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The Experimental Design of a Mobile Pressure Suit

An important objective in the development of a pressure suit for a human being is to permit the wearer full mobility, whether pressurized or not, without interfering with physical capability. Although the human skin is stretched during body motion, there is virtually no stretch along certain lines, here called "lines of nonextension." This fact was utilized as the design basis for a series of experimental pressure suits that were developed to demonstrate that it was possible to achieve natural mobility and minimal ballooning in such suits. The detailed program of investigation pursued during the phase of study being reported on was: (1) to map out these lines of nonextension; (2) to test whether string elements of high elastic modulus, a connected network, could be laid along these lines of nonextension without resulting in any constraint to mobility; (3) to obtain a highly mobile pressure-retaining layer to be constrained by the net; and (4) to construct and demonstrate an entire pressure-retaining garment system that makes use of all necessary layers and string elements in a completely connected netted covering for the body with minimal constraint to mobility at pressures up to 5 psi. The technique, result, and collateral observations relevant to each of these phases are described. A mobile, pressure-retaining garment was developed by building each structural, functional layer into the composite garment in accordance with the basic design theory.

Introduction

A full pressure suit must contain high internal pressure when worn in a low pressure environment. A layer of rubber or rubber-like material is generally used to contain a pressurized gas. However, in a low pressure environment, this pressure retaining layer balloons out or becomes rigid if confined, and interferes with the movements of body joints. The problem is to contain the pressure retaining layer, prevent ballooning, and yet permit unhampered movements of all parts of the body.

This study tests the applicability of a certain set of ideas to the engineering design problem of building a pressure suit that permits full body mobility while pressurized or not.

The following description is a brief summary of these ideas.

Since the human body tends to retain its form, taking no appreciable "set" after ordinary body deformations, its behavior is expected to conform to the laws of physical elasticity. Deformations in an elastic body are described by the strain ellipsoid, in which a small sphere of material deforms to nearly ellipsoidal shape under elastic deformation of the entire body. On the surface of such an elastic body, the projected deformations transform a small circle into an ellipse. Since all points on the ellipse are derived from points on the undeformed circle, in general, there may be two diameters in the ellipse that are not stretched. (They may be noted by superimposing the original circle on the deformed ellipse.) An extension and connection of these radial directions may be referred to as a mapping of the surface of the elastic body by "lines of nonextension." Such a theory is expected to be applicable to the surface of the human body. If so, high strength strands of material may be laid along these directions and joined at their interstices for free-rotation capability. These strands can then carry loads developed by the pressure forces transmitted against the strands, without interfering with mobile deformations of the body.

A more complete discussion of the background theory and its application to full pressure suit mobility is found in reports by Iberall [1, 2, 3].[2]

In brief form, the suit design theory is based on the following:

1 The work done in an arbitrary deformation of a wearer encased in a close fitting pressurized container can be written as

$$\Delta W = \Delta W_p + \Delta W_e$$

where ΔW = incremental work done in an arbitrary body deformation, ΔW_p = incremental work done against pressure

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[2] Numbers in brackets designate References at end of paper.

(i.e., pumping work), and ΔW_e = incremental work done against elastic forces in the containing shell.

To minimize this work, for all arbitrary deformations, each right-hand term must independently vanish,

$$\Delta W_p = 0$$

$$\Delta W_e = 0$$

2 $$\Delta W_p = \int_{v_1}^{2} p dv$$

where p = gauge pressure within the space; dv = volume change between shell and body in a body deformation.

To minimize this, p should be a constant, the minimum desired internal pressure p_0. Therefore the pressurizing source should be a sufficiently large reservoir, or a large flow capacity pressure source with good distribution around the body. Thus the pressure work can be reduced to

$$\Delta W_p = p_0 \int_{v_1}^{v_2} dv$$

$p_0 \neq 0$ (i.e., it is prescribed)

However,

$$dv = SdA$$

where S = separation of shell and body, and dA = surface area of body.

The change in area dA is characteristic of the body deformation, not of the suit. Thus in order to minimize this work, the separation S should be bounded to a maximum value S_0.

$$\Delta W_p = p_0 S_0 \int_{A_1}^{A_2} dA$$

and in fact we should try to reduce S_0 to zero or as close to zero as possible. Therefore a mobile pressure suit must be close fitting.

3 $$\Delta W_e = \Delta W_b + \Delta W_s$$

where ΔW_b = work done in bending elements of the shell, and ΔW_s = work done in stretching elements of the shell.

Again, because of the arbitrary nature of body deformations, the right-hand terms must independently vanish.

$$\Delta W_b = 0$$

$$\Delta W_s = 0$$

4 $$\Delta W_b \alpha (EI)^{-1} \alpha (Et^2)^{-1}$$

i.e., bending forces are inversely proportional to the plate modulus, which is proportional to the product of Young's modulus E and the square of the section thickness t (i.e., the stiffer the section, the less work done). However, the hoop and longitudinal stresses are inversely proportional to the product of the modulus and thickness. For a given permissible stress, Et is specified, but Et^2 must be minimized. Thus E is to be made small. This means that the elastic shell must be designed in the "membrane" region, rather than the "plate" region.

Therefore a mobile pressure suit must be made of low modulus material.

Practically this means that one chooses textile fiber moduli rather than metallic moduli (e.g., shirt material is chosen to have little bending resistance).

5 The heart of the problem is the design for low stretch work. The difficulty may be expressed in the following paradox. For a given volume of shell material, stretch work is proportional to the strain energy, i.e., the product of half of the maximum stress and strain.

$$\Delta E = \frac{1}{2} \sigma \epsilon$$

where ΔE = strain energy per unit volume, σ = stress, and ϵ = strain.

Express this first in terms of strain and then stress

$$\Delta E = \frac{1}{2} \frac{\sigma}{\epsilon} \epsilon^2 = \frac{1}{2} E \epsilon^2$$

$$\Delta E = \frac{1}{2} \sigma^2 \frac{\epsilon}{\sigma} = \frac{1}{2} \frac{\sigma^2}{E}$$

If the deflection for various arbitrary body deformations is prescribed, then the strain is prescribed. If the work is to approach zero, a low modulus material is required.

On the other hand, if the pressure is prescribed, then the load and thus the stress is prescribed. If the work is to approach zero, a high modulus material is required. However, it is impossible to make a homogeneous isotropic shell (or membrane) that simultaneously has zero and infinite modulus. Therefore there is no solution—in a homogeneous isotropic sheet.

The horns of the dilemma can be separated if it is realized that strain and deflection are only associated in a homogeneous isotropic material. Thus we must seek elsewhere for a solution.

6 Let us proceed as follows: Consider an elementary area of a thin shell (we have already ascertained that a thin shell is required). In particular consider an infinitesimal circle in the undeformed body and let the body and thus the covering shell deform. On the surface the circle will undergo rigid body displacements and rotations (which are irrelevant), a stretching transformation into an ellipse, and a warp of the circle. We are not concerned about warping work since we have already designed the shell for low bending resistance. We are concerned only with stretch work. If the original circle is transformed to the ellipse, then it is clear that in general there will be two diameters in the original circle that haven't stretched, but only rotated. The two-fold extended mapping of such diameters are principal shear lines, here to be called "lines of nonextension." Along these two lines we may lay strands of "infinite modulus" (i.e., there is no stretch). No work is required if the two strands are "pin-jointed" so as to be free to rotate. Thus a mapping by this system of lines permits the use of "infinite modulus" material to carry the load and requires small work in their pin-jointed rotations.

On the other hand, this net surface will not retain pressure and permit the large degree of surface distensibility (i.e., the strains) required. For this a continuous sheet of low modulus material, "rubber," is required. Thus, by this locally nonisotropic solution making use of two layers, the apparent paradoxical requirements for mobility under pressure can be reconciled.

