Department of Veterans Affairs

Journal of Rehabilitation Research and Development Vol. 37 No. 3, May/June 2000
Pages 297–303

Displacement between the seating surface and hybrid test dummy during transitions with a variable configuration wheelchair: A technical note

Rory A. Cooper, PhD; Michael J. Dvorznak, BS; Andrew J. Rentschler, BS; Michael L. Boninger, MD
Departments of Rehabilitation Science and Technology, and Bioengineering, University of Pittsburgh, Pittsburgh, PA 15261; Human Engineering Research Laboratories, VA Pittsburgh Healthcare System, Pittsburgh, PA 15206; Department of Physical Medicine and Rehabilitation, UPMC Health System, Pittsburgh, PA 15213

ABSTRACT—Changing seating posture can extend the amount of time a person can safely remain seated without damaging tissue or becoming fatigued. The Excelsior is an electrically powered wheelchair that utilizes sit-to-stand (STS) and sit-to-recline (STR) motions to aid in pressure relief. The motion of the wheelchair seating system must closely follow anatomical paths or ulcers may develop from the resulting shear forces. Displacement between the person and the wheelchair seating surface is one measure of these shear forces. The displacement between a Hybrid II 50th percentile anthropometric test dummy (ATD) and the seating surface of the Excelsior wheelchair was examined during STS and STR with two cushions, a Jay Active and a low-profile Roho cushion. The difference between the backrest and ATD back angles were 4.29º ± 2.13º and 1.78º ± 1.73º for the Roho and Jay cushions respectively during STS and 3.32º ± 4.21º and 10.71º ± 6.20º during STR. These were statistically significant at $p<.05$. During STS, shear displacement between the Hybrid II back and Excelsior backrest did not exceed 1.5 cm for either cushion. ATD thigh-to-seat displacements were 2.5 cm for the Jay and 3.0 cm for the Roho cushion. STR produced dummy thigh-to-seat displacements of 1.5 cm and 3.5 cm for the Jay and Roho cushions respectively. Shear displacement in the ATD back was about 3.5 cm for the Roho and 6 cm for the Jay. The latter displacement should be reduced; however, the other conditions are marginal or acceptable. Hysteresis was acceptable or better for all cushion/motion combinations, with the highest net displacement of about 2.5 cm.

This material is based upon work supported by the Paralyzed Veterans of America and the Eastern Paralyzed Veterans of America

Address all correspondence and requests for reprints to: Rory A. Cooper, PhD, Human Engineering Research Laboratories (151-R1), VA Pittsburgh Healthcare System, Pittsburgh, PA 15206; email: rcooper;pl@pitt.edu.

INTRODUCTION

Changing seating posture can extend the amount of time a person can safely remain seated without damaging tissue or becoming fatigued (1). Determining the optimal range of seating postures is difficult and is best approached by clinical teams. Reclining or stand-up wheelchairs assist in performing pressure relief. Changing seating position redistributes pressure on weight-bearing surfaces, alters the load on postural musculature, and changes circulation (2). Changing position can also facilitate respiration. Elevating the legs while lowering the torso can improve venous return, and decrease fluid pooling in the lower limbs (3).

Most clinicians are familiar with the requirements for obtaining proper static seating posture in a wheelchair; few are familiar with dynamic seating posture.

While using a stand-up or recline wheelchair, the posture of the individual changes dramatically. Therefore, it is necessary to align the pivot mechanisms with the anatomical center of joint rotation for the individual. Misalignment can place stress on the joints that may lead to a fracture or joint laxity. Shear forces in the seat and backrest can lead to the development of decubitis ulcers (4–8). If the joints of the wheelchair do not follow the anatomical paths of the user, shear forces will result. Reclining or stand-up systems that attempt to follow anatomical joint centers are called low-shear (3,9). Without an anti-shear mechanism, up to 11 cm of displacement can take place between the person's back and the wheelchair's backrest (10,11). The length of the legrests presents a potential problem (11): if they are too short, high forces can be placed upon the bottom of the feet or knees in the reclined or standing position.

As stand-up and recline wheelchairs are more complex than most manual or electrically powered wheelchairs (3), several decisions must be made prior to selecting and fitting one of them. The activities for which the wheelchair will be used must be considered. For example, will the wheelchair need to be transported, and, if so, does it fold or disassemble? Will the stand-up wheelchair be used outdoors or on uneven terrain? The manufacturer can provide folded dimensions, overall dimensions, and static stability angles. It is important to ensure that the stand-up wheelchair is in compliance with American National Standards Institute (ANSI) and Rehabilitation Engineering and Assistive Technology Society of North America (RESNA) standards (12). The purpose of this study was to examine the displacement between a test dummy during STS and STR motions.

