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Reduction of sitting pressures with custom contoured cushions

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Abstract—Previous research indicated that matching a cushion to the shape of the buttocks results in less tissue distortion and lower interface pressures. A system was developed to measure body contours and fabricate a cushion to match the measured contour. This project fabricated contoured foam cushions for 11 persons with spinal cord lesions (C5-L3). Mean pressures were compared on two flat and two contoured foams with different degrees of stiffness. Deflection characteristics on flat foam were compared to deflection on contoured foam in order to analyze loading differences. Material studies were determined by examining the load-deflection curves for flat foams of 1-, 2-, and 3-inch thicknesses. It was found that sitting on contoured foam resulted in a lower pressure distribution than sitting on flat foam ($p<0.05$), and sitting on a soft foam (ILD=45) resulted in a lower pressure distribution than sitting on a stiffer foam (ILD=55) ($p<0.05$). Results of the deflection measurements and compression tests were used to explain the loading differences at the seat interface of flat and contoured cushions. Loaded contoured foam demonstrated increased enveloping of the buttocks, decreased foam compression, and a more uniform pressure distribution. These attributes are typical of a safer sitting surface and may indicate less tissue distortion.

Key words: *custom contoured cushions, pressure ulcers, spinal cord injury, tissue interface pressure, wheelchair seating.*

INTRODUCTION

Wheelchair users often sit 12 to 16 hours a day while participating in daily activities. Sitting for a long period of time requires special seating support especially for spinal cord injured (SCI) persons and others with insensate skin. People with spinal cord injury are at high risk for the formation of pressure ulcers. Such pressure sores disrupt every aspect of a person's life—affecting health, employment, education, and social interaction. Over the past three decades, many studies have focused on the biomechanical aspects of decubitus formation. Tissue trauma is now recognized as a multidimensional process with externally applied pressure being identified as a primary contributing factor (2,6). Recently, tissue distortion has also been identified as a potentially damaging condition (5,11). These two risk factors are related because distortion results from the external forces being exerted on soft tissue.

The original analysis of contact stresses was published in 1881 by Heinrich Hertz (12). He quantified pressures resulting from an indentor contacting a surface pad. Hertz determined that as the curvature of the unloaded cushion changed from flat to concave, the peak contact pressures would decrease. More recently, theoretical and empirical experiments by W.W. Chow have indicated that matching a cushion to the shape of a penetrator would result in less indentor distortion and a lower interface pressure (4). Furthermore, a properly fitted contoured cushion would improve the pressure distribution through a decrease in potentially damaging normal and shear forces with a corresponding increase in nondistorting hydrostatic pressure. Based in part on these findings, a system was designed to measure body contours on various cushion surfaces and fabricate a cushion which matches the measured contour.

The purpose of this study was to validate the theory that a contoured cushion matching the shape of the buttocks

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will result in a safer sitting surface. Pressure measurements from the area under the ischial tuberosities were compared on flat and contoured foam, and a biomechanical analysis of the buttock cushion interface was undertaken. A more thorough understanding of the buttock-cushion interface should aid in the development of customized, contoured foam cushions for use by members of the disabled community.

PROCEDURE

Equipment

An adjustable positioning system was built to study body position, body contour, and pressure distribution (5). A contour gage, consisting of 64 probes, arranged in a 16 × 16 inch area, forms the seat of the positioning system to measure seat contours. Linear potentiometers were used to measure cushion deflection in the seating area. The probes pass through holes in a foam cushion which has been predrilled to match the 8 × 8 array. To maintain a consistent position at the cushion surface, the probes were capped with suction cups. The foam sits on a flat solid surface to prevent hammocking of the material.

Subjects were transferred into the positioning system and the seating configuration (seat and back angles, seat depth, footrest height) was adjusted to match subjects' current wheelchairs with slight variations to provide adequate support and comfort. After a subject was properly seated, the deflection of each probe was measured and stored in a computer. Once collected, the data were expanded from an 8 × 8 into a 33 × 33 array using Whittaker's Reconstruction (10) for better resolution for carving the contour. After review, the data were used to fabricate a custom contoured cushion over a 16-inch square area. The automated foam contouring system (3) consisted of two components—a computerized numerical controller (CNC) and an automated XYZ milling machine. The contour was cut with a rotating cutting tool which made sequential passes over the surface of the cushion.