7 However, these two layers will not solve the complete design problem of a pressure suit which must satisfy many additional functional requirements. If we restrict our attention to the immediate pressure suit, disregarding the life support systems which act as a supply source, we can outline the suit requirements. Minimum requirements may be expressed as functions to be provided by a series of layers. (What represents any "practical" integration of layers is a matter for considerable study in real production prototype design, as compared with the presently described experimental design.) Such functions and layers include: (a) mobility under the constraint of a *load-bearing layer;* (b) mobility under the constraint of a *pressure-retaining layer;* (c) a *thermal exchange and pressure-equalizing vent layer;* (d) *longitudinal retention layer* (load bearing may not eliminate all longitudinal elongations); (e) terminal coverings—helmets, gloves, shoes; (f) any remaining accessories—e.g., underwear layer, slip layers, covering layers, air supplies.

Other elements would be part of a life support pack, which is

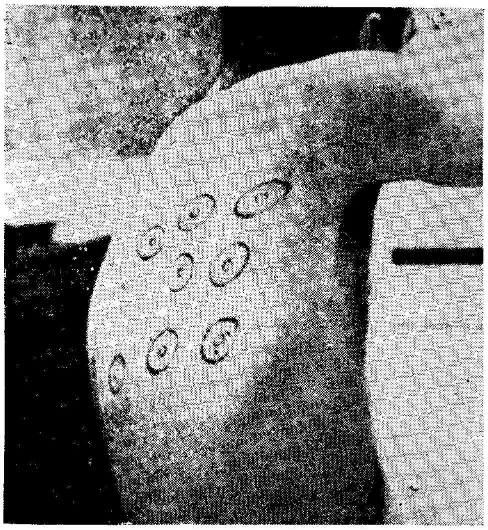

Fig. 1 Distortions of a circle of the skin to near-elliptical form

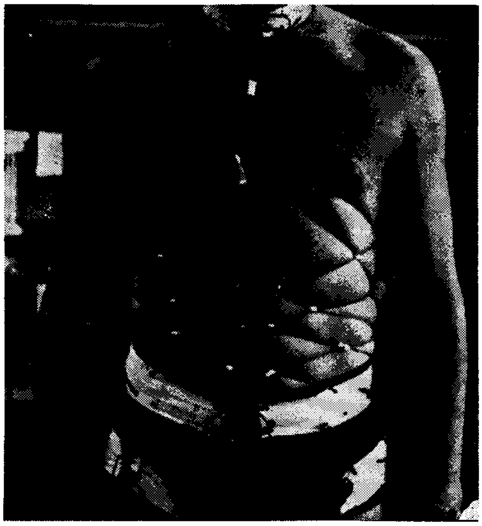

Fig. 3 Checking the system of lines of nonextension by inextensible "strings"

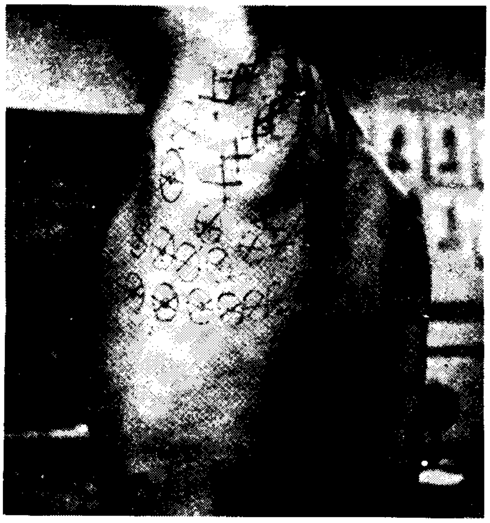

Fig. 2 Development of a family of lines of nonextension from the unchanging radii of the deformation ellipses

beyond our present scope.

In the remainder of this paper, we will cover the design solutions that we have used in the past for these various component layers.

Experimental Investigation

Mapping of Lines of Nonextension. Lines of nonextension on the body were determined as follows: A 1-in. ink circle was stamped at a particular location on the subject's skin. He was then asked to move (deform the skin of) that body region. A small circle on a body surface during an elastic displacement will deform into an ellipse. This is the result for body deformations, as illustrated in Fig. 1. Thus the assumption of small strain is satisfactory.

The two unstretched diameters of the circle provide a mapping of a two-fold family of directions, along which no extension has taken place at that point on the body. By continued point-to-point mapping on the body, a completely connected network of directions can be found which forms a system of lines of nonextension of the body for that particular deformation. The body, however, is articulated internally, with its softer elastic parts mounted on an essentially rigid skeletal frame. Experimental study of the intrinsically limited motion at each joint verifies that this system of lines of nonextension will be essentially the same for all deformations. Thus, in practice, the lines of nonextension are mapped by seeking extreme deformation positions for each point of the body, so that the circle will be stamped in a position in which length on the skin is most foreshortened in some direction, and the ellipse will be noted in another position in which the skin is most elongated in some other direction. The lines of nonextension thus determined from such extremes will then be found essentially valid for any intermediate deformations.

How an entire network of such lines of nonextension is generated from the deformation ellipses is illustrated in Fig. 2.

Such a system has been carried from region to region all over the body. There are a few moderate defects in the developing scheme. First, as lines are extended farther and farther along the mapping field, small errors in direction accumulate so that one cannot be certain how much he has strayed from the particular line of nonextension that he may be following. Second, there are lines in critical regions with a very small angle of separation. Both cases lead to divergence between a true line of nonextension and the experimental estimated line. (The errors are not at a given point, but are propagated as one follows a line of nonextension farther and farther away from a given point.) To refine the estimates, one major technique that was used, a technique that fits an operational definition of what a line of nonextension is supposed to be, was to trace the line with an inextensible "string" to demonstrate, in fact, that no essential extension existed along the experimental lines. Such strings were then used to refine the longer-range extrapolations. See Fig. 3.

These data, acquired region by region from a test subject, were transferred to a sizing manikin. The sizing manikin is a three-dimensional embodiment of dimensions for the medium regular size of the USAF height-weight sizing system. The system of lines thus developed is shown in Figs. 4 and 5 for the upper and lower parts of the body.

This final mapping placed on the anthropometric manikin was obtained by transfer from three human subjects. Their heights and weights varied over a fairly wide range, being 65, $68^{1}/_{2}$, $70^{1}/_{2}$ in., and 150, 160, 180 lb, respectively.

