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FIT, STRETCH, AND COMFORT

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If one judges correctly from the programme, most of the lectures at this Seminar will discuss the subject of comfort from the point of view of the transfer of heat and/or moisture, to and from the environment, through garment layers covering the body. When we put on a garment, however, we may or may not be aware of the feel or warmth of the fabric, but we certainly realise if the garment is too tight or too loose, that is if it fits badly. I suggest the mechanical aspects of everyday garment comfort is at least as important as these questions of heat and moisture transfer and that, although at the extremes fabric properties can have a marked effect on subjective comfort, (both completely impermeable and completely permeable clothing being in general very uncomfortable), it is the design of a garment which initially determines whether it is acceptable as comfortable or not. Many everyday garments are, in any event, relatively loose fitting and an appreciable proportion of ventilation occurs through holes rather than through the fabric of the garment.

The first part of this paper will be devoted to a general discussion of how garment design can affect comfort; the second part to a discussion of how garments designed to fit closely to the skin for reasons of appearance, function or figure control can perform satisfactorily from the mechanical point of view and yet remain comfortable.

There are four main mechancial factors relating to comfort. These are weight, ease of movement, pressure on the body surface, and the ventilation through the holes in the garment which has already been mentioned.

Weight

The most striking feature of everyday clothing where weight is concerned is the large difference between the weight of clothes worn by women and those worn by men, even making an allowance for differences in average body dimensions. It is generally true to say that men are more likely to walk out-of-doors in the same clothes as they wear inside, but nevertheless the weight difference still exists. Where strenuous sport is concerned, there is little or no difference in clothes weight between the sexes but even for indoor activities involving physical exercise, such as dancing, it is usual for men to wear relatively heavy clothing; such is the power of convention. Table I compares the typical average clothing weight, on a normal spring day, of a selection of Shirley Institute staff and their wives.

Shoes have been listed spearately as their effective weight on the standing-still body is nil, and on walking is estimated to be up to 2½ or 3 times their actual weight.

Most of the weight of mens clothes is in the jacket which, together with the contents of the pockets, weighs on average nearly 1½ Kilos - half the total clothes weight. It is true of course that some men take off their jackets during the course of the working day though it is still very unusual for executives in the UK not to wear their jackets during business meetings and the author has never seen a jacketless executive at a formal business lunch. Even without his jacket the clothes worn by the average Shirley Institute male are still 110% heavier than those of the average female, although roughly 30% of this can be accounted for by increases in average body surface

Table I
Weight of Clothes (grams)

Men	Av.	Min Max	Women	Av.	Min Max
Jacket	1100	(1000-1300)	Outerwear (Frock, or skirt & top, or dress & blouse, or skirt & jumper etc.)	480	(170 - 740)
Contents of pockets	360	(280- 400)			
Trousers	510	(400- 740)			
Contents of pockets	170	(105- 230)			
Underclothes	180	(140- 200)			
Shirt and tie	290	(280- 300)			
Pullover *	300		Underwear (Pants, vest, bra, under-skirt.)	310	(230 - 340)
			Stockings or tights	40	
Average Total	2855	(2720-3030)	Average Total	820	(540-1580*)
Socks and shoes	910	(720-1300)	Shoes	470	(375- 600)

* Worn by a few.

*Includes 400 g for surgical corset.

area. A second fact emerging from the data is that men on average carry around over $\frac{1}{2}$ Kilo of miscellaneous belongings in their pockets which the ladies usually carry in their handbags. Though we do not advocate the introduction of handbags for men this insistence on carrying so much weight in sundries, certainly does not ease the problems of the garment designer in simplifying the design and reducing the weight of the average jacket.

Mens casual clothes are, of course, much lighter than those given in the table, probably totalling on average (excluding shoes) less than one kilo. This is similar to the weight of womens clothes and, in the case of women, the difference between the weights of casual and formal wear is insignificant; casual wear may even be a little heavier than normal wear especially if slacks are worn.

