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Development of a simple approach to modify the supporting properties of seating foam for pressure relief

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Abstract—Pressure sores are a major problem frequently encountered by persons who use wheelchairs. Custom seat design, including contoured seating and various modular seating devices, has become an important option for pressure relief, especially when the market size is small and the variations of individual needs and requirements are large. An alternative approach in custom seating design for pressure relief is proposed in this paper. Holes were drilled in foam cushions to lower their supporting properties, particularly at the high pressure areas. This technique is evaluated systematically in this article. The scope of this study included: 1) a comparison of the foam material properties before and after such modifications, and 2) an evaluation of the static and dynamic degradation behaviors of the foams before and after modifications. It was found that the compression load (C-L) of the foam could be reduced by up to 46% using this simple drilling technique, while the material removed was only up to 28% by volume. It was also found that this approach would not significantly compromise the static and dynamic degradation behaviors of the foam; that is, such modification apparently did not dramatically shorten the lifespan of the foam material. Simple hole-drilling seems to be an effective approach to altering the supportive properties of foam cushions for pressure relief.

Key words: *decubitus ulcers, foam cushions, pressure relief, pressure sores.*

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INTRODUCTION

Pressure sores, frequently referred to as decubitus ulcers, pressure ulcers, ischemic ulcers, skin ulcerations, or bed sores, are localized areas of cellular necrosis mainly caused by prolonged and/or excessive unrelieved mechanical loads on the soft tissues (1–4). Numerous cushions made of different materials using various design strategies are commercially available. Most of the cushions were designed for pressure reduction, especially at the ischial tuberosities areas, while some others were designed for posture support (5). Garber and Krouskop (6) pointed out that no cushion can uniformly distribute buttock pressure for all subject groups. Sprigle et al. (7,8) found that sitting on an appropriately contoured foam cushion would lead to a relatively more even pressure distribution than sitting on one made of flat foam. Sprigle et al. (9) compared the pressure relief characteristics of some commercially available cushions and the custom-contoured cushions (CCCs). It was suggested that the CCCs offered improved pressure distribution compared with the cushions regularly used by the subjects. However, the contoured foam manufacturing process is relatively expensive and not yet readily implementable in a regular clinic. An alternative custom-modification process that is economical to use and relatively simple to implement clinically is very desirable.

Pressure reduction over the areas of the ischial tuberosities is a logical treatment modality. The aim of the project was to use the technique of hole-drilling to modify the supporting properties of foam cushions locally as a potential approach to provide a custom-modified cushion (CMC) for pressure relief. Polyurethane (PU) foam cushions, one of the most popular cushions commonly used in hospitals, was chosen as the raw material for our study. The feasibility of drilling holes in foam to modify its local supporting properties is examined systematically in this paper. The study included: 1) comparison of the foam material properties before and after such modifications, and 2) evaluation of the static and dynamic degradation behaviors of the foams before and after modifications.

METHODS

Polyurethane foam 5-cm thick (Seven Sea Chemical, Ltd. Hong Kong) was studied. Its density was 39 kg/m^3. The compression load (C-L) required to reduce its thickness by 25 percent was 215 N, and to reduce the thickness by 65 percent, 418 N was required. As it was thought that the diameter of the drilled holes should be small enough to ensure a relatively smooth sitting surface, the hole diameters studied were 4, 6, and 8 mm. Standard twist drill bits (HSS Jobber Drills, right-handed, ISO 328) with 118° point angle and 130° chisel edge angle were used. A drilling speed of 2880 rpm provided reasonably good hole finishing when compared with lower drilling speeds. The exact diameters of the drilled holes on the foam surface were measured using a travelling microscope, which showed them to be within 0.1 mm of the tool diameters.

Ferguson-Pell et al. used a 70-mm indentor to determine the compressive characteristics of 50 mm×50 mm×25 mm foam blocks (10). Cochran and Slater used a ~62.5 mm circular aluminium plate as an indentor in their experiments (11). It was suggested that an indentor of this particular size could introduce a high pressure area on the foam similar to that caused by an ischial tuberosity of a seated person. Cochran and Palmieri later used two 70-mm diameter indentors, one flat and one bevelled (12). In this study, 40 mm×40 mm×50 mm samples were cut from a large foam block with a hot wire. An indentor larger than the specimen was used in the compression test to ensure a relatively uniform state of stress. This standard testing configuration would allow ready extraction of material properties from the experimental force-deformation data. The rate of compression adopted throughout this study was 50 mm/min.

