Factors affecting seat contour characteristics

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Abstract—This project focused on identifying the influence of subject characteristics and foam properties on seat contours in order to explain the load transfer between the buttocks and cushion. Seat contours were recorded for 17 people (11 spinal cord injured and six able-bodied individuals). Contour characteristics were represented by maximum contour depth, surface area, and displaced volume. Subject characteristics were represented as intertrochanteric distance, body weight, and lower extremity muscle tone. Two foams with different degrees of stiffness (45- and 55-pound indentation load deflection [ILD]) were studied. Multiple regression equations were calculated for each of the three contour characteristics by entering in all three subject attributes. While the equations differ, all six exhibited a significant Multiple R (range: 0.79 to 0.92). Each subject characteristic was a significant predictor of at least one contour trait ($p < 0.05$). The major difference between the two cushions was the predictive ability of muscle tone. For the stiffer HR55 foam, muscle tone was the strongest predictor of all contour characteristics. Therefore, some conclusions can be drawn concerning the relationship between foam stiffness, tone, and resulting seat contours. These relationships help define the differences in load transfer as subject and cushion characteristics vary and are important in the design of contoured foam for use as wheelchair cushions.

Key words: *high resiliency foams, seat contours, tissue interface pressure, wheelchair cushions.*

INTRODUCTION

Many types of wheelchair cushions have been developed to reduce the occurrence of pressure sores. Most of these cushions were designed to reduce or alternate the pressure under the buttocks. The effect of load on tissue damage has been studied in a variety of ways and pressure has generally been accepted as a primary cause of tissue damage. Recently, tissue distortion has been mentioned as an important indication of tissue damage (4,5,6,9). Theoretical and empirical experiments (1,3) indicated that matching a cushion to the shape of an indenter results in less indenter distortion and a lower interface pressure. They concluded that a compliant contoured cushion may be effective in lessening tissue distortion of the buttocks in a seated posture.

Tissue distortion is a result of external forces being exerted on soft tissue. As a person sits on a cushion, the buttocks and the cushion deform until an equilibrium interface is reached. Sitting on a hard flat surface requires that the buttocks deform to match the flat shape. However, the use of a compliant material allows the buttocks to maintain a less distorted shape. Seat contours have been measured and studied at the University of Virginia, Rehabilitation Engineering Center (UVA-REC) for several years in order to better understand the load transfer between the buttocks and cushion. Recent studies found beneficial postural and pressure effects of custom contoured foam cushions that suggest further study (7).

Seat contours are a result of five major factors: 1) the shape of the buttocks; 2) the shape of the cushion; 3) biomechanical properties of the buttocks influenced by

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tissue thickness and stiffness; 4) mechanical properties of foam classified by ILD and density; and, 5) weight distribution on the cushion.

Buttock shape and tissue properties are very difficult to measure. However, the shape and stiffness of the buttocks and the load on the cushion are fixed for an individual, but vary greatly from person to person. Cushion shape and stiffness are measured fairly accurately and can be manipulated to study their influence on seat contours.

This project was designed to study the effect of certain subject characteristics and foam properties on seat contours. Understanding this relationship would further explain the load transfer from the buttocks to a cushion. A direct consequence of load transfer is tissue distortion and interface pressure, two factors which contribute to tissue damage (3,6,10). The results of this project could be used in the design and prescription of custom contoured cushions (CCCs) to reduce tissue distortion and produce a more uniform pressure distribution. This would be significant in providing an effective seating support to aid in the management of pressure and seating problems.

PROCEDURES

Equipment

The UVA-REC developed an adjustable positioning system to study body position, body contour, and pressure distribution on various cushion surfaces (4). Contour at the buttock-cushion interface was measured by a contour gage which forms the seat of the positioning system and consists of 64 probes arranged in a 16×16 inch area. Linear potentiometers were used to measure cushion deflection in the seating area. After the client was properly seated, deflection data were collected using a computer and stored on disk. Whittaker's Reconstruction (8) was used to expand the data from an 8×8 into a 33×33 array for better resolution. Once reviewed, the data were used to fabricate a CCC. The automated contouring system consisted of two components—a computerized numerical controller (CNC) and an automated XYZ milling machine (2).