Although the total of garments worn contributes overall to the greater or lesser burden to be carried by the wearer, certain garments contribute to discomfort out of proportion to their weight because they are supported on a relatively small area of the body. A pair of heavy trousers with a bunch of keys in one pocket and a handful of small change in the other will probably weigh about 1000g. They may be held up entirely by braces $2\frac{1}{2}$ cm in width supported over a shoulder of minimum radius of curvature 4cm. Using the equation given in the latter part of this paper, the pressure on the shoulder is found to be $60 gm/cm^2$ which, as will be seen later, is borderline where comfort is concerned. It must be admitted, however, that, in practice, a trouser will not be entirely supported by the braces; some support will be contributed by the waist band. One can think of other similar examples. The $1\frac{1}{2}$ Kilo weight of a jacket is carried on the shoulder blades; pressure again can be well above the comfort level. The relatively comfortable feel of a well-fitting jacket is substantially due to a more even distribution of pressure on the body. The straps of a brassiere may, because of their elegant narrowness, exert an even higher pressure than trouser braces. Returning to the example of trousers, the same garment can be supported by a belt around the waist. In this case, the weight is distributed over a somewhat larger area and pressure is therefore lower. Yet the man who is used to a braced trouser would feel uncomfortable with a belt and vice-versa, at least till he had become used to the change; comfort is very subjective. Similarly some people have a preference for heavy bedclothes, some for light weight, irrespective of warmth.

In the past, clothes were necessarily heavy, particularly in winter, firstly because few people owned their own transport and were therefore obliged to walk or wait around for trains, trams and buses; secondly because central heating was rare in domestic premises and thirdly because clothing design had not yet advanced to the stage of lightweight warmth. But the days of the heavy overcoat have now gone. Though, as we have seen, some garments such as men's jackets are excessively heavy, the sheer weight of outdoor clothing need not nowadays be an important comfort factor.

Freedom of Movement

Freedom of movement, the second mechanical aspect of comfort, is very much related to garment design. The clothing of modern Western civilisation is probably more restrictive in this respect than in most other parts of the world. The dictates of convenience as well as fashion are largely responsible for this. Loose fitting garments allowing very free movement, as well as hiding rather than accentuating the shape of the figure, are not very practical and may even be dangerous in certain occupations in day-to-day modern life. The problem is a complicated one because the suitability of a garment for a particular purpose depends on the operation to be performed as well as the intrinsic comfort of the garment itself. One would not attempt to dig a trench in a dressing gown! But assuming that, for practical reasons, closeness of fit is usually necessary or desirable, then obviously the garment must conform more or less to the body shape, and this can only be achieved either by allowing the fabric of the garment to drape closely to the body surface or by shaping the fabric into curved surfaces. In non-extensible fabrics the shaping can either be achieved by cutting and sewing, or by heat shrinkage stretching or shaping or other similar treatments during the making-up process. But although garments of this type may be close fitting and comfortable in one body position they become poorly fitting if the wearer moves or bends his arms legs or trunk, The fabric must buckle to accommodate the distortions consequent upon the shape change and, because of this, pressure may be applied to localised areas of the body surface. If this pressure is significant, discomfort may ensue.

To overcome these limitations moderately well-fitting garments can be designed for ease of movement either by providing adequate fullness where maximum body distortions occur (shoulders and underarm, elbows, waist and buttocks, knees) or by providing fabric stretch at these points. In sporting activities, where the maximum freedom of movement is required it is usual to achieve this firstly by wearing the minimum of clothing and often by using knitted fabrics, for football jerseys for example, which have an inherent stretch property. Clothing worn for Judo is exceptional, as freedom of movement is here derived from fullness. In more everyday clothes there is an increasing tendency towards extensible fabrics in garments of all types. Comfort requirements for stretch will be discussed later.

