Enhanced Comfort of Seating Systems through Variable Shape and Compliance

by

Michael T. Bush

B.S. Mechanical Engineering
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Submitted To The Department Of Mechanical Engineering
In Partial Fulfillment Of The Requirements For The Degree Of
Master Of Science In Mechanical Engineering

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ABSTRACT

A new type of seat cushion has been developed. The present use of the cushion is in wheelchair seating, but it may ultimately have application to general seating, particularly in situations where comfort is a significant consideration. The cushion is intended to optimally distribute the interface pressure on the seat of a wheelchair user, as well as to provide an opportunity for active pressure management. The principal goal in developing this cushion is the prevention of pressure sores (decubitis ulcers).

The theoretical and design considerations upon which the cushion was developed are presented. Experimental materials data, as well as results of a prototype system, are supplied. A prototype cushion has been produced, and additional work is ongoing.

The cushion uses vacuum to manipulate the elastic/collapse properties of open-cell foam; effectively setting a maximum pressure at the human interface. Assuming appropriate auxiliary hardware, pumps, controllers, and sensors it would be appropriate to use this cushion as the basis of an actively controlled seating system.

Thesis Supervisor: Woodie C. Flowers
Title: Pappalardo Professor of Mechanical Engineering

Acknowledgments

This thesis would never have begun, let alone been finished, without the love and support of my wife, Marie Irene Phylene Locke. She has been consistently supportive thoughout the years of my education -- we have maintained separate households for almost 6 years, and I look forward to seeing more of her now that this thesis is complete.

I thank my parents, Allen and Elizabeth Bush, for sustenance both financial and emotional. My college education has been in various stages of ebb and flow since 1979 , and their support has never flagged.

Woodie Flowers, my advisor, is due many thanks for insight, encouragement, the occasional stern word, and most especially for giving me the latitude to chase some dubious ideas. When I was looking for a project at MIT, another graduate student offered the advice that Woodie was sufficiently wonderful to work with that if he offered an assistantship I should say yes before asking what the project was. I repeat the advice for the benefit of any who might follow.

Dean Kamen, who brought three relatively green graduate students into DEKA Research and Development this year, has given us the broad latitude to pursue our ideas, and the funding to make it possible. He is due special thanks. Hopefully, the collaboration between DEKA and MIT's New Products Program will continue in the future.

Gustavo Buhacoff, a fellow graduate student on the project, has worked side by side with me thoughout. Much of the credit for this work is due to him. His thesis will deal with the later development of the prototypes, and he is welcome to whatever glory may lie in the future.

Our supervisor at DEKA, Charlie Grinnell, has been a consistently encouraging task master; optimistic at the times when we were ready to give up on the idea, but always with a hand on the reigns to keep us on track.

In addition, I would like to acknowledge the follow people for their particular assistance:

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Thanks are also due to all of the people at DEKA who have taken the time out of their work days to offer the minor but crucial bits of help and advice that made this project a reality instead of just a concept

And finally, special thanks are due to all of the people who knew me in my former life as a carpenter, and who have consistently insisted that I could and should do this....

Table of Contents

List of Figures

List of Figures (continued)

Introduction

> *"The chair is so comfortable that people who own it say that they find it virtually impossible to read complex texts while sitting in it"*
>
> A comment on the classic Eames chair, and the conceptual starting point for this research

The research leading to this thesis was initially concerned with the general problem of seating comfort. Comfort is a concept with no firm definition -- it is often defined (somewhat circularly) simply as the lack of discomfort. In addition to the attributes of a particular seat, an individual's perception of its comfort depends on his or her own characteristics, as well as the context within which the seat is being used. For instance, the traits that might be comfortable in a chair intended for "task" use (e.g. a steno chair, or a driver's seat in a car) are likely to be considerably different from those which would be important for "relaxation" seating (e.g. a sofa).

Individuals show extreme variation in body size and shape. Even among persons nominally of the same size, variations in relative proportion can be significant-- for instance, the relative length of the torso to the arms and legs is known to vary significantly between races. In addition, three distinct body types are generally recognized (*endomorph, mesomorph and ectomorph*), and each requires different accommodations to facilitate seating comfort. If the physically disabled population's special needs are also considered, the possible range of physical needs becomes quite extreme.

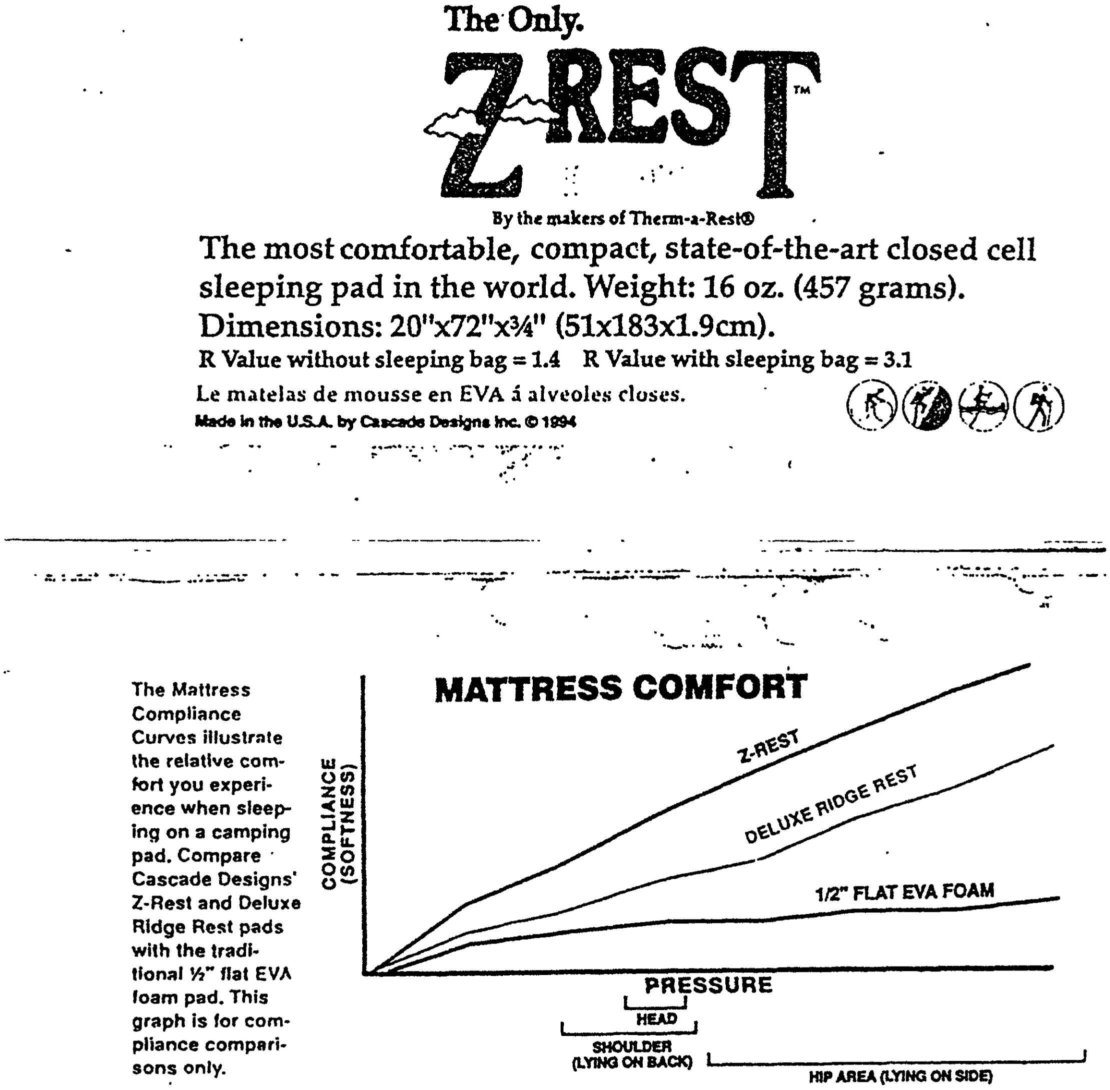
In addition to variations between individuals and from task to task for a particular individual, the time variation of the needs of even a single person performing a particular task is considerable. A seat that is quite comfortable for a brief wait may be intolerable to sit in all day long.

All of the above points suggest that a generally applicable optimal solution to the problem of developing a comfortable seat is unlikely to be achieved. To address the problem well requires an adaptive solution; one which can vary between users and over time for a particular user. Conceptually, an idealized adaptive seat might resemble the seats described in futuristic science fiction novels -- some sort of self-controlled plastic that would automatically shape itself to the form of the user, and modify its compliance to suit the needs of the moment. Ideally, such a seat would be inexpensive, light, durable, unobtrusive, and easily controlled. Reality, of course, comes up considerably short of the ideal. For the moment, the design task is perhaps better framed as attempting to develop an adaptive seat that can be controlled over as broad a range as possible for some particular type of task. In short, it has all of the requirements of a classic complex design problem.

A Shape/Compliance Perspective on Seating

In the popular imagination, "comfort" and "compliance" are often loosely linked; an example of this linkage be seen in the packaging for a "Z-rest"® camping pad which is reproduced in Figure 1. The packaging asserts that "... *compliance curves illustrate the relative comfort you experience....*" but never connects the two concepts in any real way. Consideration of this and other similar colloquial connections between compliance, shape, pressure, and comfort in seating applications points out the necessity of determining which are the primary variables and which ones are dependent. Having determined the primary variables of seating, it should be possible to apply engineering principals to generate an optimized solution.

For the purpose of analysis, a static seat might be thought of as having only two significant controllable characteristics -- shape and compliance. For the dynamic case, damping also becomes relevant, but for purposes of simplicity is neglected in this thesis. Figure 2 sketches out some of the parameters of a shape/compliance seating universe. The figure places various types of seating within a conceptual continuum.



The Only.

Z-REST™

By the makers of Therm-a-Rest®

The most comfortable, compact, state-of-the-art closed cell sleeping pad in the world. Weight: 16 oz. (457 grams). Dimensions: 20"x72"x¾" (51x183x1.9cm).

R Value without sleeping bag = 1.4 R Value with sleeping bag = 3.1

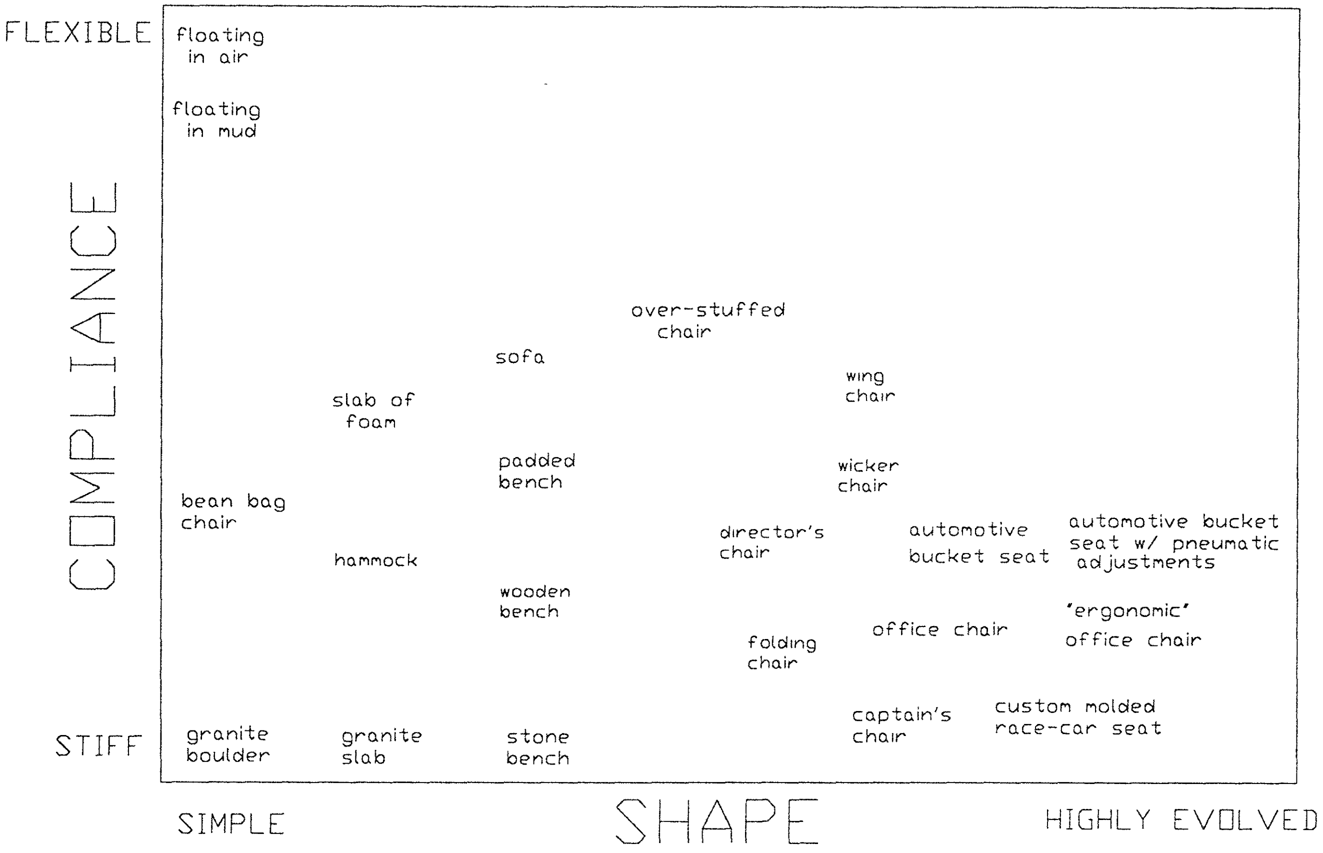
Le matelas de mousse en EVA à alveoles closes.

Made in the U.S.A. by Cascade Designs Inc. © 1994

The Mattress Compliance Curves illustrate the relative comfort you experience when sleeping on a camping pad. Compare Cascade Designs' Z-Rest and Deluxe Ridge Rest pads with the traditional ½" flat EVA foam pad. This graph is for compliance comparisons only.

Packaging for a camping pad which illustrates the popular linkage of "compliance" and "comfort"

Figure 1



A Conceptual Tool for Analysis of Seating

Shape and Compliance as Governing Parameters

Figure 2

A seat has some initial shape, and after an object has settled into it, will perhaps have a different final shape. The difference between these two states is a function of the compliance of the materials from which the seat was constructed, but is also to varying degrees dependent on the nature of the object (the user, in a particular sense) placed on the seat. The shape and compliance of the object (person) on the seat has a direct bearing on the nature of the interface..

It is interesting to note that none of the various types of seating shown in Figure 2 are inherently uncomfortable. Within a particular context, any of them can serve quite nicely. Even a granite boulder, after a long hike, makes a nice place to sit and look out over the landscape. It is unlikely that we will see one in the office chair market any time soon, however. Also, it is notable that the upper right region of Figure 2 (the region of high compliance and highly evolved shape) is empty -- the notion of an object with a complex shape that is also highly flexible is almost oxymoronic; while the initial shape might be well defined, its deflected shape would almost certainly bear little or no relationship to its starting point.

The human body is of course not a static object -- it possesses a shape and compliance of its own. To further complicate the problem, the "shape" of a human body can be varied more or less at will; a change in posture effectively changes the shape. The interplay at any given time of the properties of the seat with the properties of the person using it determine the contact surface between them, the stresses at that interface, and ultimately, perceived comfort.

It can be argued that if a (unspecified) device was able to control the nature of the contact at the human interface, it would provide the technology necessary for an adaptively comfortable seat. If it was possible to arbitrarily manipulate the shape and the compliance of an object, it should, in theory, be possible to transform the object into a seat that is comfortable, in an ongoing way, in any arbitrarily defined situation.

The interaction of a poorly defined human shape with an arbitrary seat form makes for a somewhat intractable analytic problem; even neglecting the time component and attempting to analytically determine a final resting shape is beyond the current state of technology. Most new designs are based on empirical methods of one sort or another. Design evaluation is generally based on some combination of pressure mapping and shape measurement, as well as subjective evaluations by focus groups.

Means Of Controlling Shape/Compliance Of Seating

The classic, and by far the simplest, way that a person controls the shape and compliance at his or her interface with a seat is by moving. Video tape studies have indicated that an individual will shift minorly in a seat as often as every few seconds, and make a relatively major movement once every few minutes. This redistributes the relative placement of whatever contact stresses there may be, allows blood flow into tissues that may have been constricted in the previous posture, and in general improves the perceived comfort of a seat.

However, as anyone who has ever sat through a long lecture on a folding chair knows, even the most active of squirming can not solve the problem of comfort. Furthermore, in certain circumstances, even where the seat is reasonably comfortable, it may be undesirable, difficult, or impossible for a person to make himself comfortable by periodically squirming to any significant degree. Military aircraft have long been recognized as a circumstance where this is true; research was conducted as early as the 1940's on active systems that might enhance the comfort of a pilot who might be stuck in one position for many hours.

Another significant group where squirming is not a viable solution to periodically altering the seat interface is among the spinal cord injured. Their injuries make it difficult or even impossible for them to move their lower bodies. Lack of feeling in the affected portions of their bodies may render "comfort" less of an issue, but the quality of the pressure distribution and its periodic variation are an important factor in the prevention of pressure sores (decubitis ulcers) which has important medical consequences.

Currently Available Products Which Manipulate Shape/Compliance Of Seating

Active Products

There are numerous products on the market which are to varying degrees customizable. The vast majority of these focus on changing the shape of the seat, while the compliance remains essentially unchanged. "Active" is a loose category in this regard; it includes devices that have more than one possible setting, but which may require intervention from the user to change settings

Several types of seats enhance comfort by allowing the user to change the shape at the contact plane. Simple examples of this include such mechanisms as a vertically adjustable headrest or an adjustable chair back angle or adjustable seat height. More complex examples employ devices such as mechanical lumbar adjustments or one or more pneumatic bladders. Examples of the pneumatic approach can be seen in both wheelchair and automotive seating; in a typical case:

> pneumatic bladders are placed at particular points in a seat, usually over a substrate of foam. The bladders act as balloons -- by changing the inflation pressure their shape can change significantly, moving new portions of the seat into more or less intimate contact with the user. The force of that contact is related to the inflation pressure. Since the total weight (and thus the reaction force) of the user is fixed, applying more force to one area must result in less force somewhere else. Changing the inflation of the bladders results in a different force distribution and changes the user's perception of the seat. The compliance of the bladders is surprisingly constant over their typical range of inflation, however. The overall compliance of the system is dominated by the nature of the foam substrate.

Passive Products

There are many manufacturers claiming to have developed products whose shape which is particularly conducive to user comfort. In general, these are based on empirical principals of one sort or another. A few manufacturers intimate a set of engineering principals as a design basis, but these are generally considered proprietary information and are not part of the published literature. The validity of the claims are thus difficult to verify. A few relevant examples:

> "Pin-Dot" ® makes a line of wheelchair cushions; an array of transducers (LVDT?) maps the contours of a seated person. This information is then fed into a proprietary software algorithm which generates a cushion shape that is cut with a CNC milling machine. The cushions are typically made from a single foam material. The Pin-Dot ® cushion could be thought of an extreme example of the customized shape.