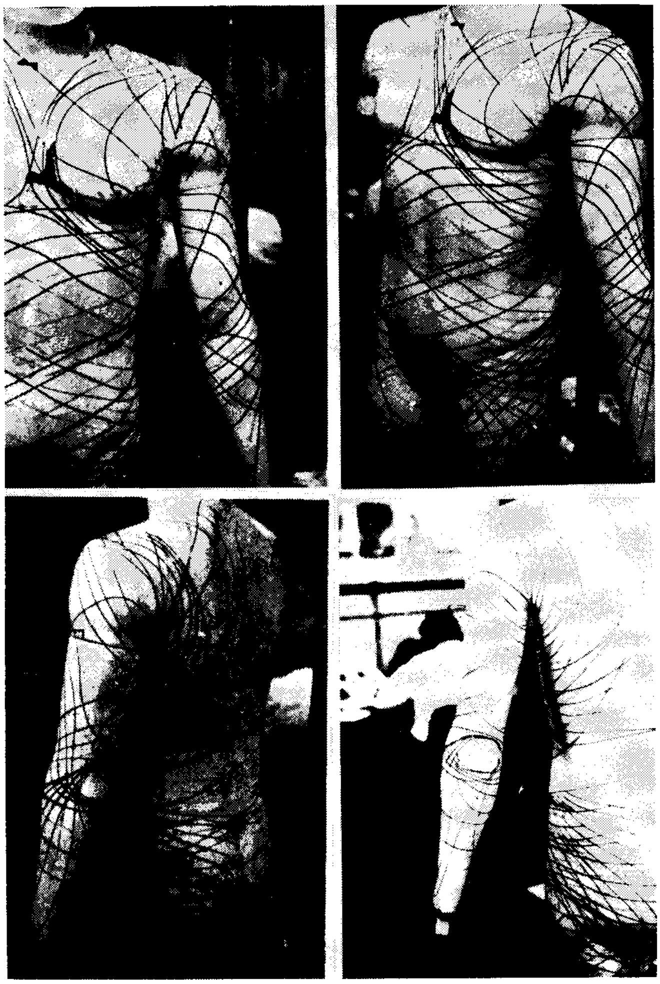

Fig. 4 Lines of nonextension for the upper part of the body

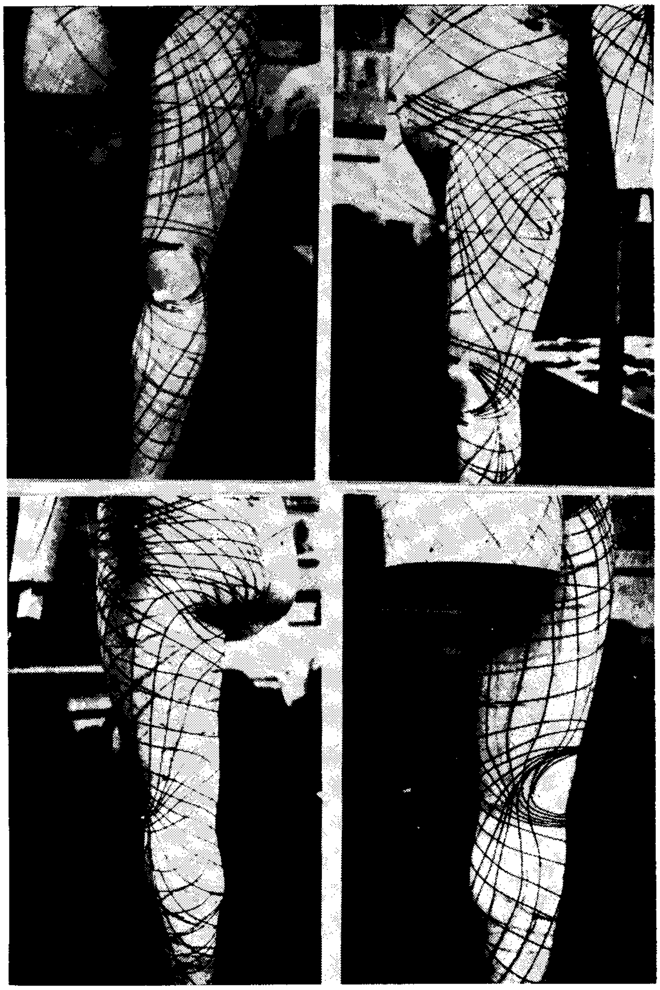

Fig. 5 Lines of nonextension for the lower part of the body

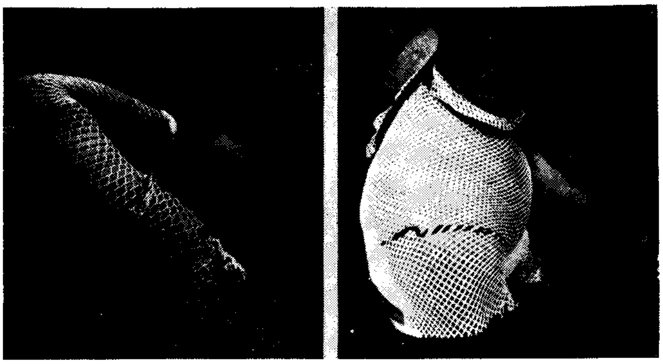

Fig. 6 Two stages in the transfer of lines of nonextension to a homoform covering of the body with inextensible netting materials

Development of a Load-Bearing Net Layer. The problem of developing a pressure-retaining, form-fitting garment that reflects these lines of nonextension can best be understood by reference to Fig. 6. This figure depicts an experimental mapping of lines of nonextension with inextensible netted material at two different stages of fitting. The one on the left is illustrative of a preliminary fitting stage, in which a rather coarse mesh of no great strength is used to outline the garment patterns. The one on the right shows a more advanced fitting stage, in which a closer mesh of appropriate high-strength Daçron netting material is used.

The material chosen for the load-bearing layer of net for the demonstration pressure suit is a woven Dacron net with four squares (diamonds) to the inch. The individual diamond strands consist of 5000-denier, high-strength, heat-stretched Dacron. Each strand has a breaking strength in the range of 50 to 100 lbs.

By laying this material on the sizing manikin so that it conformed with the lines of nonextension, patterns were developed which tended to follow the lines of nonextension in every region. While one might visualize the need for a perfect conformity with the lines to prevent any wrinkling or constraint during motion, investigation revealed that only a reasonable approximation to the lines is necessary to permit ample mobility. The novel aspect of this particular development phase was that the patterns could be developed fully on the dummy without recourse to a human subject. In the past, only approximations for netting each joint were available. Now, with data recorded on a sizing manikin (Figs. 4, 5), data from the full body surface are available for patterning.

In removing the patterns from the manikin and transferring them to a human subject, they needed only to be taken up at their borders to meet the more specific sizing need of the particular subject. Such a garment in an intermediate state of construction is shown in Fig. 7.

The generality of the solution was illustrated by transferring

Fig. 7 Net load-bearing layer transferred from manikin to human

Fig. 9 Rubber suit covered by a leotard for protection and to perform as a slip layer

Fig. 8 Two-piece form-fitting rubber suit

such garments to all three subjects, who found themselves capable of the same general body mobility, although with some differences in general garment conformity. Anticipating questions about sizing, it is our opinion that the general enclosed body volume will show much less variation from person to person than size or height variations may suggest, and that the major differences between sizes may be those involving arm and leg segment lengths. The few experiments conducted with this general suit design have supported this opinion.

Although still pictures cannot depict the quality of response in this type of covering, one may summarize the statements of those who have worn the various examples of net suit. The garment leaves the wearer with a sense of its presence at all times, even under pressure, but without any noticeable constraint to any body movement, and with no bunching of the material. The garment feels like a second skin that conforms to the body and that deforms naturally with the body. Even though the material is nonextensible, the garment feels like a stretchy garment that completely conforms to the body by stretching and shrinking without wrinkling. The difference between the two garments is that the lines-of-nonextension garment, made of inextensible materials, can carry high surface stresses in the plane of the netting.

It is this property of permitting deformation while carrying a high load, that is, the load developed by the internal pressure applied to a pressure-retaining layer, that makes this solution unique and suitable for development in a pressure suit.

Development of a Pressure-Retaining Rubber Layer. While the net material can carry load and can permit mobility, it cannot retain air under pressure. For this, an impervious but very stretchy layer is needed. If one wishes to explore the degree of stretchiness that is required to permit complete body mobility in a conformal covering, one may cover the entire body with an elastomeric material and vary the thickness to find out the point at which a wearer considers the burden undesirable. The material property that governs the loading is the product of the tensile modulus and thickness of material.

