

Sitting forces and wheelchair mechanics

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Abstract—The effects of back angle and leg height on sitting forces in a wheelchair were studied, using a force plate mounted on a wheelchair seat. Readings of both normal force (perpendicular to the seat) and shear force were measured while the chair's back angle and footrest height were changed. Pressure under the ischial tuberosities was also measured during the footrest height adjustments. Five normal subjects sat directly on the plate as well as upon ROHO and Jay cushions placed on the force plate. Returning the back to the upright position after a recline caused the normal force (\pm SD) to increase 5.4 ± 2.5 , 9.5 ± 4.0 , and 10.0 ± 2.3 kg for the hard surface, Jay cushion, and ROHO cushion respectively, while shear at the plate increased to 5.1 ± 2.2 , 11.6 ± 2.6 , and 12.3 ± 2.7 kg for the hard surface, Jay cushion, and ROHO cushion respectively. Leaning forward (away from the back) caused all the forces to return to measurements close to the starting values. The results suggest that the wheelchair user should momentarily lean forward after a recline to reduce undesired forces. If a cushion with firm thigh support is used, ischial tuberosity pressure can be reduced by lowering the leg height as much as possible, which causes a levering action by lifting the pelvis.

Key words: cushions, decubitus ulcer, force plate, pressure sore, seating pressure, shear force, wheelchair.

INTRODUCTION

Wheelchairs have adjustable supports that are traditionally positioned for occupant comfort or by common

sense. Little has been done to determine quantitatively the effect of support position on seat forces. This is especially true for shear force. Although back displacement has been used as a criterion to determine the suitability of different recline mechanisms (4), the resultant forces have not been measured. The interest in shear stems from the observation that shear force increases the possibility of inducing a decubitus ulcer. High skin shear levels have been found to lessen the normal force (downward force perpendicular to the supporting surface) needed to occlude underlying blood flow to one-half that needed when no shear is present (1). It is therefore important to reduce shear as much as possible. Another adjustable parameter which has not been fully studied is leg position. Changing footrest height may affect pressure on the ischial tuberosities and reduce the risk of ulcer formation. This study examines both the shear and normal forces under test subjects while an experimental wheelchair's back angle is changed, and the pressure under the ischial tuberosities as leg position is altered.

METHODS

Experiments were conducted on an Everest & Jennings Premier model powered reclining wheelchair (Everest & Jennings, Los Angeles, CA). It had footrests that would elevate as the back reclined, a commonly-used wheelchair feature for persons with high-level quadriplegia. The armrests were removed for these experiments. Back angle was measured in degrees from vertical, as shown in **Figure 1**. Leg height was measured by thigh angle in degrees from horizontal with the positive direction being knees elevated.

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BACK AND THIGH ANGLE DEFINITIONS

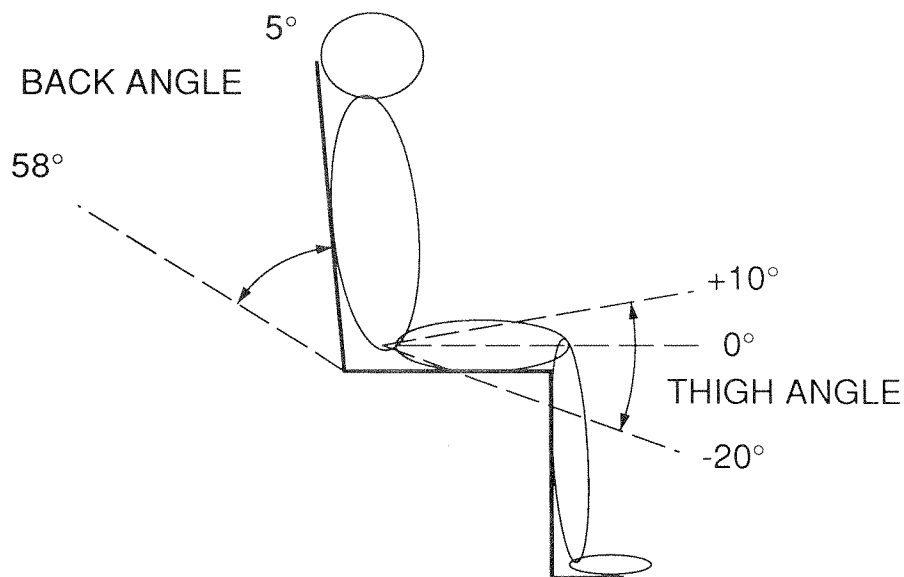


Figure 1.
Experimental setup for determining back and thigh angles.

