Part III

Sportswear and comfort

9

Physiological comfort of sportswear

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9.1 Introduction

The wear comfort of sportswear is an important quality criterion. It affects not only the well-being of the wearer but also their performance and efficiency. If, for example, an active sportsperson wears a clothing system with only poor breathability, heart rate and rectal temperatures will increase much more rapidly than while wearing breathable sportswear (Umbach, 2001, 2002). As a consequence, the wearer of the breathable clothing outperforms the other, as it is possible to withstand high activity levels for a longer period of time. Hence, it is appropriate to describe wear comfort as the 'physiological function' of sportswear.

Wear comfort is also a major sales aspect. According to the journal *World Sports Activewear*, 'comfort is the most important thing in clothing . . ., and it is coming from sportswear where consumers have become accustomed to the comfort' (Foster, 1998). Ninety-four per cent of consumers would like their clothing to be comfortable, i.e. wear comfort is number one in consumer expectations (Ullsperger, 2001). Consequently, in a survey, 98% of specialised German dealers believe wear comfort to be an important or very important property of clothing (Reinhold, 2001; Albaum, 2003).

9.2 Aspects of wear comfort

After recognising the importance of wear comfort and the physiological function of sportswear, one should define in more detail what wear comfort entails. In fact, wear comfort is a complex phenomenon, but in general it can be divided into four different main aspects (Mecheels, 1998):

- The first aspect is denoted as *thermophysiological wear comfort*, as it directly influences a person's thermoregulation. It comprises heat and moisture transport processes through the clothing. Key notions include thermal insulation, breathability and moisture management.
- The *skin sensorial wear comfort* characterises the mechanical sensations, which a textile causes at direct contact with the skin. These perceptions may

be pleasant, such as smoothness or softness, but they may also be unpleasant, if a textile is scratchy, too stiff, or clings to sweat-wetted skin.

- The *ergonomic wear comfort* deals with the fit of the clothing and the freedom of movement it allows. The ergonomic wear comfort is mainly dependent on the garment's pattern and the elasticity of the materials.
- Last but not least the *psychological wear comfort* is of importance. It is affected by fashion, personal preferences, ideology, etc. The psychological aspect should not be undervalued: who would feel comfortable in clothing of a colour he or she dislikes?

9.3 Measurement of physiological comfort

9.3.1 Wear comfort as a measurable quantity

Many people believe that comfort is something individual to each person, which cannot be quantified or measured. But in fact wear comfort is directly related to physiological processes within our bodies. To some extent it is a gift of nature, in order to recognise our physiological status and to avoid physiologically adverse situations by active behaviour. For instance, if man, whose origins are to be found in the hot climatic zones of Africa, feels uncomfortably warm, he may stop running in the sun and sit down in the shade of a tree to prevent hyperthermia.

Thermophysiological comfort is based on the principle of energy conservation. All the energy produced within the body by metabolism M, has to be dissipated in exactly the same amount from the body (Mecheels and Umbach, 1977; Mecheels, 1998):

$$M - P_{\mathrm{ex}} = H_{\mathrm{res}} + H_{\mathrm{c}} + H_{\mathrm{e}} + \Delta S/\Delta t \qquad [9.1]$$

with P_{ex} the external work, H_{res} the respiratory heat loss because of breathing, H_{c} the dry heatflux comprising radiation, conduction and convection, and, last but not least, the evaporative heatflow H_{e} caused by sweating. If more energy is produced than dissipated, the body suffers from hyperthermia. On the other hand, too high a heat loss leads to hypothermia. Both lead to a change in the body's energy content ΔS with time Δt. ΔS may be either positive (leading to hyperthermia) or negative (hypothermia), and is zero for steady state.

9.3.2 Wearer trials

As the wear comfort is directly related to physiological processes, it is possible to measure it quantitatively. An important way to measure wear comfort is to perform wearer trials with human subjects. These could be performed either 'in the field' under practical conditions or under controlled climatic and activity scenarios in a climatic chamber. The latter has the great advantages that the test conditions are reproducible and that probes can be attached to the subject's body to obtain objective data. These data may comprise heart rate (via ECG electrodes), rectal temperature, skin temperatures at different positions, temperature and humidity in the microclimate at different positions, weight loss of test person, weight gain of clothes, etc. Figure 9.1 shows such a test being undertaken.

In order to get sufficient statistics, it is necessary to test with a group of subjects. Additionally, subjects react differently in the morning from how they react in the afternoon, hence tests have to be performed at both times. Test

9.1 Wearer trial with a human subject testing bikewear in a climatic chamber.

subjects have to be acclimatised to the climatic and activity conditions in pre-tests. Data have to be statistically analysed, etc. Therefore, wearer trials with human subjects are time and cost intensive. This makes wearer trials rather inefficient in product development and certification. Thus, clothing physiological laboratory measurements have been developed to ensure more efficient product development and high reproducibility for certification purposes. However, wearer trials are still needed as a 'calibration' for the laboratory test procedures. In particular, mathematical regression analyses between the laboratory tests on the one hand, and wearer trials data on the other hand, have to be carried out in order to ensure the validity of the laboratory tests and to interpret their data. This is a crucial criterion for laboratory techniques and, in fact, only a few test methods lead to results which correlate to real human subject data (Bartels and Umbach, 2003a).

9.3.3 Skin Model

An important laboratory test method that fulfils the above-mentioned criterion of correlation to wearer trials data is the so-called Skin Model. The Skin Model is a thermoregulatory model of the human skin. It tests the thermophysiological wear comfort of textile materials. The Skin Model is internationally standardised (ISO 11092, EN 31092). For protective clothing, it is the only test method for breathability which is accepted within European standardisation.

A photo and a schematic drawing of the Skin Model is given in Fig. 9.2. The measuring unit shown is made of sintered stainless steel. Water, which is supplied by channels beneath the measuring unit, can evaporate through the numerous pores of the plate, just like sweat out of the pores of the skin. Additionally, the measuring unit is kept at a temperature of 35 ºC. Thus, heat and moisture transport are comparable to those of the human skin.