Woods showed that the material properties of PU foam varied significantly with temperature, becoming stiffer at low temperature, while high temperature usually caused softening and even irreversible chemical changes (13). Twelve samples were tested in a Hounsfield material testing machine under two different relative humidity (RH) conditions, 20±1°C, RH 78±2 percent, and 20±1°C, RH 70±2 percent. The following C-L values were measured: 25 percent C-L = force required to compress the block by 25 percent of its original thickness, and 65 percent C-L = force required to compress the block by 65 percent of its original thickness.

The results obtained under the two different environmental conditions were compared using the paired t-test. The results were significantly different at the 0.05 level for the 25 percent C-L values but not for the 65 percent C-L values. For better experimental control, the specimens in this study were all conditioned and tested at 20±1°C and RH 60±5 percent.

The modified foam blocks are shown in **Figure 1.** During the test, the whole block was compressed at a speed of 50 mm/min, and the force-deformation curve was obtained for analysis.

The loss of C-Ls due to modifications was defined as:

$$F_M=(L_B-L_A)/L_B \times 100\%$$

where,

F_M=loss of C-L after modification %

L_B=C-L value before modification, N, and

L_A=C-L value after modification, N

Figure 2 shows the load-deformation curve of the compression testing. Positions A and B mark the 25 and 65 percent compression, respectively, which were recorded immediately after 60±1 s of load relaxation.

Static degradation tests were conducted to determine the loss of the supporting properties and the thickness of the foam block after various static loading times. If the rate of loss of supporting properties in the modified foam blocks was faster than that of the unmodified ones, foam cushions that had been so modified would need to be replaced earlier than unmodified ones. The specimens were compressed continuously between two wooden plates at 75 percent deflection and tested after 7, 30, and 95 days. The 25 percent and 65 percent C-Ls of the test specimens and the thickness of the foam blocks were measured. The original thickness of the specimens was used as a reference to determine the loss of C-L and the loss of thickness. The recovery of the specimen was measured

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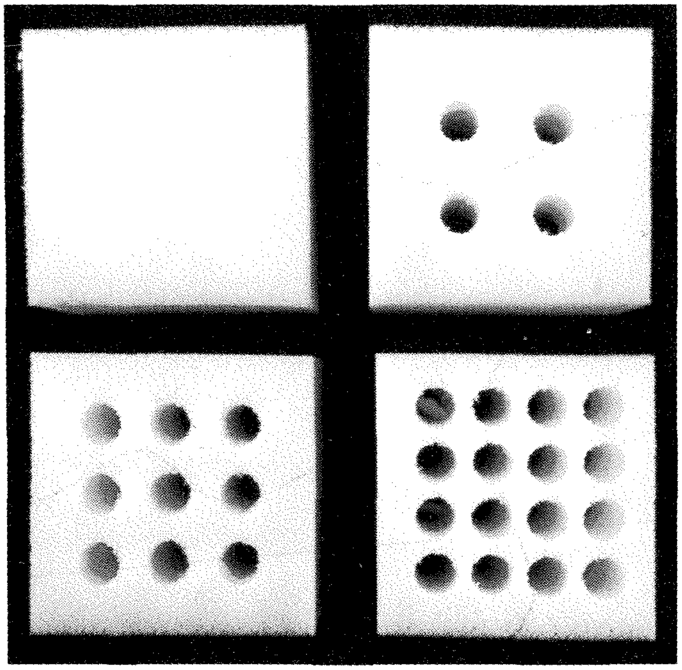

Figure 1.
Foam blocks with different hole-drilling modifications.

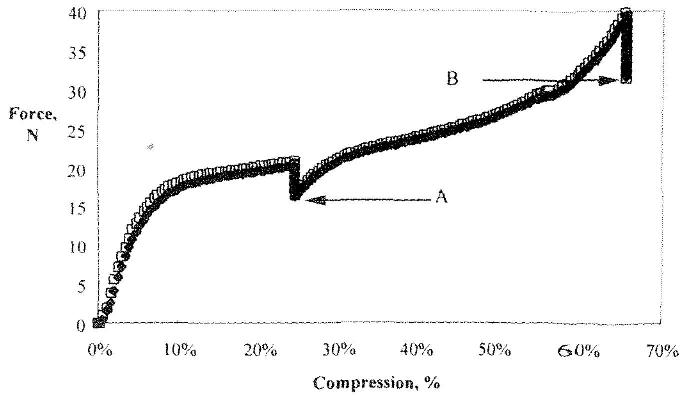

Figure 2.
Force-deformation characteristics of a 4×4×5 cm^3 control block.

at 24 and 168 hrs after 95 days of static loading. The recovery in the loss of C-Ls and the recovery of the thickness were also determined similarly.