For latex rubber, a thickness of 0.002 in. is almost unnoticeable, 0.005 in. is quite comfortable, 0.010 in. acceptable, 0.015 in. tolerable, and 0.025 in. is uncomfortable. This may be summarized (as a satisfactory range for the pertinent material property) by the spring rate, i.e., the stretching force necessary to double the length of a 1-in-wide strip of material. Assuming an elastic modulus for rubber of about 100 psi, these rubber thicknesses correspond to spring rates or stretch forces of 0.2, 0.5, 1, 1.5, and 2.5 lbs, respectively. Thus we believe that it is comfortable to tug material covering the body when the resisting forces are about 0.5 to 1.5 lbs per in. of width per 100 percent elongation. To provide a frame of reference, such rubber suits are similar to the restraint offered by a pair of dancer's leotards,

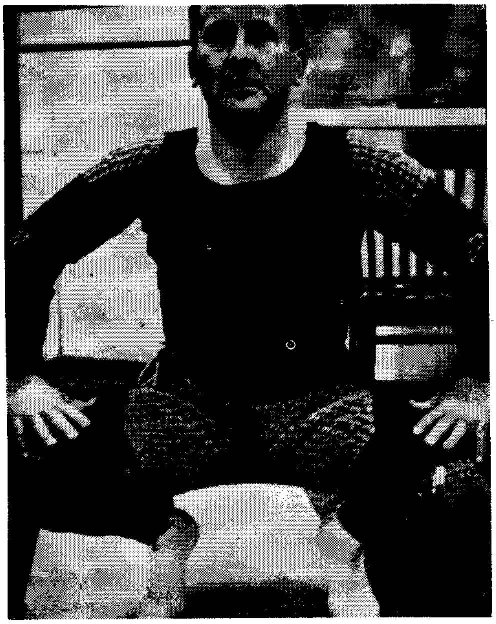

Fig. 10 Vent suit made from an industrial spacer material

being quite comparable with the thinner suits and perhaps twice as resistant with the thicker suits.

Rubber suits of about 0.012-in. thickness were obtained and used in the course of this development. They were made by being dipped on a full human form. Fig. 8 shows an example of such a suit.

The suit is dipped in four pieces: a lower section, an upper section, and two arm sections which are then cemented to the upper section.

While a number of brief experimental efforts were made to develop a strong membrane such as a stretchy, highly puckered, or crepe-rubber-coated material that would permit low stretching forces in a single layer of a strong impervious material, no satisfactory answer was found. A 0.012-in. rubber suit with a leotard covering over it was more comfortable and had greater strength than any rubber-fabric combination that could be devised. Since specialized material development was not a major objective of this study, the efforts were discontinued and the thin impervious rubber suit covered with a leotard was chosen for demonstration purposes.

This combination is shown in Fig. 9. A secondary function assigned to this leotard covering is that it should permit a mild slipping action to take up any small lack of conformity that might occur between the skin and the nearly nonslipping net. The leotard carries no load. It simply permits the high-load-bearing net to slip easily over the rubber suit without bunching it. We refer to it as a slip layer or slip suit.

Development of a Vent Layer. The combination of the items of a pressure-retaining layer and a net layer may be satisfactory to provide pressure retention, mobility, and load-bearing under pressure. However, it is not sufficient to provide thermal comfort. There are two requirements posed by a complete and closely conformal covering for a human body: The first is that the pressure should be equalized all over the body during body deformation, and the second is that the suit should be ventilated to remove heat. Both an air heat-exchanger and a liquid heat-exchanger were explored and developed in 1950. An air heat-exchanger was used in the 1958 development. In the latter development, an Air Force ventilating suit was made available and modified for the purpose.

In order not to limit the aims of this investigation by the use of available vent suits, the construction of a simple compatible vent suit was undertaken.

A line of development was pursued to further demonstrate the value of the concept of lines of nonextension. This concept could be used to guide the development of a conformal spacing garment, even if it were fairly rigid as a spacer, if the construction material had the net-like property of rotation of its "diamonds" at the interstices. A porous or fibrous spacer material could thus be used to construct the vent garment.

A vent suit utilizing such material with a dimpled form is shown in Fig. 10. It has been found that reasonably adequate conformity to the lines of nonextension can be produced in such materials with very few pattern pieces, that the garment is quite mobile, that the material can stand up under considerable abuse, that it has performed its pressure-equalizing function well, and that it has demonstrated some unexpected but useful heat-exchange properties.

The vent garment is worn over a leotard underwear layer. The underwear layer is necessary to hold perspiration and to prevent body chafing. The rubber suit is worn over the vent suit. The second leotard is worn over the rubber suit as a rubber-protecting layer and as a slip layer. (In all, five layers have been thus far identified—underwear, vent layer, rubber suit, slip suit, and load-bearing net layer.)

It was found that, even though unvented at room temperature with his head uncovered, the subject remained comfortable for periods up to 5 hr in the vent and rubber suits. When the rubber suit was removed, there was considerable water in the porous layer and condensed on the inside surface of the rubber. However, the leotard underneath was essentially dry. On the other hand, small portions of this underwear not covered by the vent suit were quite wet. Apparently this vent layer sets up a strong convection in the nonhomogeneous microatmosphere from the skin to the rubber suit, with condensation of moisture on the outermost, cooler layer. When ventilated, all body surfaces remained essentially dry.

As a spacer to provide air distribution, the material served well. Concentrations of body weight in small areas, as in sitting, and extreme flexion of body segments such as the knees and elbows did not pinch off any segment of the distribution system.

To insure a scrupulously valid demonstration of suit mobility, it was essential to guarantee, experimentally, that there was little pressure change around the body during body movement. Thus an external distribution system of a number of 3/8-in-ID tubes connected into the rubber suit were used to equalize the pressure. These were attached to openings at the chest, ankles, wrists, and in the helmet. The pressure variation around the body for extreme body movements is estimated to be no more than 2 to 5 in. of water.

Development of a Longitudinal Restraint Layer. The combination of a pressure-retaining layer, a net layer, and a venting layer may permit mobility, thermal comfort, and uniformity of pressure in a pressure suit, both inflated and uninflated; but when pressurized, the suit will still show the defect of an unacceptable longitudinal extension. The background of ideas involved in solving this problem is significant.

Although the use of the lines of nonextension permits mobility while providing a mechanism for carrying loads, not all of the load-bearing capability is available to keep a local patch of netting close to the patch of skin to which it is supposed to conform. The technical background of this problem has been discussed in reference [2].

The particular difficulties include the possibility of bulging of elliptical to circular cross sections which moves the patch away from the skin, and a possibility of "elongation" which moves the patch along the body axis. Circumferential extension is not a problem. (Nonstretching strings following the lines of nonextension insure that there will be no circumferential extension.)

Thus in the early 1950 development (reference [1]) these difficulties were explored by the following two techniques (the

Fig. 11 Longitudinal constraint layer over the chest and pelvis, connected by a slip net

difficulties were not completely understood at that time): If an all-net suit bulges, it may be restrained in regions between joints—regions in which only limited deformation capability exists. (Note that the skeletal structure in humans lends assurance that many regions of the body act like rigid bodies.) A leather-like restraint was used first. It did not appear to be adequate to restrain the bulging at that time. Therefore rigid sections were tried instead. They eliminated the bulging problem and lessened most of the longitudinal extension problem. However, an extension of perhaps 1 to 2 in. remained in the overall 70-in. length.

The possibility of transmitting loads using easily constructible nets other than those following lines of nonextension was also explored. Several types of net had been investigated (reference [1]). Besides nonslip knotted netting that followed the lines of nonextension, other mapping nets developed were "slip" nets, which take advantage of the ability to map curved surfaces with ruled line elements (such properties lie within the field of topology) to permit certain prescribed motions; namely, to provide bending freedom, or rotational freedom or torsional freedom at a joint by some nets of a nonknotted form; and some examples of nets that permit substantial increase of area during deformation.[3] The latter may be useful on limited body surfaces in which the deformation ellipse is larger than the undeformed circle. However, the choice of the net type during various suit demonstrations was always a matter of convenience and has been in flux. For example, besides the original models built at the National Bureau of Standards, an experimental demonstration net suit was built by the author and colleagues at the David Clark Corporation in 1951. Another development was started at the Molded Insulation Products Company in the same year.