Methods

Eleven persons with spinal cord lesions (C5-L3) were studied. Each subject was asked to sign a consent form and provide demographic information. All the subjects were measured on two different 3-inch, medium density (3.2 lb/ft^3), high resiliency (HR) foams with indentation load deflection (ILD) ratings of 45 and 55 pounds. Two subjects were also measured on a stiffer HR70 cushion.

Pressures were measured within a 4 1/2 inch × 8 1/2 inch rectangle using an Oxford pressure monitor (model TM700). A pneumatic transducer with a 6 × 4 cell matrix was used. The cells were 2 cm in diameter and placed on 3 cm centers. The transducer was centrally placed in the region under the ischial tuberosities. Pressures were measured at each of the 24 locations. Consecutive recordings taken in one position resulted in repeatable pressure values. Results of the calibration procedure permitted accuracy to ±5 mmHg at the 100 mmHg calibration level.

Mean pressure and standard deviation were determined for the 24 points. Peak pressures were recorded but not analyzed due to the instability of the measure. This decision was based, in part, on the results of a study into the variance of peak pressures under the ischial tuberosities (8). Clinical experience has confirmed the instability in peak pressure values which result from the variation in the location of a single transducer cell relative to a bony prominence. If a single cell was located directly under a bony prominence, it would record a higher pressure than if it was located a centimeter to either side.

Since the transducer was a fixed size, it represented a different percentage of the weight-bearing area of each subject. However, since repeated measures were taken for each subject on each cushion, the mean pressure and standard deviation accurately represent the pressures under the ischial tuberosities and can be used for analysis. Mean pressures were analyzed using a two-factor, repeated measures ANOVA. Foam stiffness (45 and 55 ILD rating) and cushion shape (flat and contoured) comprised the two factors. Therefore, the pressure distribution for each subject was determined for four cushions, flat HR45, contoured HR45, flat HR55, and contoured HR55. All statistical comparisons were evaluated for significance at a probability level of 0.05.

The contour gage was used to measure the initial deflection of flat foam. A custom contoured cushion (CCC) was cut to match the measured contour. The CCC was then placed back on the contour gage to measure further deflection of the CCC. This second contour measurement allowed analysis of how a CCC is deformed under load, compared to a flat foam, and provided immediate feedback to insure correct alignment of the subject in the contour.

Pressure was measured on the flat cushions and on each contoured cushion. Two contour characteristics, maximum deflection and displaced volume, were calculated to show how people transmit load to a cushion. Deflection values were recorded at 64 locations arranged in an 8 × 8 matrix. When loaded, foam cushions exhibit a volume loss. This displaced volume was determined from a triangular, six-point, second order approximation of a

surface which was then integrated. These contour characteristics were used in the biomechanical analysis comparing flat foam to contoured foam.

In addition to the pressure and contour measurements, standard material testing was performed. Material properties were studied to determine the load-deflection relationships for flat foams of 1-, 2-, and 3-inch thicknesses. The CCCs studied varied in thickness over the sitting surface. In order to approximate the compressive properties of contoured foam, different thicknesses of flat foam were tested. The testing procedures were taken from ASTM Schedule D 3574-86. The ILD test consisted of measuring the force necessary to produce 25 percent and 65 percent indentations. The support factor for a cushion was defined as the ratio of the 65 percent to 25 percent ILD values. Foams with low support factors tended to "bottom out" more readily in a seating application.

RESULTS

Pressure measurement values are listed in **Table 1.** Analysis of the deflection data revealed a "bottomed out" condition in some instances during which high peak pressures may result. For the HR45 foam, the mean pressures were reduced as ten of the 11 subjects sat on contoured foam. Peak pressures were reduced in eight subjects. While sitting on HR55 foam, mean pressures were

Table 1.
Pressure comparisons of flat versus contoured foam.

HR45						
Subject	Flat			Contoured		
	x	sd	peak	x	sd	peak
1	51.1	25.6	120	48.8	37.0	130*
2	48.7	19.5	100	40.7	8.7	65
3	41.2	11.4	70	35.6	7.5	50
4	32.9	6.6	45	27.0	9.6	40
5	34.8	8.9	60	33.0	8.2	50
6	43.9	11.5	70	41.5	10.8	65
7	74.2	31.3	175	62.4	30.2	145*
8	60.1	26.6	130	48.0	20.7	130*
9	41.0	21.4	110	41.1	18.8	95
10	39.9	12.4	80	37.7	11.1	65
11	65.7	43.4	130	54.2	27.1	130*
avg	48.5			42.7		