A dynamic fatigue tester (**Figure 3**) was constructed for the dynamic degradation test. A counter attached to the compressor was used to record the number of compression cycles. Fatigue was set at 50 percent deformation at ~1 Hz. The material properties were measured after 8,000 and 80,000 cycles of compression. Similar to the static degradation test, the original thickness of the specimens was used as the reference to determine the loss of C-Ls and thickness. The recovery of the specimens was measured at 1 and 24 hrs after 80,000 cycles of dynamic loading.

The loss of C-Ls in static and dynamic degradation tests were defined as:

$$F_S \text{ or } F_D=(L_o-L_f)/L_o \times 100\%$$

where,

F_S=loss of C-L in the static degradation, %,

F_D=loss of C-L in the dynamic degradation, %,

L_o=original C-L value, N, and

L_f=final C-L value, N.

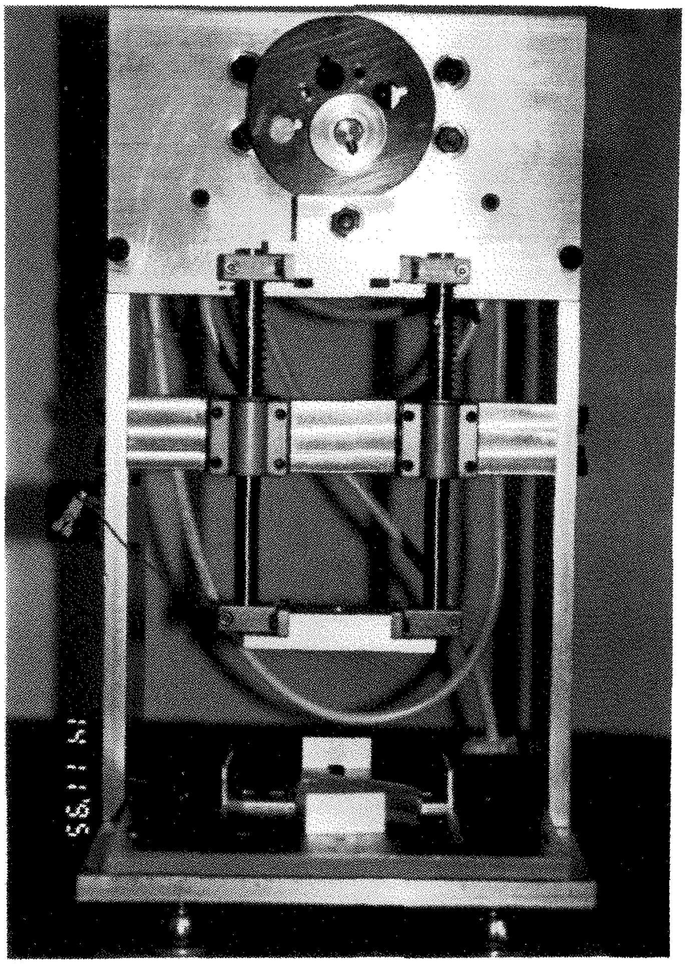

Figure 3.
The dynamic fatigue tester.

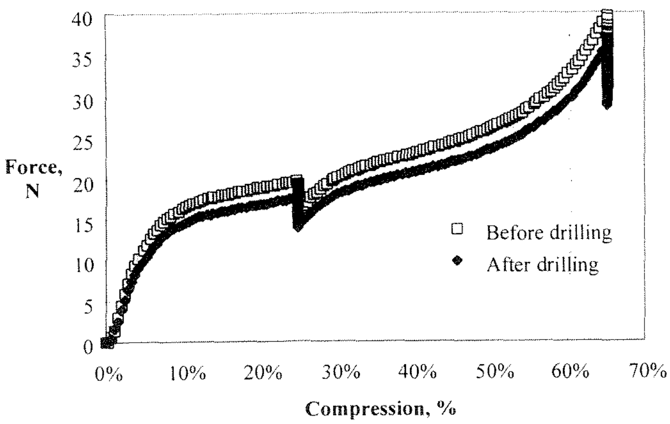

Figure 4.
Force deformation curve of a foam block before and after drilling four 6 mm holes.

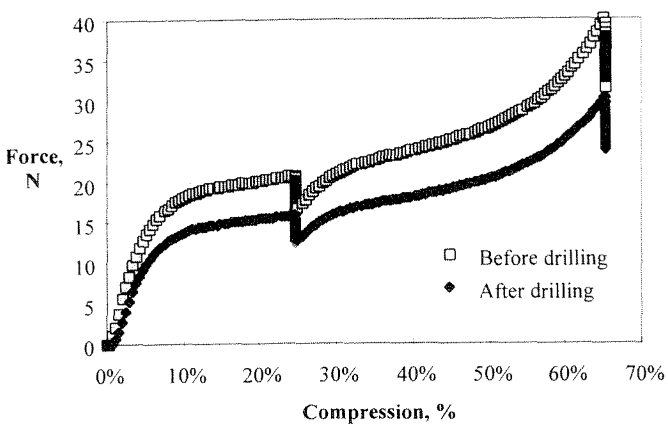

Figure 5.
Force deformation curve of a foam block before and after drilling nine 6 mm holes.