In the 1958 development (reference [2]), the investigation started with the type of rigid restraints previously used, and approximate lines of nonextension nets at the joints. It became quite clear at that time that longitudinal restraint was probably a more serious problem than bulging. To limit the longitudinal elongation to perhaps 1 in. at 5 psi, for the major lengths from the mid-chest outward to the extremities, an inordinately tight lacing had to be used in the nets. The true source of this elongation was not really understood. It was not proportional to pressure as one might expect of an elastic stretch.

The rigid longitudinal restraint was modified to a cloth-like constraint to determine if bulging really was a problem, and a multiplicity of net layers, four altogether, was used to determine if net yield was a problem. Bulging was of little concern in mobility, but there was no intrinsic reduction in elongation. It was clear that the elongation took place with the initial application of pressure load, and then remained essentially unchanged. It was also clear, however, that complete mobility required utilizing the whole system of lines of nonextension rather than portions in limited regions. Thus in a second modification there was time only to quickly make a net suit based on an approximation, using only a two-piece, front-and-back pattern. In modification we again used rigid parts for an independent longitudinal constraint. There was time, however, to relax the rigid constraint in the chest. Finally, the concept of the last necessary major element for suits emerged.

The lines of nonextension generally form a much shallower angle with the plane perpendicular to the longitudinal body axis than does a string element that will support the circumferential stresses and the longitudinal forces. The equilibrium angle for a net restraining a pressurized cylinder is about 35 deg. This reflects the two-to-one ratio between hoop stresses and longitudinal stresses in a cylinder. The lines of nonextension tend more toward 25 deg. Thus if the total pressure suit enclosure is pressurized, the forces tend to try to rotate a near-25-deg angle out to near 35 deg. This is the source of elongation. (See reference [2].) If the lines of nonextension are laced on a nearly rigid body (such as an articulated doll), the elongation can be prevented by tight lacing. It was this type of solution that had reduced the longitudinal elongation in some of the previous efforts. Once the problem was understood, a relatively simple solution offered itself: Confine the body, not by a single net layer that either follows the lines of nonextension in a nonslip knotted net or by a restraining slip net, but by a combination of both. The lines of nonextension permit mobility and provide, in the main, the circumferential load bearing and some of the longitudinal load bearing. The longitudinal restraining slip-net provides the longitudinal load bearing without limiting the large joint mobility that it is designed to retain.

Thus in the second modification in 1958 (reference [2]), longitudinal constraint consisted of a cloth-like chest covering, rigid coverings over the pelvis, thighs, legs, upper arms, forearms, and head, with slip-net lacing between pants and vest sections, pants and thigh sections, and chest and upper arm sections. This longitudinal restraint layer was applied over, and independently of, an underlying lines-of-nonextension net suit.

In the development phase being described, it was possible to design a net suit rationally by approximating a complete set of lines of nonextension, rather than by improvisations. The advantages emerged in the rationality and ease of patterning a net suit and in searching out any pattern improvements that were needed when minor mobility defects made themselves evident. Patterning errors in the net suit did not become evident until the entire garment was assembled and ready for pressurization.

It was now possible to relax the covering requirements for longitudinal restraint to what appeared to be a minimal constraint. Thus for this phase of study it was decided to try a cloth restraint over only the chest and pelvis, with a slip-net connecting the two.

The construction of this layer is shown in Fig. 11.

To understand the support system, note that the underlying net system takes the circumferential loads, and the slip-net system consisting of a lacing of slipping strings arrayed nominally

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[3] A slip net consisting of running loops was used around the neck and the waist in 1950. Further exposition will be found in references [1] and [2].

Fig. 12(a) Determining the cone of freedom of a rigid helmet

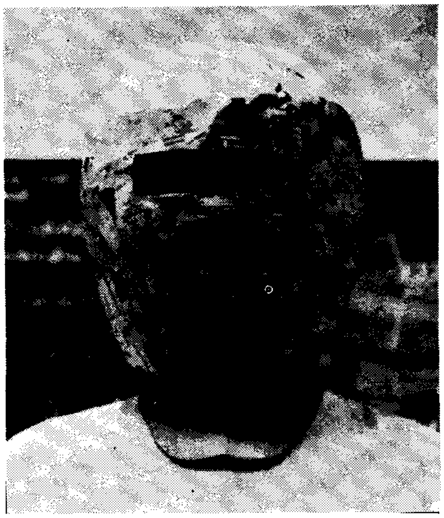

Fig. 12(b) Forming the helmet shape

Fig. 12(c) Providing helmet holddown by longitudinal restraint layer

Fig. 12 Three phases in the development of a rigid helmet

at 45 deg to the longitudinal axis permits complete waist mobility but prevents longitudinal extension.

The defect in this slip layer is that extensive research indicated no combination of material and form that would prevent the slipping strands from sawing on each other. In the experimental suit being described, the problem was minimized by redundancy of strands. However, frictional resistance piles up. We have stressed in each phase (references [1] and [2]) that a specialized antifriction bearing (e.g., roller bearings) would have to be developed to minimize these destructive forces. In the main these bearings are needed only at the two borders of cloth vest and cloth pants.

Development of a Rigid Helmet. To avoid compromising a demonstration of shoulder mobility, but yet permitting a slip-on helmet, a new fixed rigid helmet form was developed. (Earlier developments had used both conformal and fish bowl helmet forms.) The helmet permits some reasonable head mobility inside the helmet, yet does not interfere excessively with shoulder motion. Note, however, that full mobility of head and shoulder can be provided by using the lines of nonextension over the neck. If one has objection to neck constraints, however, some loss in mobility would have to be accepted in either the head or the shoulder by the use of a fixed helmet.

The design philosophy used in the helmet is shown in Fig. 12. It is based on the concept of allowing a reasonable division of the external space between head and shoulder for the mobility requirements of each. The helmet, which fixedly divides the space available to the head and acts as a stop against raising the shoulder, is designed to permit mobility of the head within the helmet.

A wire-mesh frame attached to a neck support collar permitted designing for a reasonable cone of freedom for the head, within a fixed helmet. This cone, rounded off at the top, was then molded in papier-mache, and then in a fiberglas-polyester shell. No particular refinements were designed into the helmet shell, except to provide visibility for the subject. A simple but quite effective neck seal was designed. (The rubber suit was simply pulled over a pair of rubber O-rings in the rim at the base of the helmet. Another ring was then pulled down over the rubber and into the depression between those on the helmet.) The helmet opening is minimal for a slip-on helmet, having about 7-in. lateral opening, and 9-in. fore and aft opening.

The fastening for the helmet is essentially a tie to the net suit and the holddown of the net suit by the longitudinal restraint layer garment. The tie consists of a net laced around the helmet, which is held in place by two external steel bands. Fig. 12(*c*) shows the rubber suit pulled up over the helmet and shows the uncompleted upper longitudinal restraint. In the final model, the visual opening was enlarged to give the subject greater field of view. Experience has indicated that an essential element in human mobility is that the suit wearer should have an adequate view of his feet.

Accessories. The suit was completed with the following items:

Shoes were simply a pair of high-laced, rugged work shoes.

No special provision existed for any detailed hand solution. Thus a very simple application of the lines of nonextension to the hands was used. Since the number of joints in the hands is considerable, it would take almost as much detailing for an extremely mobile hand as for an entire body. This was impractical within the existing scope and time available. However, since the body of the hand is a relatively flat segment, it is essential that a rigid constraint be used over the palm to prevent bulging.