HR55						
Subject	Flat			Contoured		
	x	sd	peak	x	sd	peak
1	53.0	22.7	130	51.3	22.7	105*
2	63.3	25.2	120	41.7	13.1	75
3	49.8	17.4	80	38.6	10.7	65
4	38.5	10.2	60	38.7	7.1	55
5	48.1	19.7	100	34.4	10.0	50
6	46.2	9.5	65	36.2	4.5	50
7	85.7	35.3	160	67.6	34.7	113*
8	72.1	28.8	140	52.4	16.7	95
9	54.4	30.3	150	53.9	19.4	110
10	46.5	12.9	90	52.8	9.1	85
11	64.7	50.1	200	50.1	26.6	130
avg	56.6			47.1		

*deflection data indicated a 'bottomed-out' condition

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reduced in nine of the 11 subjects. Peak pressures were reduced in all subjects as they sat on a contoured HR55 cushion. The standard deviations of the 24 pressure locations were reduced in nine subjects as they sat on HR45 foam, and in ten subjects while sitting on a CCC fabricated from HR55 foam.

The results of the statistical analysis are shown in **Table 2.** Both main effects, shape and stiffness, were significant ($p<0.05$). Sitting on a HR45 cushion (flat or contoured) resulted in a lower pressure distribution than sitting on a HR55 cushion. Sitting on a contoured cushion (HR45 or HR55) resulted in a lower pressure distribution than sitting on a flat foam of similar ILD. The interaction between the two factors was not significant ($p>0.10$). In other words, the pressure difference between sitting on a contoured cushion and a flat cushion was not necessarily dependent on the ILD of the foam used. The means for each factor are listed in **Table 2.**

The force-deflection curves for the three thicknesses of HR55 foam are shown in **Figure 1.** The HR45 and HR70 foams yielded similar plots with respect to deflection under load. These plots illustrate that for a proportional deflection, the rebound force decreased as the foam thickness decreased. In other words, less force is required to induce a 40 percent deflection in 1-inch foam than in 3-inch foam. The results of the compression tests for all the foams tested are included in **Table 3.**

The contour and deflection characteristics of the HR55 foam are listed in **Table 4.** The results from the HR45 tests were similar but are not included here. Some of the differences between sitting on a flat cushion and a CCC result from the displacement due to load and increase in displaced volume. The displacement under load reflects the maximum deflection of a cushion when someone is seated. Sitting on a CCC induced less displacement than sitting on a flat foam. Contouring foam also offered an increase in displaced volume with a CCC exhibiting an increase of 64 percent over a loaded flat cushion.

Table 2.
Pressure comparison on two ILDs (stiffness) of flat and contoured foam (shape).

Group means (mm Hg):

HR45	HR55	Flat	Contoured
45.6	51.8	52.5	44.9

Cell means (mm Hg):

Flat HR45	Cont HR45	Flat HR55	Cont HR55
48.5	42.7	56.6	47.1

Analysis of variance

Source	D.F.	Mean sq.	F
Subject	10	583	
Stiffness	1	10231	17.5*
Shape	1	15402	15.8*
Stiffness × shape	1	904	3.1
Subj. × stiff. × shape	10	291	

*significant at $p<.05$

DISCUSSION

Results of the pressure comparison indicated a difference in the mean pressure depending on stiffness or shape. The Hertz contact equations predicted that pressure would increase with the stiffness of a material. The results of this study agree with this theory since the HR45 foam provided seating support at lower pressure than the stiffer HR55. Generally, a softer, more compliant material will wrap around the buttocks, which results in better enveloping. Enveloping results in a larger contact area and a more uniform pressure distribution (4). Some materials are too soft for a seating application, deform too much, and reach a "bottomed out" condition during which high interface pressures result. Therefore, a tradeoff between enveloping and bottoming-out is defined.

The principal concern addressed in this study was the performance of contoured foam. The statistical results indicated that sitting on a CCC resulted in a lower pressure distribution than sitting on flat foam. In addition, peak pressures were reduced in 19 of the 22 cases despite deflection data that indicated a "bottomed-out" condition in six instances. These results are again in agreement with the Hertz equations (12) and the work of Chow (4), and constitute a basis for the development of contoured foam for wheelchair seating. Part of the effectiveness of contoured foam can be explained by studying the material properties of contoured foam and addressing the physiological factors which can be inferred from foam compression results after loading a cushion.