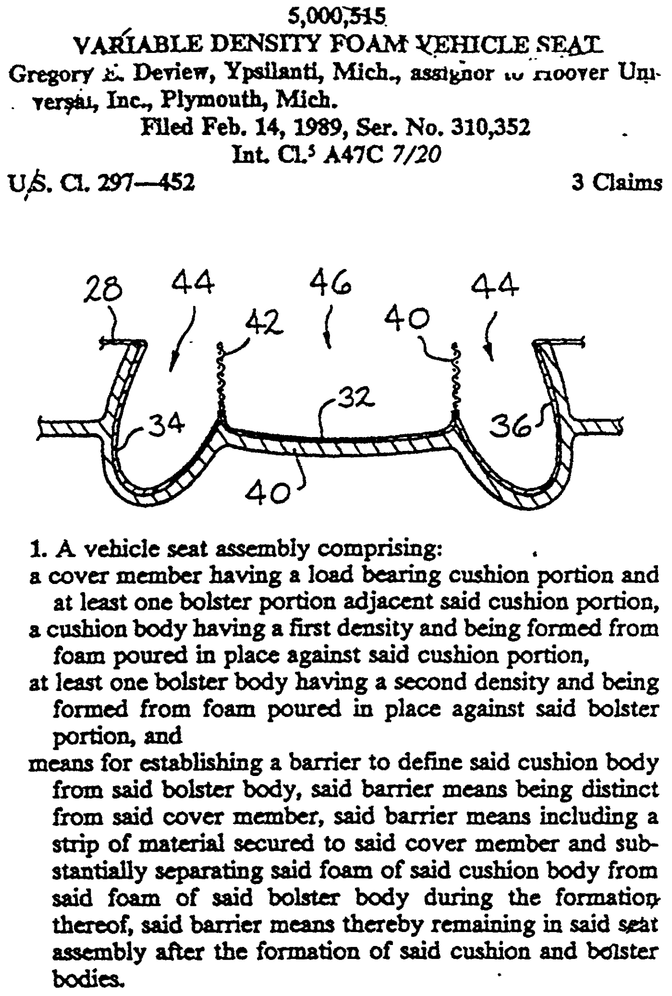
> It is possible to conceive of a machine, consisting of linear actuators, padding and appropriate controls, which could accomplish the actions of a Pin-dot custom cushion in a time-variable manner. For such a cushion, either force or position could be measured, but position would be the controlled variable. Clearly, the mass and cost of such a system would be quite high, but it serves as one bound on the conceptual possibilities of a custom cushion.

Another approach is a design type that attempts to hold the basic shape more or less constant while varying the compliance of the system. An example of this is a system sometimes used for custom fabricated wheelchair cushions:

> A clinician may construct a cushion using various grades of foam available from *EAR* Specialty Composites®, ; the particular grades of the foam have significantly different spring rates and damping characteristics. By placing different grades of the foam in different areas of the cushion, the reaction force and thus the pressure at various points of the contact plane is changed. This gives the clinician the ability to construct a cushion which has a better pressure distribution for a particular user than one which was of the same shape but constructed of a single material.
>
> Another approach that has essentially the same result can be seen in the JAY ® wheelchair cushion. In this design, gels of various densities, rather than foams, form the compliant element of the cushion. The gel is unable to support significant shear; it flows like a highly viscous fluid and acts to minimize the pressure gradient.

In addition to the custom example above, there are also various mass-market designs that use different compliance materials in various portions of the seat. For instance, patents have been issued for "variable density" automotive seating (e.g. US patent # 5,000,515, see abstract in Figure 3) on a similar principal -- a seat constructed using various grades of foam at particular locations.

It would be reasonable to argue, however, that all of these design concepts produce a seat that is of *various,* rather than *variable,* compliance. While the compliance of any particular sector can be relatively arbitrarily set at the time of construction, it is thereafter fixed.


5,000,515
VARIABLE DENSITY FOAM VEHICLE SEAT
Gregory E. Deview, Ypsilanti, Mich., assignor to Hoover Universal, Inc., Plymouth, Mich.
Filed Feb. 14, 1989, Ser. No. 310,352
Int. Cl.^{5} A47C 7/20
U.S. Cl. 297—452 3 Claims

1. A vehicle seat assembly comprising:
a cover member having a load bearing cushion portion and at least one bolster portion adjacent said cushion portion,
a cushion body having a first density and being formed from foam poured in place against said cushion portion,
at least one bolster body having a second density and being formed from foam poured in place against said bolster portion, and
means for establishing a barrier to define said cushion body from said bolster body, said barrier means being distinct from said cover member, said barrier means including a strip of material secured to said cover member and substantially separating said foam of said cushion body from said foam of said bolster body during the formation thereof, said barrier means thereby remaining in said seat assembly after the formation of said cushion and bolster bodies.

US Patent Abstract # 5,000,515

Example of a design that uses materials of more than one compliance, but for which the compliance is fixed. Within the context of this thesis, such a design would be considered *various*, rather than *variable,* compliance

Figure 3

Focus Of This Research

From surveying the existing state of seating design, it is apparent that there are numerous technologies that enable seating with a custom shape--either a shape which is customized when the device is manufactured, or which permit the user to change it periodically. There are also some technologies that allow the compliance of the device to be set to some relatively arbitrary value at the time of manufacture. We refer to this as *various* compliance seating. To our knowledge, however, there are no existing technologies that permit *variable* compliance... a technology that would enable the user to periodically set the compliance of a seat to any point within some relatively arbitrary range.

This research therefore concentrates on attempting to develop technology that could be used for *variable* compliance seating. We have developed a system with which the user could, at any time, somewhat arbitrarily set the compliance of particular portions of a seat. Assuming a suitable control system and algorithm, such a system clearly also lends itself to automation and intelligent control. This research direction seems to offer greater opportunity than other potential avenues of inquiry, and might be an enabling technology that could lead to greater seating comfort. The overall research effort is ongoing, but we have been able to develop a technology which addresses a particular aspect of the problem.

Properties of Open Cell Foam

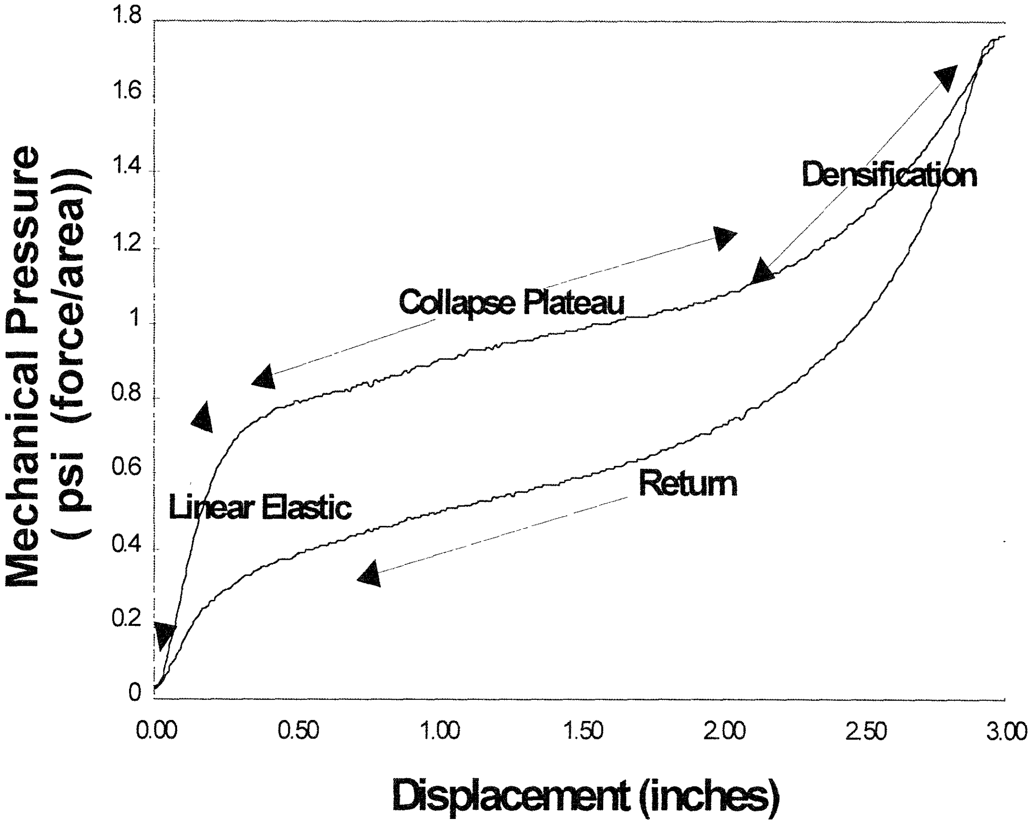
background

It is a well known property of open cell foam (poly-urethane and poly-ether, among others) that it exhibits non-linear spring characteristics. This property is caused by the cellular nature of the material, and is present to some degree in all visco-elastic open cell materials. Theoretical work as well as experimental evidence indicates that the spring property can be characterized as being initially approximately linear elastic, then passing through a (reversible) plastic phase (the "collapse plateau" in some of the literature), and finally into a second approximately linear elastic phase (sometimes called "densification") . Figure 4 illustrates this phenomena. Because the material is visco-elastic, there are significant hysteritic losses associated with deformations. The losses are related both to the nature of the material, and to the rate at which deformations occur. See Figure 5 for an example of the rate dependency of the hysteritic losses.

The linear elastic and the densification phases are due to compression of the cell walls, while the collapse plateau is due to buckling of the cellular walls of the material. Such solids are sometimes modeled as lattices of long columns. Figure 6a illustrates a typical model, which is a simplified version of a solid such as the one whose highly magnified view is seen in Figure 6b. A highly simplified one dimensional mechanism of the linear elastic / collapse / densification transition is presented in Figure 7. A typical foam suitable for seating applications would transition from its initial linear elastic phase into collapse at loads on the order of 1.0 psi.

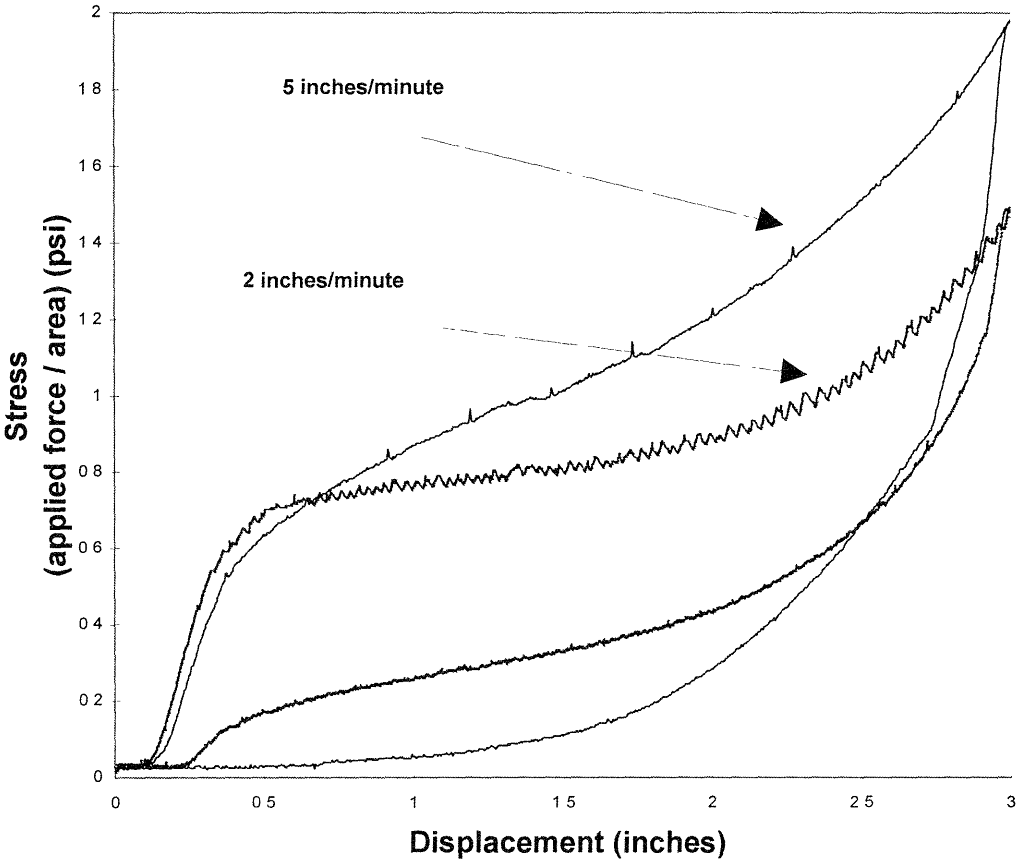
Controlled Compliance Foam

By applying vacuum or positive pressure (on the order of +/- 0.5 psig) to a pneumatically isolated mass of open cell foam (e.g. - a block of foam within an airtight skin) it is possible to control the mechanical loading necessary for the material to move from its linear elastic phase into the collapse plateau. Experimental data illustrating the phenomena is shown in Figure 8. The total force applied to the material (pneumatic + mechanical) at the transition point between the two phases remains approximately constant. Thus, given the ability to control the applied



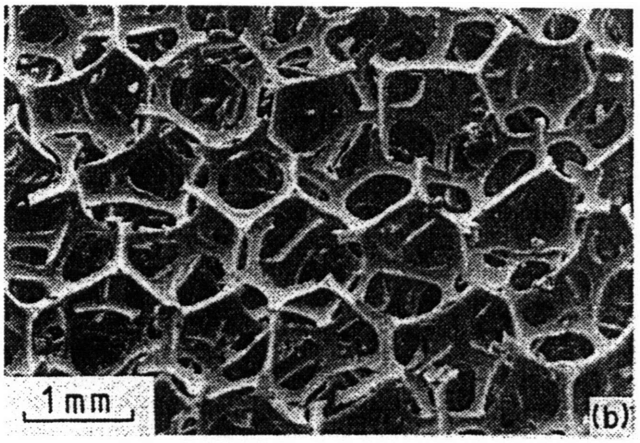
Physical Property Regimes for a Typical
Open Cell Foam Undergoing Compression

Figure 4

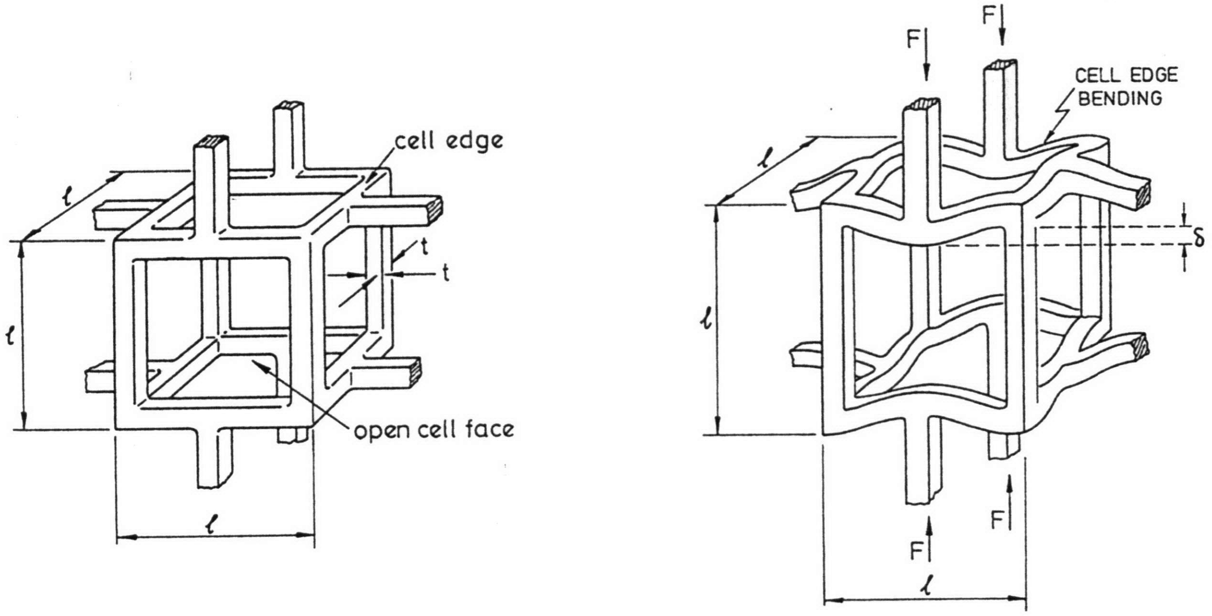


Rate Dependance of Hysteritic Losses
for a Typical Open Cell Foam

Figure 5

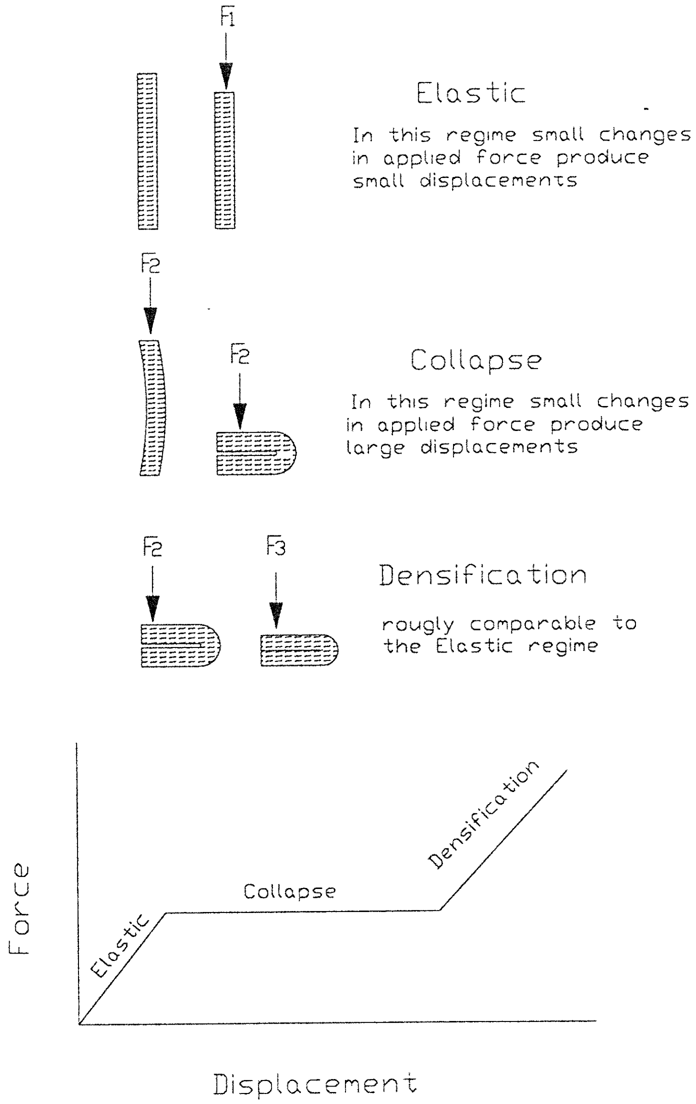


6b -- Photograph of a Representative Open Cell Foam
(from Gibson & Ashby, Cellular Solids)



6a -- 3 Dimensional Model Corresponding to the Photo in Figure 6a
The figure on the left is for the undeformed case,
the figure on the right for a foam in its linear elastic phase
(from Gibson & Ashby, Cellular Solids)

Figure 6 a & b



Elastic

In this regime small changes in applied force produce small displacements

Collapse

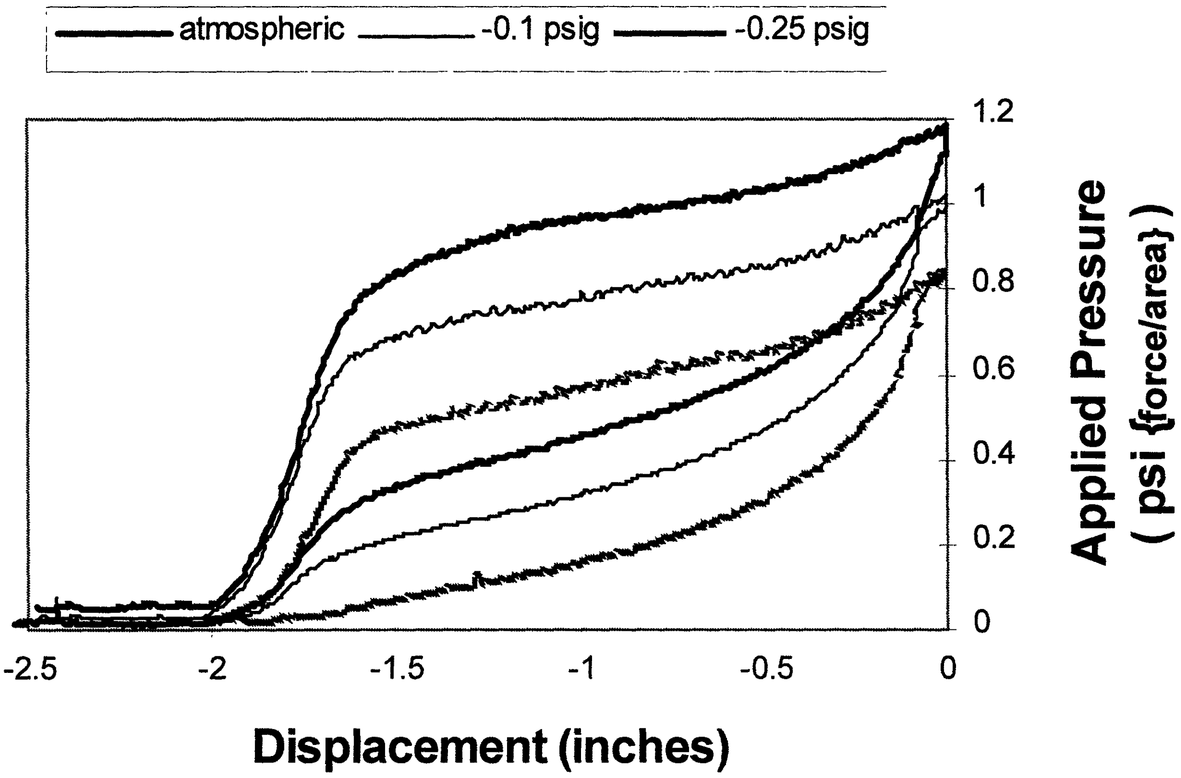
In this regime small changes in applied force produce large displacements

Densification

rougly comparable to the Elastic regime

A Simplified One Dimensional Mechanism Illustrating the Various Phases Open Cell Foam Passes Through as Load Increases

Figure 7



Typical Experimental Data Showing the
Effect of Varying Pneumatic Pressure on
the Load Bearing Characteristics of Open Cell Foam

(maximum displacement at x=zero)

Figure 8

pneumatic pressure, it is possible to control the mechanical force required to induce collapse. To our knowledge, this phenomena was not previously known.