The measurement was obtained using a board placed on the subject's lap.

An AMTI force plate (AMTI, Newton, MA) replaced the standard wheelchair seat. It was used to measure normal force, shear force, and the moment around an axis extending laterally from the center of the plate (**Figure 2**). The moment was divided by the normal force to determine the anterior-posterior position of the center of normal sitting force. Position readings closer to the rear of the plate indicate a greater percentage of force on the ischial tuberosities, while readings nearer the front indicate a greater force percentage on the thighs. As shown in **Figure 2**, normal force is positive in a downward direction, while shear force and anterior-posterior position are both positive in the anterior direction. Zero position is at the center of the plate.

Due to the thin construction of the plate, it was difficult to obtain the correct normal force readings along the edges. A modification done to improve accuracy is shown in **Figure 2**. First, a 3-mm thick sheet of hard plastic was fastened to the surface of the plate, which was cut back 4 cm from the edges of the plate. A metal sheet, of the same thickness as the plastic sheet, but with the same outer dimensions as the plate surface, was then fastened on top of the plastic sheet. This would redirect normal forces from

the edge to the center of the plate. After modification, normal force readings of a 25 kg weight placed over any portion of the plate's surface differed by less than 5 percent.

Data were collected using an Apple IIe (Apple Computer, Cupertino, CA) with an Applied Engineering 12-bit A/D converter (Applied Engineering, Carrollton, TX) through a custom interface box. Strain gauge bridge circuits in the force plate were excited with 4.5 volts. All resultant analog voltage output signals were run through a two-pole low-pass Butterworth filter with a cutoff frequency of 3.5 Hz before being digitized. Readings were calculated by averaging samples taken at 10 Hz for 5 seconds.

Two separate test groups of five subjects each were used for the back recline and leg height experiments. Informed consent was obtained from each subject. All subjects were apparently normal healthy adults, two female and eight male, ages 24 to 50. The average weight of the test subjects was 73.8 kg for the back recline study, and 79.9 kg for the leg height study.

For the back position study, test subjects were placed in the wheelchair and the footrest height was adjusted so that the tops of their thighs were horizontal. Instruction was given to relax and not voluntarily change body position during the experiment. The wheelchair back was

MODIFIED FORCE PLATE ASSEMBLY

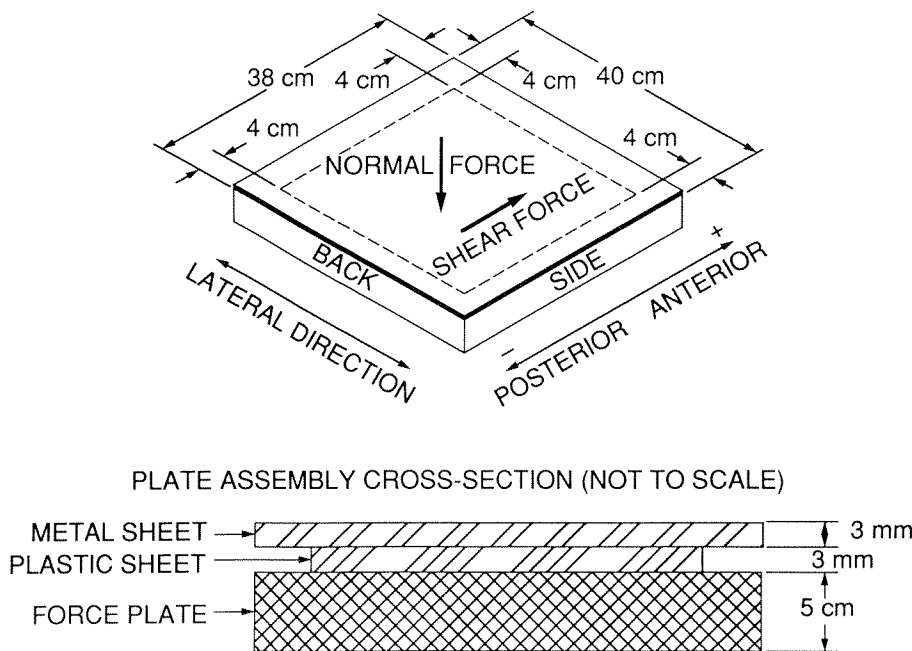


Figure 2.
Modified force plate with axes and force directions defined.