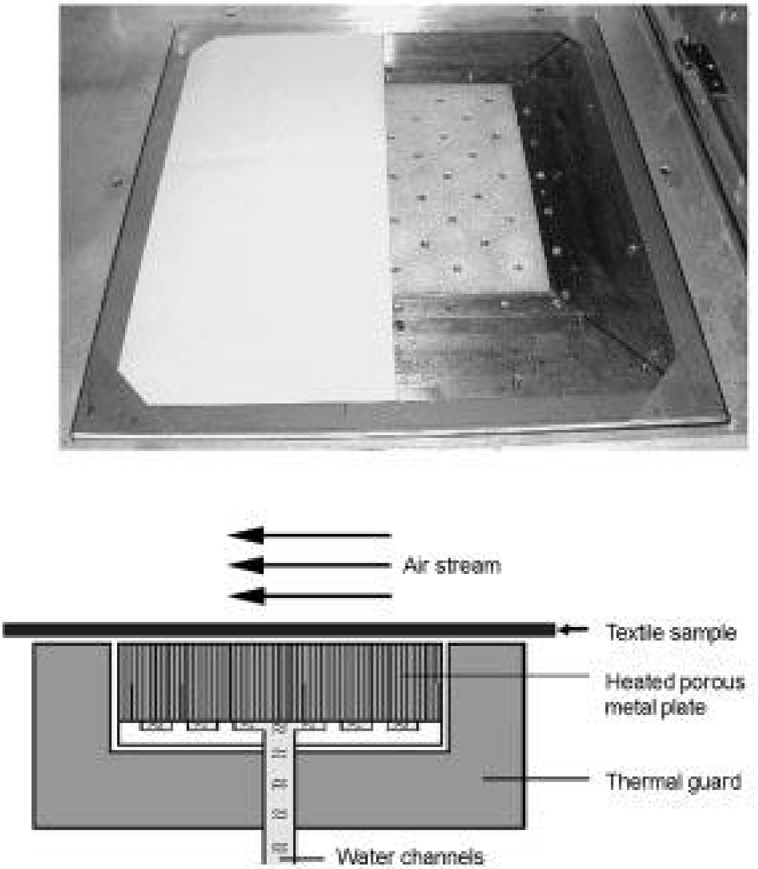
With the Skin Model, different wear situations can be simulated:

- Normal wear situations are characterised by an insensible perspiration, i.e. the wearer does not recognise that he is sweating. Nevertheless, at least 30 grams per hour of water vapour is evaporated through the semi-permeable membrane skin. For normal wear situations, thermal insulation R_{ct} and water vapour resistance R_{et} ('breathability') of the textiles are especially important according to ISO 11092 or EN 31092.

  If textiles are identically constructed, the thicker one always has the higher (and thus poorer) water vapour resistance R_{et}. In order to take into account its benefit of a higher thermal insulation, the ratio

  $$i_{mt} = 60(\mathrm{Pa/K})R_{ct}/R_{et} \qquad [9.2]$$

  is defined as the water vapour permeability index, which is a measure of the breathability with respect to a fabric's thermal insulation.



9.2 Photo and schematic drawing of the Skin Model according to ISO 11092 or EN 31092.

Last but not least, the water vapour absorbency F_i is part of the picture at normal wear situations.

- With heavier sweating, e.g. when walking upstairs, the wearer recognises that he has started to sweat, but he is not sweat-wetted yet. In these situations, the skin produces vaporous sweat impulses, which can be simulated with the Skin Model by measuring the buffering capacity against vaporous sweat F_d according to BPI 1.2.
- Very important for sport textiles are heavy sweating situations with a high amount of liquid sweat on the skin. Here, the buffering capacity against liquid sweat K_f and the liquid sweat transport defined as 'moisture permeability' F_l (BPI 1.2) are most important for a good wear comfort.
- Last but not least, the wear situation directly after an exercise is also of great relevance to sport textiles. Then, the textile might be soaked with sweat and

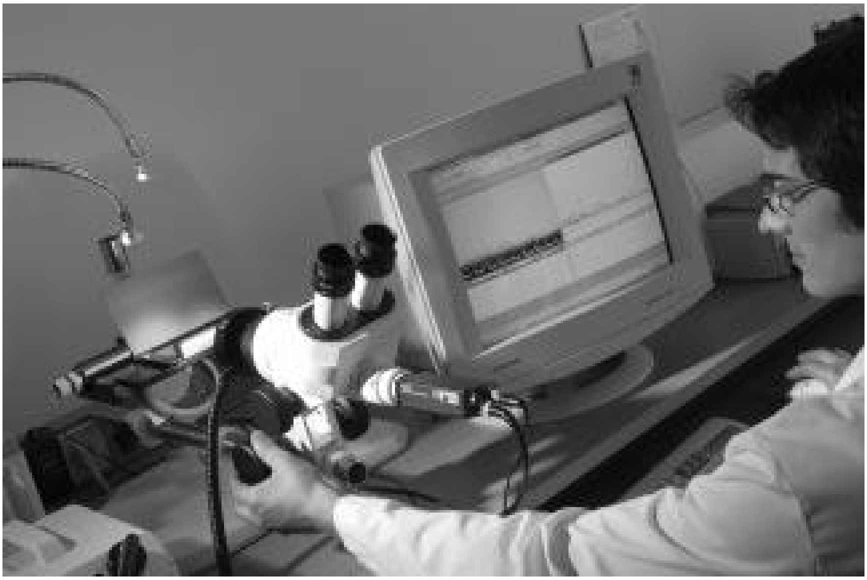
has lost its thermal insulation. This leads to the so-called post-exercise chill, which is very unpleasant. The post-exercise chill can be avoided by a short drying time Δt, according to BPI 1.3.