Applications For Controlled Compliance Foam

The immediate application of our discovery will be for use in wheelchair seating, but it may also be applicable to the general problem of seating comfort. An initial prototype has been produced, and as research continues the advantages and limitations of the device will become more apparent.

For a wheelchair cushion application, the ability to control the compliance of a seat cushion presents an opportunity to directly address the pressure at the cushion's human interface. With this ability, the maximum pressure in any particular area, and thereby the pressure gradient between sectors can be controlled. In addition, because of the active nature of the technology, such a cushion lends itself to varying the pressure distribution with time-- effectively, such a cushion can be made to squirm for the user.

In addition to our cushion's apparently unique ability to actively modify the compliance at the user interface, it has a number of other advantages over other cushions currently on the market. The materials used (foam, urethane film, tubing) are light. Even including the necessary hardware and electronics, it should be possible to create a system which is lighter than some of the current cushion designs, especially the JAY ®, which can weigh as much as 11.5 pounds. The foam, while significantly compliant, gives a relatively stable base for the user, thereby eliminating the feeling of platform instability that is a common complaint about one of the other leading wheelchair cushions (the ROHO ®).

Application of foam with controlled compliance to general seating will require additional research to establish a relationship between the empirical notion of comfort and the more quantifiable magnitude and distribution of pressure at the interface. While it seems reasonable to infer a connection between pressure and comfort, there is no clear-cut relationship. Assuming such a connection, the technology we have developed should permit development of a seating system, using active compliance control, that was more comfortable than current designs. In the absence of a clear connection, however, the additional cost and complexity of an active system is probably not warranted.

Limitations Of The Technology

The technology we have developed also has some inherent limitations. It requires both a pneumatic source and of an active controller. It must, therefore, have a pump, an electronic device (the controller) of some kind, and a power supply (either AC or battery, depending on the circumstances in which it is to be used). In addition, the system requires at least one valve and one pressure sensor for each distinct sector of the cushion.

Pressure Sores (Decubitis Ulcers)

Introduction

A wheelchair cushion which utilizes our discovery will be a significant improvement, reducing the risk of pressure sores. The cushion constrains the maximum pressure at the contact plane of the cushion, and accordingly on pressure gradient at any particular point in the cushion. Both of these factors are know to be major causal factors in the development of decubitis ulcers. Pressure sores are a major health concern to wheelchair users; they represent significant treatment costs (estimates in excess of $10,000 per sore are common in the literature) and a major health threat (approximately 5% of deaths among the spinal cord injured can be attributed to complications from pressure sores).

Medical Importance Of Pressure Sores To Wheel Chair Users

Pressure sores (decubitis ulcers) are an important health concern for wheelchair users, particularly for the spinal-cord injured. In addition to individuals with spinal cord injuries, pressure sores are a concern for the geriatric population, cancer patients, and persons with multiple sclerosis.

For wheelchair users who are not severely disabled, pressure sores are often their greatest health concern. Developing a sore subjects them to a period of weeks or months of bed-rest during which they are subject to what amounts to confinement. Further, numerous studies have documented high costs and significant health risks associated with the development of pressure sores. For example:

- over 4% of deaths among the spinal cord injured have been directly attributed to pressure sores (Geisler et al, 1977). Pressure sores are also implicated in renal failure, which is another major cause of death in this population

- Young and Burns (1981) reported that individuals with severe pressure sores averaged about $15,000 more per annum in hospital costs than spinal cord individuals who remained free of sores.
- United States Regional Spinal Cord Injury System data from 1975 to 1980 showed that 40% of spinal cord injured individuals developed pressure sores during the time period from onset of injury to initial rehabilitation discharge. Approximately 6 percent of these individuals had sever pressure sores... There was approximately a 30% incidence of pressure sores in each of the five follow up years beyond initial rehabilitation discharge. 5 to 7 percent of spinal cord injured individuals developed severe sores during each of the follow up years. (Young and Burns, 1981)

Prevention Of Pressure Sores

Until the 1970's, the majority of sores were developed in bed. However, a number of technical advances in the design of hospital beds have made it possible to reduce the incidence of sores. Currently, given sufficient commitment of equipment, it is possible to significantly reduce or even eliminate the incidence of pressure sores in bed. For the bed-ridden patient several mattresses are available which diminish the pressure and shear at the skin/mattress interface, as well as periodically varying the distribution. The rationale is to vary the pressure applied to different parts of the body over time, while keeping the pressure at any point as low as possible. Various methods are used, including flotation in dense fluids (especially mud), air-fluidized beds of glass beads, and air bladders whose inflation pressure is periodically varied. Unfortunately, all of these systems require a large and heavy body of hardware, and are generally relatively costly.

With the advances in bed design, the relative incidence of pressure sores due to seating has risen. The principal reason for this is that in the seated posture the total amount of weight to be distributed is comparable to that in a lying posture, but the available area over which the force may be spread is considerably less. A typical seated individual will have an average buttock pressure (portion of weight on buttocks divided by total area in contact with the seat) on the order of 50 mm Hg, which is roughly 2 1/2 times the 20 mm Hg pressure which is generally cited in the literature as the threshold for the prevention of pressure sores. It is not unusual to observe peak pressures in excess of 100 mm Hg.

For persons in wheel-chairs, however, particularly those with spinal injuries, their injuries often prevent the unconscious squirming of the lower body that prevents pressure sores. The most commonly prescribed pressure sore preventative is the "wheelchair pushup". The wheelchair user is advised to, at roughly 15 minute intervals, use his or her arms to lift the lower body into the air, redistributing the weight on the portion of the buttocks in contact with the seat. Clearly, such a maneuver requires significant arm strength, which is not always a possibility. Further, wheelchair users cite the obtrusive nature of the maneuver as being problematic in social situations--the wheelchair pushup can draw attention to the wheelchair use in a way that he or she might not welcome.

In addition to the activities of the wheelchair user (such as pushups), design of the wheelchair and its accessories can play a role in prevention. Factors such as proper sizing (width and depth), proper arm-rest width and height, materials selection (to promote breathability), and shape of the seat cushion all play a role. The chair also should promote proper posture -- feet bearing some weight, about 10 degrees of seat inclination, 15 degrees of back inclination and use of a lumbar pad are recommended.

Sling (hammock) style seats tend to induce pressure sores; unfortunately such seats are common, particularly for use by the elderly. Sling style seats typically produce abnormally high maximum pressures, and are known to cause particularly high shear loads. Their continued use is principally a result of their low cost and convenience for purposes of collapsing the chair.

Causes Of Pressure Sores

Decubitis ulcers are believed to be caused by oxygen starvation of affected tissues. Generally, sores are believed to be initiated in the subcutaneous tissue between the derma and the underlying muscle, but some sources believe that pressure sores can begin in the skin or in the muscular tissue near an underlying bone.

Sores can occur whenever the external pressure on tissues exceeds the capillary blood pressure. Various investigators (Husain (1953), Kosiak (1959), Nola & Vistnes (1980)) have found pathological changes in tissues subjected to localized external pressures of 60 to 100 mm Hg for a period of only 1 to 2 hours. In these experiments, mammals (rats and rabbits) were subjected to an relatively concentrated external force over a large muscle (typically the thigh). Tissue condition was evaluated by post-mortem dissection. Numerous studies of capillary blood pressure have been done over the years, but the most commonly cited work was done by Landis in 1930. He found, using a micro-injection technique, that the mean capillary blood pressure in the arteriolar limb of the capillary in human skin was 32 mm Hg. At the summit of the loop, the pressure was found to be 20 mm Hg, while in the venous limb Landis found the mean pressure to be 12 mm Hg. Other studies as recently as 1979 have found comparable results, using MRI and isotope washout methods.

In addition to excessive external pressure, various factors are implicated in the formation of pressure sores. These include

- shear strain, especially due to localized friction on the seat cushion
- wetness of the skin due to poor ventilation or incontinence. This is believed to exacerbate the effects of shear strain
- diminished elasticity of skin and muscle tissue (especially with age, as in the elderly)
- poor circulation, due to low blood pressure, arterio-sclerosis, peripheral arterial disease, or other types of vascular damage.
- poor muscle tone, perhaps due to atrophy. This factor is believed to be relevant in sores which originate in the subcutaneous tissues
- pelvic obliquity or tilting, which tends to concentrate the users weight on one side of the pelvis, increasing localized forces. This condition usually accompanies scoliosis, kyphosis, and lordosis.

Necessary Attributes Of A Seat Cushion Designed To Prevent Pressure Sores

- Exhibit Good Overall Ergonomic Design -- size, shape, materials, etc.
- Provide Pressure Management -- provide a means of lowering the maximum pressure; optimize the pressure distribution at the user interface at any particular time, leading to maximum pressures as close to average as possible, and with minimal pressure gradients
- Provide Periodic Pressure Relief -- use active measures to modify the pressure distribution over time. Classic solution for the able bodied population is squirming; provide a system which can perform this function for a disabled user.
- Be Energy Efficient -- the energy source should, if possible, be portable (a battery, rather than AC). Efficient use of power is essential if acceptable battery life is to be achieved.
- Be Light Weight -- the cushion should be as light as possible, a typical application will be in a manual wheel chair weighing about 20 pounds. Additional weight from the cushion makes propulsion more fatiguing. For power chairs, higher weight results in shorter battery life.
- Be Relatively Easily Cleaned -- especially because some users will be incontinent
- Possess Sufficient Friction On Its Upper And Lower Surfaces -- should help prevent the user from sliding out of the chair
- Be Reasonably Priced -- high-end wheelchair cushions are currently available at prices on the order of $500

Laboratory Testing

An initial hypothesis regarding the possibility of controlling the compliance of open cell foam was developed from an analysis of the general seating problem, and from reading the literature on foamed material. An experimental program was developed to examine the hypothesis

Initial Testing -- Description

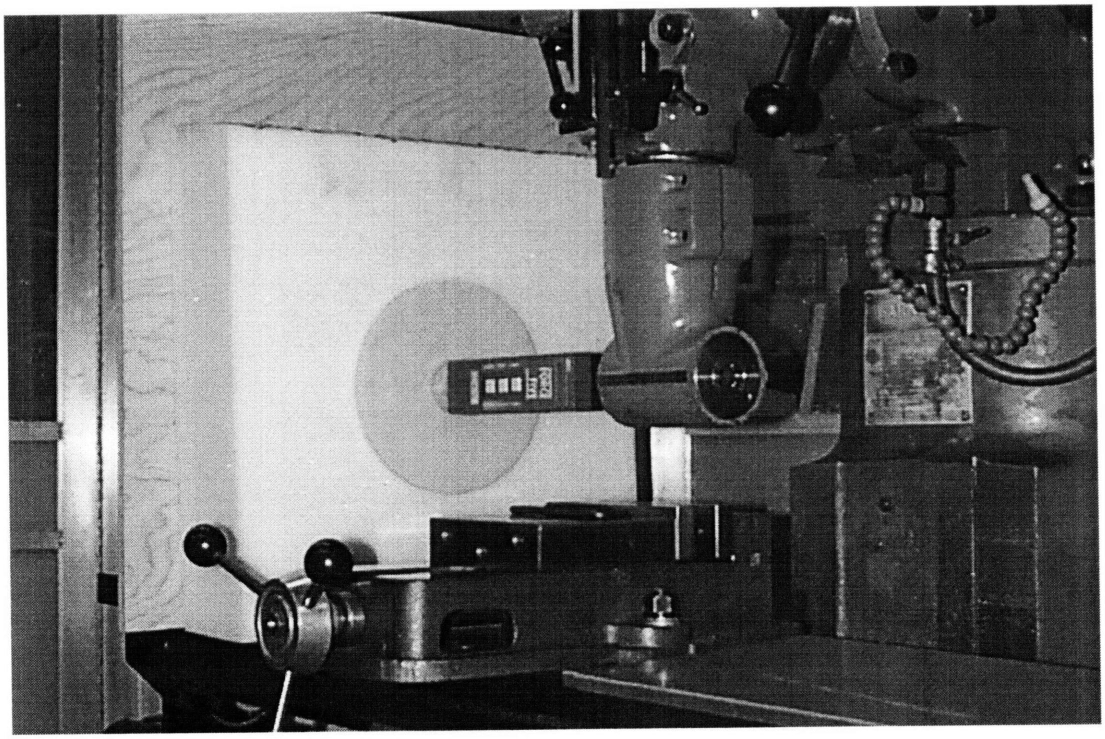
Initial testing was done with shop-built cushions on a modified Bridgeport milling machine. An custom built analog pressure controller was used to maintain an approximately constant air pressure within the cushion. A photograph of the test set-up is shown in Figure 9. Figure 10 is a photograph of a typical test cushion.

The Bridgeport was programmed to move into the cushion at a constant speed until a pre-determined depth was reached, and then reversed to its starting point. As described in the SAE specifications for testing foam materials, a 50 in^2 indenter was used. Speeds in the range of 2 to 20 inches per minute, and pressures ranging from -1.0 to +0.5 psig were examined.

Applied force was measured using a "FORCE-5" digital force gage from Wagner Instruments. The gage is 100 lbf full scale, with 0.05 lbf resolution, and gives a 0-1 volt analog output signal . The analog output was subsequently digitized using a 0-5 volt full-scale 12 bit A/D converter. The resolution of the A/D conversion was approximately twice that of the gage, and so did not degrade the signal. The force gage samples at 100 Hz.

Initial Testing -- Findings:

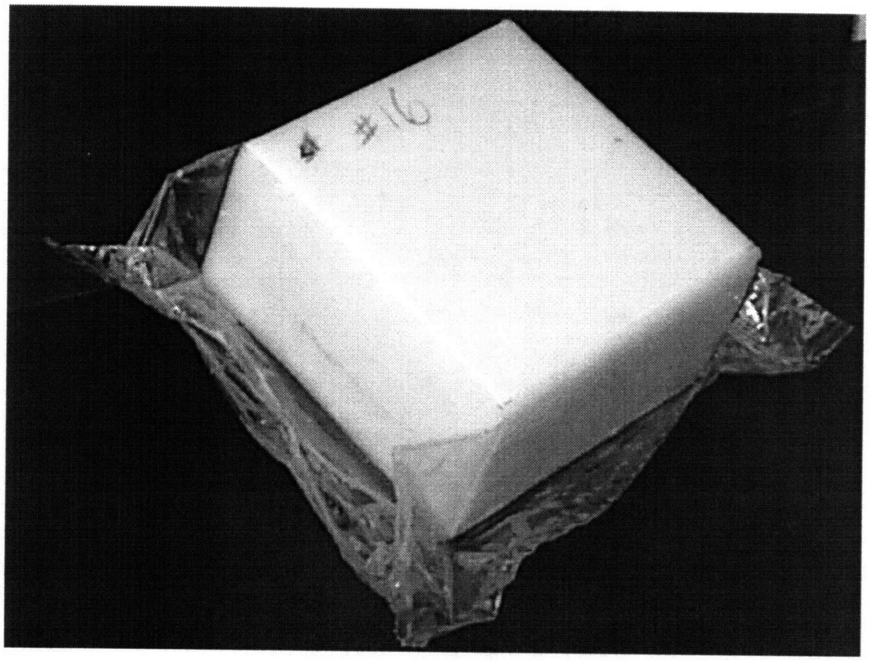
As predicted, we were able to affect the levels of applied force at which the open-cell foam moved into its collapse phase. Representative data is shown in Figure 11. The same data is plotted in Figure 12, but in this case the pneumatic pressure has been added to the mechanical pressure (force/area). At the start of the test (left side of the figure) the various tests show differing pressure levels since there is zero mechanical pressure and the pneumatic pressure is controlled to different levels. It can be seen however, that the inflection point of the three curves



Testing Setup used for Initial Testing.

The photograph shows a large (18" x 18") monolithic foam cushion; tests were also conducted with smaller (9" x 9") shop built cushions as shown in Figure 10.