Methods

Seat contours were recorded for 11 persons with spinal cord lesions and six able-bodied individuals (age range: 23 to 45 years). All the SCI subjects used commercially available wheelchairs and cushions, and none required external support for maintenance of a stable seated posture. Each subject was asked to sign a consent form and pro-

vide certain demographic information including body weight and disability level.

Subjects were transferred into the positioning system and the seating configuration (seat and back angle, seat depth, footrest height) was adjusted to match the configuration provided by their regular wheelchair and cushion. Slight adjustments were made at the request of the subject to provide adequate support and comfort. The seat and back angles varied only slightly (seat angle: 3 to 6 degrees from horizontal; back angle: 5 to 10 degrees from vertical). Contour measurements were stable despite small changes in seat and back angles.

After the subject was properly seated, deflection data were measured and stored by the computer. Custom contoured cushions were fabricated by cutting out the measured contour in foam. The CCC for a subject was then placed back on the contour gage to measure further deflection when loaded. This second iteration of contour measurement allowed analysis of the CCC deformation under load compared to a flat foam. Each subject was studied on two types of 3-inch, medium density (3.2 lb/ft^3), high resiliency (HR) foam with respective ILD ratings of 45 and 55 pounds. Eight subjects were also measured on a stiffer high resiliency foam with an ILD of 70 pounds.

Contour characteristics were represented by three numerical quantities: maximum depth, surface area, and displaced volume. Maximum contour depth (DEPTH) or indentation was determined from the greatest potentiometer deflection. Surface area (SAREA) was calculated from a first-order surface approximation using a triangular element with three points. Displaced volume (DISVOL) was determined from a triangular, six-point, second order approximation of a surface which was then integrated.

Three variables were used to describe the subjects: intertrochanteric distance (TROCH), body weight (WGT), and muscle tone (TONE). The TROCH was used as a measure of pelvic width and therefore, the overall size of the pelvis; WGT represented the load on the cushion. The TONE was intended as an index of buttock stiffness and represented the three general classifications of tone: spastic, flaccid, and normal. Subjects were queried about their lower extremity tone and were assigned to one of three groups: no SCI, spastic, and flaccid. Because of this coding scheme, TONE also represented atrophied tissue in the SCI group versus normally innervated tissue in the no-SCI group.

Two separate analyses, statistical and graphic, were performed. Multiple regression equations were calculated for each contour characteristic, DEPTH, SAREA, and DISVOL, by entering all three subject characteristics,

Table 1.

Subject and contour characteristic data for HR45 foam.

Subject	WGT (kg)	TROCH (cm)	SCI level (TONE*)	DEPTH (cm)	SURAREA (cm ²)	DISVOL (cm ³)
1	50.0	37.5	C6 (1)	4.1	1704	1290
2	55.0	39.0	C7 (1)	4.2	1706	1583
3	52.0	35.0	C6/7 (1)	3.5	1689	930
4	59.5	42.0	C5/6 (1)	2.5	1670	589
5	62.5	41.0	C5/6 (1)	3.3	1668	1061
6	66.3	39.0	T4 (1)	3.5	1698	1384
7	99.8	47.0	T12 (2)	4.7	1725	2240
8	63.5	40.5	C4/5 (2)	4.3	1697	877
9	60.0	35.0	L3 (2)	5.1	1716	1573
10	92.5	41.5	T9 (2)	4.4	1716	1866
11	54.0	33.0	L1 (2)	5.0	1703	1044
12	54.5	32.0	— (0)	2.9	1685	1088
13	59.0	38.5	— (0)	2.7	1676	781
14	67.5	40.3	— (0)	2.6	1682	1152
15	68.0	36.0	— (0)	3.8	1712	1972
16	74.8	37.5	— (0)	4.0	1719	2016
17	81.5	39.5	— (0)	4.2	1717	2578

*0 = normally innervated, 1 = spastic, 2 = flaccid

TROCH, WGT, and TONE. Equations were formed from data for both the HR45 and HR55 foams. This regression and a correlation analysis determined the relationships between each contour description and the three subject characteristics. The formed equations were not used to predict contour characteristics given the three subject characteristics. Rather, the analysis was used as a measure of the contribution of each subject characteristic in explaining the variance of each contour measurement.