A contoured block of foam produces a cushion with varying thickness over the sitting surface and, thus, with varying mechanical properties. As illustrated in **Figure 1,** the force-deflection curve of a 1-inch cushion is lower than the curve for a 3-inch cushion. The varying thickness of a CCC results in a foam surface with varying compressive properties depending on the contour depth. For example, if a contour is measured on a 75-mm (3-inch) thick cushion and the maximum displacement is 40 mm, the resulting

Table 3.
Compressive properties of HR45, HR55 and HR70 foams.

	1″ Thickness ILD (lb)		2″ Thickness ILD (lb)		3″ Thickness ILD (lb)	
	25%	65%	25%	65%	25%	65%
HR45	30.9	63.0	36.8	83.8	36.4	102.9
HR55	29.3	68.8	41.9	104.7	46.7	128.3
HR70	42.2	108.2	52.2	165.8	77.2	209.9

contoured cushion has an actual thickness of 35 mm at this location. Therefore, instead of sitting on 75 mm of foam, the person only sits on 35 mm. The areas of less thickness are inherently softer than the thicker portions and therefore demonstrate less rebound force for a particular deflection.

The other material benefit of contoured foam is the amount of deflection which occurs when sitting on a CCC compared to a flat cushion. The maximum deflection for each subject was measured as well as the subsequent deflection at this site after a CCC was fabricated and loaded. The results are shown in **Table 3.** The average maximum deflection was 31 mm, which corresponded to 41 percent deflection on a cushion with 75 mm thickness. When a typical subject sat on a CCC, the corresponding site was deflected an additional 11 mm. This deflection was only 25 percent of the thickness at that location (44 mm). Because the foam deformed less, reduced rebound force was expected. This reduced deflection was consistent at other locations of the contour. A CCC exhibited an undeformed shape that was closer to the final buttock-cushion interface so, therefore, the cushion deformed less.

The precontouring of foam affects the loading and deformation of the buttocks as well as the cushion. The distortion of tissue was not measured in this study but can be inferred from the respective foam deflections. Both the mechanism of loading and the area over which loads are transmitted are changed as a result of surface contour. These effects can be explained via changes in the enveloping property of the cushion. Enveloping results from the ability of foam to decrease in volume during compression. The ability of a cushion to wrap around the buttocks and produce side loading is related to its enveloping property. A good enveloping cushion will provide a more uniform pressure distribution and a stable sitting surface which should result in reduced stress of the buttock tissue (4,7). The volume reduction of foam under load was calculated. This reduction is considered an approximation of enveloping.

Sitting on a compliant cushion induces compression, shear, tension, and bending. The relative amounts of each are dependent on both the cushion properties and the amount of deformation required until an equilibrium is reached. Large and uneven foam compression has been related to the presence of shear stress (1). A buttock-cushion interface that approaches the undeformed shape of the buttocks would induce less normal and shear forces on the body tissues and, therefore, less tissue distortion (4,11). Based on these findings, a loaded contoured cushion demonstrated certain characteristics that strongly suggest

Table 4.
Contour characteristics of flat and contoured HR55 foam.

Subject	Displaced vol (cm^3)				Max displacement (mm)	
	Flat	CCC	Diff	(%)*	Flat	CCC
1	724	1022	299	(41)	32	3
2	852	1388	536	(63)	39	18
3	880	1377	497	(56)	37	10
4	1001	1479	478	(48)	34	10
5	1598	2780	1182	(74)	36	17
6	710	1340	630	(89)	26	9
7	505	730	225	(45)	20	7
8	439	833	394	(90)	17	8
9	1895	3364	1469	(77)	44	17
10	1118	1686	569	(51)	43	15
11	750	1256	506	(67)	34	12
Avg	952	1568	617	(64)	33	11

*denotes percent difference of displaced volume between a loaded CCC and a loaded flat foam.