Ventilation

The question of looseness of fit is, of course, closely related to that of ventilation, and is largely governed by climatic conditions. For example, the clothes worn by an Eskimo have a minimum of ventilation but those worn by an Arab very well ventilated. Ventilation usually occurs at five critical body points, two legs, two arms and the neck. One notices that in the United States, where attitudes to dress are rather more casual than in the UK, there is a much greater willingness to loosen the tie and to wear short sleeved shirts in hot weather. In this country where long sleeves might be rolled up in these conditions, ventilation on the upper part of the arm is probably reduced rather than increased because of the relatively snug fit of the rolled sleeve on the arm.

Stretch

True fitting to the body shape can only be achieved by the use of stretch fabrics which can expand and contract without buckling or wrinkling to accommodate body movement. It is this subject of stretch which will be the concern of the second half of this paper.

Stretch garments can be divided into three categories each requiring a different degree of extensibility and a different range of stress-strain properties.

(1) Comfort stretch garments are not necessarily close fitting and almost any garment may have stretch properties in this class. Their properties of extensibility are designed only to accommodate and reduce resistance to body movements particularly around the elbows, knees, back and seat where, for certain body movements, the fabric becomes bent around a curved surface. Ski pants are one particular example of this type of garment, though in this case the stretch serves a second purpose of keeping the fabric of the garment straight and smooth thus enhancing the appearance.

(2) Stretch-to-fit garments are designed to fit closely to the body contours without exerting any figure-shaping pressure. Ordinary socks, stockings and tights, leotards, and body stockings are in this class as well as some sports shirts, some pullovers, and vests. Generally these garments are knitted structures and, often nowadays, hosiery and sportswear in particular incorporate stretch nylon. Swimwear as well as being in the stretch-to-fit class is sometimes also expected to perform some figure-shaping function.

(3) The third group are what might be termed power-stretch garments. These exert some control over the shape of the body by exerting some compressive pressure on the surface. They may also be used to support various parts or may be used for medical reasons. It is, of course, a misunderstanding to believe that these garments can reduce the size of the figure. As flesh is practically incompressible, they can only redistribute the total volume.

Stretch and Comfort

There are two questions which can be asked in respect of the relation between stretch and comfort.

(1) What level of extensibility is required to accommodate body movements?

(2) What pressure is applied to the body as a result of the stress developed in the fabric of the garment and at what pressure level is discomfort apparent?

The amount of extensibility required in wear at any particular part of a garment depends on three factors

(a) The extension required to make the garment a good fit in the relaxed condition.

(b) The body surface extension (skin extension) at the particular body position.

(c) The amount of slip between the fabric of the garment and the skin surface.

The fitting extension (a) only applies where garments are required to be a more-or-less skin tight fit to the body contours. In these cases a fitting extension is necessary to ensure that the garment does not become loose and buckled on those parts of the body where the surface area decreases when the body joints are moved. The main body positions where fit-stretch may be required are the back of the knee, the inside of the elbow, the front top of the thighs, under the arms and the shoulders, particularly the front of the shoulders.

Figures for body surface extensions (b) have been given by a number of writers perhaps the most notable are those given by Kirk and Ibrahim[1]. Some of their results are illustrated in Fig 1. The figures are in each case average strains measured over a distance on either side of the site in question. The first figure is the vertical strain, the bracketed figure the horizontal strain. Maximum extensions are of course, somewhat greater than those shown. For example, horizontal crotch extensions on sitting are 42% for men and 35% for women. Full details are given in Kirk and Ibrahims paper.

The actual amount of stretch required in a garment is rarely, if ever, as great as the local skin extensions. This is because some of the stretch demand can be obtained from fabric on either side of the area in question. The extent to which this is possible depends on the degree of slip of the garment fabric over the body (c). This, in its turn depends on the type of garment, the distance of fixing points and the friction between the garment and skin or the garment and underclothes.

Kirk and Ibrahim[1] have pointed out that all these factors are related by equations similar to the following: (see Figure 2)

Extended skin size = relaxed garment size + garment fit extension + garment stretch extension + garment slip.

where: Relaxed skin size = Fitting garment size = Relaxed garment size + garment fit extension.