The loss of thickness in the static and dynamic degradation test were defined as:

$$T_S \text{ or } T_D=(t_o-t_f)/t_o \times 100\%$$

where,

T_S=loss in thickness in the static degradation test, %

T_D=loss in thickness in the dynamic degradation test, %

t_o=original thickness of the specimen, mm, and

t_f=final thickness of the specimen, mm.

RESULTS

Effects of Hole-Density on the Supporting Properties

The force-deformation curves for blocks with different modifications are plotted in **Figure 2** and **Figures 4–6. Figure 2** shows the curves of two control tests. The two curves almost overlap each other, demonstrating the repeatability of the test. The curves show a relatively higher stiffness initially and then the stiffness becomes smaller for compression between 10 to 40 percent. From roughly 50 percent compression onward, the foam picked up stiffness again. The force deformation curves showed the two occasions when the 25 and 65 percent C-Ls were measured.

Figure 4 shows the force deformation curves of the foam block before and after modification by drilling four 6 mm diameter holes. The results for deformation up to approximately 5 percent did not show much difference. Afterward, the force deformation curves before and after modification began to diverge. It was interesting to note that the differences stayed roughly the same beyond 10 percent compression. The 25 percent C-Ls were 15.8 N and 14.0 N for the block before and after modification, respectively, and the corresponding 65 percent C-Ls were 31.5 N and 28.8 N, respectively. The loss of C-L at 25 and 65 percent compression was found to be 11.1 and 8.6 percent, respectively.

The force deformation curves of the foam block before and after modification by drilling nine 6 mm holes are shown in **Figure 5**. The curves exhibited similar features as noted in the four-hole block. The 25 percent C-Ls of the foam were 16.5 N and 12.6 N before and after modification, respectively. The corresponding 65 percent C-Ls were 31.5 N and 24.0 N. The loss of the 25 and 65 percent C-L due to modification was 23.7 and 24.0 percent, respectively.

The force deformation curves of the foam block before and after modification with sixteen 6 mm holes are shown in **Figure 6.** The curves separate after 2–3 percent compression, and the difference stays approximately the same up to 25 percent compression. Afterward, the two curves diverge further. The 25 percent C-Ls were 15.2 N and 9.4 N for the unmodified and modified block, respectively. The corresponding 65 percent C-Ls were 30.8 N and 14.5 N. The loss of C-L at 25 and 65 percent compression due to modification was 38.2 and 53.2 percent, respectively.

The effect of hole size for a given loss of surface area was studied. This part of the study compared a block of sixteen 4 mm holes with a block of four 8 mm holes. The losses of surface area were both 12.6 percent, that is, the remaining surface area of each block was the same but the sizes and densities of holes were different. The results indicated that the 25 percent C-Ls were 15.5 N and 12.0 N before and after modification for both cases. The 65 percent C-Ls were 33.5 N and 25.0 N for the block with 4 mm holes before and after modification and 32.5 N and 25.5 N for the block with 8 mm holes, respectively. The results in the loss of the 25 percent and 65 percent C-Ls revealed little difference (within 4 percent) between the two blocks. The sizes of the holes studied did not seem to affect the loss of the C-Ls much, as long as the overall loss of area was roughly the same.

In order to examine how the loss of C-Ls depended on the loss of area, the compression load test was repeated again using foam blocks with four 6 mm (7.1 percent loss of surface area), four 8 mm (12.6 percent), nine 6 mm (15.9 percent), twelve 6 mm (21.2 percent), and sixteen 6 mm diameter holes (28.2 percent). The loss of the C-Ls at 25 and 65 percent are plotted against the loss of foam surface area in **Figure 7.** The results indicated that the loss of both the 25 and 65 percent C-Ls was linearly proportional to the loss of foam surface area with slopes of 1.58 and 1.72, respectively. The linear regression analysis showed that the R-squared values of the loss of the 25 and 65 percent C-L with the loss of surface area were both at 0.96. For easy clinical reference, the lines of regression for the loss of the 25 and 65 percent C-L were combined and could be expressed as:

$$\% \text{ loss of C-L} = 1.65 \times (\% \text{ loss of foam surface area})$$

It should be noted that this simple relationship only applied to this specific type and thickness of polyurethane foam. This could provide an important rule of thumb for modification of an actual foam cushion in clinics.