METHODS

Description of Test Wheelchair

The Excelsior is an electrically powered wheelchair that provides STS and STR. The number of actuators and controls required on the Excelsior is lower than most similar products as it uses a unique set of hinges, linkages, slides, and a linear actuator to generate wide ranges of motion (ROM). This chair has an upholstered backrest and rigid seat pan; it was selected because of its ability to generate both reclining and standing positions.

The seating dimensions for the Excelsior as measured according to Section 20, part 14 of the ANSI/RESNA Wheelchair Standards (13) are presented in **Table 1.** We also recorded the overall dimensions,

Table 1.
Seating dimensions of the wheelchair.

Dimension	Sitting	Standing
Seat Plane Angle	0º	19.58º
Effective Seat Depth	505 mm	465 mm
Seat Width	445 mm	440 mm
Effective Seat Width	460 mm	440 mm
Seat Surface Height	500 mm	680 mm
Backrest Angle	6.4º	7.4º
Backrest Height	620 mm	450 mm
Backrest Width	455 mm	450 mm
Headrest in Front of Backrest	0 mm (75 mm)	-20 mm (100 mm)
Headrest Height Above Seat	711 mm (940 mm)	530 mm (760 mm)
Footrest to Seat	435 mm	605 mm
Footrest Clearance	50 mm	55 mm
Footrest Length	350 mm	350 mm
Backrest to Leg Angle	96.7º	96.7º
Leg to Seat Surface Angle	104.1º	174.1º
Armrest Height	260 mm	525 mm
Front of Armrest to Backrest	310 mm	330 mm
Armrest Length	430 mm	435 mm
Armrest Width	75 mm	75 mm
Armrest Angle	0.75º	-2.15º
Distance between Armrests	480 mm	480 mm
Fron Location of Armrest Structure	N/A	N/A

All measurements at the fixed or minimum value; maximum values, where applicable, in parentheses; N/A=not applicable.

mass, and turning space of the stand-up wheelchair in the sit-down and stand-up configurations, see **Table 2. Table 3** presents the dimensions from the footrest to the top of the highest point on the wheelchair, the footrest to the top of the hip/upper torso support, and from the footrest to the vertical center of the knee/lower leg support according to Section 20 of the ANSI/RESNA Standards. The speed and acceleration of the test wheelchair were recorded according to Section 20, part 13 of the ANSI/RESNA Wheelchair Standards, see **Table 4.**

Table 2.
Wheelchair dimensions in seated and standing positions.

Seated	Dimension
Overall Length with Footrests	1,310
Overall Length without Footrests	910
Overall Width	685
Overall Height	1,350
Minimum Turning Radius	720
Turn-around Width between Walls	1,470
Standing	
Turning Radius	850
Turn-Around Width	1,480

All measurements in mm.

Table 3.
Critical dimensions related to the footrests.

Footrest Condition	Dimension
Highest Point	1,655
Top of Hip/Upper Torso Support	1,170
Center of Knee/Lower Leg Support	475

All measurements in mm.

Table 4.
Maximum speed, acceleration, and retardation of the electric-powered wheelchair.

Condition	Sitting	Standing
Speed Forward	2.32	2.31
Speed Uphill, 3°	2.03	2.04
Speed Uphill, 6°	1.69	1.55
Speed Backward	1.67	1.64
Acceleration: Forward	1.7	1.9
Deceleration: Joystick Release	2.1	2.4
Deceleration: Full Reverse	2.7	3.0
Deceleration: Power Off	2.4	2.9

All measurements at the maximum value; speeds in meters per second; acceleration and deceleration in meters per second squared.