The relative size of the contributions of these factors to the total extension depends on the stress-strain properties of the garment fabric, friction on the body surface or underlying layers of clothes, the magnitude of the skin extensions relative to the total available garment extension, and to the size, shape and fixing points of the garment outside the particular region under consideration.

The actual stretch of garments in wear is generally found to be very considerably less than that of the underlying skin extension. For example, table 2 shows the stretch in wear at the seat of various garments with the subject in the sitting position. The actual maximum skin stretch was about 40% at the measuring point. This is greater than any of the measured fabric extensions and the difference can be accounted for by local fabric slip. (Most of these results are also derived from Kirk and Ibrahim)

These results also show the difference between garments which are well constrained and those which are relatively unconstrained.

It is perhaps worth noting on the other hand, that the actual stretch demand in a garment fabric may in some instances, be much greater than even the maximum skin extension. This is because garments, before they can be worn, have to be put on. Some measurements were made on stretch swimwear some years ago, illustrate this point well. Although the maximum extension of the garment in wear was 26%, the stretch in putting on and taking off was

Table 2

Garment	Fabric Stretch (maximum)	Actual Fabric Stretch
Women's slacks	30	17
	60	27
Men's slacks	30	13
	60	16
Women's shorts	60	17
Women's skirts, dresses, slips etc	60	12
Men's underpants	50	7
Women's swimsuit	80	3

much greater than this at the shoulder straps and waist. In Figure 3 figures in brackets are putting-on and taking off extensions, unbracketed figures are fabric extensions in wear. Available fabric stretch in the horizontal direction was about 100%, and in the vertical direction, 80%.

Returning to the question of the stretch-comfort relationship; any garment can be uncomfortable as a result of body movement if either the friction against the body is high, thus preventing slip, or if the pressure applied to the body is high when the garment is stretched around a curved body surface. Obviously stretch in a garment aids comfort because, for a given fabric extension, fabric tension is lower and body pressure lower.

Insofar as a pressure is necessary for a frictional force to exist and friction can increase pressure by causing fabric restraint, it is difficult to separate the effects of these mechanical comfort components. The effects of body pressure alone can, however, be assessed.

When a fabric is stretched over a curved body surface (Figure 4) the pressure on the body surface is given by

$$P = \frac{T_1}{r_1} + \frac{T_2}{r_2}$$

where T_1 and T_2 are the tensions/unit length in the garment fabric in the two major directions characterised by radii r_1 and r_2. Tensions can be derived from a knowledge of the extension of the fabric in use and its load-extension relationships. Radii can be directly measured. Most body surfaces, other than near joints, may be regarded as roughly cylindrical and in these cases the equation reduces to $P = \frac{T}{r}$, T being the tension/unit length in the extended fabric direction and r the radius of major curvature.

A rough assessment of discomfort threshold (the level at which pressure becomes uncomfortable) may be made by stretching a band of elastic material around a part of the body, and making a judgement of the level of comfort. A number of simple experiments have been carried out along these lines, in which subjects were asked to wear $2\frac{1}{2}$ cm wide elastic bands of various sizes around their arms and legs and to judge the comfort or rather discomfort, first of all on initially putting-on the band, and then after wearing it for one hour during normal activity. As an indication of discomfort subjects were asked at the end of the hour's wear, whether they had been distracted by the presence of the bands. Pressure was calculated using the simple formula. Generally speaking, it was found that a band which was slightly uncomfortable initially, became acceptable after a period whereas one which was very uncomfortable initially became even more intolerable as time passed. A note was also made of the time taken for marks on the skin surface to substantially disappear after wearing the bands for one hour.

Figure 5 shows a plot of pressure on the body against the time for marks to disappear. Open dots were observations which were considered 'comfortable', closed dots 'uncomfortable'. It will be observed that at pressures above 70 g/cm^2 approximately the persistence time of marks increases rapidly above $\frac{1}{2}$ hour and the bands simultaneously became uncomfortable.