A contour plot was made by graphing the row of data points passing through the greatest cushion indentation. This plot provides a transverse cross-section view of the contour shape. Data points were connected using a cubic spline fitting technique. This technique was used for visual rather than analytical purposes. Contour shapes from each cushion were compared to illustrate the ability of cushion stiffness to govern the shape of the buttocks.

RESULTS

The subject and contour characteristics for both foams are listed in **Tables 1** and **2**. The results of the multiple regression and correlation analyses are shown in **Tables 3** and **4**. In the regression analysis, $p < 0.05$ was accepted for determination of statistical significance. For the HR45 foam, more than 55 percent of the observed variability in

DEPTH, SAREA, and DISVOL could be explained by the three subject characteristics. For the DEPTH equation, TROCH, WGT, and TONE were all significant predictors. The SAREA equation showed that WGT and TROCH were significant predictors. Only WGT seemed to significantly predict DISVOL. Of the independent variables, only WGT and TROCH exhibited a significant correlation. Significant correlations existed between DEPTH-TONE and DISVOL-WGT. For the dependent variables, SAREA was significantly correlated with both DEPTH and DISVOL.

The HR55 foam equations exhibited a strong linear relationship (Multiple R range: 0.89 to 0.92) between the subject characteristics and each contour description. TONE was the only significant predictor in the DEPTH and SAREA equations. In the DISVOL equation, both TONE and WGT were significant predictors. All three contour characteristics were significantly correlated. TONE was significantly correlated with all three dependent measures and the WGT-DISVOL correlation was significant. Two subject characteristics, WGT and TROCH, again were significantly correlated.

Examples of cross sections of contour plots for two subjects with spinal cord lesions at C6/7 and T12 are shown in **Figures 1** and **2**, respectively. Contour characteristics are also displayed. These graphs illustrate the differences between contours of similar depths. Seat contours varied in shape and width with respect to foam stiffness. As shown

Table 2.

Subject and contour characteristic data for HR55 foam.

Subject	WGT (kg)	TROCH (cm)	SCI level (TONE*)	DEPTH (cm)	SURAREA (cm ²)	DISVOL (cm ³)
1	50.0	37.5	C6 (1)	3.1	1681	750
2	55.0	39.0	C7 (1)	3.5	1691	1001
3	52.0	35.0	C6 (1)	3.2	1682	724
4	59.5	42.0	C5/6 (1)	1.7	1663	439
5	62.5	41.0	C5/6 (1)	2.0	1667	505
6	66.3	39.0	T4 (1)	2.6	1672	710
7	99.8	47.0	T12 (2)	4.4	1713	1895
8	63.5	40.5	C4/5 (2)	3.7	1696	880
9	60.0	35.0	L3 (2)	4.3	1697	1118
10	92.5	41.5	T9 (2)	3.6	1698	1599
11	54.0	33.0	L1 (2)	3.9	1689	852
12	54.5	32.0	— (0)	1.2	1658	186
13	59.0	38.5	— (0)	1.5	1661	274
14	67.5	40.3	— (0)	1.0	1655	140
15	68.0	36.0	— (0)	2.0	1666	513
16	74.8	37.5	— (0)	2.0	1668	551
17	81.5	39.5	— (0)	2.3	1669	789

*0 = normally innervated, 1 = spastic, 2 = flaccid

Table 3.

Multiple regression and correlation results—HR45 foam.