reclined at increasing angles beginning in a full upright position of 5 degrees from vertical and reclined in 5-degree intervals until a full recline position of 58 degrees was obtained. It then was returned to the upright position using the same intervals. Readings were taken at each interval. Two more recline cycles were then done, stopping to measure only at the 5- and 58-degree positions. Finally, the subject was asked to momentarily lean forward to remove any shears that might have accumulated over the back, and a final reading was taken. None of the intermediate positions were held for more than 30 seconds while the test was in progress.

The effects of leg position were also investigated. With the wheelchair back in full upright position, measurements were taken with the feet dangling, and then with the thighs at -10 , 0 , and $+10$ degrees (**Figure 1**). Thigh angle was changed by elevating the feet. Pressure under the ischial tuberosities was monitored with a Scimedics pressure evaluator (Scimedics, Inc., Anaheim, CA) at each thigh angle. Pressure readings were recorded by hand at each position.

Each subject was tested separately on ROHO cushions (ROHO Inc., Belleville, IL) and Jay cushions (Jay Medical Ltd., Boulder, CO), and also on the force plate with no cushions. When sitting directly on the force plate, a block of wood 1.4 cm thick was placed under the plate to keep

the subjects at the same relative height in the chair. The order in which the cushions were used by each subject was randomized.

RESULTS

Table 1 and **Table 2** give the means and standard deviations (SD) of forces on the cushions as a function of the back angle. Normal forces were standardized by dividing each subject's normal force reading by their body weight, averaging these values at each test position, and then multiplying by the average body weight of all subjects. This technique was chosen to give results in kilograms for a representative subject with an average body weight of 73.8 kg. **Figure 3** and **Figure 4** show the results of normal and shear force measurements over the complete range of recline. Both the normal and shear force data were adjusted so that the graphs show change starting from zero. All the force values are given in kilograms equivalent at normal gravity in order to be easily compared to body weight.

The measured force and shear changes from the ROHO and Jay cushions were indistinguishable from each other, while the hard surface changes showed less force

Table 1.

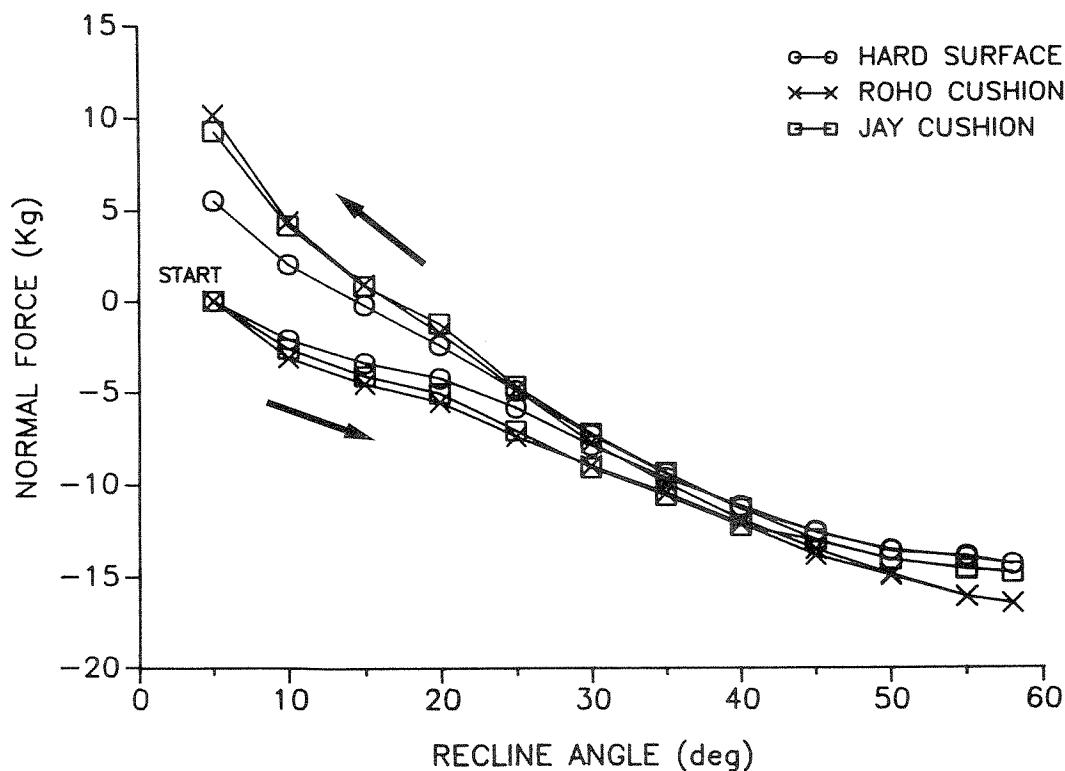
Shear and normal forces at various back angles.