9.3.4 Skin sensorial test apparatus

Also the skin sensorial wear comfort of textiles can be tested by special laboratory apparatus (Bartels and Umbach, 2001a, 2002). As an example, in Fig. 9.3 the measurement of the surface index i_O is shown, which characterises the textile's surface roughness or 'hairiness'. If a textile is too smooth (flat), it clings to sweat-wetted skin. If too many and too stiff fibre ends are present, the textile feels scratchy. Hence, a good compromise is required. Other skin sensorial parameters are the wet cling index i_K, the sorption index i_B, the number of contact points with the skin n_K, and the fabric's stiffness s.

9.3.5 Wear comfort vote

From the Skin Model measurements as well as from the skin sensorial tests a thermophysiological and a skin sensorial wear comfort vote, respectively, can be calculated (Bartels and Umbach, 2003b). They range from 1 'very good' to 6 'unsatisfactory'. Thermophysiological and skin sensorial wear comfort vote can be combined to an overall wear comfort vote predicting the perceived wear



9.3 Measurement of the surface index for the characterisation of the skin sensorial wear comfort of textiles.

Table 9.1 Comparison of the wear comfort vote *WC* of elastic sport underwear predicted by equation 9.3 and as obtained in wearer trials with human test subjects (Bartels, 2003b)

Sample no.	Prediction	Wearer trials data
15	2.8	2.5 ± 0.5
19	1.9	2.3 ± 0.5

comfort in practice. For sport T-shirts or underwear the formula for the overall wear comfort vote *WC* is

$$WC = -0.171F_l + 0.293\Delta t - 16.047i_{mt} - 0.153F_i + 0.449WC_S + 2.649 \qquad [9.3]$$

with the above-defined physiological parameters, and

$$WC_S = -2.537i_{mt} + 0.0188i_K + 0.00229i_B + 0.0209|9 - i_O| + 0.00171n_K + 0.0386|16 - s| + 0.36 \qquad [9.4]$$

the skin sensorial wear comfort vote for knitwear.

Comparisons of thousands of wearer trials show that the accuracy of this prediction is better than 0.5 degrees within the six-step scale (Umbach, 1993a; Bartels and Umbach, 2003b). This prediction accuracy is very good, as test persons are only able to recognise differences of 0.5 or more. An actual example for elastic sport underwear is shown in Table 9.1 (Bartels, 2003b).

9.4 Applications

In the following it is shown how the described clothing physiological techniques can be used to improve the wear comfort of sport textiles. Some recent results are presented, with examples of products that have interesting market potential.

9.4.1 Elastic sport textiles

Need for research

Elastic textiles can improve the ease of movement of clothing. Thus, elasticity enhances the ergonomic wear comfort. Additionally, elastic textiles allow fashionable patterns, which may improve the psychological wear comfort, too.

However, the use of elastic yarns can also cause problems: elastane fibres are non-hygroscopic and hydrophobic, i.e. they cannot absorb moisture within their structure, nor are they wettable by liquid sweat (Umbach, 1993b, 2001). This reduces the thermophysiological wear comfort. In addition, elastane yarns are very smooth (flat), which worsens the skin sensorial wear comfort.

As consumers expect elastic textiles to be more comfortable than other constructions, the Hohenstein Institutes recently performed a research project on the thermophysiological and skin sensorial wear comfort of elastic textiles, i.e. those aspects of wear comfort which are problematic for these types of construction. In particular, various elastic knitwear for sport applications was investigated. Just as for other research projects referred to later, readers who are interested in details, may obtain a technical report (in German) from the Hohenstein Institutes (Bartels, 2003b).

During the research project it was found out quite soon that many of today's usual elastic knitwear constructions are problematic with respect to their physiological properties. Some manufacturers seem to believe, for example, that the use of microfibres and elastanes would automatically result in a good sport textile. But if only filaments are used, these constructions usually lead to a very smooth, flat and unstructured inner surface facing the skin. This causes in some cases only a poor skin sensorial wear comfort, which is clearly negatively perceived by the wearer.

In general, it should be pointed out that wear comfort is never the consequence of only one single parameter like 'use of microfibres'. On the contrary, all physiologically relevant construction parameters have to be adjusted to the intended field of application (e.g. sportswear), in order to achieve a good wear comfort.

In the following, some of the deficiencies found during the research project are discussed. But also recommendations for the optimisation of the wear comfort are given, which will allow elastic sport textiles with a good thermophysiological and skin sensorial wear comfort to be produced.

Fibre composition

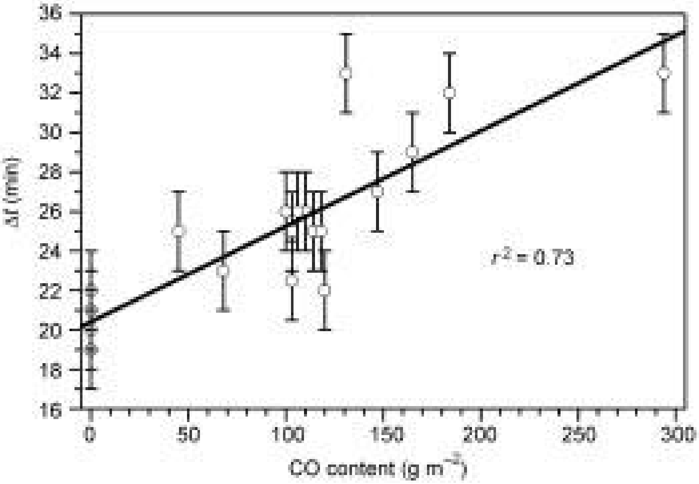
If the wear comfort of textiles is discussed, many people firstly ask for the fibre composition. In particular, it has to be clarified whether

- *hygroscopic* natural fibres such as cotton or regenerated fibres such as viscose, modal or lyocell fibres, or
- *non-hygroscopic* man-made fibres such as polyester, polyamide or polypropylene

are recommendable.

Some manufacturers prefer natural materials such as cotton. Cotton has excellent properties for everyday clothing worn in normal wear situations with only a limited amount of sweating. In these situations, cotton can buffer smaller sweat impulses and, hence, keep the microclimate drier and more comfortable.