The static stability of the Excelsior wheelchair was tested in three configurations (sit-down, stand-up, and recline) using the test procedures specified in Section 1 of the ANSI/RESNA Wheelchair Standards. During the stand-up static stability tests forces were applied according to Section 20, clause 19 of the ANSI/RESNA Wheelchair Standards (13). The forces applied to the wheelchair are based upon the maximum mass of the occupant. In this case the maximum mass (M) of the occupant was 100 kg. According to the standard, the force applied to the knee restraint is equal to the mass of the occupant times the gravitational constant, see Equation 1. We used a gravitational constant (g) of 9.8 m/sec^2. All forces were applied with a 50-mm wide nylon strap.

$$F_{knee} = Mg = 100 \cdot 9.8 = 980 \text{ N} \quad [1]$$

The force specified by the ANSI/RESNA Wheelchair Standard for the hip/torso support device is given in Equation 2. This force is applied parallel to the plane of the floor. The force given in Equation 3 is also applied to the hip/torso support device, but at an angle of 45° inclined from the floor. The hip/torso support is also tested with a force directed downward at 45° with respect to horizontal, see Equation 4.

$$F_{hip} = 0.20Mg = 0.20 \cdot 100 \cdot 9.8 = 196 \text{ N} \quad [2]$$

$$F_{hip\_elevated} = 0.1Mg = 0.1 \cdot 100 \cdot 9.8 = 98 \text{ N} \quad [3]$$

$$F_{hip\_decline} = 0.5Mg = 0.5 \cdot 100 \cdot 9.8 = 490 \text{ N} \quad [4]$$

The results of the static stability tests are presented in **Table 5.** After each test, the body supports were inspected for permanent deformation or failure.

Relative Displacement Measurement

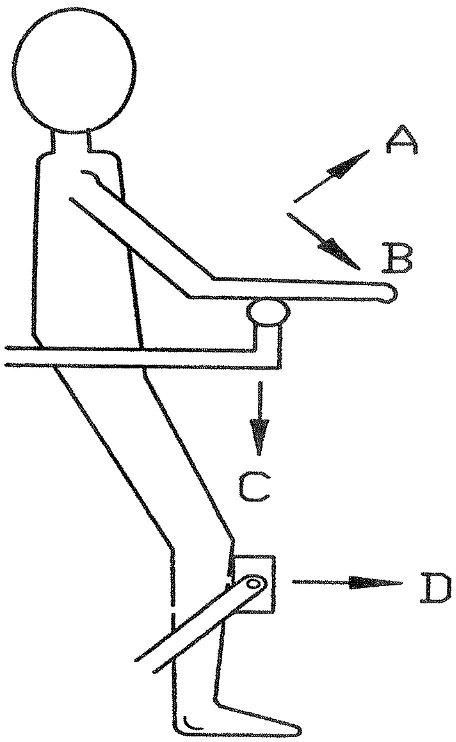
To measure the displacement for the Excelsior electric powered wheelchair, a 50th percentile anthropometric test dummy (ATD), the Hybrid II, was utilized (14). Displacement between the ATD and wheelchair seating surface is a measure of shear, see **Figure 1.** To minimize shear between the ATD and wheelchair seat, the displacement between the body and seating surface ideally should be zero for the full ROM, see **Figure 2.** The motions of the wheelchair and ATD were recorded with an OPTO<i>TRAC</i> infrared active marker motion analysis system (Northern Digital, Inc., Waterloo, ON, Canada). Markers on the hip joint, pelvis, ribs, thigh, and knee of the ATD were recorded at 10 Hz. Markers were

Journal of Rehabilitation Research and Development Vol. 37 No. 3 2000

Table 5.
Static stability tip angles for the Excelsior.

Test Condition	Sit Down	Recline	Stand Up
Downhill: Wheels Unlocked	23.5º	36.5º	13.5º
Downhill: Wheels Locked	23.9º	37.2º	17.9º
Uphill: Wheels Unlocked	28.4º	26.2º	24.4º
Lateral Stability	24.5º	26.8º	17.8º
Downhill Force D	N/A	N/A	0º
Downhill: Force C	N/A	N/A	9.4º
Downhill: Force A	N/A	N/A	7.8º
Downhill: Force B	N/A	N/A	0º

Downhill and uphill=direction the wheelchair is facing.



Forces:
Directions of force application in **Table 5.**

also placed on the backrest of the wheelchair, the backrest pad, and the seat of the wheelchair, see **Figure 3.**

Motion of the markers was recorded in the sagittal view, as the chair went through a complete STS and stand-to-sit cycle. Data were also recorded as the chair

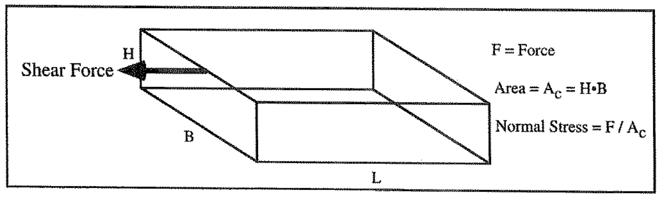


Figure 1.
Shear stresses act orthogonal to normal stresses, and may cause little change in tissue thickness.