		Normal force (kg)			Shear force (kg)		
		Hard	ROHO	Jay	Hard	ROHO	Jay
Initial upright position	ave	51.8	60.3	55.8	2.76	5.30	3.95
	SD	1.18	1.54	1.54	1.98	2.03	1.34
Full recline position	ave	37.4	43.7	41.1	-4.40	-1.08	-3.22
	SD	3.61	4.23	4.31	1.61	0.839	1.58
Return to upright position	ave	57.4	70.4	65.2	7.91	17.69	15.5
	SD	1.65	1.85	3.44	2.19	4.38	3.13
Upright position after lean	ave	51.6	60.0	57.5	3.42	8.17	7.57
	SD	1.42	2.03	4.09	1.63	6.79	1.12

buildup as the back was being returned to a vertical position. All subjects noted a "squeezed" feeling corresponding to this measured seat force buildup as they reached the full upright position. This buildup of forces was largely eliminated by the forward lean of the subject away from the back, which released force buildup along the back and returned the forces to very near the starting values.

Moving the chair back to full recline from full upright

position reduced the normal seat force by 14.5 and 16.8 kg and changed shear by 6.3 to 7.2 kg on all surfaces. In all cases, the direction of shear reversed. The major differences between surface types showed up only when the back was returned to the upright position. At return to full upright position, the ROHO and Jay cushions showed a normal force (\pm SD) increase of 10.0 ± 2.3 and 9.5 ± 4.0 kg, respectively, from initial readings, while the hard

**Figure 3.**

Normal force versus recline angle of the back (degrees from vertical). The data show the change in force with the starting value defined as zero. Arrows indicate the direction of movement.

Table 2.

Ischial tuberosity pressure, anterior-posterior position and normal force at different thigh angles.

		Pressure (mm Hg)			Position (cm)			Force (kg)		
		Hard	ROHO	Jay	Hard	ROHO	Jay	Hard	ROHO	Jay
Legs dangling	ave	157.6	68.4	59.8	2.30	1.94	3.10	75.9	79.8	76.9
	SD	26.1	4.39	11.3	1.18	1.34	1.35	3.06	4.06	3.27
Legs at -10 degrees	ave	211.6	65.8	76.6	-4.36	-0.640	-1.84	60.0	67.8	63.1
	SD	45.0	4.02	7.20	1.06	1.34	1.28	2.71	3.60	2.27
Legs at 0 degrees	ave	251.2	70.6	85.2	-6.62	-2.17	-3.92	55.5	64.7	59.4
	SD	35.4	3.85	7.85	0.370	1.29	0.963	2.32	3.91	2.91
Legs at +10 degrees	ave	256.2	73.4	86.6	-7.65	-3.40	-5.48	53.4	62.0	57.0
	SD	27.1	4.98	7.89	0.493	1.26	0.719	1.79	3.00	2.13

surface showed an increase of only 5.4 ± 2.5 kg. The ROHO and Jay cushions showed shear force changes from rest of 12.3 ± 2.7 and 11.6 ± 2.6 kg, respectively, while shear on the hard surface changed to 5.1 ± 2.2 kg from a resting position. The data accumulated from the two subsequent recline cycles revealed no force buildup with any of the three surfaces.