Static Degradation

Losses of C-L after various periods of static compression were examined. The 25 percent C-Ls were recorded at days 0, 7, 30, and 95. The loss of the 25 percent C-Ls at various periods were obtained by comparing to the value at the day 0. The loss of the 25 percent C-Ls after 7 days of compression was 25 percent for the control block and 23, 29, 20, and 26 percent for the blocks with 4, 9, 12, and 16 holes (6 mm), respectively. The corresponding losses of the 25 percent C-Ls at day 30 were 33, 32, 35, 29, and 34 percent, and at day 95 were 45, 45, 46, 44, and 48 percent, respectively (**Figure 8**). A sharp loss (~25 percent) in term of reduction of the 25 percent C-L was noted during the first 7 days of compression. Further degradation became more gradual. Apparently, there were no substantial differences between the unmodified and the modified foam blocks in terms of the loss of 25 percent C-Ls at day 7. Similarly, the differences were not substantial at days 30 and 95. Hence, foam block modifications of this type apparently did not lead to substantial differences in the rate of static degradation as expressed in terms of the loss of the 25 percent C-L within the bench-testing period (3 mo).

The loss of the 65 percent C-Ls after 7 days of compression was 15 percent for the control block and 16, 8, 18, and 21 percent for the blocks with 4, 9, 12, and 16 holes (6 mm), respectively. The corresponding losses at day 30 were 19, 21, 12, 29, and 28 percent, and 34, 37, 27, 34, and 31 percent, respectively, at day 95 (**Figure 9**). A sharp loss (~15 percent) was noted during the first 7 days of compression. Further degradation became more gradual. The variations in the loss of the 65 percent C-Ls for different durations of compression seemed to be a bit higher than for the loss of the 25 percent C-Ls. These results showed that drilling holes on the foam surface might have some impact on the 30-day static degradation rate. However, the differences seem to become smaller at 90 days.

At day 95, the foam blocks were allowed to recover. After 24 hrs of recovery, the loss of the 25 percent C-L returned to the levels of 31, 31, 36, 31, and 34 percent for the control block and for the blocks with 4, 9, 12, and 16 holes (6 mm), respectively. After 168 hrs (1 wk) of recovery, the corresponding loss of the 25 percent C-L returned to the levels of 26, 23, 28, 23, and 25 percent, respectively (**Figure 10**). The unmodified foam block did not show a substantial difference in the recovery behavior after 24 and 168 hrs when compared with the modified foam blocks.

The loss of the 65 percent C-L returned to the levels of 23–27 percent after 24 hrs, and to 18–22 percent after 168 hrs of recovery (**Figure 11**). A sharp recovery was noted for the first 24 hrs. The recovery rate seemed to be roughly the same for the modified and the unmodified blocks. The unmodified foam blocks did

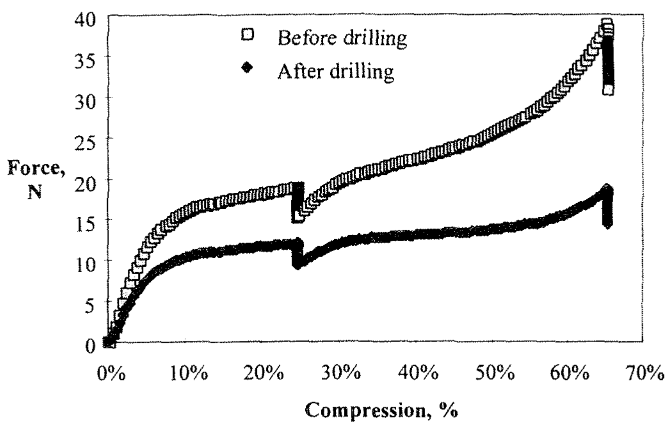

Figure 6.
Force deformation curve of a foam block before and after drilling sixteen 6 mm holes.

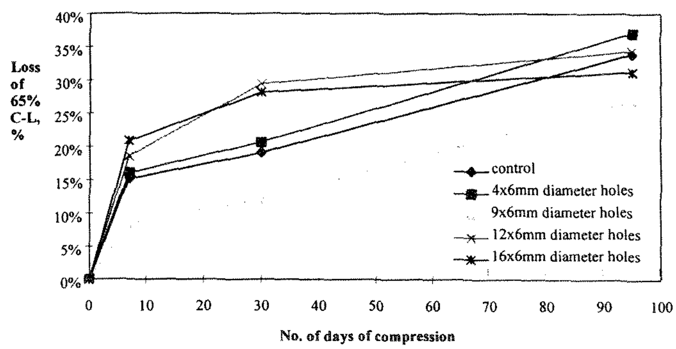

Figure 9.
Static degradation test: the loss of 65 percent C-L for various periods of static compression.