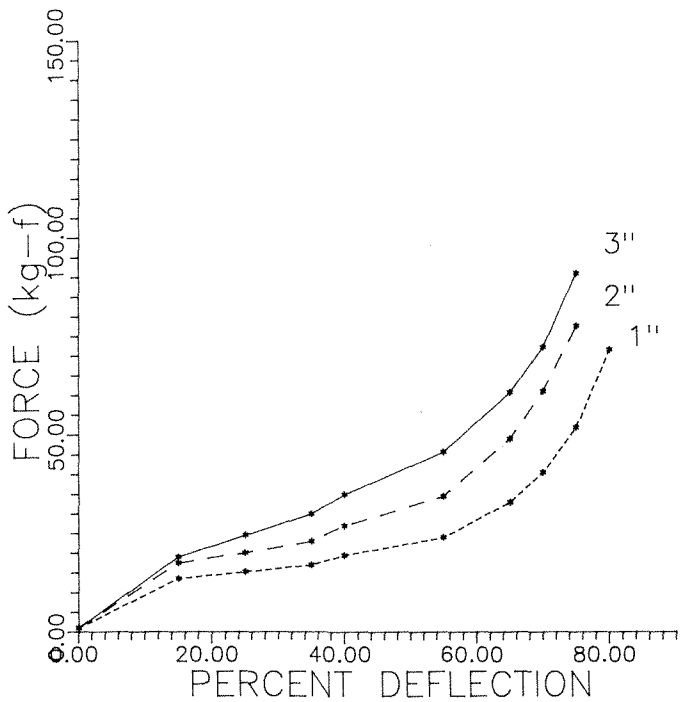

Figure 1.
Force-deflection curves of HR55 foam.

an improved seat interface.

The results indicated a 64 percent increase in displaced volume. The buttocks will be encompassed more because of this increase. In addition, further deflection was reduced at the site of maximum indentation suggesting less compression at the site of greatest load transferral. In fact, less compression occurred throughout the gluteal region resulting in more even foam compression, less surface tension, and decreased shear effects as the cushion and buttocks reached equilibrium. The mean pressures on flat and contoured HR55 foam are included in **Table 1.** The standard deviations of the 24 pressure locations are also shown. The pressures measured on a CCC exhibit less variability and therefore may represent a more uniform pressure distribution. These three important attributes—increased enveloping, decreased foam compression, and a more uniform pressure distribution—are typical of a safer sitting surface and may indicate less tissue distortion.

Contoured foam cushions, when compared to flat foam, seem to provide a seat interface that is potentially less damaging to soft tissue. The material properties of the compliant foam contribute to lower interface pressures as a result of reduced resistance to deflection once contoured and loaded. In other words, as contour depth increases, the foam becomes less stiff because of reduced thickness in this region. The buttock-cushion interface seems to exhibit less tissue distortion, reduced foam compression gradients, and induced shear due to the shape of the unloaded cushion. Even though many factors can contribute to tissue damage, contoured foam cushions seem to reduce the damaging effects of external loading, and seem to be an appropriate alternative for wheelchair use.

Subsequent studies have investigated the effect of CCCs on functional and postural considerations (9). Research comparing CCCs to available commercial cushions was conducted to identify strengths and weaknesses. The results of the research and the clinical evaluation were used to design a contoured cushion that offered a safe sitting surface without affecting the user's functional abilities.

REFERENCES

1. **Bennett L, Himanshu P:** Transferring load to flesh: Part IX. Cushion stiffness effects. *Bull Prosthet Res* 10(31):14-37, 1979.
2. **Bennett L, Kanner D, Lee BK, Trainor FA:** Shear vs pressure as causative factors in skin blood flow occlusion. *Arch Phys Med Rehabil* 60:309-314, 1979.
3. **Brienza D:** Design of a CAM system for custom contoured wheelchair cushions. Master's thesis, University of Virginia, 1988.
4. **Chow WW:** Mechanical properties of gels and other materials with respect to their use in pads transmitting forces to the human body. PhD diss., University of Michigan, 1974.
5. **Chung KC:** Tissue contour and interface pressure on wheelchair cushions. PhD diss., University of Virginia, 1987.
6. **Krouskop TA:** A synthesis of the factors that contribute to pressure sore formation. *Med Hypotheses* 11:255-267, 1983.
7. **Reddy NP, Patel H, Cochran GVB, Brunski JB:** Model experiments to study the stress distributions in a seated buttock. *J Biomech* 15(7):493-504, 1982.
8. **Souther SG, Carr SD, Vistnes LM:** Wheelchair cushions to reduce pressure under bony prominences. *Arch Phys Med Rehabil* 55:460-464, 1974.
9. **Sprigle S:** Biomechanical analysis of contoured foam for use by spinal cord injured persons. PhD diss., University of Virginia, 1989.
10. **Stearns SD:** *Digital Signal Analysis.* Rochelle Park, NJ: Hayden Book Company, 1983.
11. **Swart ME:** Physico-mechanical aspects of decubitus prevention. *Int J Rehabil Res* 8(2):153-160, 1985.
12. **Timosheko SP, Goodier JN:** *Theory of Elasticity,* 2nd ed. New York: McGraw-Hill Book Company, 1951.