The results of the leg height study are shown in Figure

5 and Figure 6, as well as in Table 2. It can be seen that as the legs were elevated, the normal force was reduced, while the center of force was shifted backward. This was due to the thighs being lifted off their supporting surfaces and their weight being transferred to the feet. The rearward weight shift was somewhat linear with the ROHO cushion, but with the hard surface and Jay cushion it shifted more quickly as the legs were raised from a dangling posi-

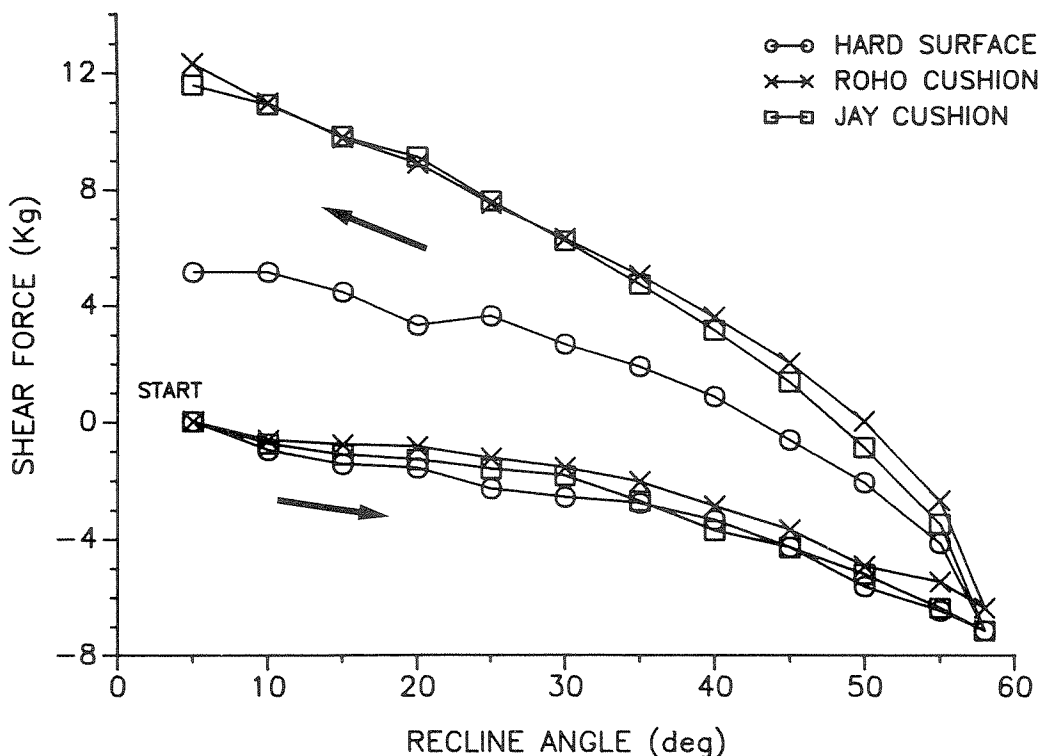


Figure 4.

Shear force versus recline angle of the back (degrees from vertical). The data show the change in shear with the starting value defined as zero. Arrows indicate the direction of movement.

