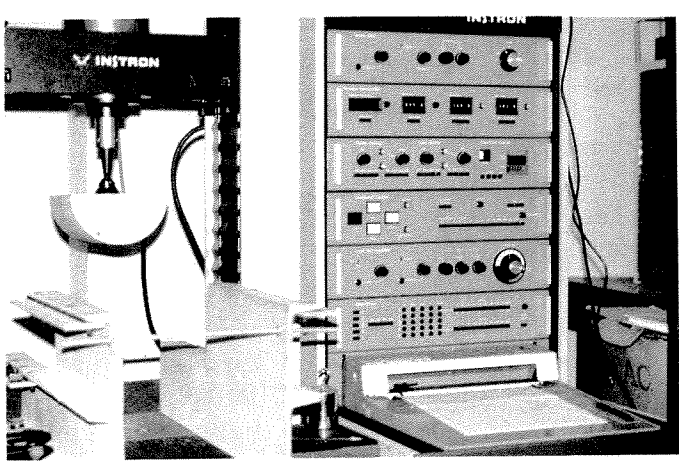

Figure 4.
Test setup.

cm to 1.5 cm thickness is commonly used as a solid seat back insert for wheelchairs. The range of vertical height adjustment was determined for each device, and two tests were performed at the maximum and minimum height settings (**Table 2**).

2. The horizontal adjustment, when available, was set such that the anterior surface of the headrest pad was located 4 cm anterior to the seat back surface. This setting was based on the standard upright seating position of an anthropomorphic test device. In the upright position, there is an approximate distance of 4 cm between the anterior plane of the seat back and the rear portion of the head. This setting also corresponded to the average mid-range value of the headrests tested.
3. The adjustment hardware for the horizontal and vertical adjusters was tightened using a torque wrench to approximately 2.25–3.0 N-m. This was done for consistency between tests and to prevent horizontal slip from occurring. The restraints were marked prior to the test to determine if any horizontal slip occurred during loading.
4. The headrest/plywood unit was fixed to the Instron base, oriented so that the base of the headform was located flush to the bottom edge of the headrest pad. This orientation gives optimum headform contact throughout any rotation of the head or headrest. The headform was adjusted so that its centerline was parallel to the centerline of the headrest pad. A preload of 5–10 N was applied to define surface contact and the zero point. An Instron crosshead speed of 100 mm/min was used to apply the load. The load was applied to the headrest through displacement of the headform attached to the Instron crosshead. Load-deformation information was collected continuously as the headform was displaced 14 cm. Permanent deformation was recorded photographically, and the modes of failure were recorded during testing.
5. Load-displacement information was recorded on a chart recorder and by data acquisition software at 9.1 samples/sec. Values obtained from the acquired data included: maximum load, displacement at maximum load, partial energy, energy to yield, displacement at yield, and yield load. The yield was found using the slope-threshold method, which determines the slope in the initial linear region of the curve and then finds the point on the curve where the slope decreases to a fraction of

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Table 2.
Headrest height settings.

Height	AEL	Dan Mar Mini	Dan Mar Sweep	Miller's Fixed	Miller's Swingaway	Otto Bock Single Axis	Otto Bock Multi Axis	Techni Seat
Minimum	10.8	11.4	20.3	10.2	11.4	16.2	10.8	11.4
Maximum	20.9	26.6	30.5	30.5	36.8	32.3	35.5	15.5

All measurements in cm.

0.6 of the initial slope. The energy function calculated the energy under the load-displacement curve between specified limits. Partial energy was calculated for a headform displacement of 9.0 cm, which corresponds to a 45° angular displacement of the head.

The partial energy and maximum load were used to determine whether the unit met the criteria for the performance of the headrest system.

RESULTS

The load-deflection data recorded are displayed in **Figures 5** through **12** for the eight headrest configurations tested. Each figure displays four curves representing the two tests each at the minimum and maximum vertical adjustment heights. As expected, the curves show greater strength of the headrests when positioned at their minimum height. The similarity of the curves at each height adjustment demonstrates repeatable results. The characteristics of each curve, including local maxima and minima, result from the mode of deformation or failure of the headrest. From the data, information on the yield points, maximum loads achieved, and the energy absorbed during deformation can be obtained. Each figure also includes a box which defines the acceptable performance criteria of reaching a load of 587 N within 9 cm of deflection.

Three major deformation modes were observed in the course of testing: 1) the plastic deformation of the vertical adjuster, 2) the plastic deformation and/or failure of the attachment receptacle, and 3) the yielding of the plywood board. Combinations of the different types of deformation were also observed.

The AEL headrest (**Figure 5**) experienced no yielding of the vertical adjuster. Failure occurred in the attachment receptacle and in the plywood. At the minimum height setting, extensive board failure occurred as the T-nuts were pulled out of the plywood. No horizontal slip resulted in any of the tests, and only a slight downward rotation of the headrest pad was observed.