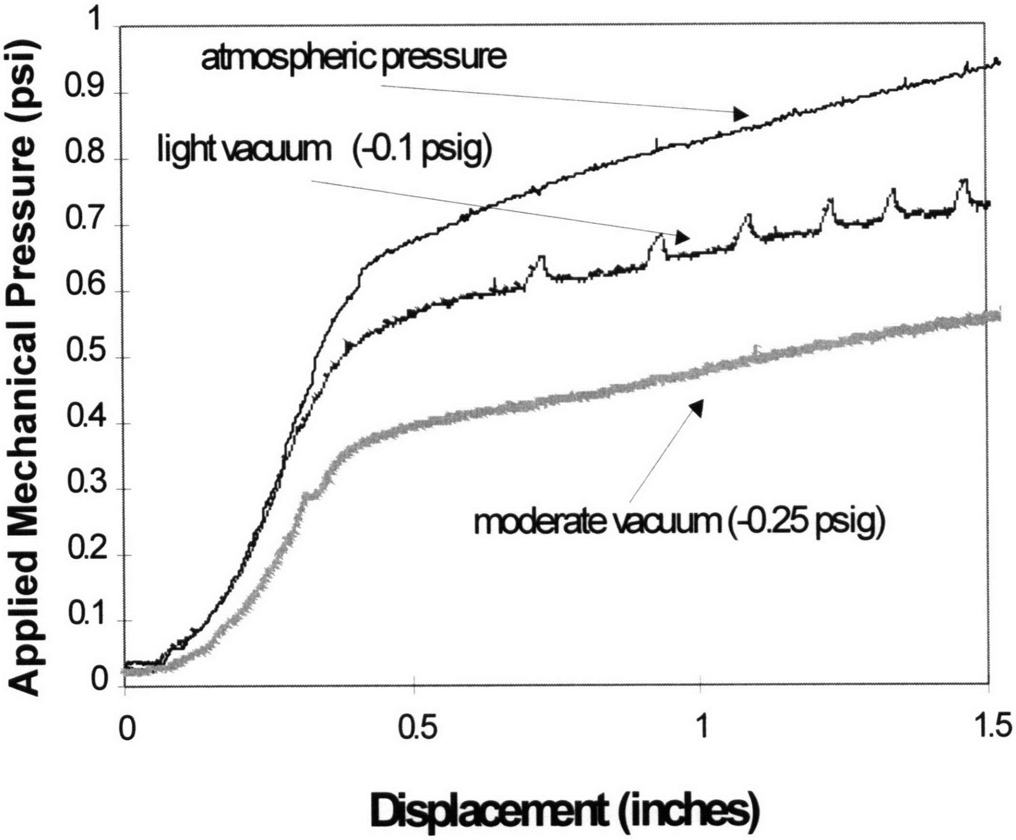
Figure 9



Top View

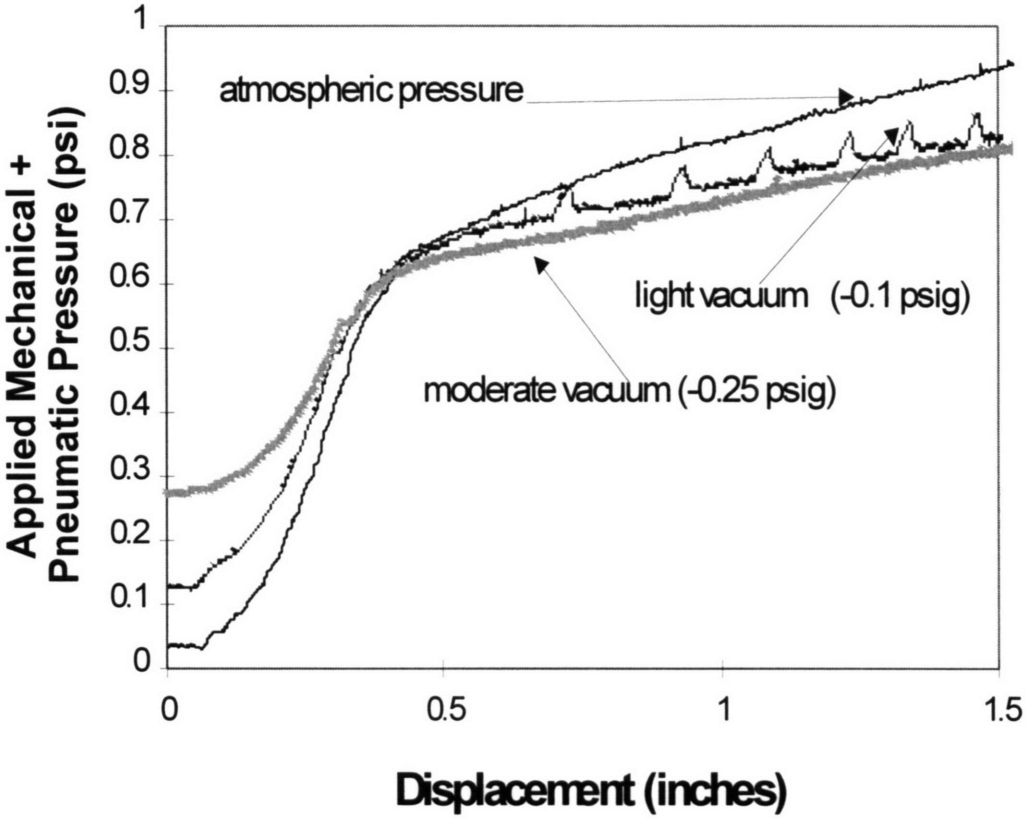
Bottom View of a Typical Test Cushion

Figure 10



Effect of Applied Pneumatic Force on the Mechanical Force Required for Open Cell Foam to Move from Linear Elastic Behavior into the Collapse Plateau

Figure 11



Graph Illustrating the Relative Constancy of Total Force (Pneumatic + Mechanical) at which Open Cell Foam Transitions from Linear Elastic Behavior to the Collapse Plateau

Figure 12

comes at essentially the same pressure level. The difference in the slopes after the inflection points is an artifact of the testing procedure, due to the pneumatic impedance of the cushions and the inadequacies of the controller used.

Pneumatic impedance of the cushion, its associated ports, fittings and air lines, as well as the valves and pumps had a significant effect on the performance of the system. Our initial tests used and a 9" x 9" x 4.5" cushions covered with 6 mil vinyl, and used 1/8" ID ports, lines, and fittings for the pneumatics. The valves used had a 1/16" orifice, and a 50 in^2 round indenter was used to compress the cushion. When a bare piece of foam of these dimensions is compressed to approximately 25% of its initial volume and then released, it rebounds to its initial volume in approximately 1/4 second. For the test cushions in the initial configurations, it took over 10 seconds to rebound from a compressed state 25% of its initial volume to its full size.

The severe impedance limitation of the original test setup led us to significantly increase the ID of all fittings and air lines. Air lines and fittings were increased to 3/8" ID, and valves to a 1/8" orifice. Components were replaced sequentially, and significant improvement was seen with each change. We also experimented with the number of ports to the cushion, but found that this was not a significant parameter. In the new configuration, a test cushion rebounds to its initial size in approximately 1 second. We considered this acceptable performance.

Controller performance was marginal. Even after considerable adjustment and filtering, the controller was only marginally stable. The controller tended to exhibit significant overshoot from the set points, and in some circumstances would oscillate. These effects can be seen in the data in Figure 12 above; odd peaks and valleys in the measured force correlate directly to unplanned oscillations of the pneumatic pressure. In addition, this controller made it difficult to change set points and to record data.

Finally, having used a milling machine as the base for our initial tests prevented developing a closed loop controller. The displacement control on the Bridgeport could only be preprogrammed; it did not permit the installation of a feedback loop of any kind. We hoped to conduct a series of minor hysterisis loop tests in which the applied force was the controlling variable, but were unable to do so because of the nature of our testing apparatus. This led to the construction of our second testing apparatus.

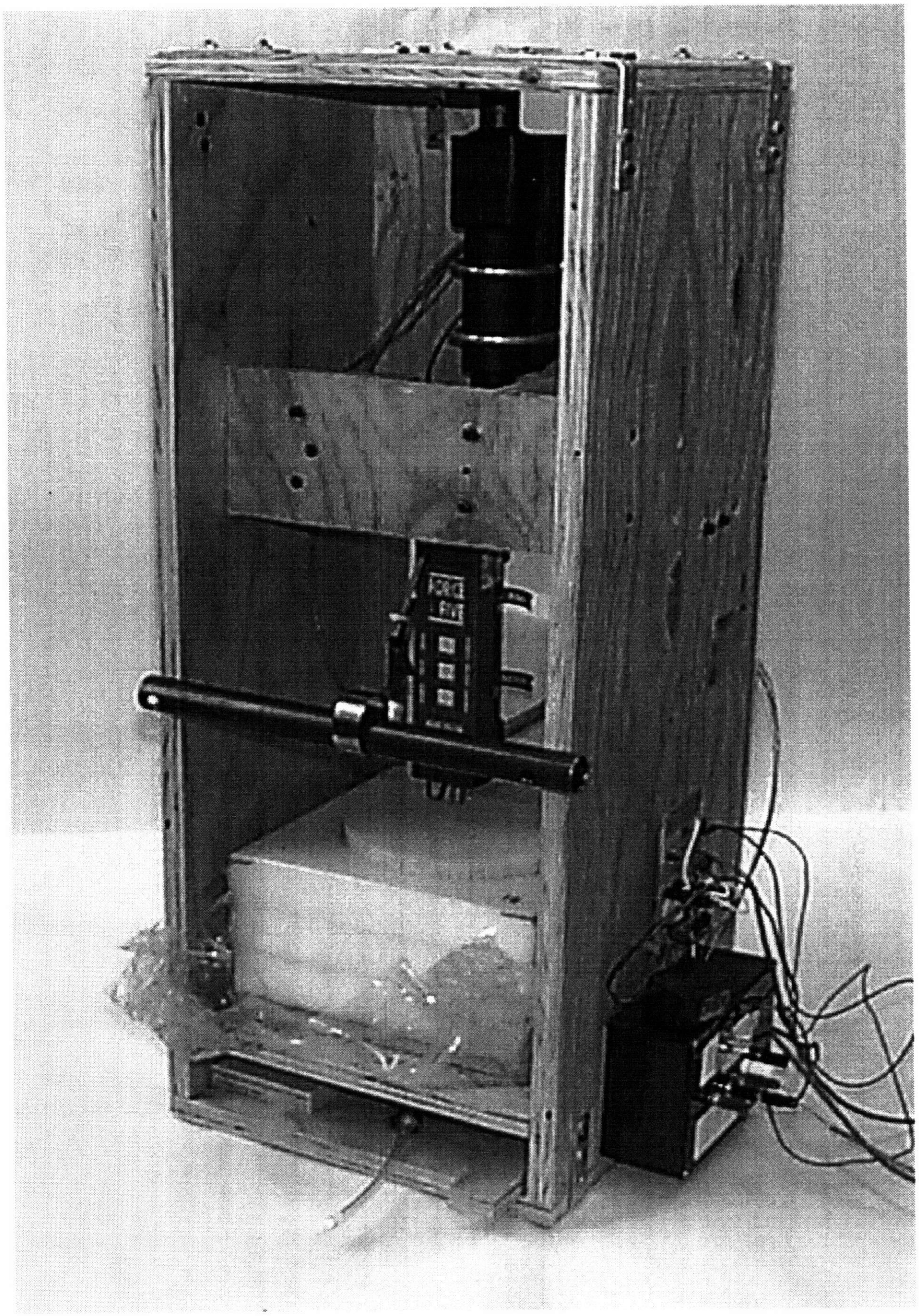
Second Generation Testing -- Description

A new testing rig was designed for later laboratory testing. The apparatus is shown in Figure 13. A rigid 3/4" plywood frame reinforced with steel strapping serves as the base for a linear actuator. (LINAK model #25.115-7.9-24VDC). The actuator velocity varies with applied voltage, and for the voltages used (8 to 24 VDC), speed ranged from approximately 10 to 30 inches per minute. The force gage (FORCE-5 100 x 0.05 lbf) used in the initial tests is mounted to the actuator, and in turn transfers the load to the 50 in^2 indenter. A potentiometer was geared to the actuator with a 80 tooth per inch timing belt and a timing pulley, which allowed repeatable resolution of better than 0.005".

The analog controller was replaced with a digital controller developed using the Labview software package for later tests. The new digital controller runs on a 486 DX 33, operates at approximately 80 Hz, and delivers considerably improved performance. The extraneous peaks such as seen in Figure 12 above were eliminated. The digital controller can be configured to use either force or displacement as its primary input. Generally speaking, force has been the controlling variable in this series of tests. The new controller is able to archive force, position and air pressure data at any chosen rate up to the controllers top speed of 80 Hz. In general, test data was collected at a rate of 10 Hz.

Second Generation Testing -- Findings

A typical test consisted of ramping the force upon the cushion up to a given set point, and then executing a series of minor hysteritic loops. The maximum force for any particular test ranged from 10 to 75 lbs, which, given the use of a 50 in^2 indenter, corresponds to a mechanical pressure of 0.2 to 1.5 psi. The minor loops ranged in size from 5 to 15 lbs (0.1 to 0.3 psi).



Testing Apparatus used for Second Generation Laboratory Tests

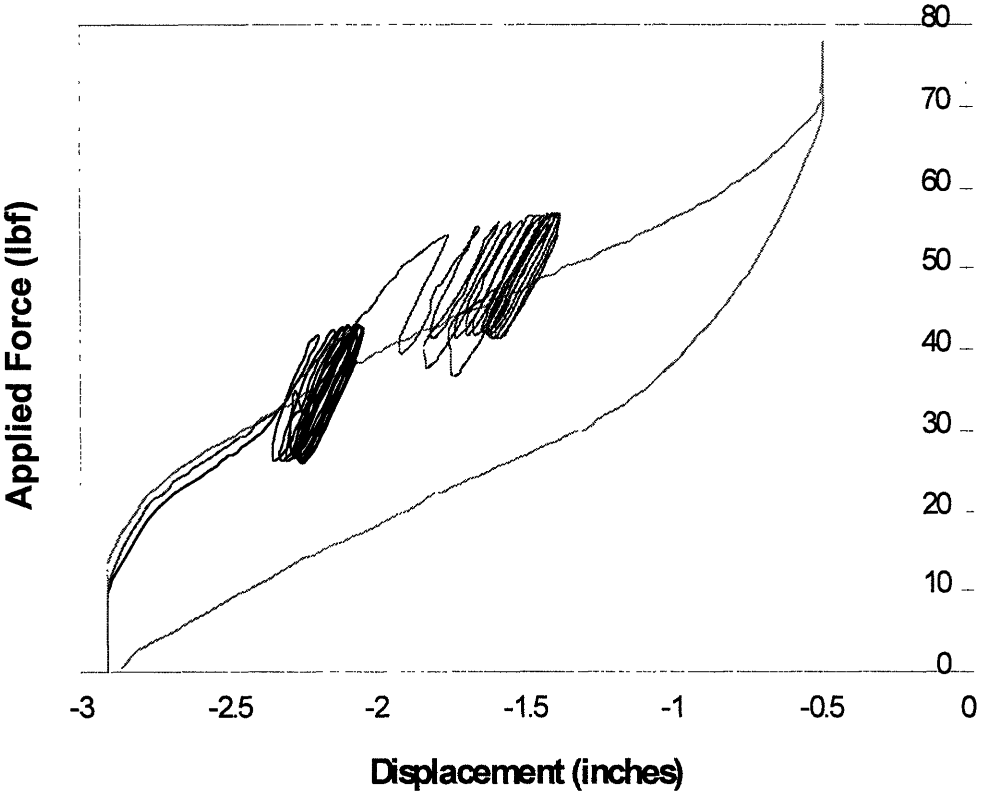
Figure 13

Results of a representative minor loop test are given in Figure 14. In this test, one series of minor loops is conducted about a point that places the apex of the loop just below the point where the foam makes its transition from elastic behavior to collapse. Another set of minor loops, of the same magnitude as the first, is conducted with the low point of the loops just above the transition to the collapse plateau. As can be seen in the figure, the loops above the transition to collapse show a pronounced creep which is not present in those below it.

Additional tests were conducted at a constant maximum force. In these tests, the actuator was pressed into the material until a proscribed maximum force was reached, and then held at this force. Results of a pair of representative constant force tests are given in Figures 15 and 16.

In the tests connected with Figures 15, a bare piece of foam 9" x 9" x 4.5" was loaded to 35 and 45 lbf (0.85 and 0.95 psi, respectively). For this particular material, the collapse transition point at atmospheric pressure falls at about 40 lbf (0.9 psi). It can be seen from the slope of the lines in Figure 15 that the test above the transitional loading shows considerably greater creep than the test below it.

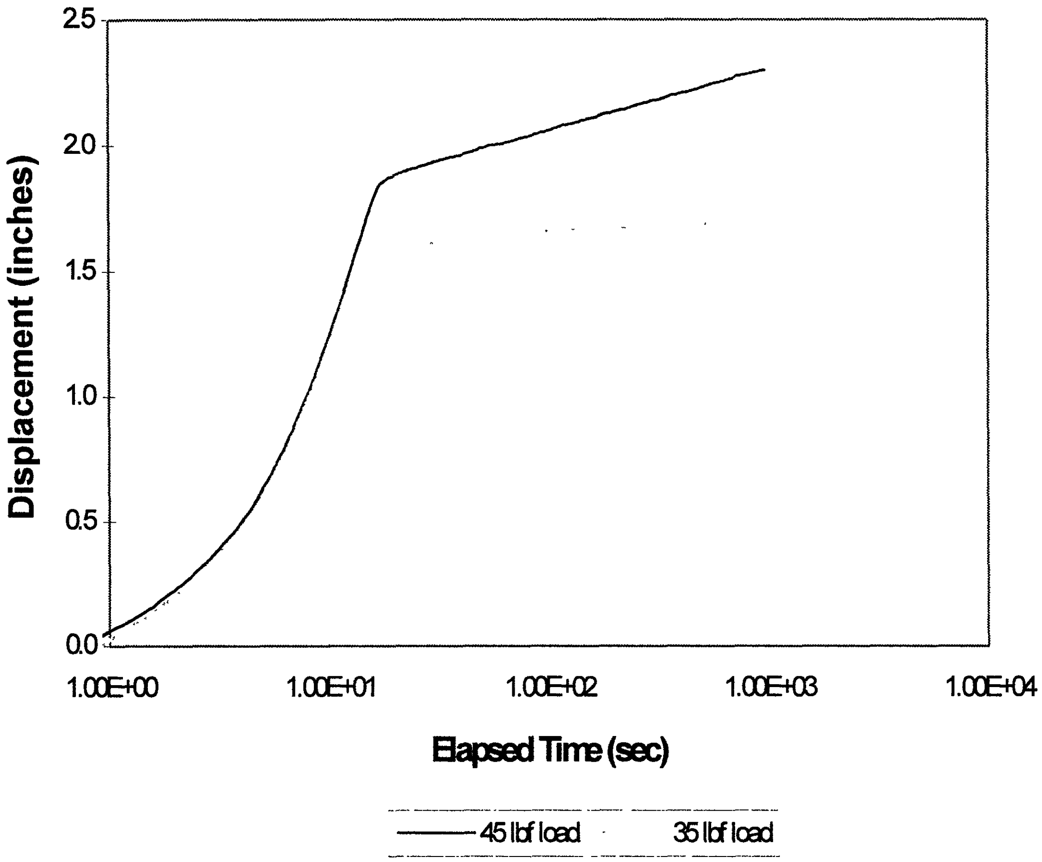
Figure 16 shows the results of a similar test, but one where the collapse transition point has been moved by use of vacuum to approximately 30 lbf (0.6 psi). The foam used was of the same type as in Figure 15 above. Note that, as before, the test which is loaded well below the transition point gives essentially constant displacement, and the one well above the transition point shows significant creep. The test near the transition point falls somewhere between the two-- it shows some creep, but not nearly as much as the one well above it.



Minor Hysterisis Loops Near The Transition From Linear Elastic Behavior To The Collapse Plateau.

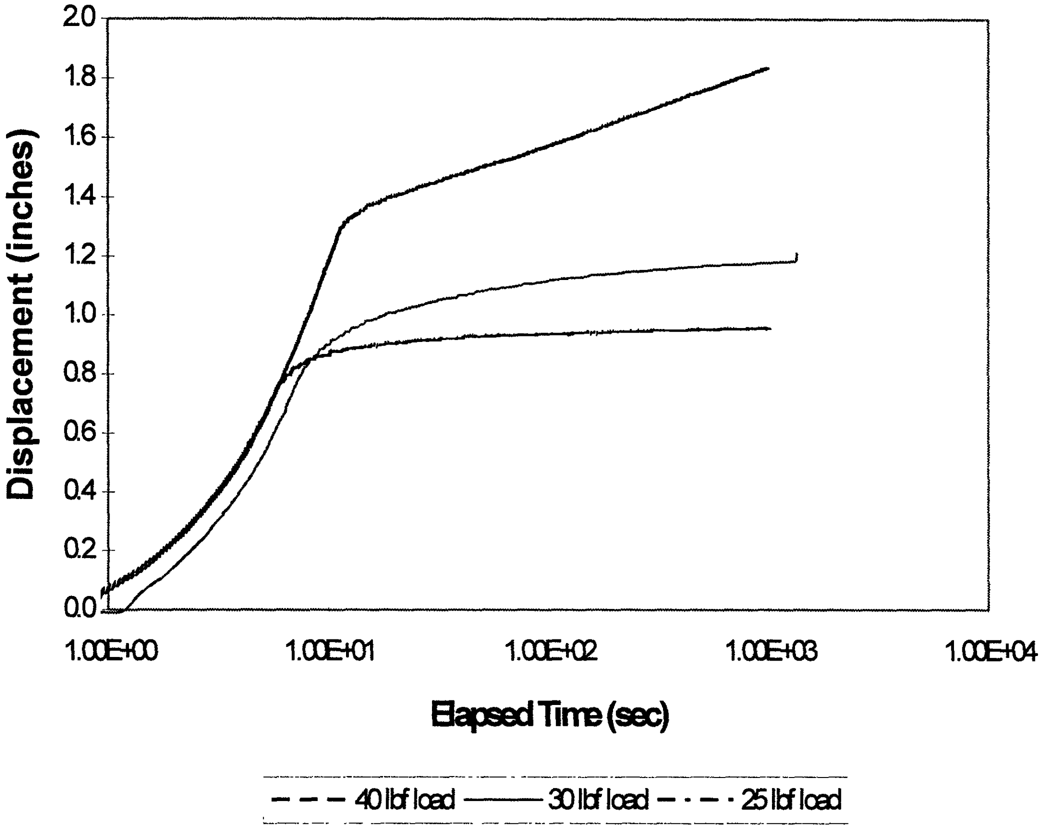
The envelope of the major loop is also shown; the relatively steep slope of the major loop is due to the relatively high indentation speed used.