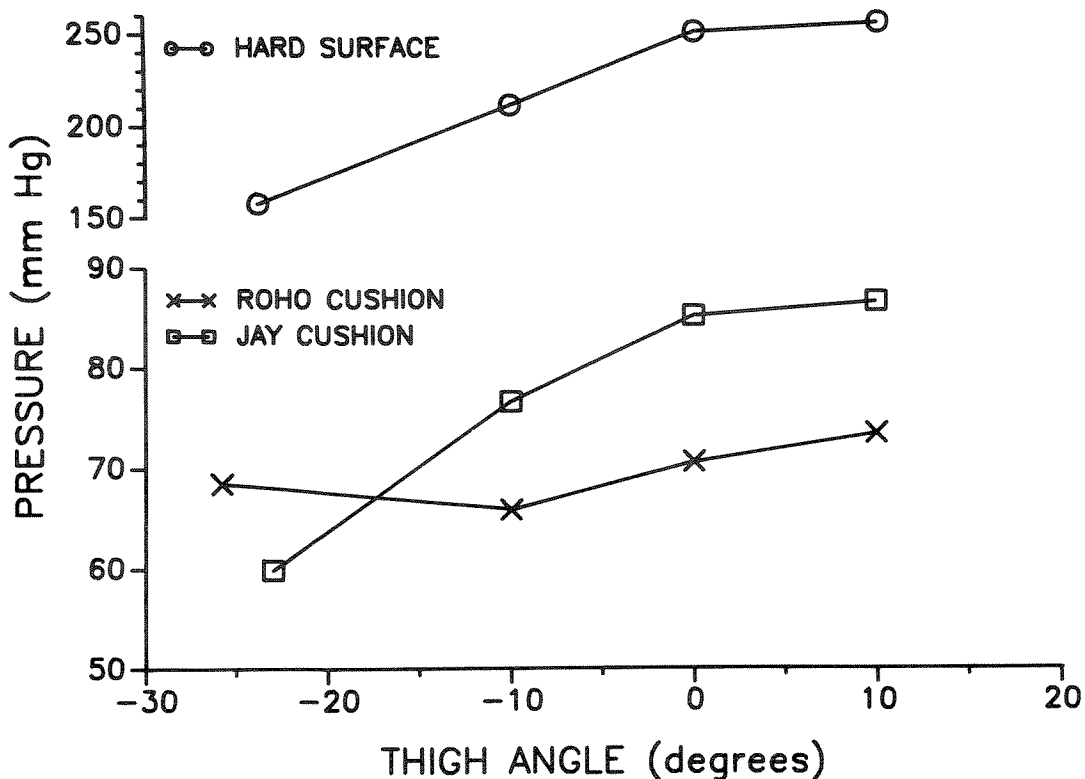


Figure 5.

Pressure on the ischial tuberosities as the legs were raised. The left-most point of each curve represents data taken with the legs dangling.

tion to -10 degrees. As the thighs were elevated from -10 degrees, the rates of weight shift approached each other. Pressures on the hard surface were very high and greater than with either cushion. As the legs were elevated, the pressure on the hard surface increased from 150 mmHg to 250 mmHg. Leg elevation while on the ROHO cushion produced a small pressure change from 68 to 73 mmHg, while on the Jay cushion a greater change occurred, from 60 to 87 mmHg. The thigh angle also varied with surface when the feet were dangling. The steepest angle was produced by the ROHO cushion, followed by the hard surface, with the Jay cushion allowing the thigh to drop the least amount.

DISCUSSION

In this study we have examined the changes in shear and normal seat forces brought about by back support and footrest height adjustment on a wheelchair. Ideally, knowledge of both the localized pressures and shears acting on the skin are desired. The system developed by Bennett and associates for measuring localized shear, pressure, and blood flow worked only with skin pressed against a hard

surface (2). No practical device exists today that can accurately measure localized shear when used with soft cushions. The exact level of localized shear is unknown, but may follow the overall shear as indicated by the force plate.

The differences in initial normal forces can be explained by the different thigh support properties of the three surfaces. Lowering the feet transfers part of thigh and leg weight from the feet to the force plate, resulting in higher normal total force readings, but lower pressure over the ischial tuberosities. This is particularly true for the Jay cushion and hard surface.

The reclining of the wheelchair back results in a reduction of normal force, which helps alleviate tissue pressure. It also causes a reversal of shear force from forward to rearward. This shift in shear direction could change internal stress patterns and transfer some load to other tissue areas.

The forces encountered during the back elevation phase changed significantly as the full upright position was approached. Raising the chair's back from full recline to full upright position increased normal force by nearly 27 kg and added about 9 kg to shear force on the cushions. The increased forces, especially the shear forces, were found to be uncomfortable for even short periods, and could