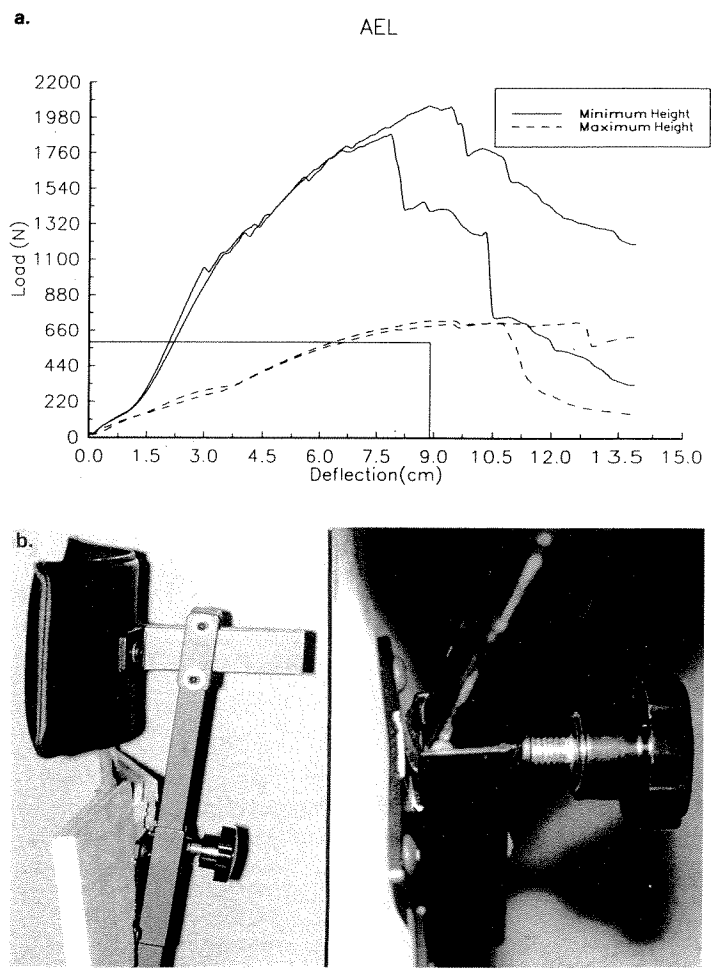

Figure 5.
AEL: a) load-displacement curves; b) mode of deformation.

Tests on the Dan Mar Mini headrest (**Figure 6**) resulted in the bending of the single vertical adjuster

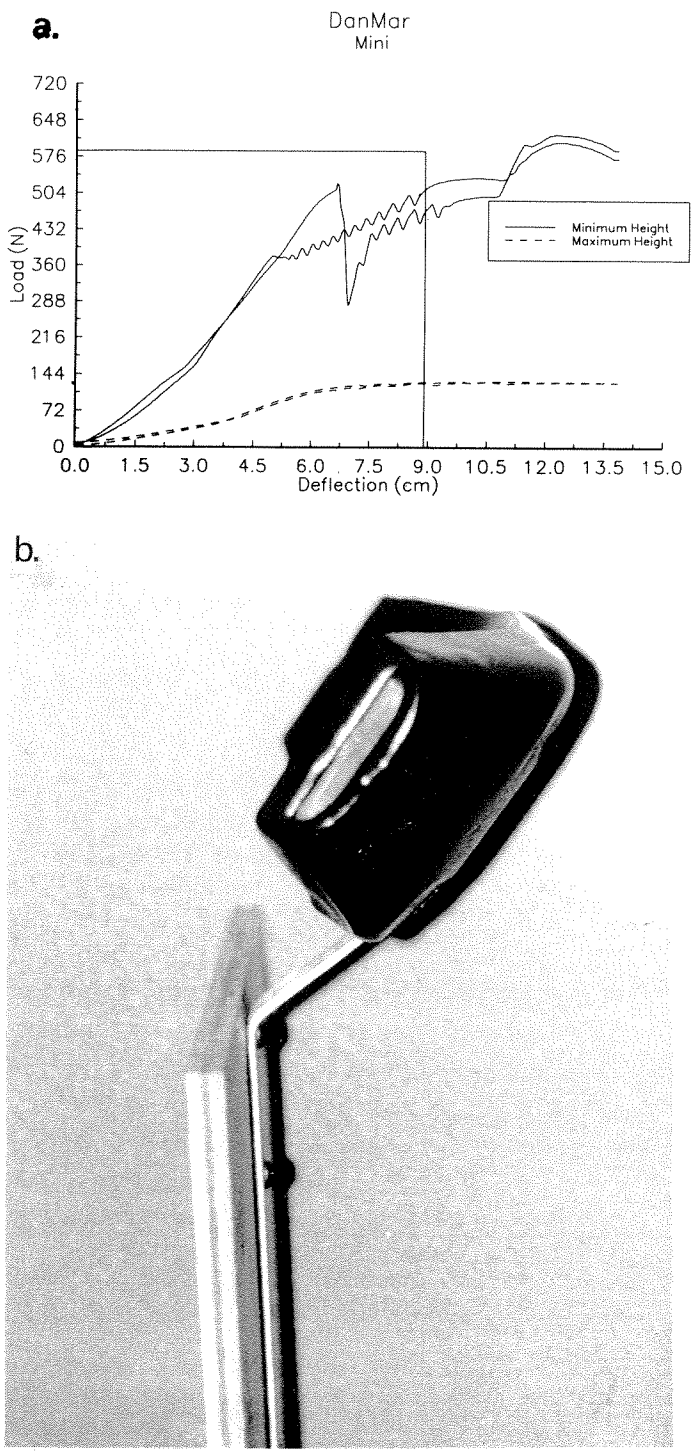

Figure 6.
Dan Mar Mini: a) load-deflection curves; b) mode of deformation.

bar. The vertical bar of the Mini headrest is directly bolted to the plywood, and bending occurred at the top attachment point. The minimum height adjustment resulted in a shorter moment arm and greater bending of the bar. The spikes observed in the figure are a result of the headform pivoting on the headrest pad as deformation occurred. The minima are caused by a series of slips of the headform on the headrest pad. The large drop in load experienced in one of the minimum height tests was due to a slight yielding of the plywood.