Dependent variable			Independent variables			
	Multiple R	R²		Beta	T	Sig T
DEPTH	.810	.66	DISLEV	.712	4.25	.0009
			TROCH	−.598	2.60	.0194
			WGT	.573	−2.66	.0220
DISVOL	.805	.65	DISLEV	−.143	−.842	.4152
			TROCH	−.426	−1.88	.0833
			WGT	1.03	4.61	.0005
SAREA	.749	.56	DISLEV	.272	1.43	.1738
			TROCH	−.645	−2.55	.0244
			WGT	.948	3.80	.0022
Correlations: 1-tailed significance *−.01 **−.001						
	DEPTH	DISVOL	SAREA	WGT	TROCH	DISLEV
DEPTH		.526	.812**	.285	−.038	.661
DISVOL			.844**	.717**	.235	−.077
SAREA				.556	.061	.271
WGT					.676*	.163
TROCH						.242
DISLEV						

Table 4.
Multiple regression and correlation results—HR55 foam.

Dependent variable			Independent variables			
	Multiple R	R ²		Beta	T	Sig T
DEPTH	.892	.79	DISLEV	.894	6.94	.0000
			TROCH	−.225	−1.30	.2152
			WGT	.214	1.26	.2305
DISVOL	.916	.84	DISLEV	.687	6.00	.0000
			TROCH	−.089	−.583	.5699
			WGT	.574	3.81	.0022
SAREA	.904	.82	DISLEV	.850	6.94	.0000
			TROCH	−.114	−.697	.4984
			WGT	.301	1.87	.0847
Correlations: 1-tailed significance *−.01 **−.001						
	DEPTH	DISVOL	SAREA	WGT	TROCH	DISLEV
DEPTH		.864**	.969**	.208	.136	.875**
DISVOL			.931**	.626*	.465	.759**
SAREA				.363	.295	.872**
WGT					.676*	.163
TROCH						.242
DISLEV						

in **Figure 1**, the second contour measurement in the stiffer HR55 foam was slightly deeper than the first HR45 measurement, yet was narrower and exhibited less displaced volume. **Figure 2** contains plots of contours on HR45, HR55, and HR70 foams. These contours also exhibited increasing surface area and displaced volume with decreasing stiffness despite similar maximum depths.

DISCUSSION

The regression equations differed greatly for each foam. The HR55 equations seemed to reflect a stronger linear relationship between contour description and subject characteristics. This may have occurred because contours on the softer HR45 foam were influenced by a number of different factors of which only a few are entered here. While a significant amount of variance was explained regardless of foam stiffness, the HR55 equations exhibited more predictive ability. The combined effects of body weight, intertrochanteric distance, and disability level resulted in better prediction of contour as foam stiffness increased. All three contour descriptions seemed to be strongly related. Since depth, surface area, and displaced

volume were all simple quantifications of a contour shape, the high intercorrelations were not surprising. However, each quantity was unique as evidenced by the different regression equations and the varying predictive ability of each subject characteristic. Each contour description provided a unique contribution to the biomechanical analysis of the seated posture.

Maximum contour depth may give some indication of how load is transferred. Cushion deflection is dependent on the distribution of applied force. A deep indentation denotes high loads being absorbed by the cushion and may indicate a "bottomed out" condition. A person with low body weight but a deep contour is probably transmitting load through a small area and will experience high pressures in the region of high deflection.

Displaced volume is a measure of the volume reduction which occurs during compression of foam. The ability of foam to decrease in volume allows it to envelop a material. It is the enveloping of a material that allows the cushion to "wrap around" the buttocks and produce side loading to improve the weight distribution (3). A good enveloping cushion provides a more uniform pressure distribution and a stable sitting surface. Displaced volume was significantly related to body weight on both foams.

Figure 1.
Contour plots of C6/7 quadriplegic.

Figure 2.
Contour plots of T12 paraplegic.

This relationship is not surprising since foam is expected to compress under load; however, a high displaced volume does not necessarily signal an unsafe seating situation. Possibly, an improved sitting situation would result if high displaced volumes existed with relatively low cushion deflections. This situation would combine a high level of envelopment without the elevated rebound forces caused by high cushion indentations.

An increase in surface area is one way to lower pressure distribution given a certain load. A flat foam cushion offers some increase in surface area as the cushion deforms under load. The instrument used in this study did not provide total contact area; however, the total surface area of the cushion was calculated. The surface area of a loaded CCC is greater than that for a loaded flat foam.