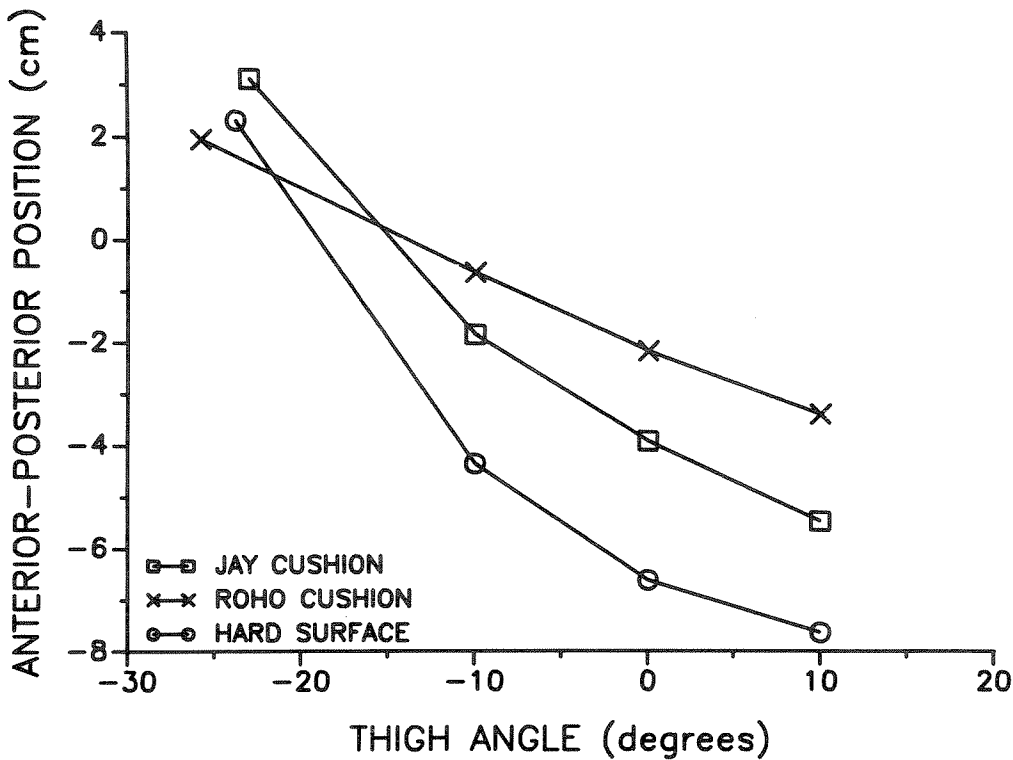


Figure 6.

Anterior-posterior position of sitting normal force versus thigh angle as the legs were raised. The left-most point of each curve represents data taken with the legs dangling.

be potentially harmful if sustained in patients with minimal sensation. This situation is caused by the sliding of the skin along the chair's back during the recline phase. A simple solution to eliminate the increased force is to momentarily lean the wheelchair occupant forward to remove contact with the back after each return to the upright position. This reduced shear force by more than a factor of two and reduced normal force by 10 percent, returning it to its pre-recline value. Other recline systems, such as a "tilt in space" wheelchair or the four-bar linkage design by Warren and associates (4), would be expected to yield different results due to differing chair back movement patterns in relation to the chair seat.

The problem of disabled people shifting downwards in their chairs was not reproduced during repeated reclines. As testing was performed upon able-bodied subjects, unconscious postural muscle activity might have played a part in the lack of sliding. Another factor may be the length of time that the subjects were held in full recline. As mentioned earlier, this time was approximately 30 seconds.

Some interesting points can be made concerning the leg height experiment. When the thighs were in the zero-degree position, the ROHO cushion showed 15 mmHg less

pressure compared to the Jay cushion; but with the legs dangling, the Jay cushion produced the least pressure by 9 mmHg. The ischial pressure while on the ROHO is relatively independent of leg height, while a subject sitting on a Jay cushion can change the pressure through leg height changes. Bush (3), working with hard sitting surfaces, also reported this effect.

The tendency of the tuberosity pressure to drop while support is removed from the feet could be enhanced by shifting the thigh's pivot point rearward. With firm support surfaces such as that provided by the Jay cushion, this pivot point is on the front edge of the cushion. If the top of the cushion were to be shaved down near the front, and an elevation built up closer to the cushion's center, the extra thigh weight ahead of this new pivot point would cause a greater lever action for lifting the tuberosities. Although with the ROHO the pivot point may be nearer the tuberosities, the nature of the cushion causes it to apply constant pressure to the skin regardless of depth into the cushion and no levering action occurs.

It should be noted that it is not practical to leave the feet totally without support. However, if most of the leg weight were supported by the cushion, with only enough weight placed on the feet to keep the heels on the footrests,

the same effect would be produced. Wheelchair occupants might then, in fact, need only rock forward for pressure relief. This would require further study to verify.

CONCLUSION

Two major phenomena are demonstrated in this study. First, having the user lean forward after a wheelchair back recline will greatly reduce undesired force. Secondly, wheelchair cushions with firm material under the thighs will facilitate reduction in ischial tuberosity pressure when the leg height is lowered as much as possible. Implementation of these two findings may help to reduce tissue damage in wheelchair-bound individuals.

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