Figure 7 displays the tests on the Dan Mar Sweep headrest. The Sweep restraint contains two vertical bars bolted directly to the plywood. For all test cases, the

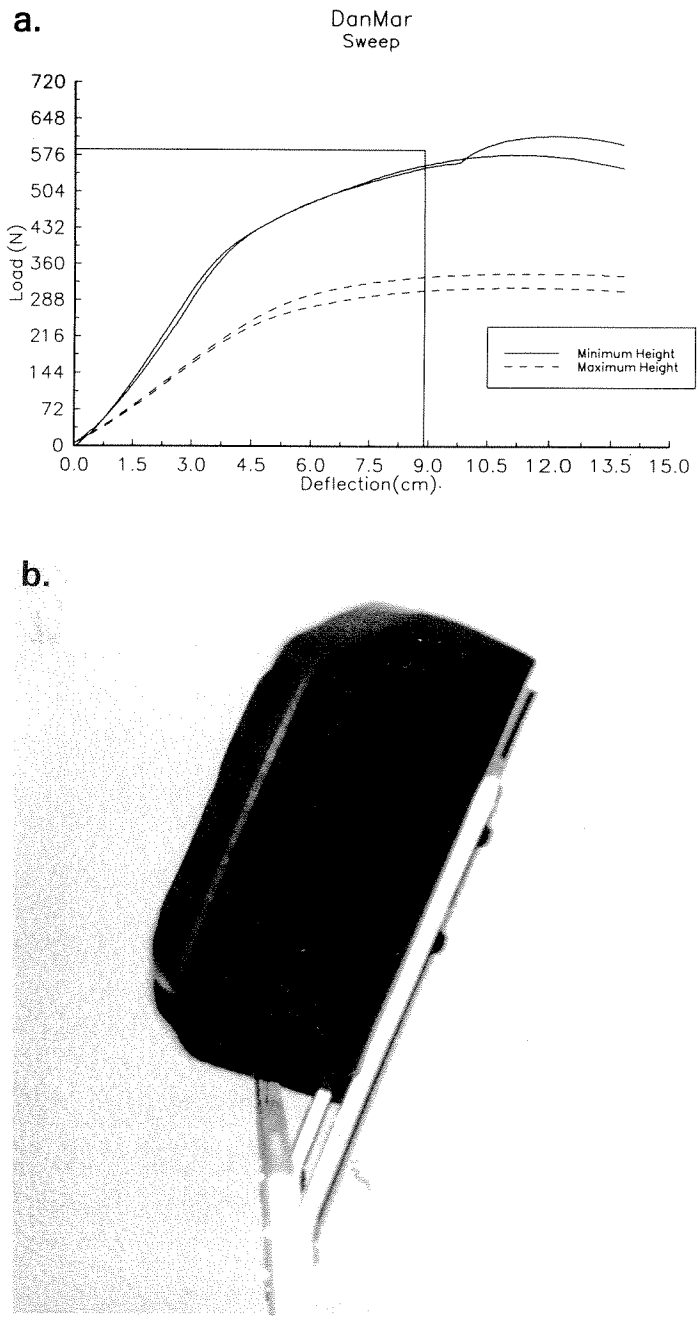

Figure 7.
Dan Mar Sweep: a) load-deflection curves; b) mode of deformation.

vertical bars bent at the top point of attachment to the plywood. No yielding of the plywood was observed in any procedure.

Miller's Fixed headrest exhibited failure of the receptacle and board (**Figure 8**). At the maximum height setting, deformation of the receptacle and yielding of the vertical adjuster occurred at relatively low loads. At the minimum height setting, the receptacle rotated and deformed between the bolt attachments, pulling away from the plywood. During one test, the T-nuts pulled out at approximately 1,200 N. Tests at the maximum height adjustment also resulted in a deformation and slight rotation of the receptacle. The vertical adjuster also exhibited elastic yielding and there was slight yielding of the plywood. No horizontal slip occurred during testing, and the headrest pad rotated downward approximately 45° during each test.

Figure 9 displays the results of tests performed on a Miller's Swingaway headrest. The minimum height adjustment shows much greater strength than the maximum setting. At the minimum adjustment, no deformation of the vertical adjuster or the receptacle