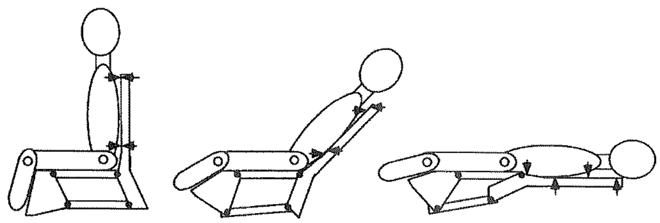


Figure 2.
Schematic for reclining wheelchair seat. Arrows indicate the displacement between the user's back and the wheelchair backrest. Unless the back slides or the wheelchair's pivots follow the body's anatomical joint centers, shear forces will result.

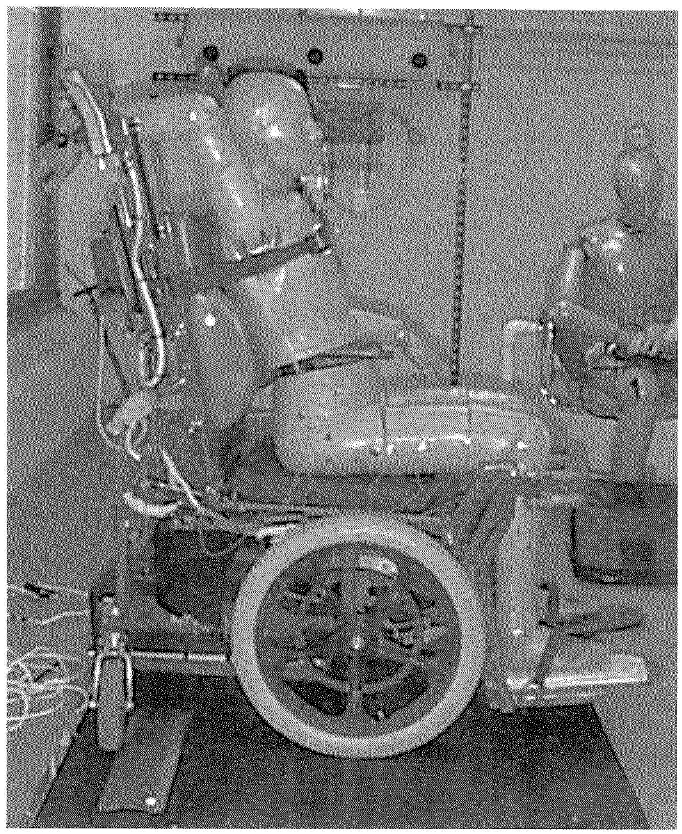


Figure 3.
Shows the wheelchair/ATD setup, infrared marker placement, and OPTO<i>TRAC</i> motion analysis camera.

went through a complete STR and recline-to-sit cycle. The ATD was repositioned to its proper seated position after each complete cycle. Tests were performed with the ATD seated on a low-profile Roho and Jay Active cushion. The motion data were analyzed using a custom program written using MatLab software (The Math Works, Inc., Natick, MA). The Excelsior wheelchair also allows the user to nearly reach a full reclined position, as well as standing. The wheelchair user can transition from STS and then to recline through the operation of simple switches. Therefore, we examined the shear displacements of both of these motions.

RESULTS

Sit-to-Stand Motion Analysis

We calculated two curves for each set of data. **Figure 4** shows the relative change in the ATD back angle versus seat angle for the Jay and Roho cushions, respectively. The figure shows that the motion of the ATD back closely follows the path of the wheelchair backrest with either the Jay or the Roho cushion. This is indicated by the similarity of the dotted and solid lines in the figures. The mean±SD difference between the backrest and ATD back angles were 4.29°±2.13° with the Roho cushion and 1.78°±1.73° with the Jay cushion. A two-tailed T-test showed that these were statistically significant ($p<0.05$).