Figure 14



Creep Under Constant Load For An Open Cell Foam With Transition From Elastic To Collapse Phase At Approximately 40 Lbf.

Figure 15



Creep Under Constant Load For An Open Cell Foam With Transition From Elastic To Collapse Phase At Approximately 30 Lbf.

Figure 16

Prototype Cushion

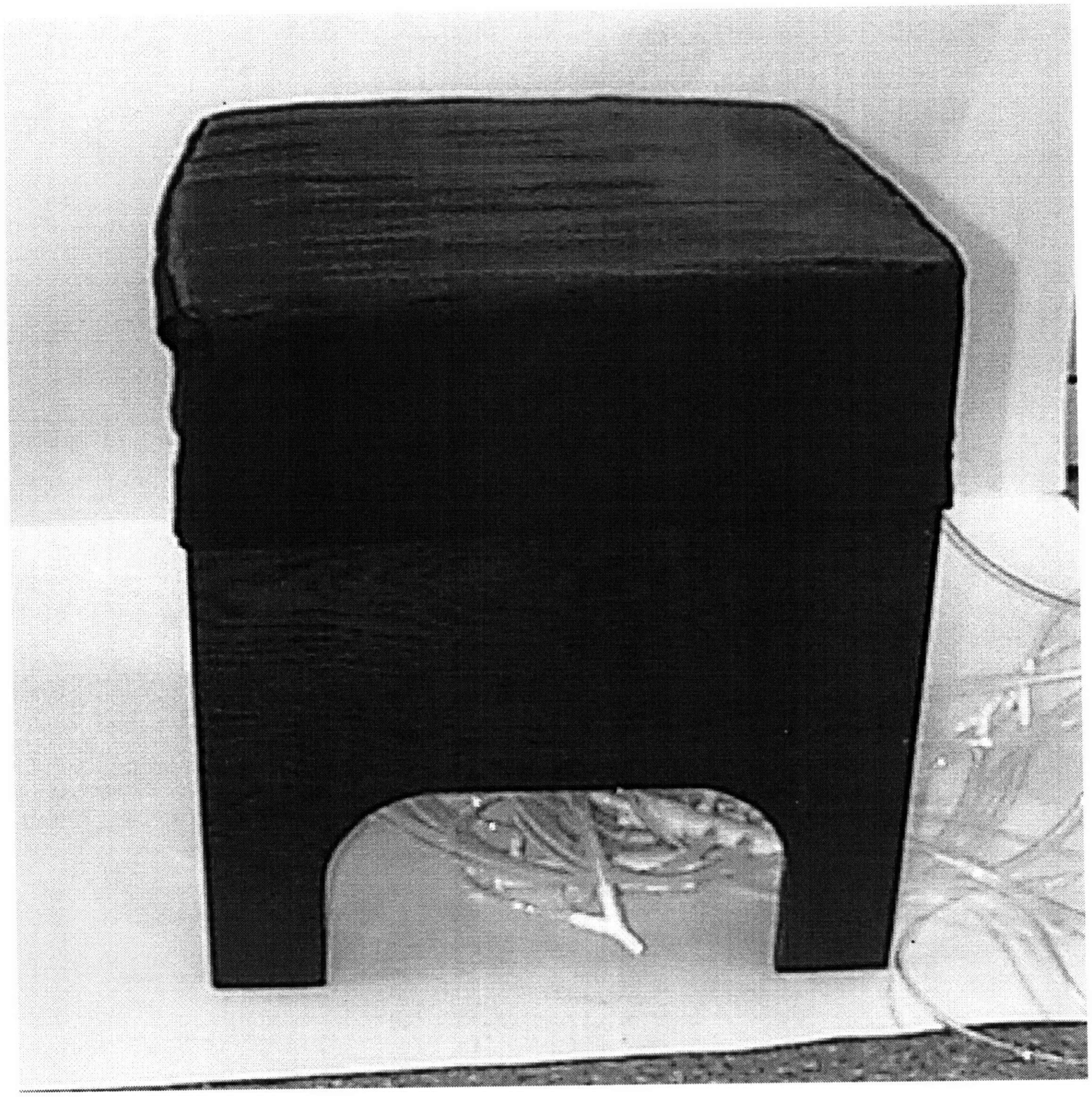
Description

Based on the results of our laboratory tests, a prototype cushion was designed and constructed. The cushion consists of a 6x6 matrix of sealed foam cubes inside a fabric cover. The individual cubes can be connected to manifolds in relatively arbitrary groupings, subject to the constraint that no more than 8 groups can be accommodated. Each of the groups is plumbed to a 1/8" orifice valve with 1/4" ID tubing, and the valve is connected to a manifold. A Labview based digital controller similar to the one used in the second generation laboratory tests allows the pressure in each of the zones to be set to an arbitrary pressure between +0.5 psig and -1.0 psig. The cushion rests on a simple plywood stool, and a photograph of the entire assembly is shown in Figure 17.

The individual cubes consist of a 3" x 3" x 4.5" tall pieces of open-cell foam, sealed inside of a close-fitting shell of 2.5 mil urethane. The cubes are fitted with a tubing fitment suitable for connecting to standard 1/4" ID tubing fittings. Two cubes are shown in Figures 18. Two sets of cubes have been fabricated; one of a firmer foam, and another of a softer type. The initial set was of the softer type, but they proved to be to soft for use with human subjects. When a subject sat on the softer type cubes, the total elastic range was exceeded, and the subject "bottomed out" on the underlying plywood substrate. The second generation of cubes (the firmer set) was fabricated from the stiffest foam that was readily available, but are still somewhat softer than would be ideal. Subjects lighter than average find the second generation cubes suitable, but for most users bottoming out is still a problem. More appropriate foam is currently being sought.

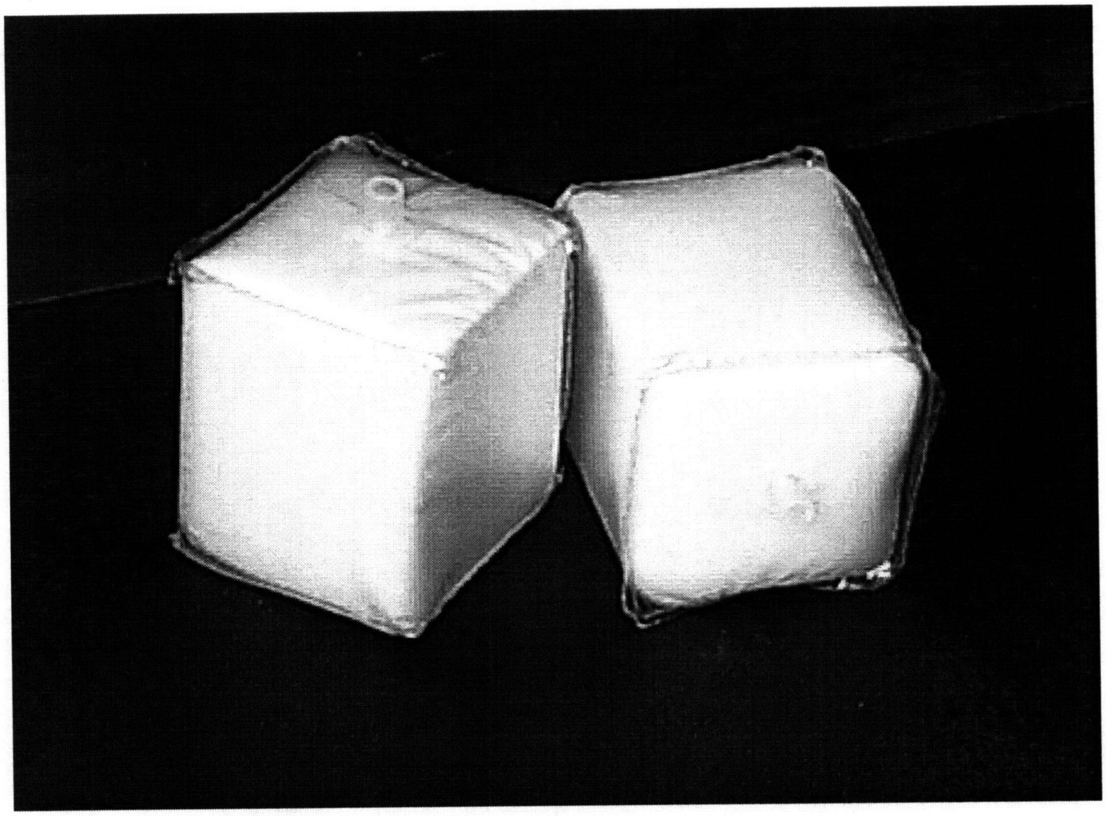
The individual cubes are connected in parallel into zones ranging from 2 to 6 cubes per zone. A two cell zone with the associated hardware is shown in Figure 19. The zone configuration used in preliminary testing of the prototype is shown in Figure 20.

The cubes are held in place relative to each other with a fabric matrix; the matrix restrains the cubes horizontally while permitting them to slide relatively freely in the vertical direction. The upper surface of the fabric matrix is covered loosely with a stretch fabric; the fabric is attached only along the outer perimeter of the cubes. The lower edge of the outer perimeter of the fabric



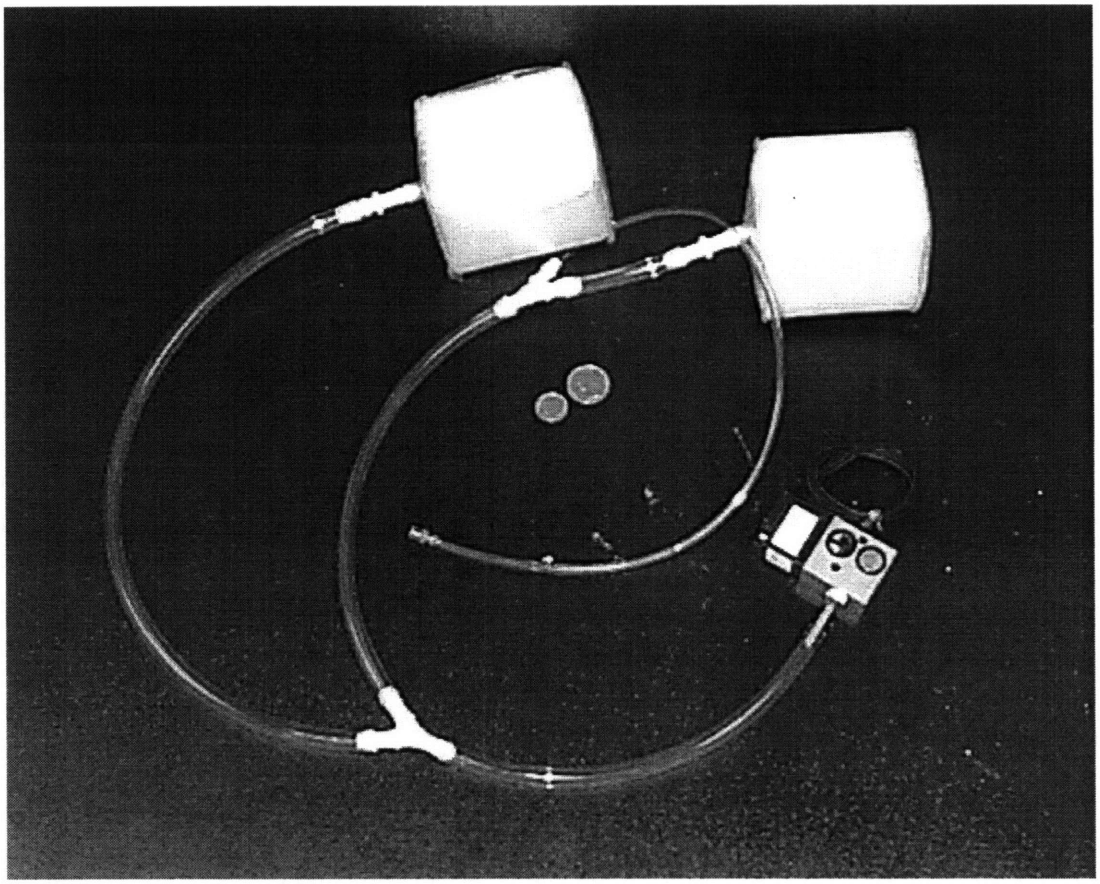
Prototype Cushion With Associated Plumbing Resting On A Simple Stool

Figure 17



Two of the Foam Cubes Used in the Prototype Cushion.
The foam is sealed in 2.5 mil urethane, and has a 1/4" ID port.

Figure 18



A Two cell zone for use in the prototype cushion. The smaller tube with the free end connects to a pressure transducer. The valve has been disconnected from the manifold and is included for clarity. A dime and quarter in the center of the image give a sense of scale.

Figure 19

1	1	1	2	2	2
1	5	5	6	6	2
1	5	5	6	6	2
1	7	7	8	8	2
1	3	3	4	4	2
3	3	3	4	4	4

Zone Layout for the Prototype Cushion
Cells are on the same zone all have the same number

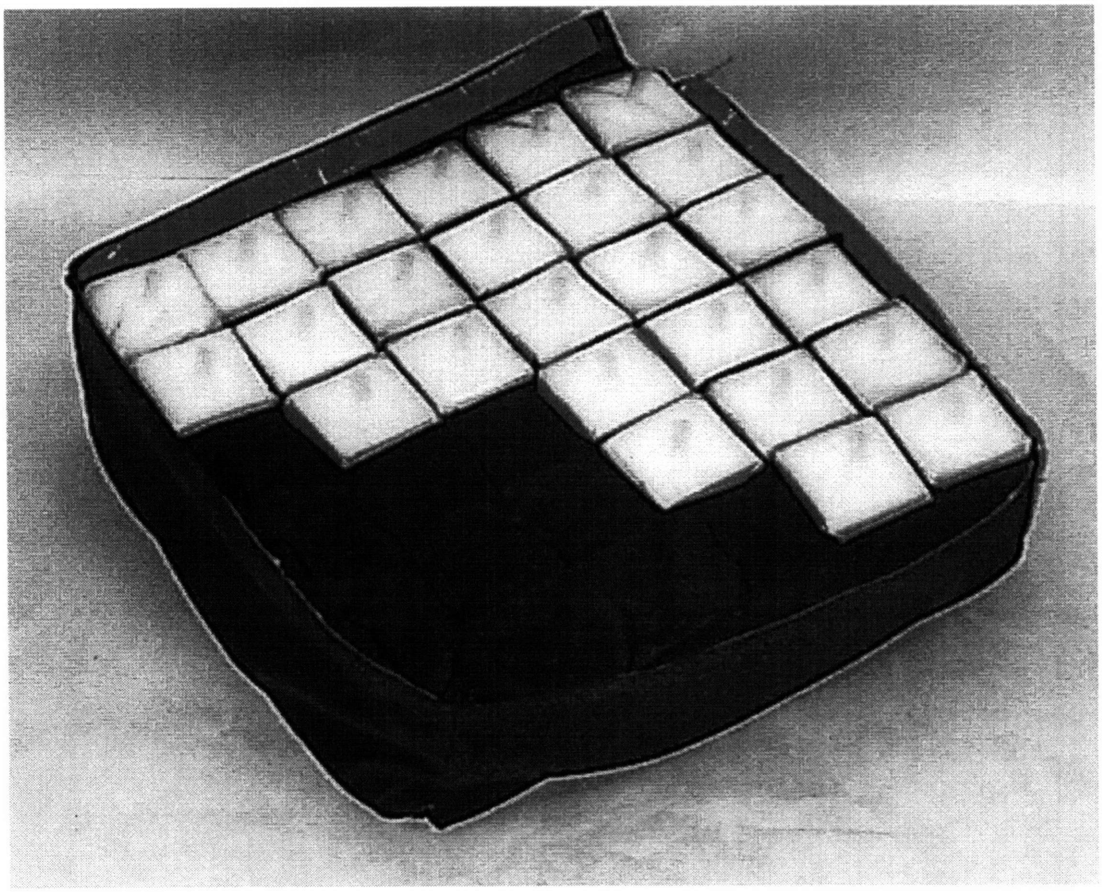
Figure 20

is fitted with hoop and loop fastener (Velcro ®) so that it can be attached to the sides of the stool on which the cushion rests. A photograph of the fabric matrix (from below), with some of the foam cubes in place, is shown in Figure 21.

The entire cushion rests on a simple square stool, which is shown in Figure 22. The stool was fabricated from 3/4" plywood. The top of the stool has 5/8" holes drilled through it on 3" centers; this permits access to the tube fittings from below. A photo of the underside of the stool, with fittings and manifolds in place, is shown in Figure 23.

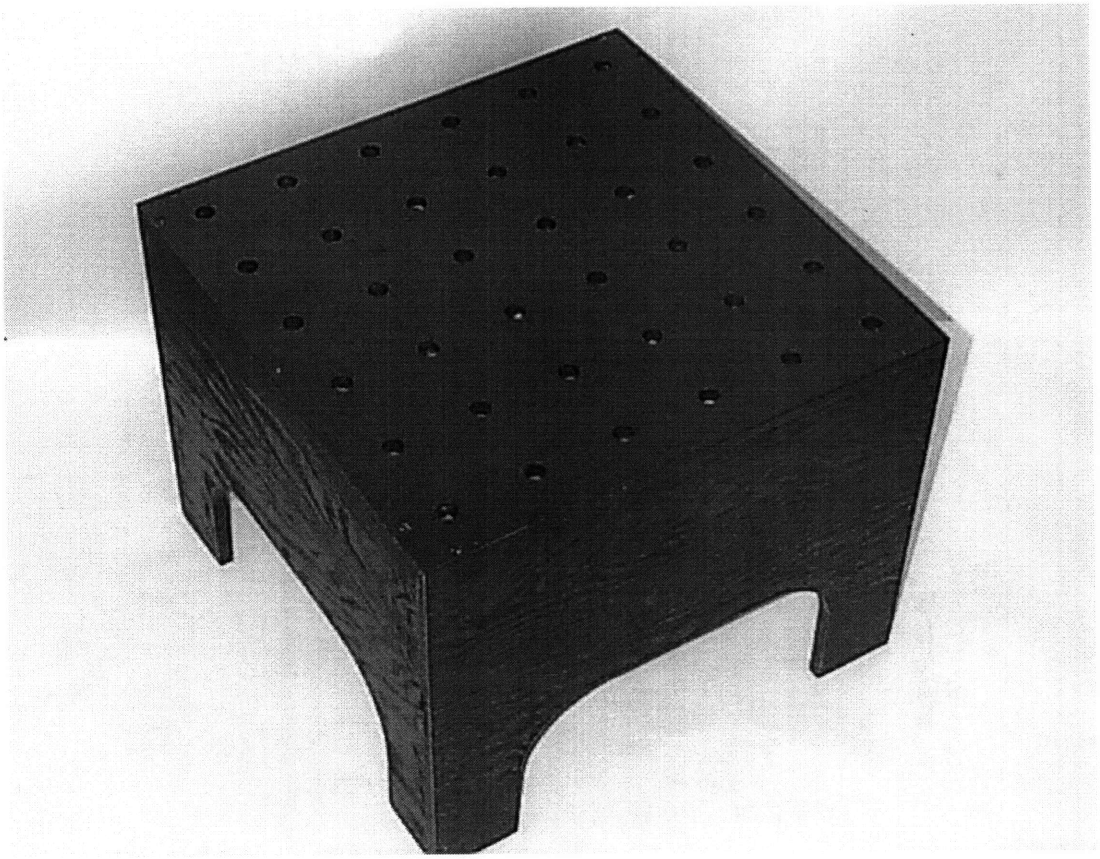
The prototype uses two simple positive displacement pumps, one to provide vacuum and the other for positive pressure. The two pumps feed reservoirs which are nominally held at +/- 5 psig; the reservoirs are permitted to swing up to 1/4 psig above and below their set-points. The pumps run continuously, feeding a 3-way valve. If the reservoirs are below nominal pressure, the valves open the reservoirs to the pumps. If the reservoir is at or above nominal pressure the 3 way valve closes the reservoir and allows the pump outlet to flow (at no head) to the atmosphere.