But in the field of sport textiles, which are confronted with a high amount of liquid sweat for prolonged times, cotton is only recommendable at the outer side of two face materials and in combination with a synthetic inner side at the skin.



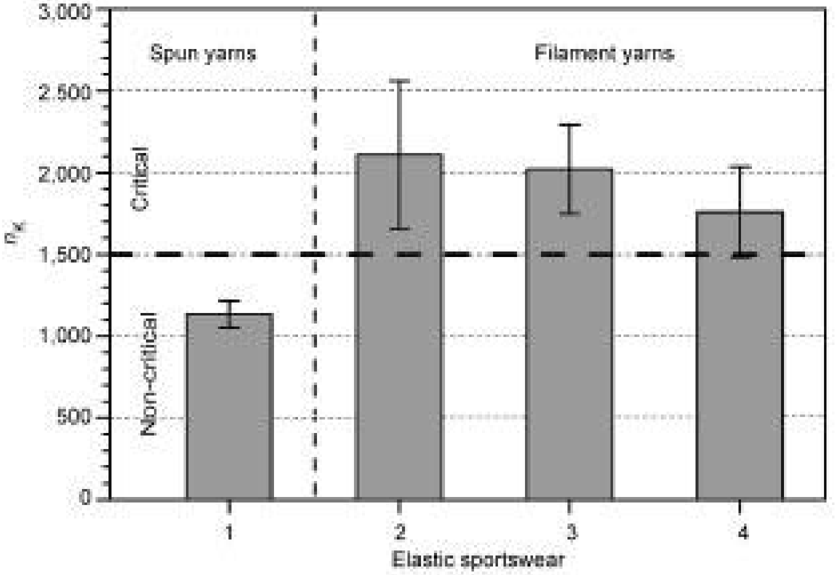
9.4 Drying time Δt as a function of the cotton content of elastic, knitted sport textiles (Bartels, 2003b).

If cotton (or regenerated fibres like viscose) are used as the only or main fibre component, the textile is soaked with moisture quite rapidly and becomes a wet, clinging cover for the body. The hygroscopic fibres also lead to a distinct and physiologically problematic lengthening of the drying time. This is illustrated in Fig. 9.4. With an increasing amount of cotton, the drying time Δt lengthens. If Δt becomes too long, the post-exercise chill is unavoidable, as the sweat wetted shirt loses its thermal insulation. In fact, a short drying time is one of the main prerequisites for a good wear comfort of a sport textile (see equation 9.3).

Figure 9.4 clearly proves that the drying time correlates nicely to the proportion of cotton in the textile. But the regression coefficient $r^2 = 0.73$ also shows that other construction parameters are of interest, too, and that the amount of cotton alone is not sufficient for a comprehensive specification of the drying time. Indeed, for most parameters relevant to comfort, these other constructional parameters are much more important than the fibre composition. Therefore they are discussed in the following.

Knitting construction

In the above-mentioned research project (Bartels, 2003b) it was also shown that the knitting construction of many of today's elastic sport textiles is physiologically problematic. The use of filament yarns, especially, not only for the elastane but also for the blended fibres, frequently leads to too smooth and flat textile surfaces directly at the skin. These foil type textiles show too many contact points with the skin, are perceived as too smooth and clinging to sweat-



9.5 Number of contact points n_K between skin and textile for four different knitted elastic sport textiles. Only the sample made mainly of spun yarns offers a non-critical value of $n_K < 1{,}500$, whereas filament constructions fail this criterion (Bartels, 2003b).

wetted skin. Using the scale from 1 'very good' to 6 'unsatisfactory', these constructions have to be marked as 5 'poor' with respect to their skin sensorial wear comfort.

In order to optimise the wear comfort, the inner side of the textile has to be structured. From the knitting technology point of view, this can be achieved by rib or honeycomb structures. Using spun yarns and in contrast to filament yarns, protruding fibre ends are generated, which act as spacers between skin and textile. As an example, in Fig. 9.5 the number of contact points between skin and textile n_K of four elastic sport textiles is given.

Only the specimen made mainly of spun yarns offers a value of $n_K < 1{,}500$, but all filament constructions are located in the critical area of $n_K > 1{,}500$.

If filaments cannot be avoided, one should at least use textured yarns. However, even these cannot usually compete with spun yarns with respect to their skin sensorial properties.

Finishing

The textile's finishing substantially influences its wear comfort (Umbach, 1988). Some of these finishes, like modifications of handle, softeners, or resin finishes, may be hydrophobic, i.e. water repellent. From the physiological point of view this is undesirable, because not only water but also sweat is repelled by the hydrophobic textile. The textile does not take up the sweat, or transport it to the outside. As a consequence, the sweat stays at the skin. But moist skin can be irritated much more easily than dry skin – the best known example may be the nappy which has to keep baby's bottom dry by conducting urine into absorbing materials inside the nappy. Analogously, sport textiles have to conduct sweat from the skin in order to prevent skin irritations or even moisture-generated dermatoses.

It is for these reasons that hydrophilic, i.e. water-liking, finishes should be preferred. It has been shown (Bartels, 2003b) that elastic textiles can rapidly absorb moisture. For instance, one sample with an elastane content of 11% took up a sweat droplet within only 0.1 seconds.

Finally, it should be clearly stated that the finishing is essential for the wear comfort of textiles and not a secondary construction element, which can be varied in any way one likes.

9.4.2 Biofunctional textiles

There is no common definition of the term 'biofunctional textiles' in the literature, but they comprise materials which are, for example, antimicrobial or fungicidal, and textiles which can absorb substances from the skin, such as sweat components. These materials have become important to many different textile applications (Mucha *et al.*, 2003). In the field of sportswear in particular, biofunctional textiles are used to suppress the build-up of sweat odours. Therefore, antimicrobial finishes or fibre modifications are frequently applied to sport textiles today. Alternatively, cyclodextrin finishes are used (Buschmann *et al.*, 1998), in order to act as 'cage molecules' enclosing malodorous substances.