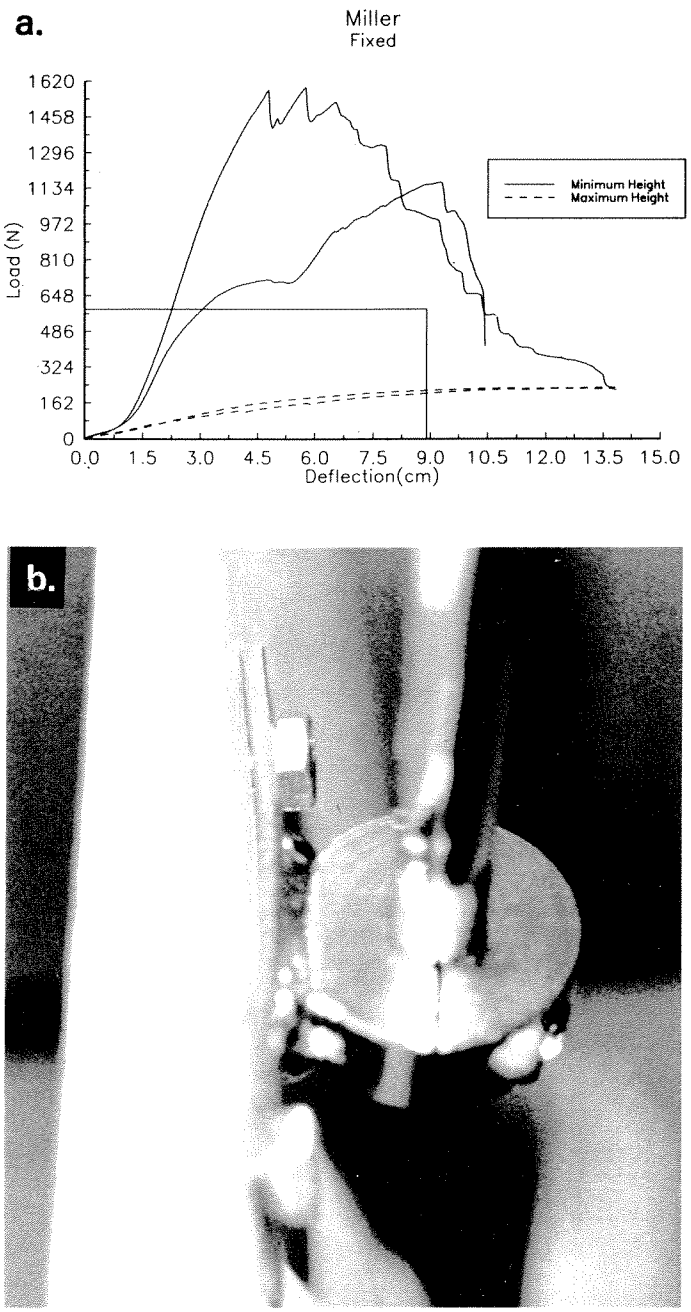

Figure 8.
Miller's Fixed: a) load-deflection curves; b) mode of deformation.

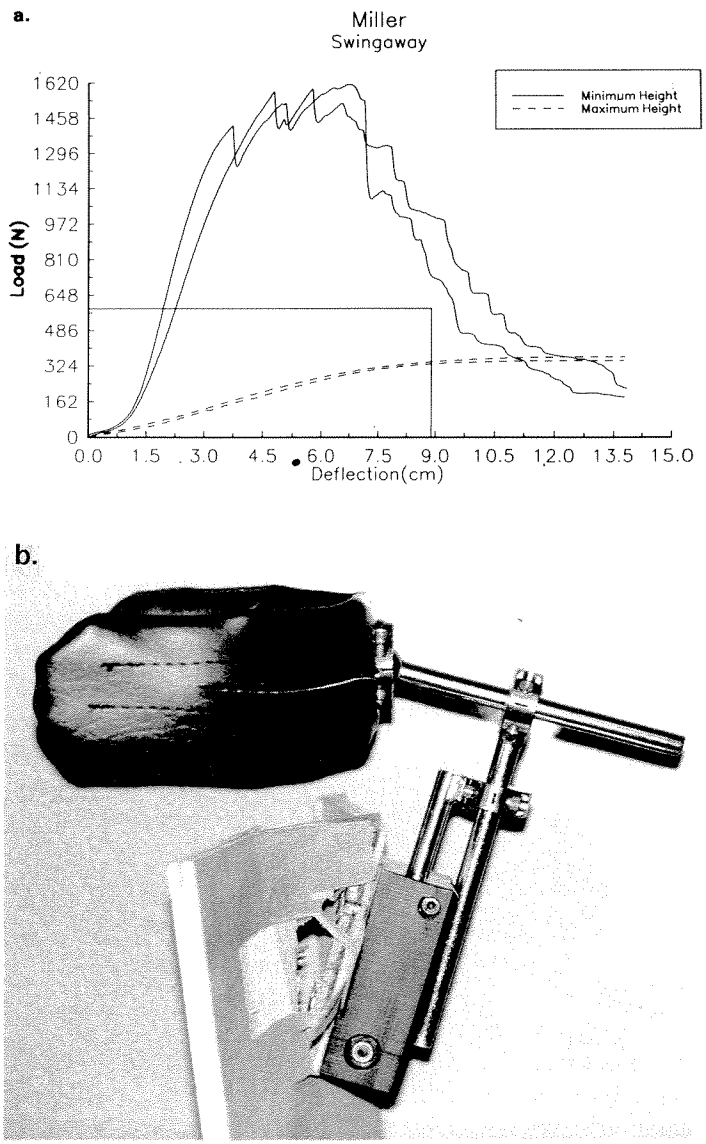

Figure 9.
Miller's Swingaway: a) load-deflection curves; b) mode of deformation.

was observed. The failure occurred as the board began to yield at loads around 1,500 N. At the maximum height setting, the receptacles remained intact and no board yielding was noted. Deformation took place through the bending of the receptacle rod that contained the mount for the vertical adjuster and through slight elastic yielding of the vertical adjuster. No horizontal slip occurred in any of the tests performed.

The Otto Bock Single-Axis Offset headrest contains a 15° bend in its vertical adjuster to offset the headrest pad. In all cases, plastic deformation occurred at this offset angle. **Figure 10** displays the results of the tests and shows different curve characteristics for the two height settings. Deformation at the minimum setting involved only bending at the offset, since this position coincided with the point that the maximum moment was applied. At the maximum setting, bending of the adjuster occurred at the offset and at the point at which the bar was clamped, where the bending moment was maximum. No horizontal slip and no receptacle deformation or board yield was observed in any of the cases.