Two manifold and valve configurations have been tested with the prototype. The first used two valves per sector, and two manifolds-- one for positive pressure, the other for vacuum. This configuration is shown schematically below in Figure 24. The two valve per sector configuration has the advantage of being relatively pneumatically efficient, but would involve a high hardware cost, as well as the additional weight incurred because of the additional valves. As the number of zones increases, this configuration becomes less and less desirable. The second manifold and valve configuration uses only one valve per sector, and utilizes a single manifold which alternates between vacuum and positive pressure. This configuration is also shown in Figure 24. The one valve per sector configuration has the advantage of being efficient in its use of valves. However, considerable energy is wasted in toggling the manifold between the positive pressure mode and the vacuum mode, which would be a problem for a battery operated system. The prototype can be configured in either mode, and analysis with an aim towards choosing between the two is ongoing.



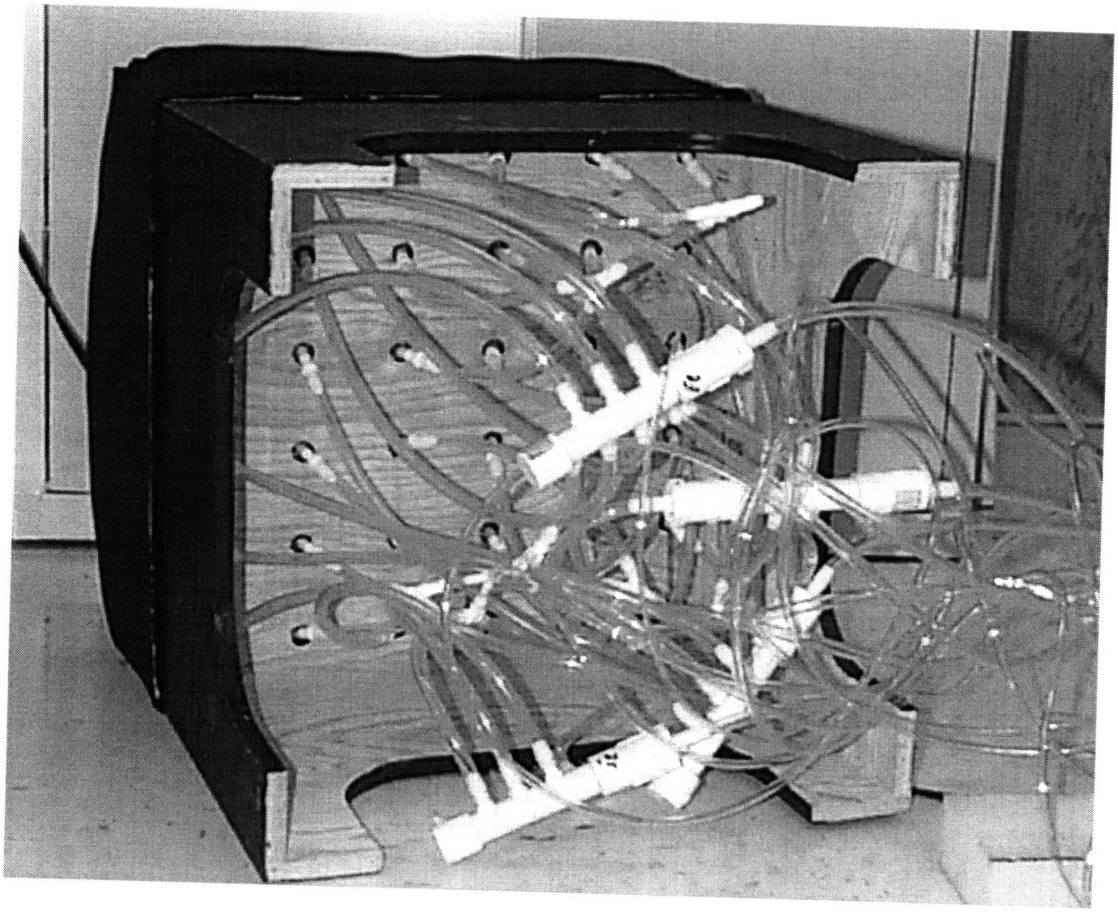
Fabric Cover and Retaining Matrix (from below)
Some foam cubes are included for clarity.

Figure 21



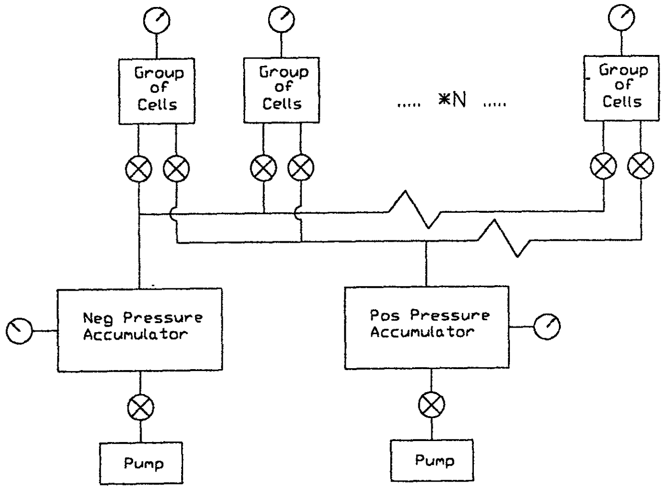
Stool that supports the prototype cushion.
Holes in the base provide access for the pneumatic lines

Figure 22

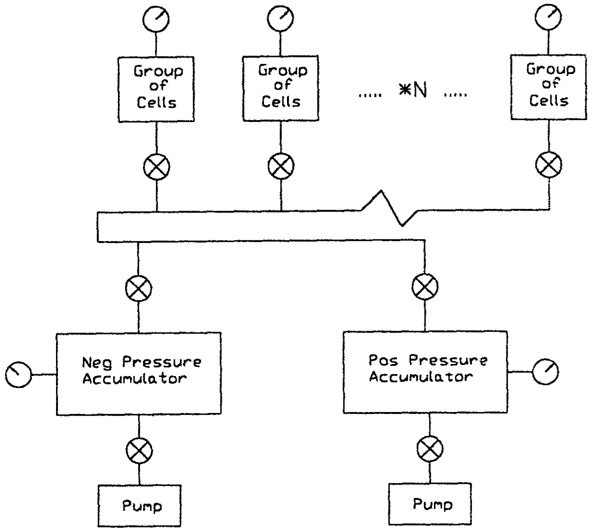


Underside of Prototype Showing Tubing Connections and Zone Manifolds

Figure 23



Schematic for a cushion design that uses two valves per zone.



Schematic for a cushion design that uses a single valve per zone. In this configuration, the buss alternates between vacuum and positive pressure

Figure 24

Prototype Test Results

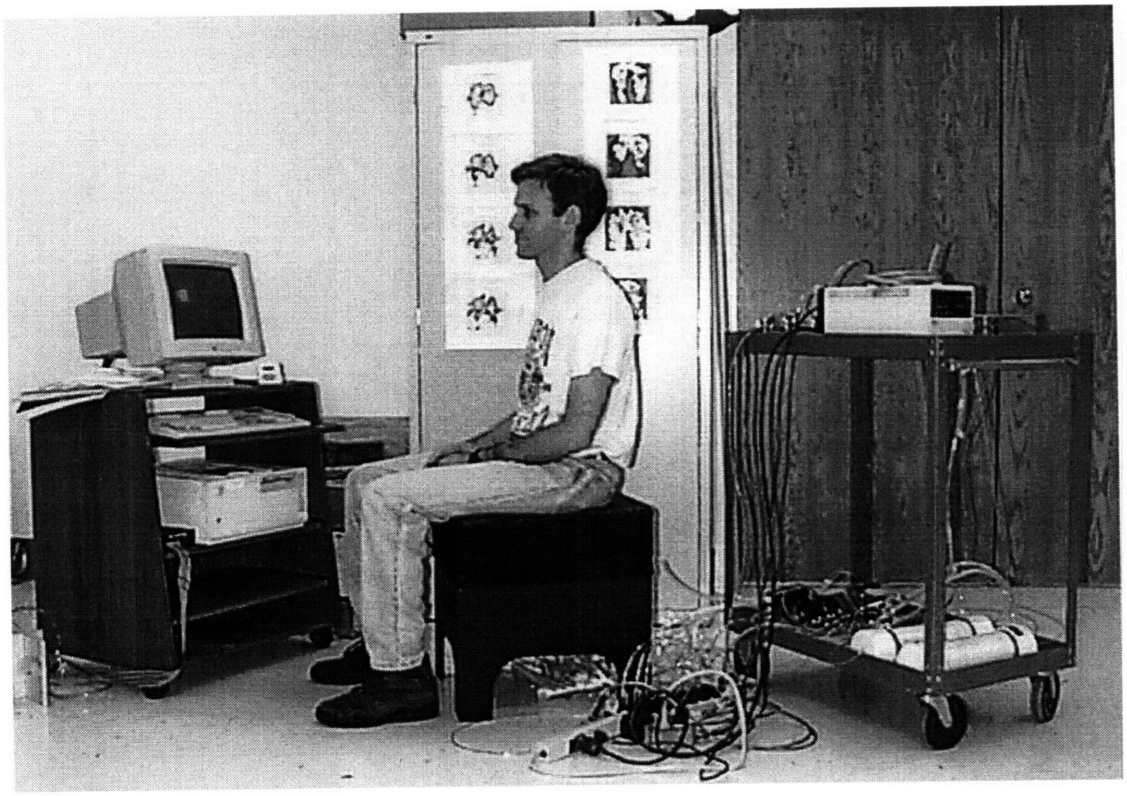
Two types of tests were conducted with the prototype cushions; the first with an artificial buttock, and the second with a human subject. . Representative photos of a human subject on the prototype cushion, along with associated hardware and test equipment, are shown in Figure 25. For both sets of tests measurements were conducted with an force sensing mat (model AF 173, from FSA Force Sensing Systems, Winnipeg, Canada), a 15 x 15 array of force sensors. The sensors are arranged on regular 1-1/16" centers, within a slippery, stretch cloth cover.

The results from the force sensing mat are of only qualitative value; the uncertainties of measurements conducted using the FSA mat are considerable, the device has approximately a 20 minute time constant, which makes dynamic measurements of any kind suspect. In addition, the FSA sensor mat sometimes does not seem to conserve mass -- an integration of pressure across the area of the mat has been seen to vary by greater than 15% for a constant load.

Artificial Buttock Tests

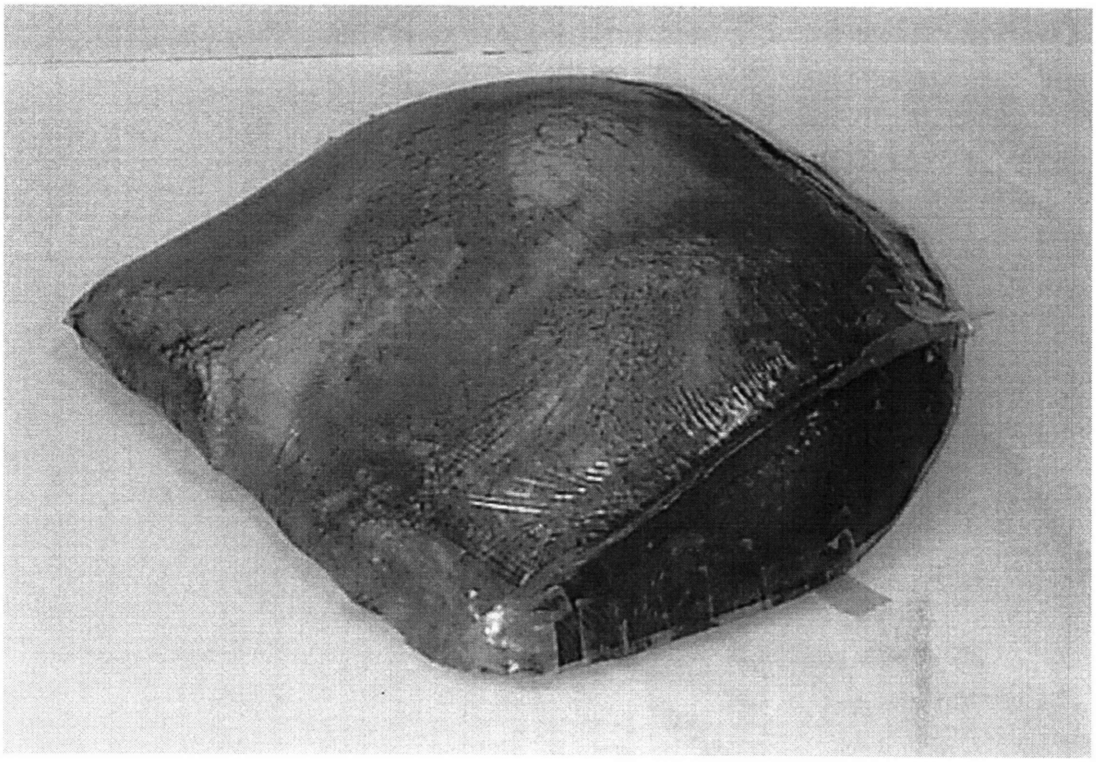
An artificial buttock (a plaster cast from a human subject, padded with medical grade silicon gel, shown in Figure 26) was placed on the prototype cushion and loaded with steel weights to a total weight of approximately 50 pounds. Contour maps of the pressure distribution at the contact plane between the buttock and the cushion were taken for the uncontrolled, atmospheric case, as well as for light (~ -0.1 psig) and moderate (~ -0.25 psig) vacuum. The contour maps for these three cases are shown in Figures 27,28, and 29 respectively. As can be seen by comparing the figures, applying vacuum to the cushion significantly changes the peak loads and the distribution of pressure on the buttock. For the atmospheric case, the maximum pressure in any cell is 43 mm Hg, while for the light vacuum case it is 38 mm Hg and for the moderate vacuum case it has been reduced to 36 mm Hg. In addition, the total area bearing load increases for the vacuum cases.

A histogram of the loads in the atmospheric and moderate vacuum cases is shown in Figure 30. The pressure distribution for the vacuum case is shifted to the lower bins of the histogram, relative to the distribution for the atmospheric case. In Figure 31, the data from the atmospheric, light and moderate vacuum cases is presented as a line chart. The data for each test has been sorted from largest to smallest, and then plotted in order. The atmospheric case is consistently



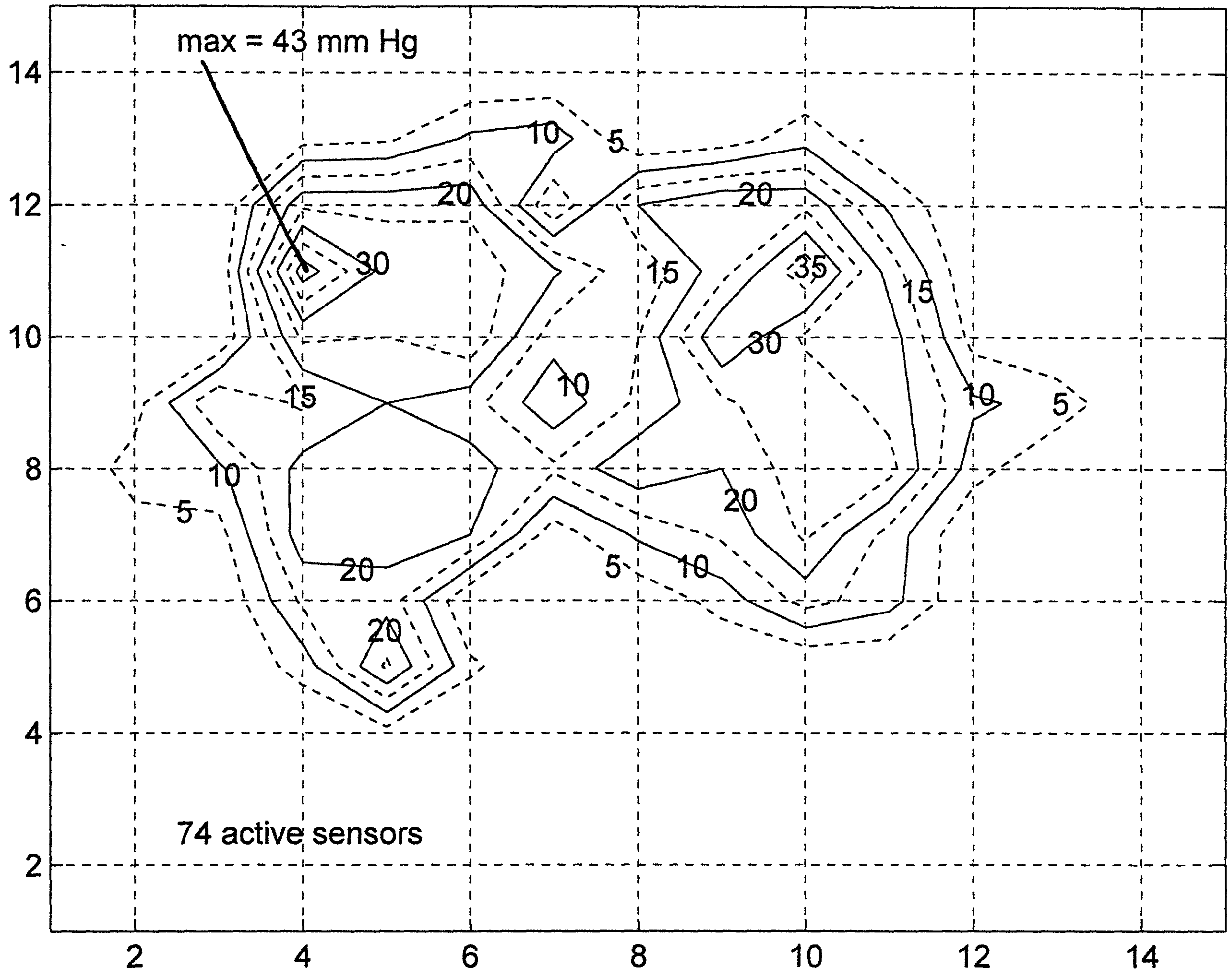
Human Subject on the Prototype Cushion
with Associated Apparatus

Figure 25



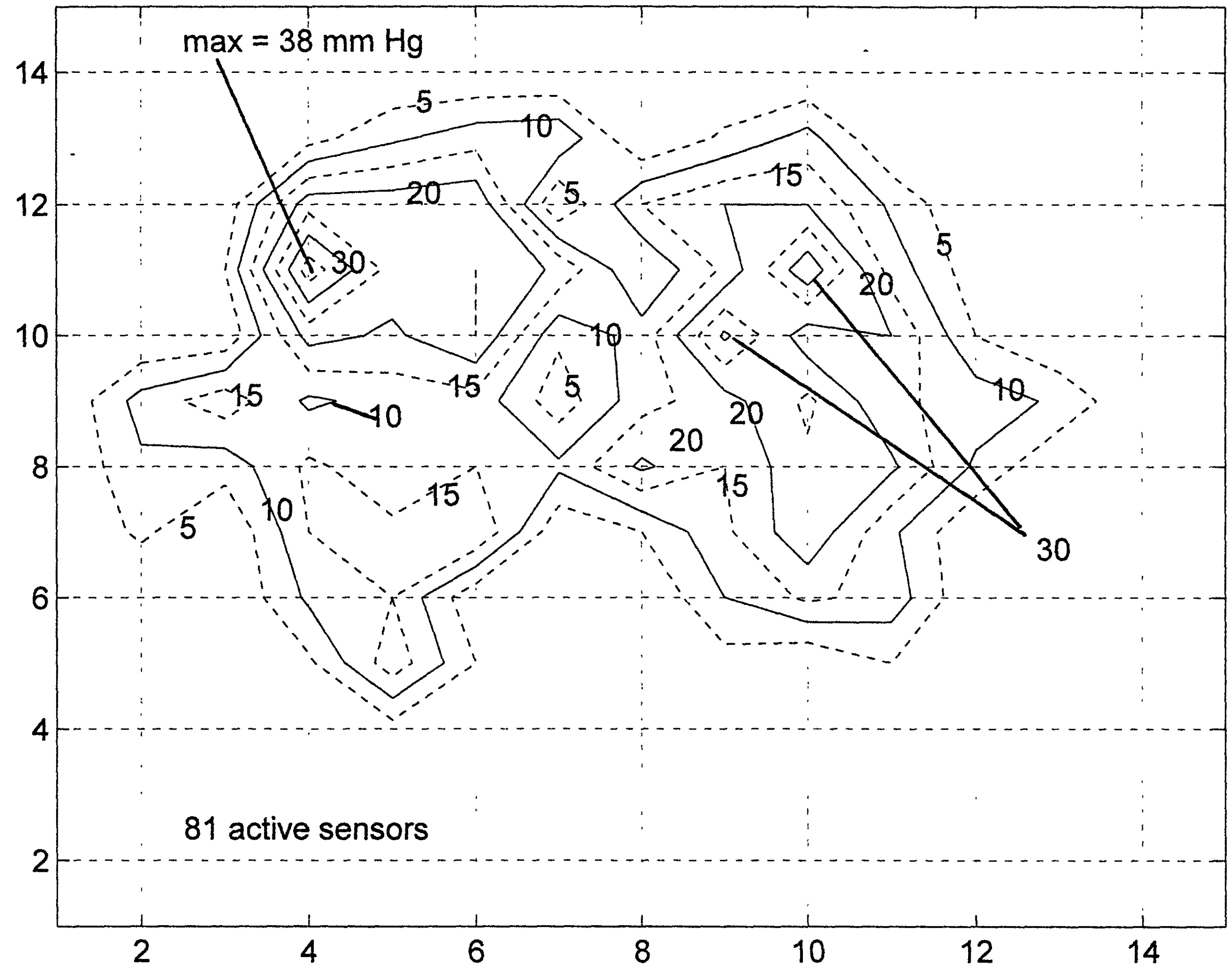
Artificial Buttock Used for Tests of the Prototype Cushion