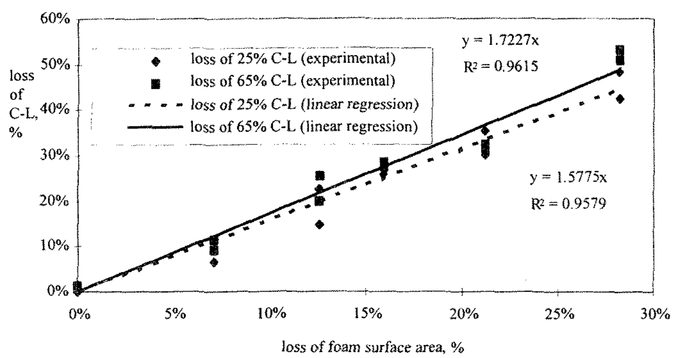

Figure 7.
Loss of 25 and 65 percent C-Ls as functions of loss of foam surface area.

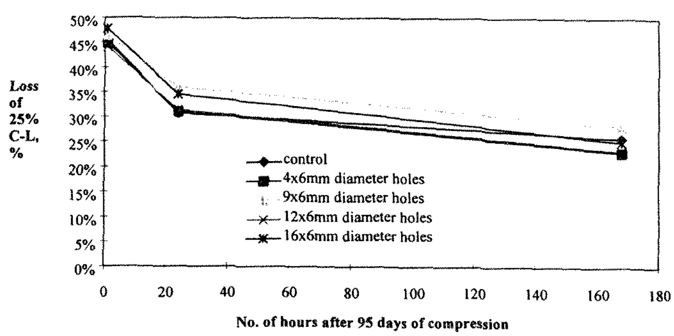

Figure 10.
Recovery after the static degradation test: the reduction in the loss of 25 percent C-L for various periods of recovery after 95 days of static compression.

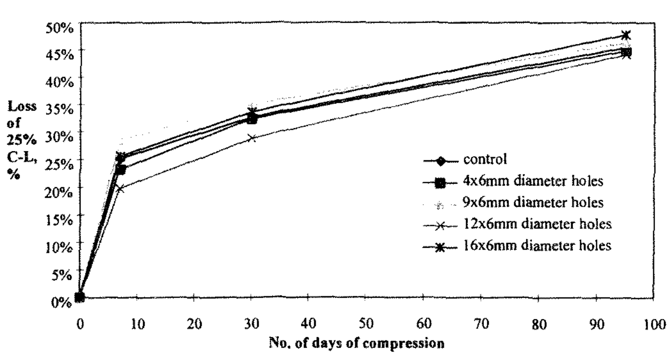

Figure 8.
Static degradation test: the loss of 25 percent C-L for various periods of static compression.

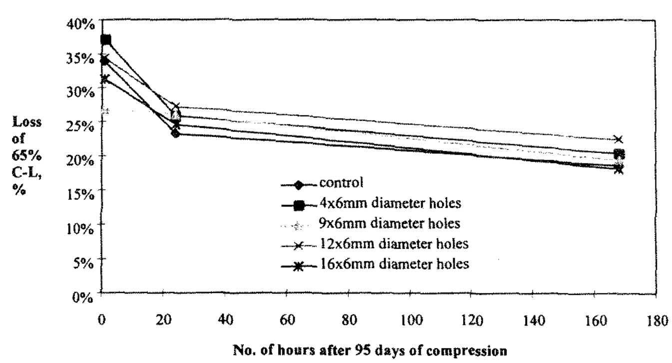

Figure 11.
Recovery after the static degradation test: the reduction in the loss of 65 percent C-L for various periods of recovery after 95 days of static compression.

Table 1.
Static degradation test: the loss of thickness after various periods of static compression.

		Loss of Thickness		
Specimen	**Area**	**7 days**	**30 days**	**95 days**
Control	0	1.5	2.2	3.5
4 x 6 mm	7.1	2.1	2.8	3.7
9 x 6 mm	15.9	2.5	4.1	4.7
12 x 6 mm	21.2	2.4	3.6	4.7
16 x 6 mm	28.3	3.5	4.3	5.3

Specimen = number and diameter of holes; figures = percentages of loss; area = surface area removed by drilling.

not show a substantial difference in the recovery behavior when compared with the modified foam blocks. From **Figures 10** and **11,** the results suggested that the recovery seemed to be still continuing even up to a week. Based on the above results, it was noted that the foam block might still retain about 75 percent of its original C-Ls after 3 mo of static compression if allowed enough time for recovery.