Just recently, the influence of different biofunctional treatments of textiles on their wear comfort has been surveyed for the first time (Bartels, 2003c). Apart from other constructions for workwear or leisure wear, three different types of knitted sport textiles were investigated concerning their thermophysiological and skin sensorial wear comfort. These results are discussed subsequently.

It turned out that, from a physiological point of view, different biofunctional modifications were not comparable. Some caused a clear and perceivable worsening of the wear comfort, whereas others had no influence at all. The materials for sport applications were not finished, but their fibres were modified. Interestingly, this fibre's inherent biofunctionality may cause clear differences from normal, non-biofunctional textiles.

In Table 9.2 the sport textiles investigated are described. The wear comfort votes according to equations 9.4 and 9.3 for the skin sensorial and the overall wear comfort, respectively, are given. In each case the biofunctional textile is compared with an identically constructed reference material which has no biofunctional modification.

Table 9.2 Skin sensorial wear comfort vote WC_S and overall wear comfort vote WC according to equations 9.3 and 9.4 of biofunctional, knitted sport textiles and their non-modified reference materials (Bartels, 2003c). WC and WC_S range from 1 'very good' to 6 'unsatisfactory'; their experimental error is 0.3

Sample no.	Sample description	WC_S	Judgement	WC	Judgement
7	Polyamide with fibre-inherent bacteriostatic agent based on silver	4.8	Poor	3.0	Satisfactory
8	As sample 7 but without antimicrobial agent	3.3	Satisfactory	2.0	Good
9	Polyester/acrylic, acrylic fibre with inherent bacteriostatic agent	3.9	Sufficient	1.0	Very good
10	Polyester, as sample 9 but without antimicrobial acrylic fibres	2.7	Satisfactory	1.0	Very good
13	Polyester/cotton 65/35, polyester fibre with inherent silver ions on ceramic substrate	1.9	Good	1.5	Good
14	Polyester/cotton 65/35, as sample 13 but with normal polyester fibre	1.6	Good	1.6	Good

It can be seen from the table that the skin sensorial comfort especially may be significantly worsened by the biofunctionality of the textile. Sample no. 7, with a bacteriostatic agent, has to be judged as 'poor' with respect to its skin sensorial properties, whereas the reference material is at least 'satisfactory'. Also, no. 9 worsens the skin sensorial wear comfort vote. This specimen is rated only as 'sufficient', but the reference material is 'satisfactory'. These differences can be clearly perceived by a wearer. Here, the only biofunctional modification which does not lead to a significant worsening of the skin sensorial wear comfort, is the modified polyester fibre with inherent silver ions on a ceramic substrate. But for applications other than sportswear, additional biofunctional modifications did not negatively affect the wear comfort (see Bartels, 2003c, for details).

The modified polyester fibre does not reduce the overall wear comfort either. Sample no. 9's textile construction is good enough to mask the worsening caused by the biofunctional acrylic fibre, so that it gets the same very good rating as its reference material. But sample no. 7 only offers a 'satisfactory' overall wear comfort, whereas its reference is judged to be 'good'.

It should be mentioned that the wear comfort votes given in Table 9.2 are affected not only by the biofunctionality of the textile but also by their different constructions. Hence, one can only deduce the influence of the biofunctionality in comparison with its reference material, but not to another biofunctional textile, which is differently constructed.

It is interesting to discuss now why some of the biofunctional modifications worsen the wear comfort. In the case of the sportswear samples nos 7 and 9 in Table 9.2, the reason is a hydrophobic fibre surface. Textile no. 7 needs more than 9 minutes to soak up a single sweat droplet; sample no. 9 does not take it up at all during a 10 minute test. But their reference materials nos 8 and 10 need just 25 and 12 seconds, respectively, to take up the same amount of sweat.

As discussed in the previous section, these hydrophobic textiles cause problems with sweat transport and lead to a moist skin, which can be easily irritated. In addition, the hydrophobic surface is perceived as clinging more to sweat-wetted skin. As clinging feels very unpleasant, the wearer subjectively recognises the difference to the hydrophilic reference materials.

Another biofunctional textile construction which was discovered to be disadvantageous during the survey (Bartels, 2003c) is the inclusion of biofunctional filament yarns instead of spun yarns. As discussed in the previous section, non-textured filament yarns lead to too smooth (flat) textile surfaces, which have too many contact points with the skin and easily cling to sweat-wetted skin.

If cyclodextrins are applied to textiles, the exact finishing process is crucial for the wear comfort. Some of the finishes lead to crosslinking between the cyclodextrin molecules, causing a stiffening of the textile, which is again problematic from a skin sensorial point of view. Additionally, these crosslinking cyclodextrin finishes effect a more hydrophobic textile surface.

These problems with cyclodextrin textiles can be overcome by special finishes, which selectively link the cyclodextrin molecules to the fibres (Buschmann *et al.*, 1998). However, the finishing recipe is also important, because overdosing would again lead to crosslinking between cyclodextrins.

9.4.3 Foul weather protective clothing

Textile constructions

For many outdoor sports such as cycling, running, sailing, climbing, etc., foul weather protection is required. For these applications, waterproof and yet water-vapour-permeable ('breathable') textiles are state of the art. Because of the high market potential, today numerous constructions are available. They can be divided into two main groups:

- Laminates, in which a ready-made membrane is glued to a textile carrier.
- Coatings, in which the polymer melt is directly applied to the textile carrier.

Membranes as well as coatings may become water vapour permeable by a microporous construction. Here, the membrane's pores are larger than water vapour molecules, which can diffuse through the membrane. On the other hand, these pores are narrower than even the smallest water droplets, which cannot pass. A well-known example of this type of membrane is the first generation of Gore-Tex.