The degree of detailing that was provided in the gloves was sufficient to permit, even in these relatively undeveloped gloves, good hand mobility. For example, it was possible for the subject to write while pressurized, to handle tools, and to do fairly small coordinated tasks.

The pressure and ventilating supply were only rigged for the purposes of laboratory demonstration. Pressure outlets were

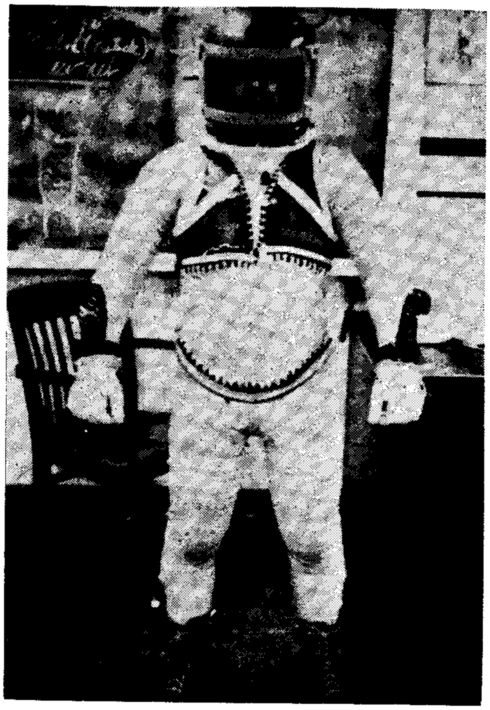

Fig. 13(*a*) Standing erect

Fig. 14(*a*) Standing erect at no pressure

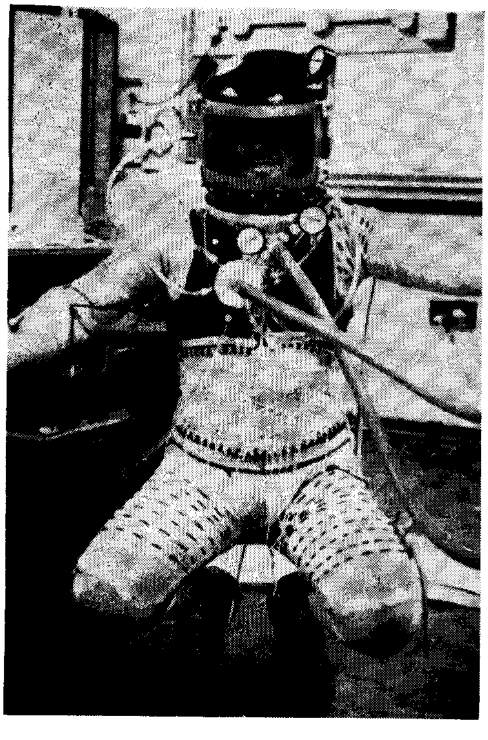

Fig. 13(*b*) Performing deep knee bends

Fig. 13 Subject in an unpressurized suit

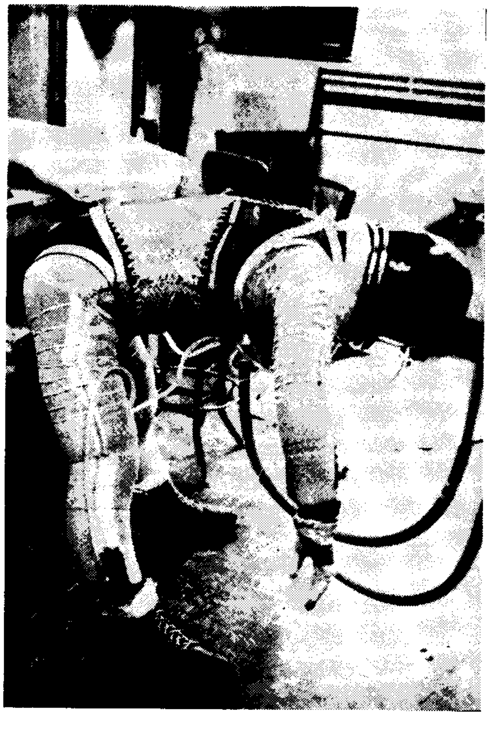

Fig. 14(*b*) Bending at 3 psi

Fig. 14 Subject under pressurized and unpressurized conditions

provided in the rubber suit at the shins and in the forearms. These consisted of internal standoffs to prevent air blockage and of tubes with 5/16-in. ID. A main suit inlet, a tube with 11/16-in. ID, was provided in the chest region. Two 1/8-in. standard pipe outlets were provided in the helmet.

These outlets were interconnected and supplied as follows: A large capacity, two-stage, tank-pressure regulator (inlet, 50 to 2000 psi; outlet, adjustable 0 to 30 psi) supplied breathing quality air through a 3/4-in-ID hose to the main suit inlet. A tee at the suit provided a direct path to one of the helmet

Fig. 15(*a*) Front view

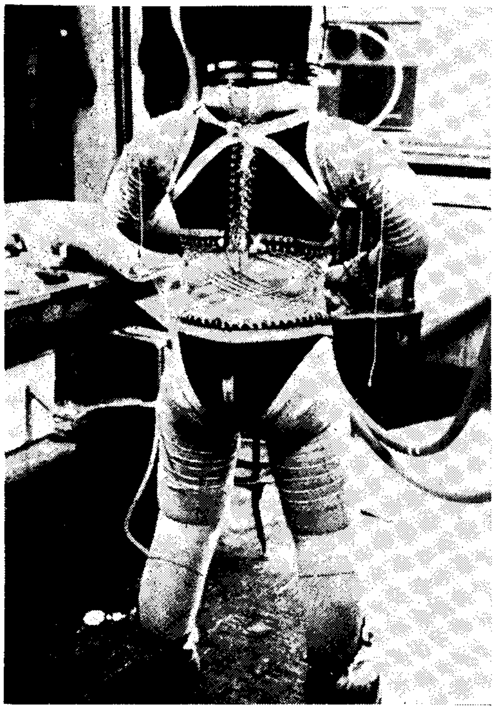

Fig. 15(*b*) Back

Fig. 15 Suit pressurized to 3 psi

Fig. 16(*a*) Pressurized to 3 psi

Fig. 16(*b*) Unpressurized

Fig. 16 Overhead arm capability under pressurized and unpressurized conditions

inlets through a 5/16-in-ID plastic tube. Identical plastic tubes collected vent air from the helmet, the two forearm stations, and the two shin stations. Air was exhausted through a 3/4-in-ID tube to a 3/4-in. valve. Controlling the suit air supply thus consisted of adjusting the pressure regulator to a desired pressure level and adjusting the 3/4-in. exit valve to provide the subject with a desired flow.

Pressure gauges were mounted in the helmet at the outlet and at tee connections at the wrist and shin so that any variation in pressure would be visible to all observers in laboratory demonstrations.