Figure 26



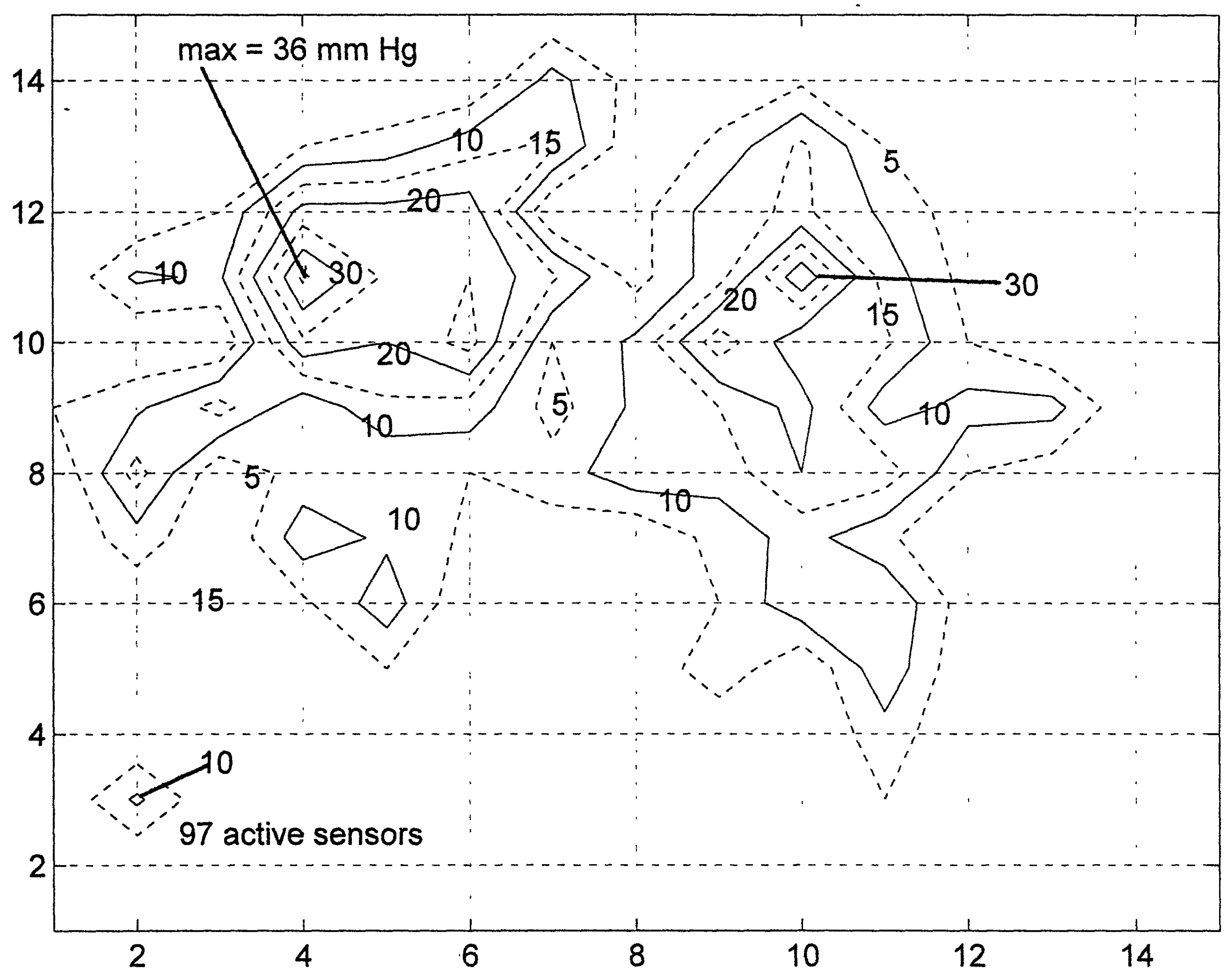
Contour Plot of Interface Pressure on
Artificial Buttock Resting on Prototype Cushion
Uncontrolled, Atmospheric Pressure
All pressure readings in mm Hg

Figure 27



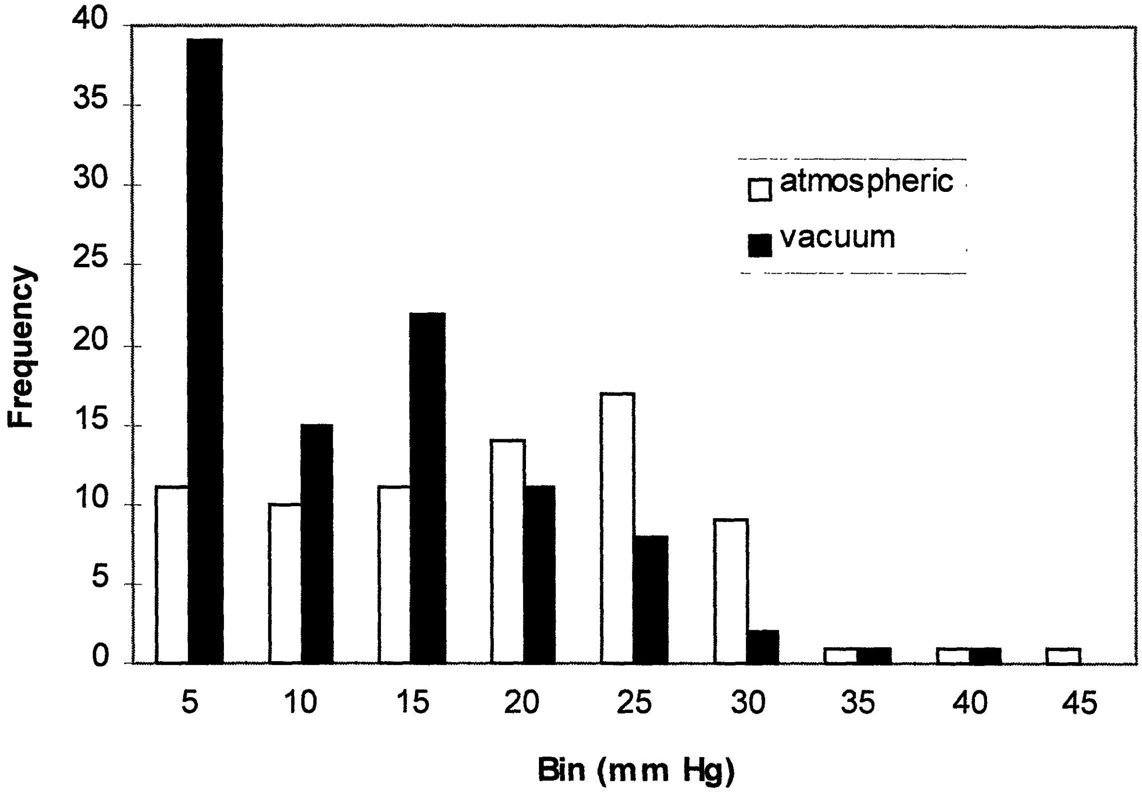
Contour Plot of Interface Pressure on
Artificial Buttock Resting on Prototype Cushion
Air Pressure Controlled to ~ -0.1 psig (light vacuum)
All pressure readings in mm Hg

Figure 28



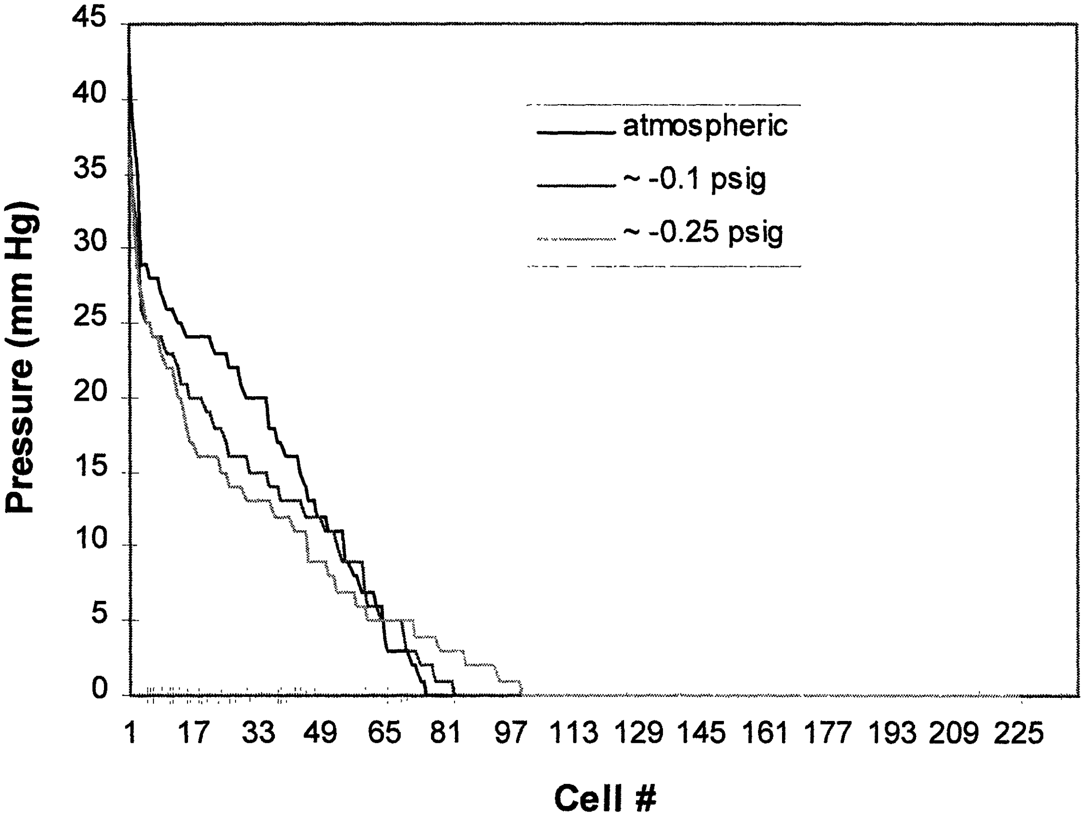
Contour Plot of Interface Pressure on
Artificial Buttock Resting on Prototype Cushion
Air Pressure Controlled to ~ -0.25 psig (moderate vacuum)
All pressure readings in mm Hg

Figure 29



Histogram showing change in load distribution due to application of vacuum for artificial buttock on prototype cushion

Figure 30



Sorted Line Chart Showing The Distribution Of Force
For An Artificial Buttock On A Prototype Cushion
At Atmospheric Pressure, ~ -0.1 And ~ -0.25 Psig

Figure 31

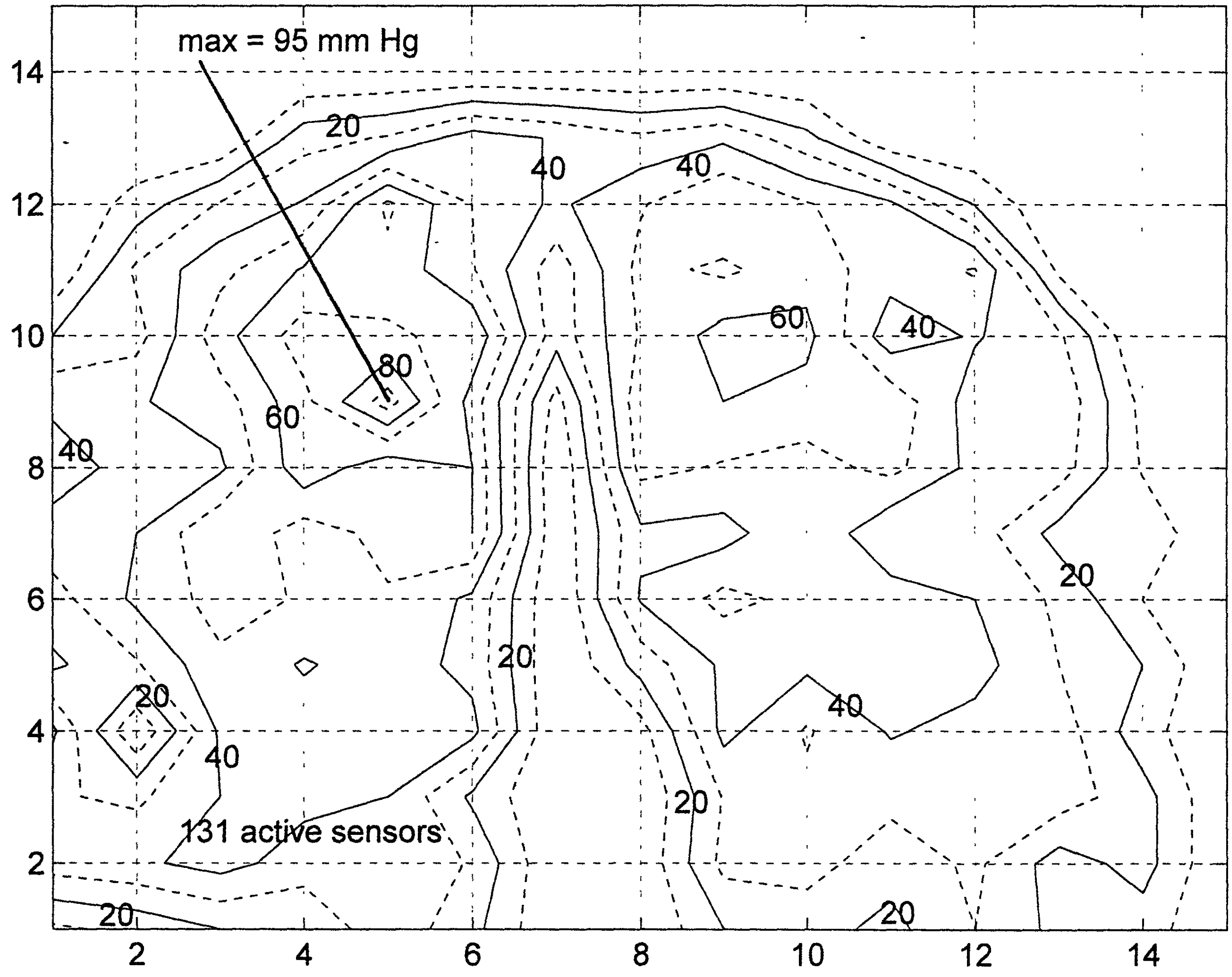
higher than either of the other two, until it reaches the lower end of the range, at which point the lines cross. This shows that the reaction forces for the atmospheric case are concentrated in a relatively fewer number of sensor zones, and are slightly higher in each. The vacuum cases, however, constrain the maximum force, and spread the load to a larger number of cells.

Human Subject Tests

A female subject of relatively small stature (~ 5'2" inches tall, 100 lbs) was seated on both the higher density prototype and on a monolithic block of foam of the same size and type as the prototype. The prototype cushion shows a significant improvement over the monolithic foam, lowering the maximum pressure observed from 95 mm Hg for the monolithic cushion to 67 mm Hg for the prototype under moderate (~ -0.2 psig) vacuum. Contour plots of the results are shown in Figures 32 and 33, respectively. Initial results are encouraging, but because of uncertainty about the cushion (due to bottoming out of the subject), additional test results are not presented.

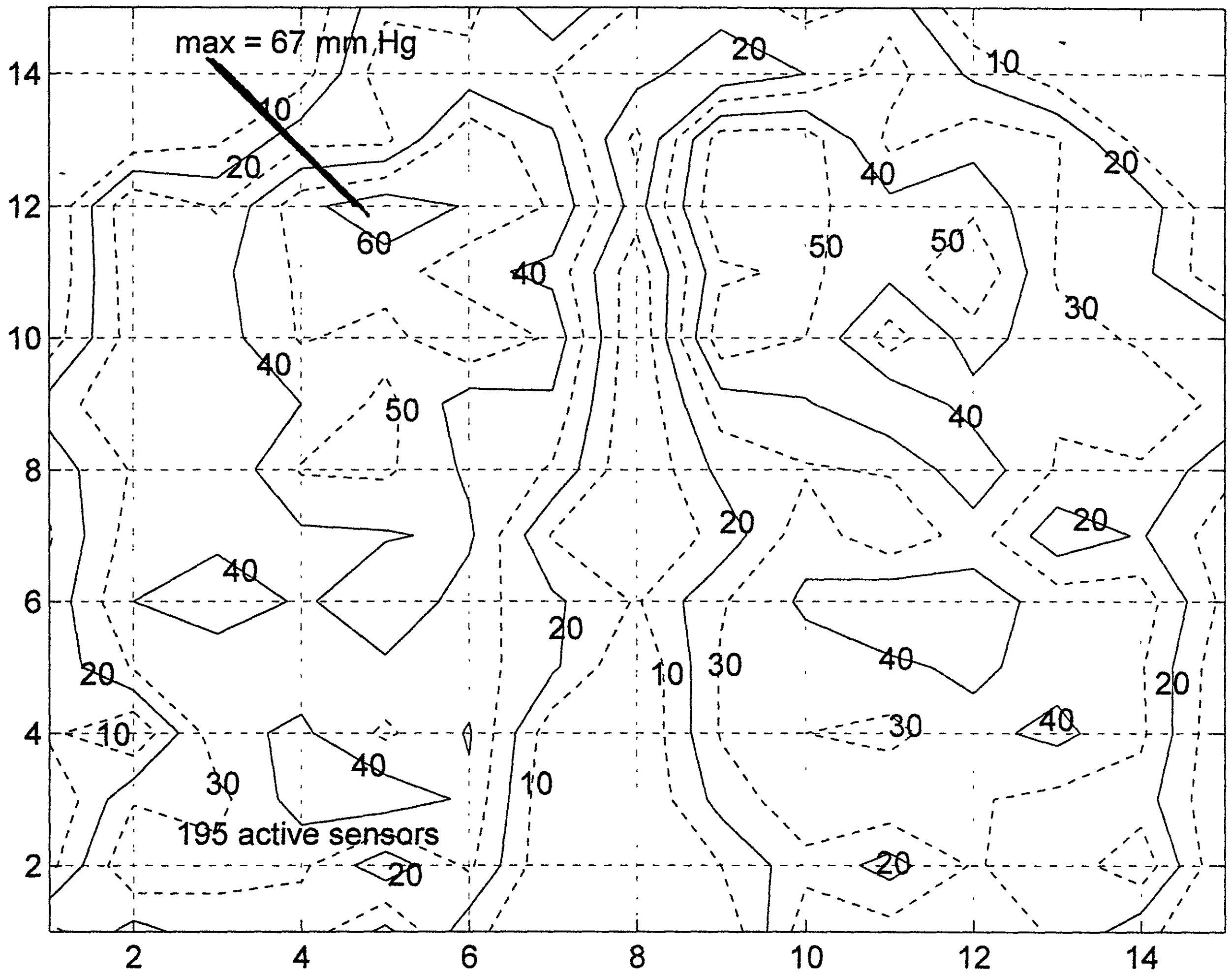
In addition, the extremely long time constant (roughly 20 minutes) of the pressure sensor mat makes data from human subjects (who are never stationary long enough for the mat to come to stasis) extremely uncertain. The results of these tests should only be considered preliminary.