One might expect the persistence time of pressure marks, if not the discomfort threshold, to be associated with the closing off by external pressure of blood vessels near the skin surface. A normal systolic arterial blood pressure averages about 120 mm Hg i.e. about 160 g/cm^2. One would expect average capillary blood pressure to be very roughly half this, i.e. about 80 g/cm^2; it may or may not be coincidental that this appears to be similar to the comfort threshold. Some future worker may care to investigate whether there is any statistically significant correlation between blood pressure and discomfort threshold pressure over a wide range of individuals.

Kirk and Ibrahim do not quote figures of comfort pressure in their paper. However, data which they give of fabric stretch and body pressure on the one hand and fabric stretch and comfort on the other, indicate that the discomfort threshold is between 0.4 and 0.7 lb per square inch i.e. between 30 and 50 g/cm^2. The lower value could be explained by the different method of assessing comfort; subjects were asked to express a preference for garments of different extensibility properties. Significantly 95% of the subjects rejected garments exerting a pressure of more than 1 lb/sq inch (70 g/cm^2), a similar result to our own. In a later paper[2] on foundation garments Ibrahim implies that a pressure of 25 g/cm^2 is acceptable but 140 g/cm^2 as extremely uncomfortable, again suggesting a discomfort threshold at about the same level as previously.

The clothing field in which body pressures are highest is, of course, that of foundation garments. This paper will finish with some reflections on the comfort of these garments.

Throughout the ages, what has been regarded as a fashionable shape for the female body has changed continually, and at any given time different nations and races have supported different ideals. From the sixteenth century in Europe here has, however, been a more-or-less continuous tradition of a much compressed waistline (for those who could manage it) and of garments specifically designed to fulfil a compressive function on the waist and/or abdomen. The corset first appeared in Spain and was originally worn as an outer bodice rather than as an undergarment but its function was the same. In the days before elastic fabrics, figure moulding was achieved by firstly designing a tight garment often with lacing down the back; the reader will be familiar with illustrations of ladies of fashion being laced by their maids. Compression having been accomplished by tightness, shaping was then achieved by making parts of the garment rigid with 'bones' either of bone, metal or wood.

The modern girdle which has been described as form persuasive rather than form compelling, is a very different garment. It owes its relatively light weight to its use of synthetic elastomer fibres such as Lycra or Spanzelle.

One would not argue with the suggestion that the old corsets were generally intolerably uncomfortable, and in many cases dangerously so; permanent deformation of the figure being not uncommon. One might argue that the more modern girdle, though undoubtedly very much more comfortable than its Victorian counterpart, is not ideally designed from the mechanical point of view, for the function it has to perform. What the girdle does, in effect, is to stretch an elastic band around the waist and hips, its object being to flatten the abdomen, stomach and seat. The tension in the band must be roughly the same all round the body, so the pressure on the body will depend only on the surface curvature at any given point. Measurements on the waist profiles of a number of women have shown that, on average, the body curvature at the sides is roughly $3\frac{1}{2}$ times greater than that at the front and in only 13% of cases was this ratio less than $2\frac{1}{2}$. It follows that the unwanted pressure on the sides of the waist is, on average, $3\frac{1}{2}$ times greater than the desired figure flattening pressure on the front.

Lemmens[3] gives data on the range of pressures generated in use by different types of garment exercising some (if a little) figure control. Swimwear pressure varies, according to Lemmens, from 10 to 20 g/cm^2, modern corsets from 30 to 50 g/cm^2 and knitted foundations, presumably of the modern girdle type, from 20 to 35 g/cm^2. With a front pressure of 35 g/cm^2 a side pressure of above 115 g/cm^2 could be generated - well above the threshold discomfort level. The same author gives figures of between 30 and 60 g/cm^2 for the pressure generated at elasticated sock-tops and in medical stockings. As we have indicated, higher pressures than 60 g/cm^2 would probably be unacceptable.

Figures quoted by Ibrahim for the measured pressure in 'figure persuasive' garments are somewhat lower than these and were generally less than 20 g/cm^2.

Because comfort is so subjective it is not easy to fix limits between which a garment is effective but not uncomfortable although, surprisingly, the difference between what is acceptable and what is not, does not seem to vary much from individual to individual.