The shear displacement between the ATD and the backrest are shown in **Figure 5** for the Excelsior wheelchair with the Jay and Roho cushions, respectively. The shear displacement between the ATD back and the Excelsior backrest does not exceed 1.5 cm for either cushion. The shear displacement between the thigh of the ATD and the Excelsior seat is greater than that for the backrest, but remains less than 2.5 cm for the Jay and 3.0 cm for the Roho cushion.

When going through a STS, the body may shift. Therefore, after multiple STS cycles there may be some cumulative effect related to the hysteresis of the shear displacement. **Figure 5** shows the shear displacements for the back to backrest and thigh to seat for the ATD and Excelsior with the Jay and Roho cushions, respectively. The hysteresis is less than 0.5 cm for either cushion, with the exception of thigh-to-seat displacement with the Roho, which had a hysteresis of about 2.5 cm.

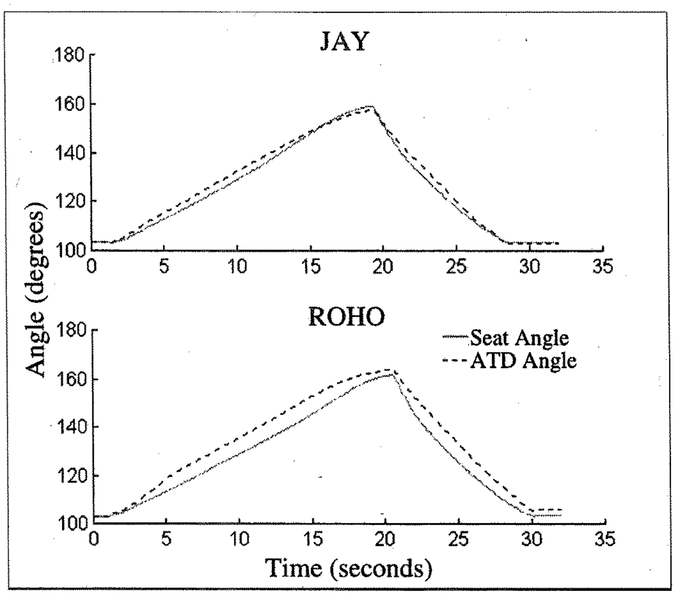


Figure 4.
Shows the relative change in the ATD back angle versus seat angle for the Jay and Roho cushions during a complete STS cycle. The dotted line represents the motion of the ATD, whereas the solid line represents the motion of the Excelsior backrest.

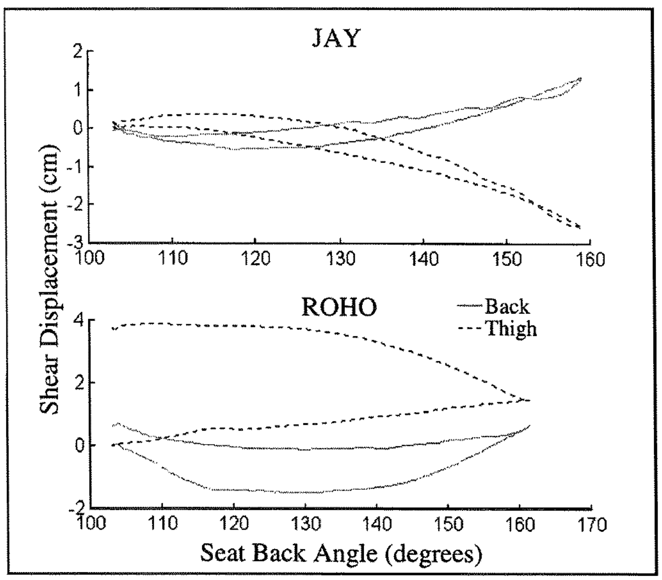


Figure 5.
Shows the shear displacement in cm of the ATD back to the backrest and the ATD thigh to the seat as the seat angle of the excelsior chair changed during STS operation.