Figure 11 shows the outcome of tests performed on the Otto Bock Multi-Axis Offset. In this headrest, the minimum setting also exhibited much greater strength than the maximum. At the minimum height adjustment, failure occurred at the point on the vertical adjuster that was initially curved for an offset of the headrest pad. Slight yielding of the board at the higher loads resulted as the restraint further deformed. The vertical adjuster bent at the point of attachment to the receptacle at the maximum height settings. No receptacle deformation or horizontal slip occurred in any of the tests.

The Techni Seat headrest test results are shown in **Figure 12.** The same mode of failure occurred during all test conditions, as the vertical adjuster bent at the top of the attachment receptacle. No deformation of the receptacle nor yielding of the plywood was noticeable.

A summary of the mechanical properties determined from the testing is presented in **Table 3.** Two criteria were for the device to reach a minimum load of 587 N and require a minimum energy of 29.8 J for a 9 cm displacement of the headform. The headrests that met these criteria at minimum height were: AEL, Miller's Fixed, Miller's Swingaway, Otto Bock Single-Axis, and the Otto Bock Multi-Axis. The AEL was the only headrest that also met the criteria at maximum height.

The Dan Mar Mini and Sweep headrests meet the energy criterion at their minimum height, but failed to reach the critical load within a 9 cm displacement (See **Figures 6** and **7**). Except for AEL, the headrests did not meet the criteria at their maximum height setting. The Techni Seat restraint failed for its full range of adjustment.

Another criterion was for the headrests to maintain their functional integrity up to a load of 890 N. The

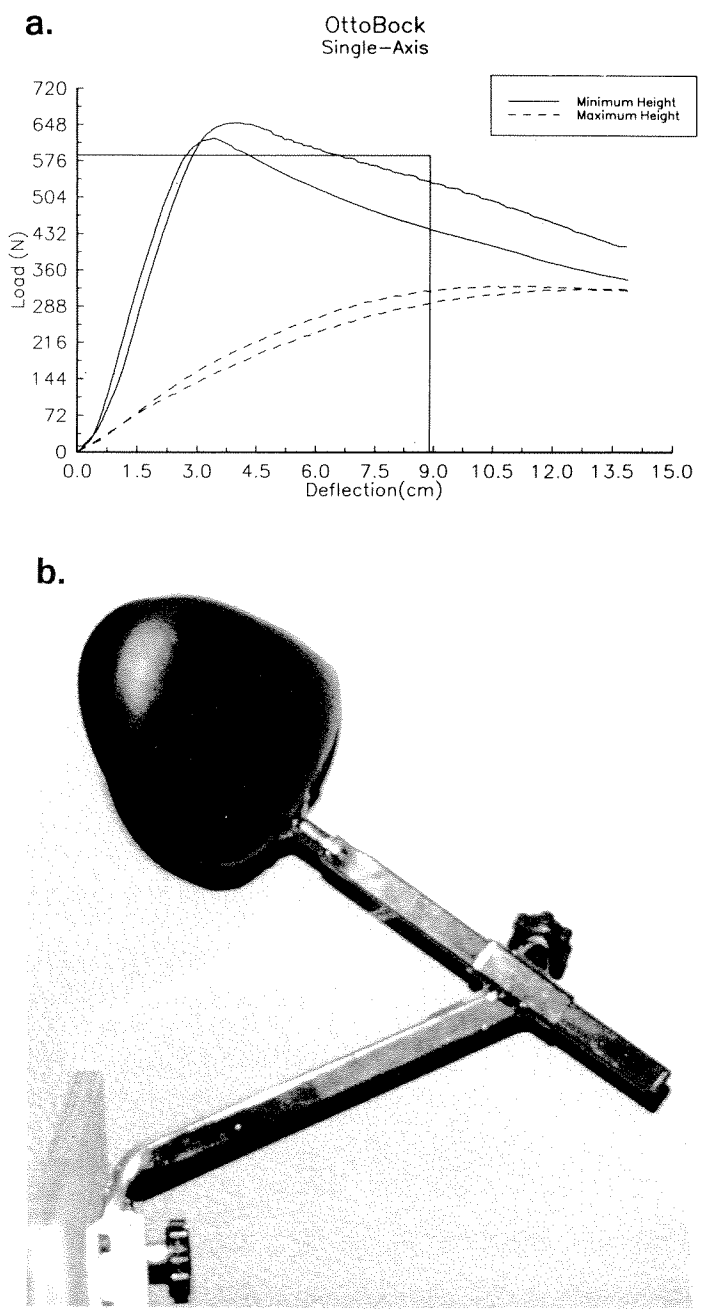

Figure 10.
Otto Bock Single-Axis: a) load-deflection curves; b) mode of deformation.