An alternative membrane or coating principle is called 'hydrophilic'. Here, functional end groups are chemically applied to the macromolecules of the membrane or coating. The polymer film is totally closed and watertight, but water vapour molecules can jump from one functional end group to another and migrate to the outer side. An example of this type of membrane is Sympatex.

Both principles, microporous and hydrophilic, can be combined. In this case, a hydrophilic covering layer is applied to a microporous membrane, as realised in Gore-Tex second generation.

Laminates can also be divided into different groups:

- Two-layer laminates comprise a textile carrier and a membrane. If the membrane is stuck to the outer shell material, this two-layer laminate is usually combined with a loose lining, which mechanically protects the membrane.
- The membrane can also be connected to the lining. This 'liner' construction is combined with an outer shell or upper material.
- In three-layer laminates, upper material, membrane and lining are fixed together.

Liquid sweat transport

All laminate or coating constructions have to face a principal dilemma: the membrane cannot distinguish between rain, which has to be blocked, and liquid sweat, which should be transported. Hence, in heavy sweating situations, which are quite common in sports, watertight constructions usually offer only a limited or poor wear comfort.

In a recent research project (Bartels, 2003a), the properties of a new type of foul weather protective clothing have been investigated in detail. The idea is to use a hydrophilic lining instead of a common hydrophobic one. Then, a sweat drop is soaked up by the lining and is spread over a large area. It is still impossible to transport the sweat through the membrane as a liquid. But now the moisture is offered to the membrane for diffusion at a much larger area. Pre-tests showed a clear improvement of the liquid sweat transport via this principle (Böhringer, 2000; Bartels and Umbach, 2001b; Glimm, 2001).

In Table 9.3 the investigated samples are described. They were obtained from a German textile manufacturer. Specimens differ in the finishing of the lining (hydrophobic or hydrophilic) and in the laminate construction (two-layer laminate plus loose linings, and three-layer laminates). Upper material and lining construction are identical. Water vapour resistances R_{et} may vary slightly,

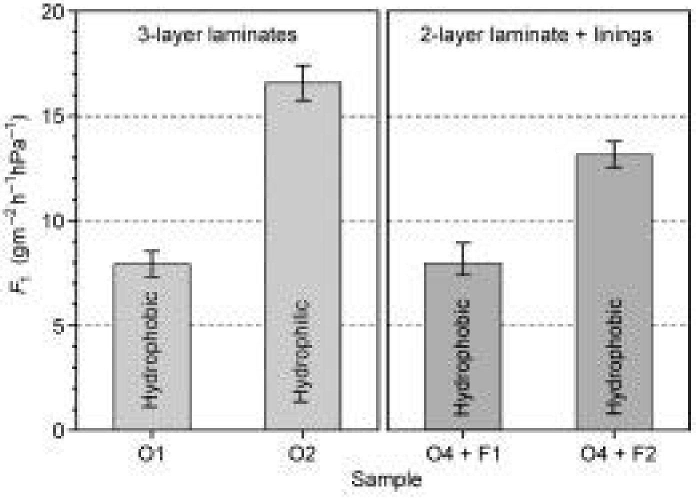
Table 9.3 Samples of foul weather protective clothing used for the study on the influence of a hydrophilic lining (Bartels, 2003a). All specimens contain a hydrophilic polyester membrane. Upper material and lining construction are always identical. The water vapour resistance R_{et} was determined according to ISO 11092, EN 31092. The lower R_{et}, the better the breathability

No.	Description	R_{et} m^2 Pa/W
O1	3-layer laminate, hydrophobic inner side	10.6 ± 0.5
O2	3-layer laminate, hydrophilic inner side	7.2 ± 0.3
O4+F1	Combination of 2-layer laminate + hydrophobic lining	12.4 ± 0.6
O4+F2	Combination of 2-layer laminate + hydrophilic lining	12.4 ± 0.6

but can all be judged as having good breathability (Umbach, 1986). Data on tests of additional laminates or other physiological parameters, such as buffering capacity against vaporous sweat impulses, drying time or thermal insulation can be found in the technical report (Bartels, 2003a).

In Fig. 9.6 the liquid sweat transport (moisture permeability) F_1 of the laminates measured by means of the Skin Model (see section 9.3.3) is shown. Comparing the results of a hydrophobic and a hydrophilic inside, in both cases, three-layer laminate as well as two-layer laminate with loose lining, the hydrophilic variant is found to have considerable advantage.

In the case of a two-layer laminate in combination with two differently finished linings, using the hydrophilic material increases the liquid sweat transport by 65%



9.6 Liquid sweat transport (moisture permeability) F_1 (according to BPI 1.2) of the foul weather protective textiles described in Table 9.3 (Bartels, 2003a). The higher F_1, the better the liquid sweat transport.

in comparison with the usual hydrophobic variant. This advantage can be directly attributed to the lining's finishing, as both combinations, O4+F1 and O4+F2, have identical water vapour resistances R_{et} (see Table 9.3).

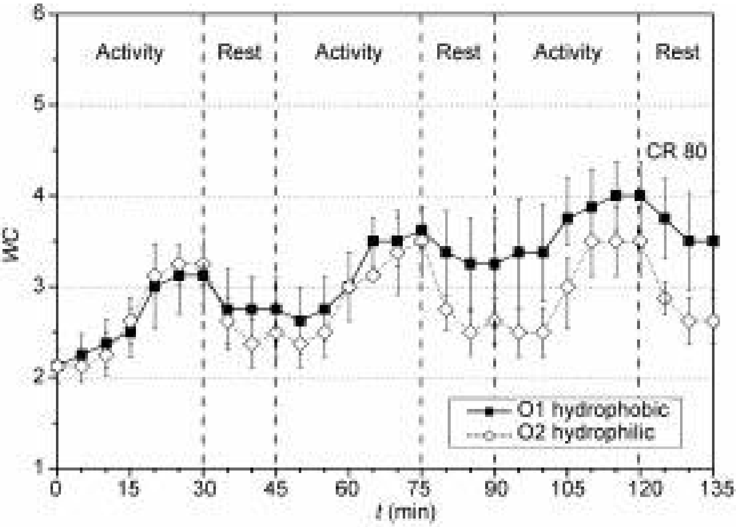
For the three-layer laminates investigated, the improvement is even greater. Here, the liquid sweat transport is more than doubled when utilising a hydrophilic inside instead of a hydrophobic one. However, in this case at least part of the effect may be due to the slightly better (i.e. lower) water vapour resistance R_{et} of the hydrophilic variant (see Table 9.3).