As stated at the beginning of this paper, a great deal has been written and said concerning the heat and moisture vapour transmission aspects of comfort, and relatively little published concerning the mechanical aspects. My final quotation suggests however that these may be more closely related than has been suggested hitherto. Although the quotation reads like a Victorian or Edwardian handbook on home-medicine, it comes from Arthur Mee's Children's Encyclopaedia published about 1936. Some readers may have possessed a copy in their youth.

'Why is Tight Clothing Bad for Us?'

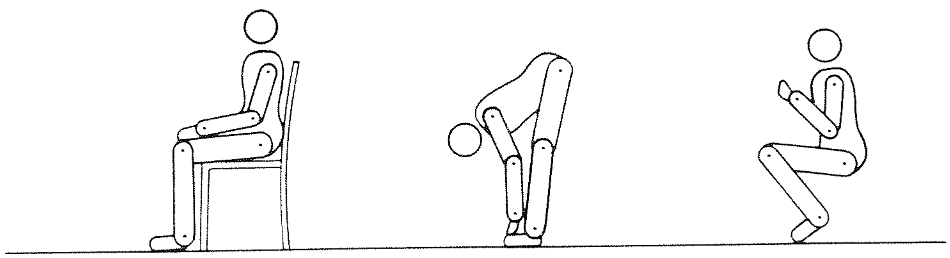
'All our clothing from head to foot should be worn loose. Anything tight on the trunk of the body interferes with the movements of deep easy breathing and injures our health. Tight clothing is bad also because it interferes with the proper circulation of the blood through the body. Many foolish people suffer from cold feet because they wear boots so tight that blood is unable to get to them. Such people almost deserve to have cold feet and corns and chilblains and all the other unpleasant consequences of wearing tight footgear. The proper way to keep warm is by our blood, not by cotton or leather; and the way to help the blood do its work is to give it room to flow instead of tightening the veins and stopping its circulation.'

References

1. W. Kirk, S.I. Ibrahim, Tex. R.J. (1966), 36, 37
2. S.I. Ibrahim, Tex. R.J. (1968), 38, 950
3. J. Lemmens, Industr. Text. Belge, (1966), 8, No.1, 71.

PERCENTAGE BODY STRAINS RELATIVE TO STANDING POSITION

(Data by Kirk and Ibrahim)



MEN	Seat: 27 (20) Knee: 41 (21)	Seat: 35 (21) Back: (47)	Elbow: 50 (24) Knee: 49 (29)
WOMEN	Seat: 27 (15) Knee: 43 (19)	Seat: 34 (17) Back: (47)	Elbow: 51 (25) Knee: 52 (28)