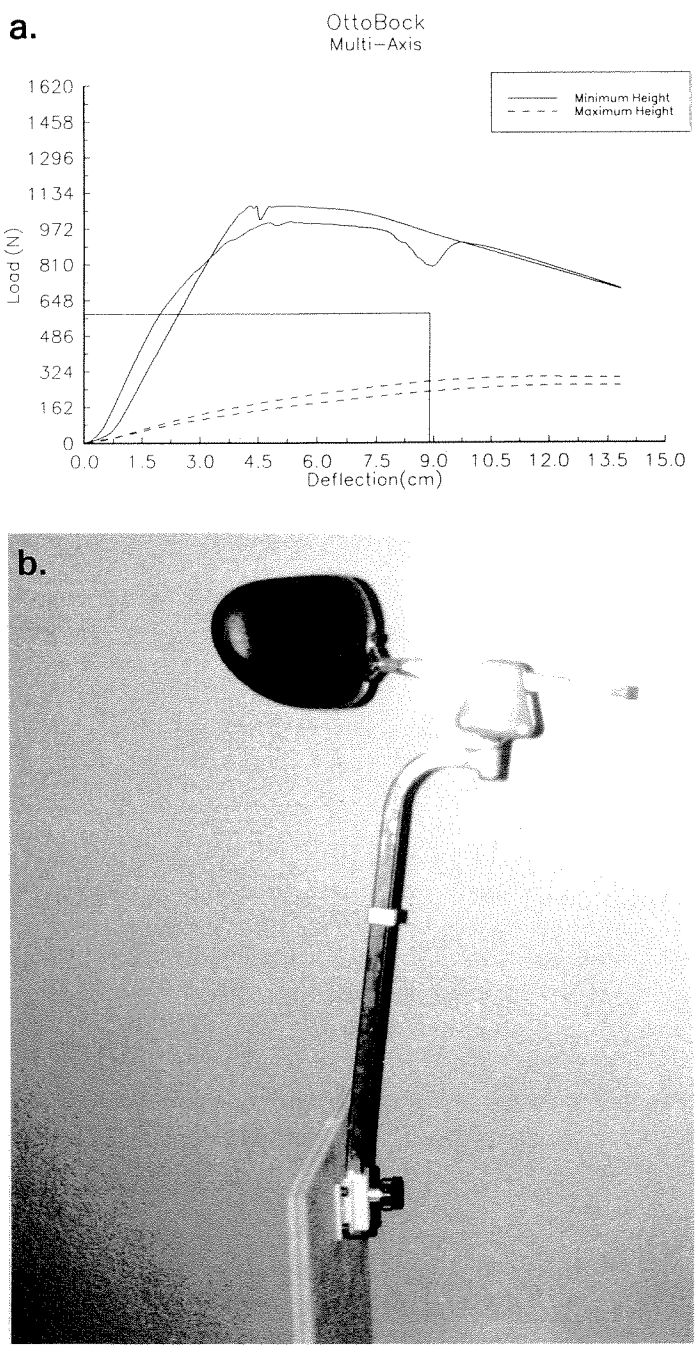

Figure 11.
Otto Bock Multi-Axis: a) load-deflection curves; b) mode of deformation.

restraints that reached this load at minimum height included: AEL, Miller's Fixed, Miller's Swingaway, and the Otto Bock Multi-Axis. These restraints did not fail or lose their integrity until the plywood board yielded and the T-nuts were pulled out at loads from 1,000 to 1,200 N.