The largest difference between the results for the two cushions tested is the predictive ability of lower extremity tone. For the HR45 foam, TONE was a significant predictor of contour depth only, but on the stiffer HR55 foam, TONE was the strongest predictor for maximum depth, surface area, and displaced volume. TONE not only represented the level of muscle tone in the lower extremities, it also reflected the presence of SCI, which results in a reduction of tissue mass in the gluteal region. Therefore, some conclusions can be drawn concerning the relationship between foam stiffness, the extent of tone, the presence of SCI, and resulting seat contours.

The able-bodied subjects did not deflect the HR55 foam nearly as much as the two SCI groups, with the flaccid paraplegics inducing the most compression. As tone decreases, the area of load transferral decreases as well. A person with normal tone can transmit load over a greater area; and on a stiff cushion, regardless of body weight, he/she will not deform a cushion as much as someone with flaccid tissue. The load transferral of a flaccid paraplegic will be concentrated in a much smaller area under the ischial tuberosities which allows for greater cushion deflection. The effect of tone will probably increase as foam stiffness becomes greater. Some subjects were measured on an even stiffer HR70 foam. Normal subjects induced very little deflection (< 10 mm), whereas a SCI subject of similar weight produced a much greater indentation (> 30 mm).

All three of the subject characteristics, body weight, intertrochanteric distance, and lower extremity muscle tone are important predictors of contour in soft foam. However, as foam stiffness increases, muscle tone becomes such a strong predictor that the other two variables seem less powerful.

These results may be used for the clinical prescription of a cushion for different types of SCI persons. A

paraplegic may need a stiffer or thicker cushion to avoid a "bottomed-out" condition. Quadriplegics may require a material which provides greater envelopment and more stability. Because the cushion "wraps around" the buttocks, balance may be improved and there should be less friction because the buttocks tend not to slide during normal daily activity.

The contour plots reveal that contour characteristics were dependent on cushion stiffness. Contours with similar depths exhibited differences in shape and size as illustrated in **Figures 1** and **2**. Polyurethane foam is 4 to 5 times stiffer in shear and 10 times stiffer in tension than it is in compression. As a cushion's ILD is increased, the foam becomes extremely stiff in shear and tension. Sitting on a cushion induces pure compression, shear, surface tension, and bending. Shear, tension, and bending can occur outside the projected area of load. Pure compression occurs directly under the site of load transferral. Successive iterations of seat contours measured on a stiff foam demonstrate the effect of increased shear and tension moduli. The contours are narrower and the cushion doesn't envelop the buttocks as well as evidenced by the lesser displaced volume.

Foam deflection tends to occur more exclusively in the area under the ischial tuberosities through which most load is being transmitted. Successive iterations of a stiffer foam do not "wrap around" the buttocks as well since this requires the foam to assume shear and tensile strain. These results verify the influence that foam stiffness has on seat contours. Successive iterations of contour measurement do not approach any certain shape or size. Instead, the shape of the buttocks is partially dictated by the type of foam used.

The results indicate that seat contours are affected by several subject and cushion characteristics. All these factors influence the method of load transferral from the buttocks to cushion. Since subject characteristics are generally fixed for an individual, this study demonstrated the consequence of changing cushion characteristics while accommodating for physical parameters. Foam stiffness will change the way load is transmitted to a cushion and therefore will affect the seat contour. Wheelchair users require appropriate body support to provide not only protection from tissue trauma but also adequate posture and stability.

The study of seat contours has provided useful information for proper positioning of SCI persons. The physical characteristics of a person can be used to identify potential problems at the seat interface and material properties of a cushion can be chosen to compliment the characteristics of the user. Other studies have concluded that

contoured foam provides an inexpensive, yet effective method of managing seating problems (7). This project helped identify the influence of material and contour characteristics and should help direct further study into contoured seating systems for the positioning needs of non-disabled individuals and persons exhibiting all types of disabilities.

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