Nevertheless, the comparison between the three-layer laminates and the two-layer laminate plus loose linings is also interesting. On the one hand, for the hydrophobic materials O1 and O4+F1, no difference is found regarding F_1. But for the hydrophilic variants, the three-layer laminate O2 offers an advantage over the two-layer-plus-lining combination O4+F2. Referring to the value of O4+F2, the liquid sweat transport F_1 of O2 is 26% higher. This result can be understood by (a) a closer fit between lining and membrane in the three-layer laminate and (b) the better water vapour resistance R_{et} of O2. In conclusion, for the investigated materials and heavy sweating situations with a continuous appearance of liquid sweat on the skin, which is typical for many sport applications, the three-layer laminate is preferable.

It should be mentioned that for clothing intended to be used in everyday life, such as street- or leisure wear, which usually only needs to buffer short impulses of liquid sweat, the buffering capacity K_{f} is more important than the moisture permeability F_1. Again hydrophilic materials have to be preferred, as only these variants are able to achieve a satisfactory buffering capacity (Bartels, 2003a,d). But the comparison of a two-layer laminate with loose lining and a three-layer laminate is different from the long-term heavy sweating situation: as the loose lining is able to take up more liquid sweat than the inside of a three-layer laminate, which is glued to the membrane and, hence, has less geometrical space available, a (short-term) liquid sweat impulse can be buffered even slightly better (but not necessarily perceivably better) by a two-layer laminate plus lining than by a three-layer laminate. Thus, for normal street- or leisure wear or those sport applications with usually lighter activity (e.g. golf), a two-layer laminate plus lining is a good alternative to a three-layer laminate. It should also be clarified that for the transport of vaporous sweat (as for many normal non-sportswear situations), the lining's finishing has no influence at all.

To check whether the advantages in liquid sweat transport, which were found by the Skin Model measurements described above, can be perceived by a wearer, trials with human test subjects were performed. As an example, cycle jackets made of the three-layer laminates O1 and O2 were investigated (see Fig. 9.1). Both jackets had identical patterns, hence differences can be attributed directly to the different materials.

Also the (short-sleeved) two-layer functional underwear, cycle shorts, cotton socks and trainers were kept identical. Four young healthy men served as test



9.7 Wearer trials with human test subjects, subjective wear comfort vote *WC* of two different foul weather protective textiles as a function of time *t*. *WC* ranges from 1 'very good' to 6 'unsatisfactory'. Errors correspond to the 80% confidence range and represent the variation in answers of different test persons (Bartels, 2003a).

persons, wearing each clothing system twice. Hence, eight single trials per sample were performed.

The activity scenario simulated riding a bike in a hilly environment. Alternately, the test persons had to cycle 30 minutes on an ergometer with an external power of 100 or 120 W, depending on their personal fitness ('uphill'), and to sit on the ergometer for 15 minutes without cycling ('downhill'). Altogether, three activity–rest cycles were performed, leading to a test duration of 135 minutes in total.

Temperature and relative humidity were controlled by a climatic chamber being 20 °C and 50%, respectively. In addition, a wind machine was placed in front of the bicycle ergometer to simulate the airstream. Wind speed was higher during rest cycles, which represent the downhill situation, than during activity.

A detailed description of the wearer trials and a comprehensive discussion of various objective and subjective data can be found in Bartels (2003a). Here, the main subjective perceptions of the test subjects are presented.

In Fig. 9.7 the overall wear comfort is drawn time dependently. Again, *WC* ranges from 1 'very good' to 6 'unsatisfactory'. During the last test cycle especially, the test persons' judgement is clearly better for sample O2 with hydrophilic inside in comparison with the hydrophobic variant O1 by 0.9, which has to be regarded as really perceivable. The difference is also statistically significant at levels up to $p > 0.95$.

Table 9.4 Wearer trials with human test subjects, acceptance *A* of different foul weather protective textiles. *A* is obtained from the answers to the question 'Would you like to buy such a jacket?', with 0 = no and 1 = yes. Errors correspond to the 80% confidence range and represent the variety in answers of different test persons (Bartels, 2003a)

Sample	*A*
O1	0.25 ± 0.23
O2	0.75 ± 0.23

In Table 9.4 the acceptance *A* is given. *A* is obtained from the answers to the question, 'Would you like to buy such a jacket?', with 0 = no and 1 = yes. *A* shows a clear and, with $p > 0.95$, statistically highly significant difference: 75% of the test persons would like to buy the jacket made of O2, whereas only 25% would like to buy the O1 variant.

In more detail, the test persons perceived O2 (hydrophilic) as drier than O1 (hydrophobic). Additionally, the test persons perceived O2 as faster drying during rest periods. Only 13% of the test persons felt O2 to be unpleasant, but 50% disliked O1.

In conclusion, a hydrophilic inside leads to an improvement of the liquid sweat transport through foul weather protective clothing which is not only measurable by the Skin Model but also perceptible by wearers. Hence, this construction is recommendable, especially for active sports clothing.

9.4.4 Textile combinations

Up to now, the wear comfort of single textiles has been discussed. However, in practice, combinations of different materials are often worn. This situation is much more complex, as it is dependent not only on both materials' properties but also on the way both components act together. In particular, the moisture management of liquid as well as of vaporous sweat is affected. Here, with the example of foul weather protective clothing worn together with functional underwear, these linked effects are discussed. Again, further details and examples can be found in the technical report (Bartels, 2003a).