Sit-to-Recline Motion Analysis

The wheelchair remained adjusted as it had been for the STS trials. **Figure 6** shows the change in the angle of

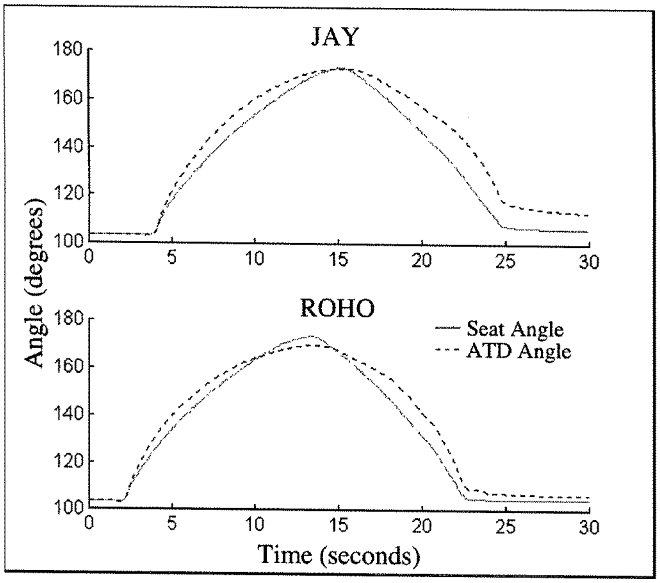


Figure 6.
Shows the relative change in the ATD back angle versus seat angle for the Jay and Roho cushions during STR. The dotted line represents the motion of the ATD, whereas the solid line represents the motion of the Excelsior backrest.

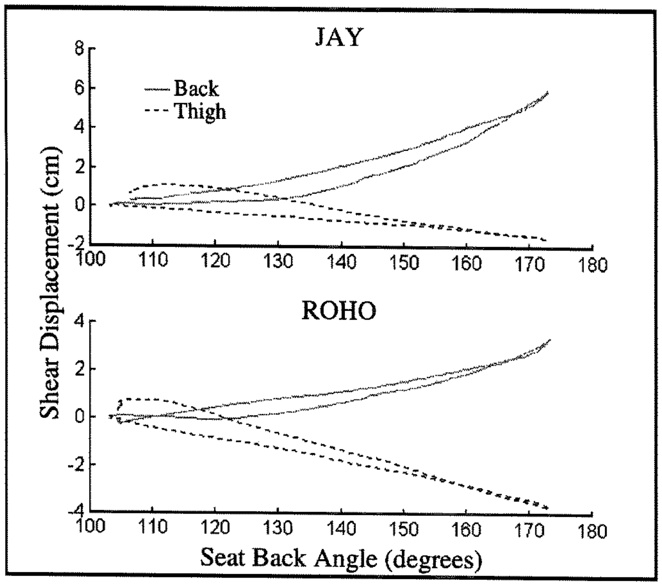


Figure 7.
Shows the shear displacement in cm of the ATD back to the backrest and the ATD thigh to the seat with respect to the seat angle of the excelsior chair during a complete STR cycle.

the ATD and the Excelsior backrest with the Jay and Roho cushions, respectively. This figure shows that the ATD and Excelsior back follow different paths. The shape of the curves for the ATD back changes from the Jay to the Roho cushion. The mean±SD difference between the backrest and ATD back angles for the Roho and Jay cushions were 3.32º±4.21º and 10.71º±6.20º, respectively. These were significantly different ($p<0.05$). The Roho cushion also had a higher maximum angle than the Jay.

The shear displacement for the STR of the ATD with regard to the Excelsior wheelchair for both the Jay and Roho cushion are shown in **Figure 7.** The Jay cushion yields a shear displacement of about 6 cm between the ATD back and the Excelsior backrest. The Roho cushion yields about 3.5 cm of shear displacement for the back. The shear displacement between the ATD thigh and the Excelsior seat was less than 1.5 cm for the Jay, and about 3.5 cm for the Roho cushion.

As with the STS, the STR of the wheelchair can result in shifts in the body's position with respect to the wheelchair. To examine the possible cumulative effect due to the body shifting, the hysteresis was examined. For the Jay cushion, the hysteresis was about 1 cm, and the Roho was less than 0.5 cm (see **Figure 7**).

DISCUSSION

Our results show that the shear displacements were small for the STS. The Excelsior hinge mechanism did a reasonable job of reducing shear displacements over large angular changes, and that the cumulative shear displacements of repeated STSs were small. The shear and angular motion of the dummy showed some variation to the changes between the two cushions, as could be seen by the different waveforms in **Figure 5.** Results from testing with the Jay cushion show that the Excelsior and ATD exhibit similar shear displacement when going through STS and STR. The Jay and Roho cushions showed a similar waveform for the STR. The Jay had the highest backrest shear while the Roho had the highest thigh shear displacement. The shear displacements and hysteresis for the back and thigh are within acceptable limits for the STS for both cushions (10). The shear displacements for the back and thigh are marginal for the STR on the Roho. The thigh displacement for the Jay is marginal for the STR. The back displacement for the Jay for the STR should be reduced. During the STR there can be significant upward and forward displacement of the tissue covering the coccyx and posterior to the pelvis.