When the thicknesses were compared, the unmodified foam blocks showed differences in the loss of thickness (**Table 1**). The higher the hole density, the greater the loss of thickness due to static compression. However, the loss of thickness even after 95 days of compression seemed to be relatively small (<6 percent) when compared with the loss of the 25 percent C-L (~46 percent) and the loss of 65 percent C-L (~33 percent). Thus, clinically, one could not monitor the cushion supporting properties merely by measuring the cushion thickness. McFadyen and Stoner (14) studied the retention of supportive properties of PU foam wheelchair cushions. The loss of the 25 percent indentation load after 12 hrs of 75 percent compression was about 20 percent. In this study, the loss of 25 percent after 7 days of compression was ~25 percent, and ~45 percent after 95 days. Their results showed that foam could lose its stiffness very quickly during the first several hours of static compression.

Dynamic Degradation

The loss of the 25 percent C-Ls after 8,000 cycles of compression was 29 percent for the control block. The corresponding values were 29, 32, 32, and 32 percent for the blocks with 4, 9, 12, and 16 holes (6 mm), respectively. The corresponding losses after 80,000 cycles of compression were 37, 42, 47, 45, and 45 percent, respectively (**Figure 12**). After 8,000 cycles of compression, the supporting properties of the modified blocks did not show any substantial difference compared with the unmodified one. However, after 80,000 cycles of compression, the unmodified block exhibited a 37 percent loss of the 25 percent C-L, which was lower than the corresponding values for the modified blocks. The differences were less than 10 percent. Drilling holes on the foam surface did not seem to substantially increase the dynamic degradation of the foam block measured in terms of the loss of the 25 percent C-L after 8,000 cycles of compression. Drilling holes apparently could slightly increase the dynamic degradation of the foam block when measured in terms of the loss of the 25 percent C-L after 80,000 cycles of compression.

The losses of the 65 percent C-Ls after 8,000 cycles of compression were noted to be all within 4 percent. The corresponding losses of the 65 percent C-Ls after 80,000 cycles of compression were all within 8 percent (**Figure 13**). These values were much smaller compared with those of the loss of the 25 percent C-L. Increasing the number of cycles of compression from 8,000 to 80,000 did not seem to cause substantially more degradation in the 65 percent C-L. One should note that the depth of the imposed dynamic compression was 50 percent of the block thickness. This 50 percent dynamic compression apparently did not much affect the 65 percent C-L of the block.

Upon recovery, the loss of the 25 percent C-Ls returned after 1 hr to the levels of 31, 36, 43, 41, and 41 percent for the control foam block and for the blocks with 4, 9, 12, and 16 holes (6 mm), respectively; and

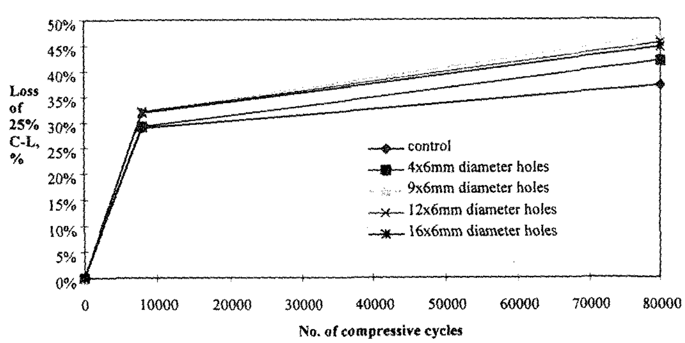

Figure 12.
Dynamic degradation test: the loss of 25 percent C-L for various periods of cyclic compression.

back to the levels of 25, 30, 32, 35, and 31 percent, respectively, after 24 hrs of recovery (**Figure 14**). Thus, after a day of recovery, the foam blocks might regain ~70 percent of their original 25 percent C-L values.

The losses of thickness after 8,000 cycles of compression were about 3 percent for all the foam blocks tested and the losses of thickness after 80,000 cycles of compression were about 5 percent. The losses of thickness after 8,000, and 80,000 cycles of compression were again relatively small (**Table 2**). Hence, loss of thickness apparently did not reflect the loss of material properties due to dynamic degradation.