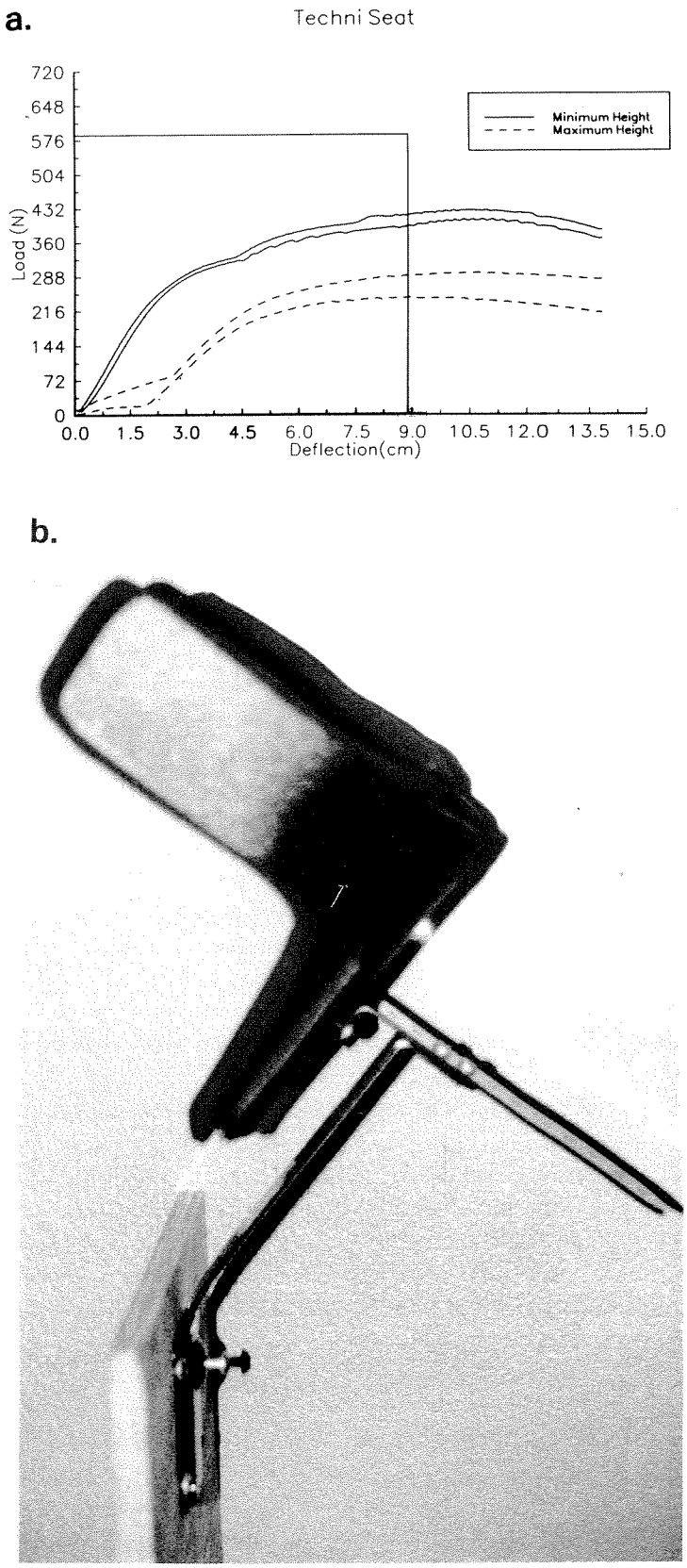

Figure 12.
Techni Seat: a) load-deflection curves; b) mode of deformation.

Table 3.
Static test results.

Headrest Height Setting	Maximum Load (N)	Displacement at Maximum (cm)	Energy (J)
AEL			
Minimum	1962.08	7.89	117.62
Maximum	718.66	10.05	37.90
Dan Mar—Mini			
Minimum	615.24	12.41	30.63
Maximum	212.55	11.21	10.53
Dan Mar—Sweep			
Minimum	595.62	11.44	33.95
Maximum	326.41	10.54	18.78
Miller's—Fixed			
Minimum	1268.30	11.54	72.49
Maximum	229.21	11.99	12.08
Miller's—Swingaway			
Minimum	1601.59	6.26	96.09
Maximum	354.72	11.98	18.65
Otto Bock—Single			
Minimum	636.28	3.68	44.13
Maximum	325.16	11.49	16.89
Otto Bock—Multi			
Minimum	1038.57	4.81	72.55
Maximum	277.82	12.03	13.77
Techni Seat			
Minimum	418.25	10.10	26.72
Maximum	268.75	9.71	17.78

These results are an average of two tests.

DISCUSSION

Determination of the test procedure and criteria was based on several assumptions. An assumption was made that the wheelchair will remain intact during a crash, including the frame and upholstery or seat back. The assumption was valid because the study is aimed at developing a methodology to assess the crashworthiness of the positioning devices. The wheelchair must be assessed separately. A second presumption was that the headrests were all attached to the seat back with T-nuts and secured with quality hardware. All the models tested were designed to install onto a rigid seat back using T-nuts for mounting. The adjustments were all tightly secured with a torque wrench within a preset torque range to reduce the variability of testing. The study was not intended to evaluate cases with weak or improper installation and securement.

The mechanisms of injury from rear collision vary according to anatomical factors. However, studies on cervical injury from rear impact are performed using cadavers and test dummies for obvious reasons: these studies accept the anatomical differences between vehicle occupants and cadavers in order to investigate the cervical injury region. This study acknowledges that the neck musculature of wheelchair users who require headrests might differ from a nondisabled subject population, depending on disability. However, the assumption was made that neck musculature should have no effect on protocols developed to test headrest integrity. This assumption was supported by the accepted use of cadaver spine and test dummies during crash situations and by Seletz, who stated that active muscle forces have no effect on head motion in rear collision since they do not react in time (12). The effect of differences in neck musculature is further reduced by the fourth assumption, which was that the head is always in initial contact with the headrest pad. Both Mertz and Patrick and Foret-Bruno et al. found that as the distance between the head and head restraint increased, the rotation of the head and the load on the restraint increased (9,11). This assumption was made because wheelchair users who utilize headrests do so to provide maximum support of the head, and the headrest is adjusted to contact the head during their typical postures.

The procedure developed to evaluate headrests resulted in repeatable and predictable results (**Figures 5** to **12**). The percent variation of the values of energy and maximum load for a repeated test was below 10 percent for the majority of the tests, with the largest variability reaching about 16 percent. This variation is quite acceptable, considering the number of adjustments on a headrest system and that inconsistent adjustment between repeated tests could cause significantly different results. The average value of the two tests performed at each height adjustment was used to determine if the restraint met the criteria. In all cases, if the average met the test criteria, the original values obtained for each test also met the criteria, showing repeatability.

A noteworthy result is the fact that in all cases in **Table 3,** the minimum height adjustment withstood higher loads than the maximum setting. This outcome was predictable since the longer the length of the vertical adjuster, the longer the moment arm would be for the force applied at the headrest pad, resulting in a greater moment applied to sections of the vertical adjuster. However, the headrest system is more complex than a simple beam in bending, and a relationship between the maximum load sustained and the height adjustment of the headrest could not be established. The number of

adjustable components of the headrests, resulted in several modes of deformation or failure of the headrest, precluding a simple relationship between the height setting of the headrest and the load required to displace the headform 9 cm. More tests performed at height adjustments between the lower and upper limit should be carried out to determine whether a relationship can be found to predict the failure loads at a certain setting.

The headrests tested, except for AEL, should not be adjusted to their maximum height during transport, since they are unable to sustain any significant loading at this setting. Maximum height settings can be avoided with the proper location of the attachment hardware and an adequate seat back height.

The determination of the mode of deformation allows for improvement in design for increased strength and safety. In the cases where the plywood seat back failed, the load required was above 890 N. Failure of the plywood occurred when the headrest did not absorb the energy through its own deformation. These headrests were able to limit the displacement of the headform and should prevent critical rotation of the head in the event of a crash.