When an individual sits on a cushion, a number of activities take place. The interaction between the cushion and body tissue determines the user's comfort, function, and clinical safety. Distribution of stresses within the seating tissue affects the safety and effectiveness of the cushion. Wheelchair cushions are designed to provide pressure distribution for safe long-term seated posture, postural support, protection from vibration, and protection from shock. Poor distribution of stresses can lead to skin breakdown through a number of means. Normal stress is defined as force divided by the area over which it is applied, see Equation 5. High stresses can occur with large forces or with small areas.

Tissue either compresses or stretches in response to normal stress. Localized stresses are a consequence of sitting. Normal stresses act perpendicular to the skin, whereas shear stresses act parallel to the skin. Sitting causes both normal and shear forces to exist within the seating tissue. Shear stress is applied force divided by the cross-sectional area, see Equation 6.

Normal stress over a bony prominence can cause a decrease in blood flow, ischemia, which causes anoxia, a lack of oxygen and nutrients (2). Anoxia and lack of nutrients promote tissue death, necrosis (3,5). When normal stresses are applied, capillaries are pinched off; they are occluded when external pressure exceeds the internal tissue pressure. Capillary blood pressure is in the range of 32 mmHg as measured in the finger nail beds of healthy subjects, but can be as low as 12 mmHg (3). Friction and shear can cause skin abrasions (9). Shear also causes strain within the body tissue and can cause capillary occlusion (5). When shear is present, the tolerance for normal stresses is reduced (4).

The shear displacement plots from STS varied in shape with the type of cushion. There were differences in the magnitude of shear displacement due to the type of cushion for the STR. The shear displacement and, especially, the forward/upward force from the backrest while transitioning from STR could result in a pressure sore. Extending and tapering the backrest padding could reduce the potential for tissue trauma. The hysteresis is acceptable for the seat and back with either cushion.

REFERENCES

1. Trefler E, Hobson DA, Taylor SJ, Monohan LC, Shaw CG. Seating and mobility for person with physical disabilities. Therapy Skill Builders; 1993 Tucson, AZ.
2. Webster JG, editor. Prevention of pressure sores: engineering and clinical aspects. Philadelphia, PA: Adam Hilger; 1991.
3. Cooper RA. Wheelchair selection and configuration. New York, NY: Demos Medical Publishers; 1998.
4. Chow WW, Odell EI. Deformations and stresses in soft body tissues of a sitting person. J Biomech Eng 1978;100:79–87.
5. Bennet L, Kavner D, Lee BK, Trainor FA. Shear versus pressure as causitive factors in skin blood flow occlusion. Arch Phys Med Rehabil 1979:60;309–14.
6. Agrawal VP, Chandra R. Optimization of a chair mechanism for partially disabled people for sitting-standing and sitting-lying motions. Med Biol Eng Comput 1979:17;671–82.
7. Ferguson-Pell MW. Design criteria for the measurement of pressure at body/support interfaces. Eng Med 1980;9:209–14.
8. Gilsdorf P, Patterson R, Fisher S, Appel N. Sitting forces and wheelchair mechanics. J Rehabil Res Dev 1990;27(3):239–46.
9. Goosens RHM, Snijders CJ. Design criteria for the reduction of shear forces in beds and seats. J Biomech 1995;28(2):225–30.
10. Warren C.G. (1982) Reducing Back Displacement in the Powered Reclining Wheelchair, Arch Phys Med Rehabil, Vol. 63, pp. 447-449.
11. Warren CG, Ko M, Smith C, Imre JV, Reducing back displacement in the powered reclining wheelchair. Arch Phys Med Rehabil 1982;63:447–9.
12. McLaurin CA, Axelson P. Wheelchair standards: an overview. In: Todd SP, editor. Choosing a wheelchair system. J Rehabil Res Dev 1990;Clin Suppl 2:100–3.
13. ANSI/RESNA wheelchair standards part 1 & 2, rehabilitation engineering society of north america. Washington, DC: RESNA Press; 1998.
14. Nahum AM, Melvin JW. Accidental injury: biomechanics and prevention. New York, NY: Springer-Verlag; 1993.

Submitted for publication May 19, 1999. Accepted June 24, 1999.