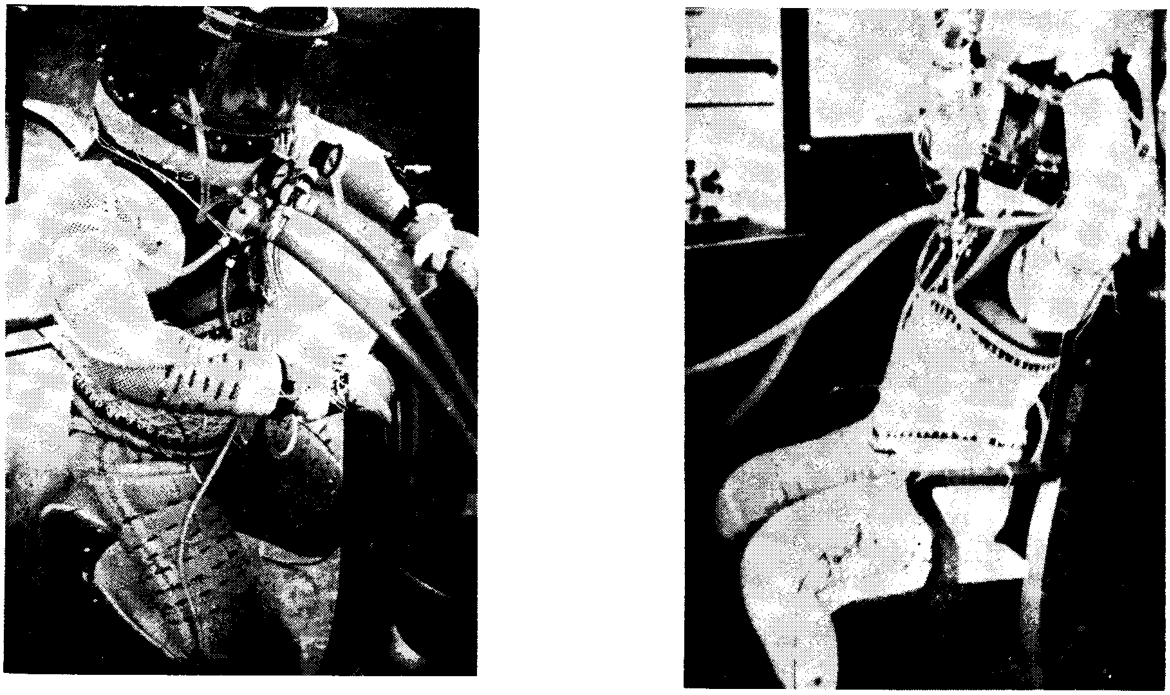

Fig. 17(*a*) Knee bends

Fig. 17(*c*) Sit

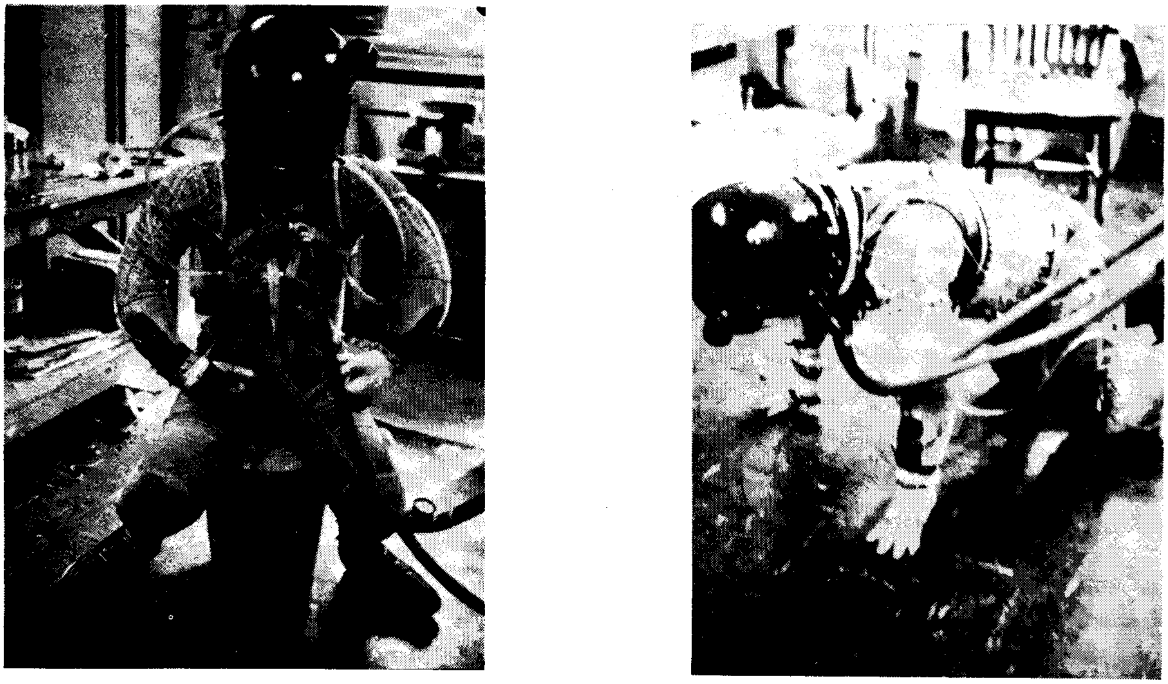

Fig. 17(*b*) Squat

Fig. 17(*d*) Kneel

Fig. 17 Subject performance at 3 psi

Overall Suit Assembly. The general appearance of the entire suit assembly may be noted in a series of photographs included to indicate, as far as is possible in still pictures, the mobility that was achieved by applying these principles. The pictures are examples from the state of development being reported on, taken at random whenever various successful elements were added to the assembly. Viewed as a culmination of the development of ideas from their onset in 1950 and as an example of the seventh such prototype in a series of ten (the tenth hopefully being operational), they indicate that in principle and in practice a pressure suit of great mobility can be developed by the application of physical and anthropological principles. Greater mobility

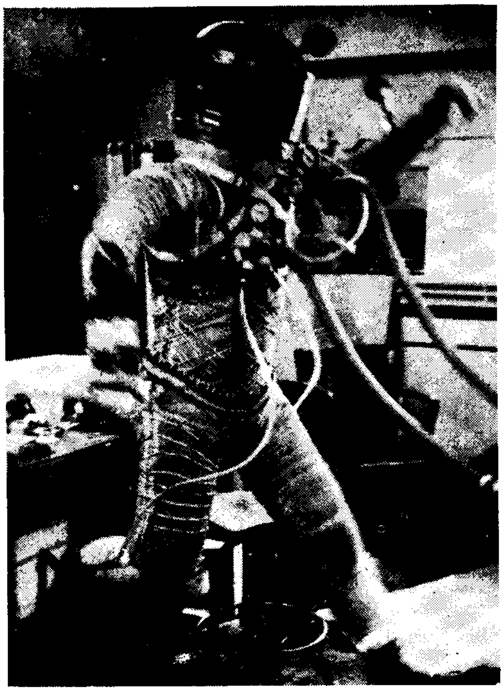

Fig. 18(a) To jump

Fig. 18(b) To write

Fig. 18 Capability of a subject at 3 psi

is well within the present knowledge, and simply requires considerably more effort and greater attention to detail.

Fig. 13 shows a subject in an unpressurized suit, (*a*) standing erect in the suit, and (*b*) performing a deep knee bend. The figure shows a front view of the assembly and the general nature of the crotch mobility, and depicts how lines of nonextension are used in the crotch.

Fig. 14 is presented as the first of a series of illustrations of mobility of the major joints and joint complexes that are problem areas of pressure suit design; the waist, shoulder, and pelvis. Fig. 14 shows a subject, (a) standing erect in the suit with no pressure, and (b) bending in a pressurized condition (3 psi).

Front and back views of the suit under 3 psi pressure are shown in Fig. 15. Overhead arm capability with and without pressure is shown in Fig. 16. Deep knee bend capability, squatting capability, sitting capability, kneeling capability (all at 3 psi) are shown in Fig. 17. Jumping capability and writing capability at 3 psi are shown in Fig. 18.

The general theory and operation were explained and demonstrated at both unpressurized and pressurized to 3.75 psi conditions.

The mobility demonstrated at pressure consisted of the following types of movements: bending the elbows, rotating the upper arms through their cones of action, clasping the arms in front of the body, flexing hands and fingers, writing, manipulating hand tools, rotating the waist through its cone of action, walking, rotating the thigh through its cone of action, bending the knee, sitting, squatting, performing deep knee bends; doing push-ups, jumping in the air with legs astraddle, jumping in the air with legs scissored, getting down on all fours and standing up unaided.