Fig 1

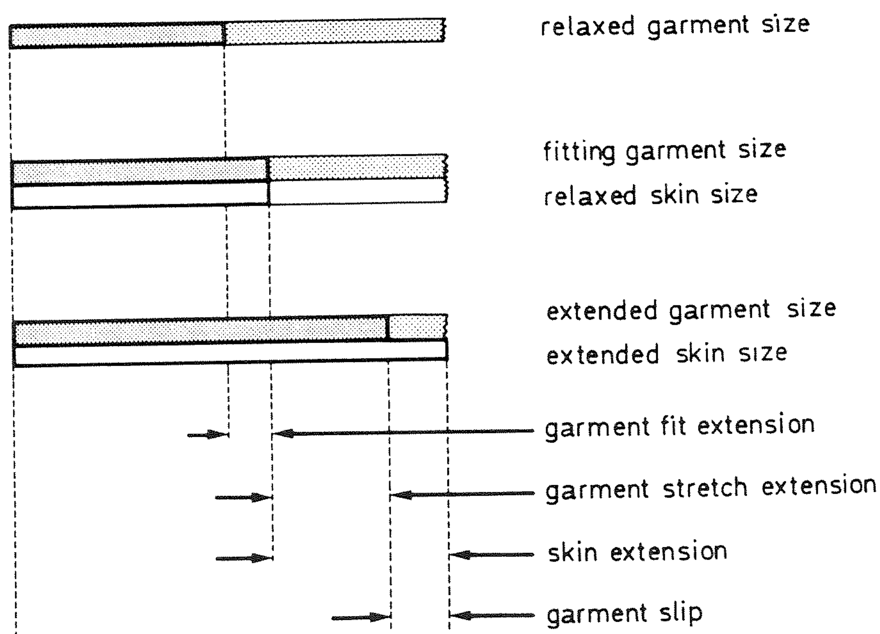


Fig 2

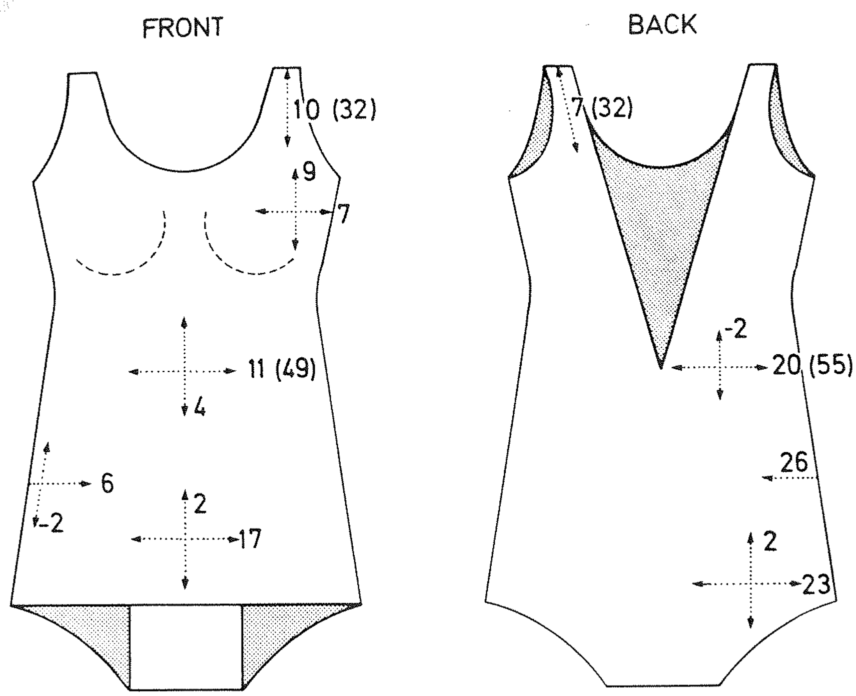
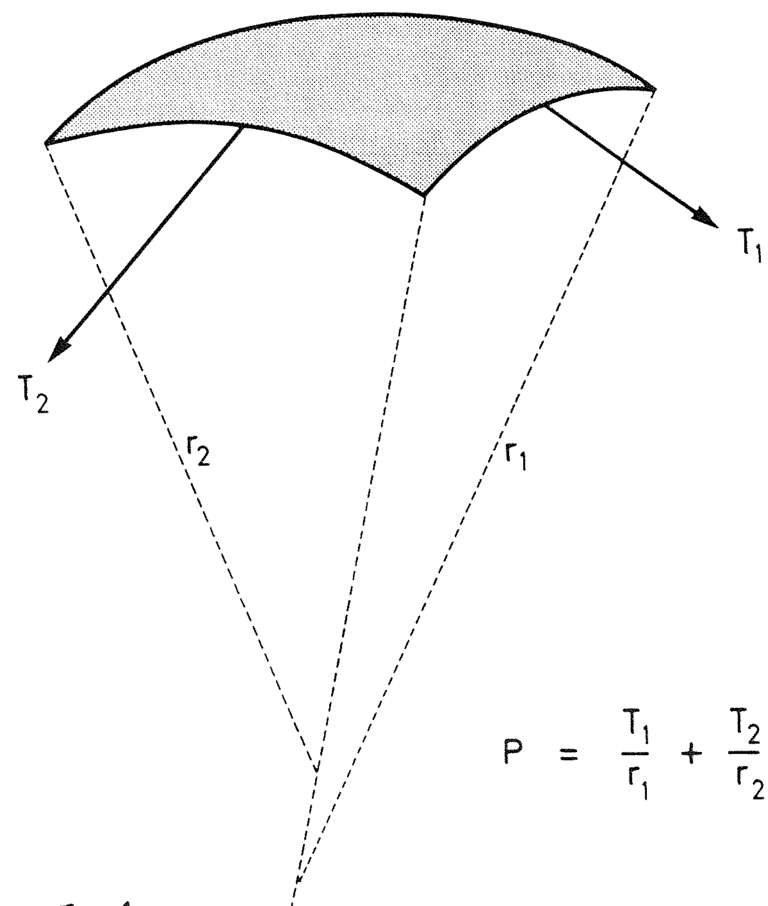
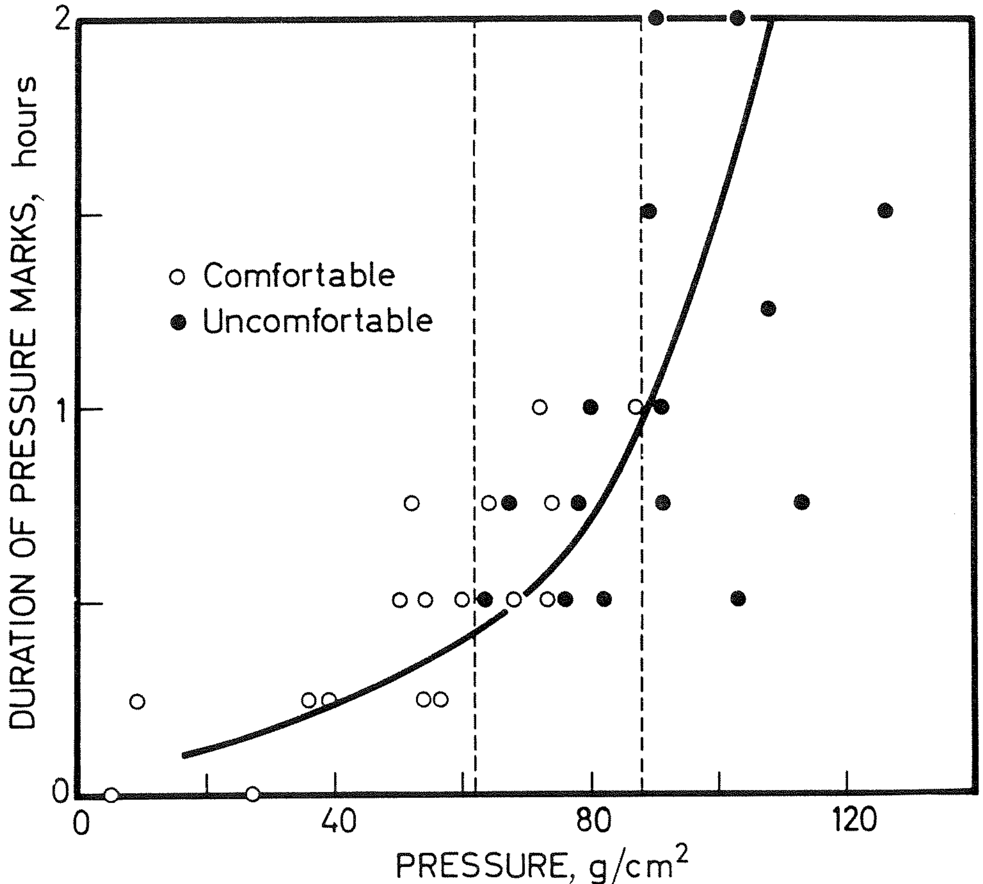


Fig 3



$$P = \frac{T_1}{r_1} + \frac{T_2}{r_2}$$

Fig 4



2
1
0
0
40
80
120
DURATION OF PRESSURE MARKS, hours
PRESSURE, g/cm²
○ Comfortable
● Uncomfortable

Fig 5