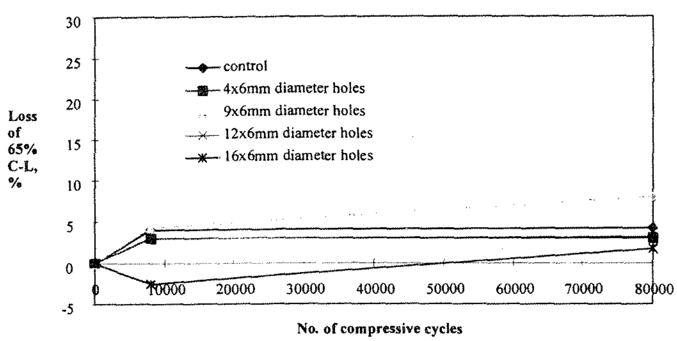

Figure 13.
Dynamic degradation test: the loss of 65 percent C-L for various periods of cyclic compression.

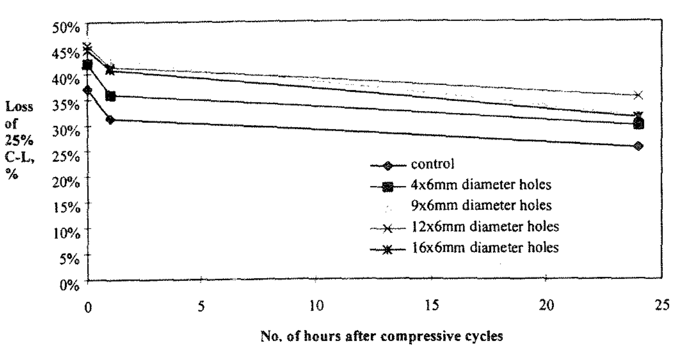

Figure 14.
Recovery after the dynamic degradation test: the reduction in the loss of 25 percent C-L for various periods of recovery after 80,000 compressive cycles.

CONCLUSION

Results in this study suggested that hole-drilling could decrease the supporting properties of foam material in terms of the C-Ls. Results also indicated that the loss of both the 25 percent and the 65 percent C-L was linearly proportional to the percentage loss of the foam surface area, with a slope of 1.65. For easy clinical reference, for this specific type and thickness of PU foam and for through thickness drilling, the regression lines could be expressed as:

$$\% \text{ loss of C-L} = 1.65 \times (\% \text{ loss of foam surface area})$$

Hence, by varying the number of holes or the loss of surface area, one may proportionally modify the supporting properties of the foam cushion locally. In the static degradation test, where the foam block without modification and the foam blocks with different densities of holes were compared, the modified foam blocks did not show any substantial difference when compared with the unmodified blocks in terms of the loss of 25 and 65 percent C-Ls after 3 months of static compression. In the dynamic degradation test, when the control foam blocks were compared with the modified blocks after 8,000 cycles of compression, the unmodified foam blocks again did not show substantially similar losses of C-L. However after 80,000 cycles of compression, the unmodified foam blocks seemed to survive slightly better compared to the modified ones in terms of loss of 25 percent C-Ls. The difference was within 10 percent. Therefore, hole-drilling on the foam surface apparently had not substantially increased the rate of dynamic degradation of the blocks using the present degree of modification. Both the static and dynamic degradation tests showed that for both unmodified and modified

Table 2.
Dynamic degradation test: the loss of thickness after various periods of cyclic compression.

Specimen	Area	Loss of Thickness 8,000 cycles	80,000 cycles
Control	0	3.1	5.0
4 x 6 mm	7.1	2.9	4.0
9 x 6 mm	15.9	2.7	4.3
12 x 6 mm	21.2	3.1	4.7
16 x 6 mm	28.3	3.0	4.6

Specimen = number and diameter of holes; figures = percentages of loss; area = surface area removed by drilling.

foams, the sharpest loss of the 25 percent C-L occurred in the first 7 days of compression and/or the first 8,000 cycles of compression. It was also noted that the loss of thickness was relatively small when compared with the loss of C-Ls in both the static and dynamic degradation tests. Hence, modification of the local supporting properties by hole-drilling on the foam cushion surface could be an effective method to reduce sitting pressure, which should be important to alleviate the problem of pressure sores. Moreover, the modification procedure is simple and easy, and the material cost very low. The process is also easily implementable in a regular clinical workshop.

RECOMMENDATIONS

Based on the present work, further studies are proposed as follows:

1. The present paper studied uniform density of holes with diameters of 4, 6, and 8 mm. Further explorations of modification patterns using variable hole densities and diameters would be useful, particular to ensure a more gradual transition between the modified zone and the unmodified zone in the actual seating design.
2. Only 50-mm thick PU foam was used in this study. Foam cushions of various thicknesses, densities, and/or initial supporting properties might provide slightly different results after modification.
3. In the present study, holes were drilled through the foam. Drilling to various depths could also be explored.
4. Foam cushions are usually used with covers. The effectiveness of this technique in pressure reduction when the cushions are used with covers should also be examined.

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