Work is currently underway to fabricate a prototype which will not be susceptible to bottoming out, and a more appropriate force sensing tool is being sought.



Contour Plot Of Interface Pressure
On The Seat Of Small Female Subject
Seated on a Monolithic Cushion Of The Same Type Foam As Prototype
All Pressure Readings in mm Hg

Figure 32



Contour Plot Of Interface Pressure
On The Seat Of Small Female Subject
Seated on a Prototype Cushion Controlled To ~ -0.2 Psig
All Pressure Readings in mm Hg

Figure 33

2d Simulation of a non-linear spring on a buttock shaped solid

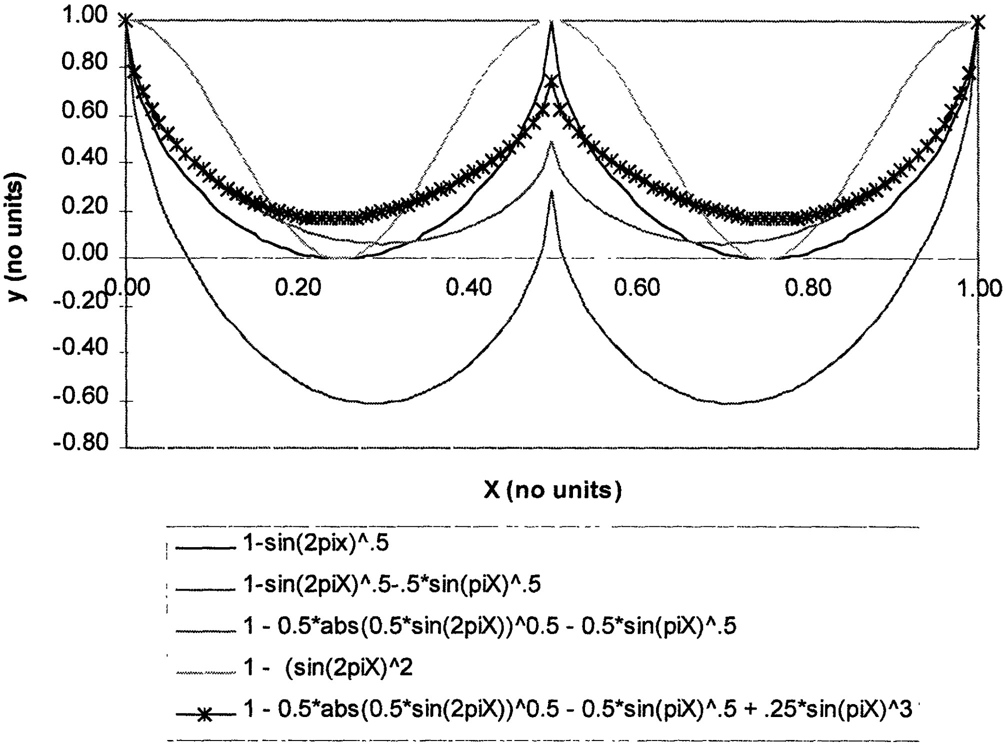
To provide insight into the forces at work in the prototype cushions, a simple 2d static simulation of a buttock shaped object pressed into an elastic solid was constructed. The simulation results behave as expected for foam that enters the collapse plateau, and confirm the trends of the experimental work. Simulation results could be used to identify t he important parameters for selecting foam for later prototypes.

Simulation Parameters:

The buttock model is assumed to be infinitely stiff, and shear effects in the cushion are neglected. The model buttock shape is a convenient mathematical construct which resembles the anatomy along the midline of the real physical case. Neither the shape nor the infinite stiffness in the simulated buttock is truly representative of the anatomical case, but for first order analytic purposes the simplifications seem worthwhile. A variety of simulated buttock shapes for which simulations were examined are shown in Figure 34, as is the shape for which results are presented.

Linear elastic, as well as non-linear {elastic / collapsing and elastic/collapsing/densifying} solids more characteristic of foam were considered. The linear case represents a foam which is stiff enough that it never collapses. The elastic/collapsing case represents a situation in which the foam bears sufficient load to enter the collapsing phase, but does not deflect enough to enter the densification phase. The elastic/collapsing/densifying case is most representative of our experimental results, modeling a situation where the leading edge of the solid moves far enough into the foam to generate loads in excess of the load at the upper limit of the collapse plateau. For simplicity, the elastic spring constant (K) of the solid is taken to be 1.0, and the collapsing region is assumed to have a spring constant of 0.0. The experimental data for foam subject to low speed correlates well with these nominal K values; the spring rate for the collapse region of compression is much, much less than the spring rate for the elastic regions. A depth of penetration into the solid elastomer of 60% of the buttock height is assumed in the linear case. For the non-linear cases, energy is conserved such that the total potential energy (due to compression) of the solid is equal to that of the linear case.

Various Buttock simulation curves



Buttock Form For Which Simulation Results Are Presented

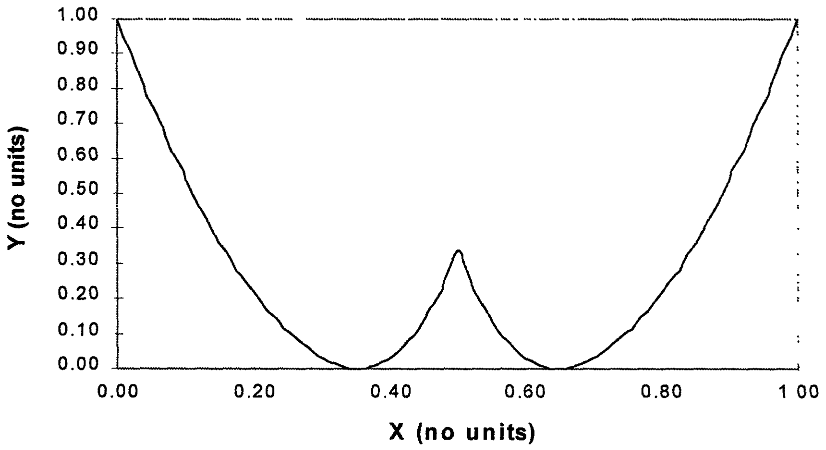


Figure 34

Simulation Results:

Elastic/Collapsing cases

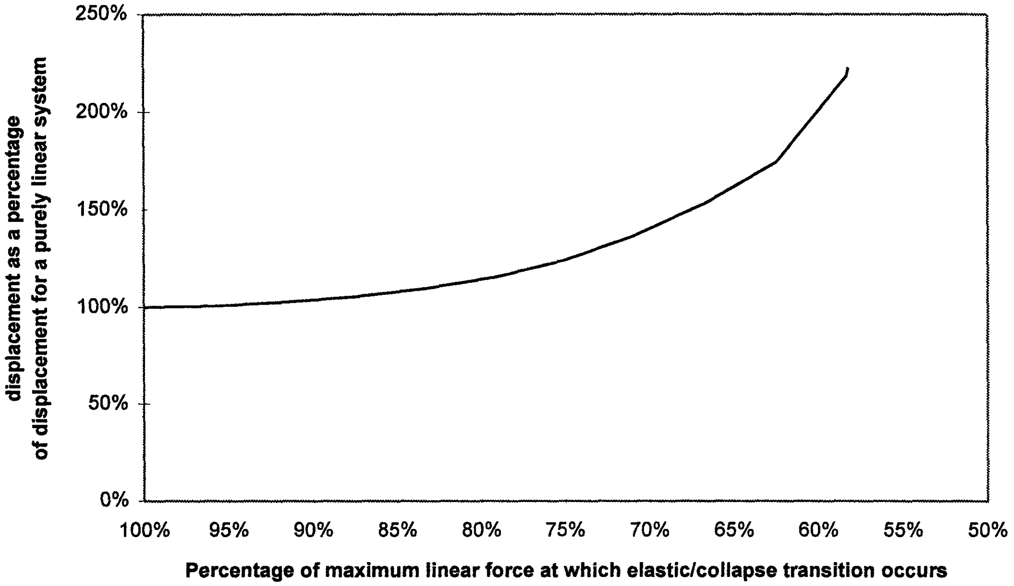
In these cases the elastomer's spring characteristics are assumed to have no densification phase. The transition from elastic to collapse is specified by the percentage of the maximum force in the linear case at which it is placed.

Figure 35 shows the displacement of the simulated buttock as a function of the force level at which the elastomer enters its "collapse" phase. The force level is specified as a percentage of the maximum force exerted in the linear case . The displacement increases as a second order effect; for systems where the transition from elastic to collapse of the non-linear elasticity curve is placed at less than about 75% of the maximum linear force the displacement becomes quite large, tending towards infinite displacement for lower values, and implying that the results of the simulation are invalid for such regimes. Figure 36 shows the applied force as a function of location on the simulated buttock by the elastomer for a variety of elastic/collapsing distributions.

Elastic/Collapsing/Densifying Cases:

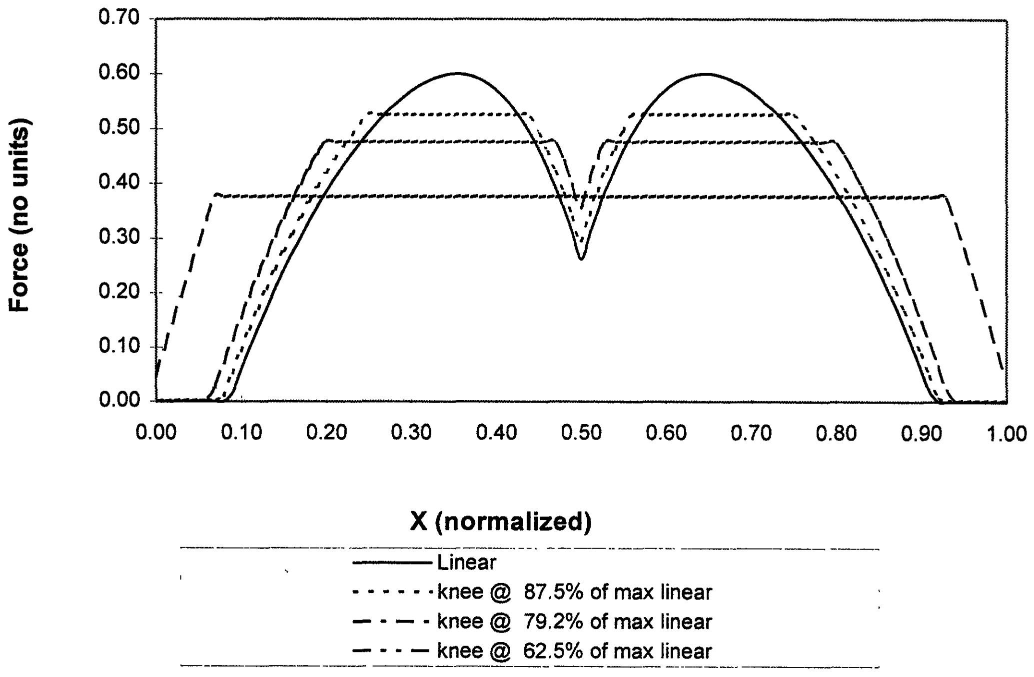
In these cases the elastomer's spring characteristics are assumed exhibit all three phases of a typical foam (linear elastic, collapse, densification). The transition from elastic to collapse is specified by the percentage of the maximum force in the linear case at which it occurs, and the transition from collapse to densification is somewhat arbitrarily placed at the first plus 25% of maximum force in the linear case. For example, if the first transition is set at 80% of the maximum force in the linear case, the second transition occurs at 105% of the maximum force in the linear case.

Figure 37 shows the displacement, maximum force and median force on the simulated buttock for the elastic/collapse/densification case as a function of the placement of the first transition. As the elastic/collapse transition is placed at lower and lower levels, the displacement increases considerably more slowly than in the elastic/collapse cases shown in Figure 35. Also, as the transition point from elastic to collapse behavior occurs at lower levels of applied force, the maximum force on the buttock diminishes for a while, and then begins to increase again.



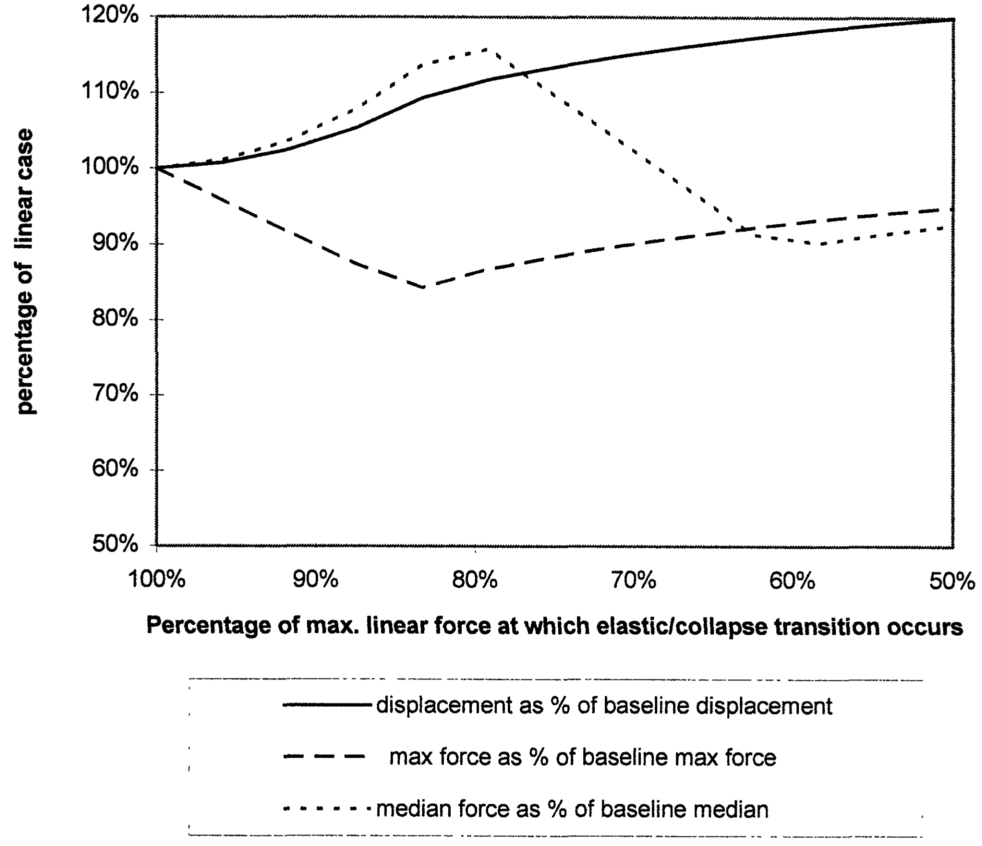
Effect of Shifting the Elastic/Collapse Transition Point
on Displacement of a Simulated Buttock
Resting on a Non-linear (elastic/collapsing) Elastomer

Figure 35



Interface Force as F(x) for Simulated Buttock
Resting on a Non-linear (elastic/collapsing) Elastomeric Solid

Figure 36



Effect of Shifting the Elastic/Collapse Transition Point
on Interface Force and Displacement of a Simulated Buttock
Resting on a Non-linear (elastic/collapsing/densifying) Elastomer

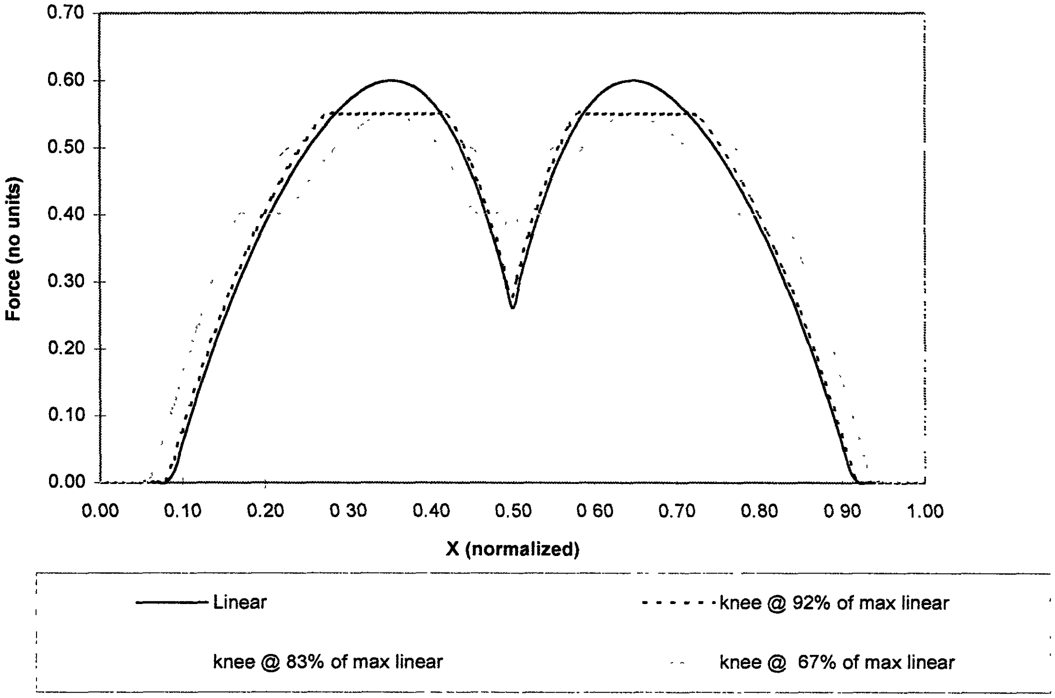
Figure 37

force seen in the linear case. For this particular set of force/displacement curves the maximum force curve reaches its minimum at about 85% of the maximum force for the purely linear elastic case. Lower maximum forces can be reached by assuming elasticity distributions with a longer collapse plateau.

Figure 38 shows the force applied on the simulated buttock by the elastic/collapsing/densifying elastomer. The force distribution does not spread nearly as broadly as it does it the elastic/collapsing case (Figure 36). Further, the distinctive lower pressure in the cleft of the buttock remains below that of the peaks, rather than flattening out as it did in the elastic/collapsing case. The maximum force on the buttock is minimized just at the point where the second elastic region is entered; this can be seen in the slight hump in the center of the buttock for the 83% case.

Value of simulation for future design iterations:

The simulation shows that placement of the two transitions of the elasticity curve will be significant parameters in the selection of the open cell foam for future design iterations. We know from the experimental work that the cushion must be stiff enough that the subject does not "bottom out" -- essentially this can be translated into a requirement that the foam's transition from elastic to collapse should occur above the average pressure on the contact plane. Further, for the effect of the cushion on the pressure distribution to be significant, the length of the collapse plateau of the foam must be a significant percentage of the displacement at which the foam begins to collapse. With some further development, even this simple analytic model of the cushion system will be a valuable design tool.



Interface Force as F(x) for Simulated Buttock
Resting on a Non-linear (elastic/collapsing/densifying) Elastomeric Solid

Figure 38

Summary

Technology which appears likely to enable significantly improved wheelchair cushions has been developed. By varying the air pressure within a volume of open cell foam, the mechanical pressure required for the foam to move from linear elastic behavior into its collapse phase can be controlled. This allows development of a device which constrains the maximum pressure at the contact plane between a cushion and its user, as well as moving the pressure distribution to a lower range; consequently diminishing the pressure gradients at the interface.

Laboratory tests have been completed, a prototype has been constructed, and initial tests of the prototype have been completed. A simple 2d simulation of the system for design analysis has been constructed. Development work is ongoing. The technology may also be relevant to the more general question of seating comfort, if a relationship between pressure distribution and comfort can be established. At this time, this relationship seems reasonable but has not been experimentally verified.

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