While the suit had been tailored for the shortest of our original three subjects, it was decided, during a demonstration, to try the suit on another fourth subject. The test was undertaken to determine if a suit tailored for one subject could be immediately wearable by another person without too many fitting adjustments. The trial is shown in Fig. 19.

Summary and Conclusions

Following the theory of a pressure suit permitting high mobility, which has been described in earlier efforts:

A complete set of lines of nonextension has been determined from three subjects, and these lines have shown themselves to be quite general for the human form.

A net suit patterned piece-by-piece from a woven high-strength Dacron net with constant-sized diamonds has been constructed as a form-fitting, load-bearing garment for a medium-sized subject. The conformity of this suit to the body during all body deformations is excellent.

A thin (approximately 0.012 in.) rubber suit has been fabricated, by dipping on a three-dimensional form, to be conformal with a human body.

Conformal high-strength and nonstretching cloth garments have been fabricated for the chest (as a vest) and pelvis (as very brief shorts) and laced together with a slipping-string net pattern.

The combination of a gas-retaining rubber layer, a load-bearing net layer that follows the lines of nonextension, and a slip net structure in the waist, forms a pressure-retaining, form-fitting garment capable of providing easy and natural mobility of all body joints, both with and without pressure, with minimum ballooning under pressure. This has been demonstrated in the 0 to 5 psi range above ambient pressure.

Easy mobility has been demonstrated for a variety of types of motions.

In greater detail, the functional layers of the suit include:

An underwear layer to absorb perspiration and to prevent body chafing.

A vent suit made of a fiber-like industrial spacer material, which was also patterned to follow the lines of nonextension, to equalize pressure over the body surface and to permit passage of heat-exchanging and ventilating air through this porous spacing layer.

A thin rubber suit to retain pressure yet permit body mobility.

A stretchy knitted-cloth layer to protect the thin rubber against cuts, tears, and penetration, and to provide some slip against pinching.

A high-strength net suit that follows the lines of nonextension. This layer retains loads developed in the rubber suit by the in-

Fig. 19(a) Unpressurized

Fig. 19(*b*) 2 psi

Fig. 19(c) 3 psi

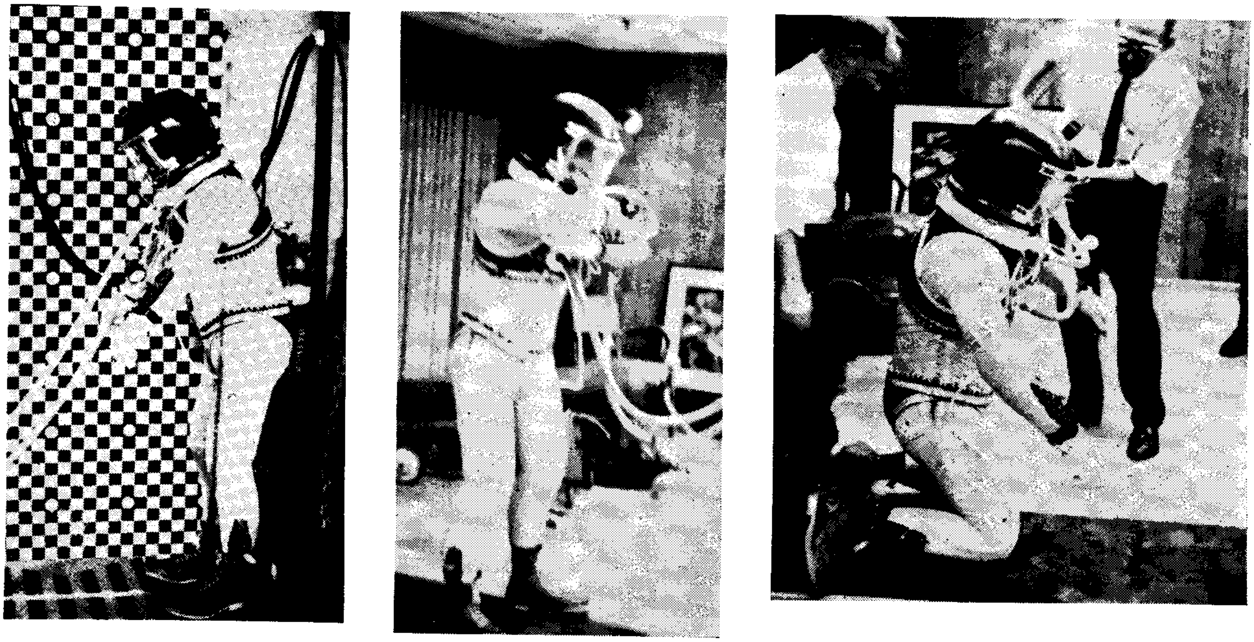

Fig. 19(*d*) 3.75 psi

Fig. 19(e) 3.75 psi

Fig. 19(*f*) 3.75 psi

Fig. 19 Demonstrations by Subject D (unpressurized and at various pressures)

ternal pressure, completely in the circumferential and radial direction (i.e., against ballooning) while permitting mobile deformation of the joints, and restrains most, but not all, of the longitudinal deformation in the pressurized suit.

A cloth vest and pants that are laced together by what is considered to represent a "slip-net." This constraint limits the rest of the longitudinal deformation that is otherwise restrained by the lines of nonextension net only with great difficulty.

Conventional high-laced work shoes are provided, although special purpose, lightweight shoes involving the same netting principles could be developed.

Conventional dress gloves are used and are restrained by similar netting principles, with a rigid constraint over the palm to prevent ballooning. For finer, more complete finger and hand mobility, a much greater detailing of the hands by the same principles as are used in the rest of the suit is necessary.

A fixed, rigid, slip-over helmet was constructed to demonstrate the smallest slip-over sized helmet that could be used, and to illustrate the degree of conflict and compromise that it poses to shoulder mobility.

For demonstration purposes, an external distribution system carries ventilation air into the suit at the chest and helmet and away from the suit by a spider manifold of tubes connecting to both ankles, both wrists, and the helmet. This further assures uniformity of pressure for test purposes.

Having completed a design theory and fully demonstrated its experimental feasibility, there remains the task of engineering research and development of the most suitable materials and a structural integration of layers into a possible operational suit.

Acknowledgment

Support for this research was provided by the Bureau of Aeronautics, Navy Department (reference [1]) and the Aeromedical Laboratory, U. S. Air Force (references [2, 3]). A collateral study was supported by Quartermaster Corps, U. S. Army. The author gratefully acknowledges permission from the Rand Development Corporation to publish this material.

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Journal of Basic Engineering

May 30, 2000

Note to Norrie:

Here is a copy of the 1970 open report in ASME J. of Basic Engineering. If you want you can make as many good copies (figures have to be judged good) as you want for astronauts or the press. What you have to surmise that my work then in 1947 was always under wraps and so I could not and did not show it around casually. The first report was 1951. The second report came out in 1958 (for so Scotty Crossfield's X-15 suit). The first 1951 demonstration was after we build a suit at David Clark's place at the Navy's request. The second demonstration was for the Air Force. All during that period, Navy and Air Force had me teaching the art to potential contractors, so they all got it from me. Then the 3rd demo was in Rand's lab, and I got a release so the first public record was this 1970 paper. Namely, that was the first fundamental theory and practical demonstration that the ideas worked. What none of the astronauts understood except possibly Scotty Crossfield, who I teased horribly about it, was that their suppliers did not develop the basic idea (Glenn, for example, thinks his taylor did it, Scotty thought Dave Clark did it. Sci. Am June 2000 thinks Hamilton Standard did it. Nope, I did it.

I consider that the 50th anniversary of my basic group development at NBS was about 1997.