The majority of the tests resulted in the plastic deformation of the vertical adjuster, which often caused the hardware to fail to withstand the necessary applied loads and fail to limit displacement of the headform to a noninjurious range. The knowledge that the vertical adjuster is a weak component of the device and bends upon loading can be used to redesign headrest hardware. To provide maximum protection, the vertical adjuster should be designed to have a yield load greater than the 587 N it is required to withstand. This will ensure that head excursion is limited to within a safe range. Since the maximum elastic moment is determined from the section modulus and the yield strength of the material, the required section modulus can be calculated from the load required, the material yield strength, and the maximum height of the vertical adjuster. As demonstrated in the test results, the maximum height of the adjuster will be the worst case. From the section modulus, the required dimensions of the adjustment bar can be determined. In addition, consideration should be given to using more compliant mounts for attaching the vertical adjuster to the seat back. However, the primary function of the headrest to provide support for the head as part of the wheelchair seating system must not be compromised.

Other guidelines that might be useful when designing a headrest include choosing a material such as a mild steel (1018 low carbon steel) or a high grade aluminum (6061-T6 aluminum) to construct the adjuster. These materials have a high yield strength and will improve the performance of the headrest under bending loads. Also, a square cross-sectional area for the adjuster bar will provide the most resistance to rotation within the attachment hardware. Use of tubing, versus solid bar or rod, allows for greater strength per amount of material and allows for a lighter headrest. A square shape will also provide more bending resistance than a thinner flat stock. The Techni Seat headrest did not meet the criteria at any height adjustment and is constructed from a stainless steel metal sheet.

Some vertical adjusters may contain offsets resulting from bending or angling of the adjustment bar. The Otto Bock headrests both contained offsets that were the point of weakness on the headrest. This part of the adjuster yielded first, even though larger moments were applied to other sections of the bar. Vertical adjustment bars containing these offsets may yield at lower loads than calculated for the bar's section modulus. This must be considered when designing the system, and a larger section modulus will be required to sustain the necessary applied loads.

The size of the headrest pad should also be considered. In FMVSS 202, the federal government specified size requirements for motor vehicle head restraints. These requirements are most likely defined to allow for various sized occupants from the 5th percentile female to the 95th percentile male. The width requirements may also have been determined to prevent head excursion under dynamic conditions when the head has shifted. The larger the headrest pad, the better the chance of it contacting and supporting the head in a collision. FMVSS 202 specifies a minimum width of 17 cm for bucket seats. This requirement should also apply to the design of wheelchair headrests used during vehicle transport. **Table 1** shows that all the restraints tested in this study met the size requirement.

Although the static tests performed intentionally isolated the headrest from the rest of the seating system, and thus did not take into account the seat back, seat back stiffness should be considered. The dynamic studies performed by Mertz and Patrick and Foret-Bruno et al. concluded that seat back stiffness affected the amount of load seen by the head restraint (9,11). Under dynamic loading, as seat back stiffness increases, the load on the head restraint increases. As the seat back deforms, less load is transferred to the head restraint.

The move toward improving wheelchairs for vehicle transport may result in increased seat back rigidity to provide the strength necessary to maintain integrated occupant restraints. The increased stiffness will necessitate the use of headrests and affect the load requirements. Currently, most wheelchairs do not provide rigid back support. In the event of a vehicle crash, this flexibility reduces the loads on headrests as compared to those seen in a vehicle seat, since the wheelchair seat and seat back will dissipate some of the energy as it deforms. In addition, the seat back deformation reduces the rearward acceleration of the head, requiring the headrest to resist less force. Dynamic testing of wheelchairs with headrests is necessary to determine the influence of wheelchair seat backs and the loads that the headrest will experience in a rear end collision. With a less rigid seat back than a motor vehicle seat, the loads that must be withstood may be lower than those required by FMVSS 202. The energy criteria would decrease and more headrest models may be effective in a crash. However, the less rigid seat backs may result in other spinal injuries. Ideally, seat backs and headrests should be optimized as a system.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the methodologies performed on the sample of products, the following conclusions may be drawn:

1. The data obtained from the testing showed the methodologies developed yielded repeatable results.
2. Minimizing the height of the vertical adjustment bar of a headrest will provide the greatest resistance to loading from the head and limit head excursion. Bar height can be minimized by proper wheelchair back height and location of the mounting hardware.
3. The headrests tested exhibited three modes of deformation: 1) plastic deformation of the vertical adjuster, 2) plastic deformation and/or failure of the attachment receptacle, and 3) yielding of the plywood board. In some cases, combinations of these types of deformation were observed. Based on the observed mode, design improvements can be determined.
4. The majority of the tests resulted in bending of the vertical adjusters. This knowledge can be used to determine the required material and dimensions of the adjustment bar necessary to prevent bending at the predicted loads.
5. Headrests with offsets obtained by a bending or angling of the vertical adjuster failed at the offset point, showing this point to be the weakest.
6. Commercially available headrests, with a few design improvements, can be effective in preventing neck injury in rear-end collisions.

The findings of the study led to the following recommendations for future research:

1. Dynamic tests on the products should be performed to further validate use of static procedure for determination of crash performance.
2. Dynamic testing is also required to determine the magnitude of the loads on the headrest that can then be used to validate or change the pass/fail criteria of the static methodologies.
3. Dynamic testing should also be performed on wheelchair seating systems, including combinations of the various adaptive seating components to assess their interaction.
4. Design improvements, especially ones that reduce stress concentrations and design for gradual changes in stiffness, can be implemented and the products retested for their effectiveness.

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