Liquid sweat transport

The foul weather protective laminates given in Table 9.3 were also tested in combination with functional underwear. Here, results with the underwear materials U1 and U6, which are described in Table 9.5, are shown. U1 has a cotton outside. U6 is fully synthetic and constructed according to the denier gradient principle, i.e. capillaries are located at the outside smaller than at the inside in order to enhance the liquid sweat transport (Umbach, 2001).

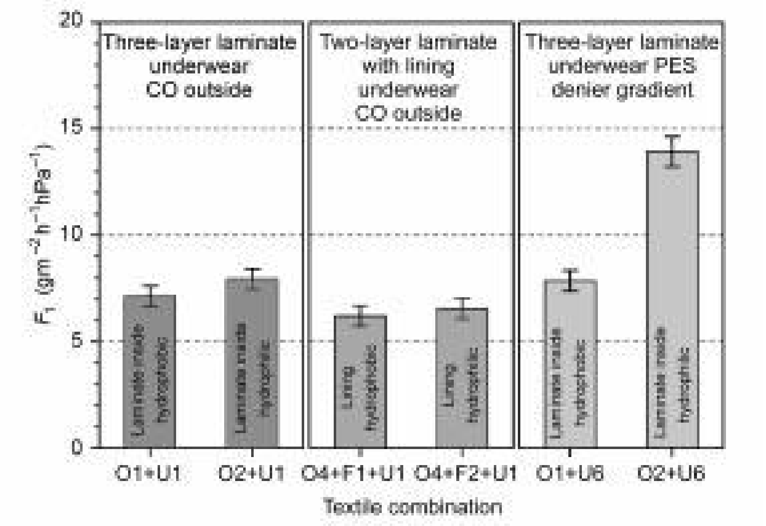
Table 9.5 Functional underwear materials tested in combination with foul weather protective laminates. For characterisation, the thermal insulation R_{ct}, the water vapour resistance R_{et} and the water vapour permeability index i_{mt} (see equation 9.2) according to ISO 11092, EN 31092 are also given. Their experimental errors are 3×10^{-3} m^2 K/W, 0.3 m^2 Pa/W, and 0.025, respectively

No.	Description	R_{ct} 10^{-3} m^2 K/W	R_{et} m^2 Pa/W	i_{mt}
U1	CO/PES/PA 48/42/10, two layers, inside: PES functional fibre, outside: CO	27	4.6	0.35
U2	CO/PP/PA 60/36/4, two layers, inside: PP, outside: CO, hydrophobic treatment	25	4.0	0.38
U3	PP-filament, two layers, outside honeycomb structure, hydrophobic treatment	13	2.2	0.35
U4	PES, four layers, from inside to outside: moisture-conducting layer, moisture-storing layer, windtight membrane, upper material	25	5.5	0.28
U5	PES-filament, two layers, outside: honeycomb structure	13	2.2	0.37
U6	PES profiled fibre, denier gradient, 140 g/m^2, inside: roughened, hydrophilic treatment	30	3.4	0.54
U7	PES, two layers, inside: roughened, outside: roughened	28	3.4	0.50
U10	PES, L/R rib with two threads, spun yarn at skin if textile is unexpanded + textured multiple filament	38	5.5	0.41

In Fig. 9.8 the liquid sweat transport F_l for different combinations is given. F_l varies widely and depends on the underwear as well as on the laminate. As a consequence of the increased thickness in comparison with a single laminate, F_l is reduced for the combination (see also Fig. 9.6).

In all cases the liquid sweat transport is higher if the upper material possesses a hydrophilic inside or lining, but sometimes the advantage is quite small. As for single upper materials, the three-layer laminates perform better than two-layer laminates with loose lining.

On the other hand, an influence of the underwear on the liquid sweat transport is obvious. In combination with a highly permeable upper material, underwear U6 (PES, denier gradient) is preferable to U1 with cotton outside. In addition, purely synthetic underwear materials usually dry somewhat faster than those with a cotton component, and drying time is found to be of major importance for the overall wear comfort of functional underwear, as assessed by human test subjects in wearer trials (for details see Bartels, 2003a).



9.8 Liquid sweat transport (moisture permeability) F_1 (according to BPI 1.2) of combinations of foul weather protective laminates and functional underwear (Bartels, 2003a). The higher F_1, the better the liquid sweat transport.

As a main result, Fig. 9.8 clearly shows that upper material and underwear have to perform together optimally. In this case, the combination of the three-layer laminate with hydrophilic inside O2 and the purely synthetic denier gradient underwear U6 offer by far the highest, and thus best, liquid sweat transport.

This result can be interpreted to the effect that the hydrophilic and non-hygroscopic underwear U6 takes up the moisture very fast without binding it too much, but transports it quickly to the outside. There, the hydrophilic inside of O2 can take over the moisture and transport it to the membrane for diffusion. Hence, all components of a clothing ensemble have to be optimally compatible with each other in order to guarantee good wear comfort.

It should be mentioned that for combinations with thicker and thus less water-vapour-permeable upper materials, two-layer underwear with cotton outside may be even better than pure synthetic ones (Bartels and Umbach, 1999). In addition, the hygroscopic cotton fibres are able to absorb vaporous sweat, which is preferable in more ‘normal’ wear situations with only a low amount of sweating. In such everyday scenarios the influence of the underwear dominates, whereas the laminate is of minor importance.

Vaporous sweat transport

During active sport it is likely that liquid sweat occurs on the skin. However, there are a lot of sport activities in which a lower physical strain is common, e.g.

in walking, golf or sailing. In addition, even for active sport it would be favourable if the amount of liquid sweat on the skin was as low as possible (Bartels and Umbach, 2001a). Hence, the vaporous sweat transport is also of great importance for the physiological wear comfort of sportswear.

Again, the whole clothing combination determines the amount of vaporous sweat which can be transported to the outer layers. The interrelation between the clothing components is complex and is discussed here in detail, once more with the example of functional underwear plus a foul weather protective laminate.

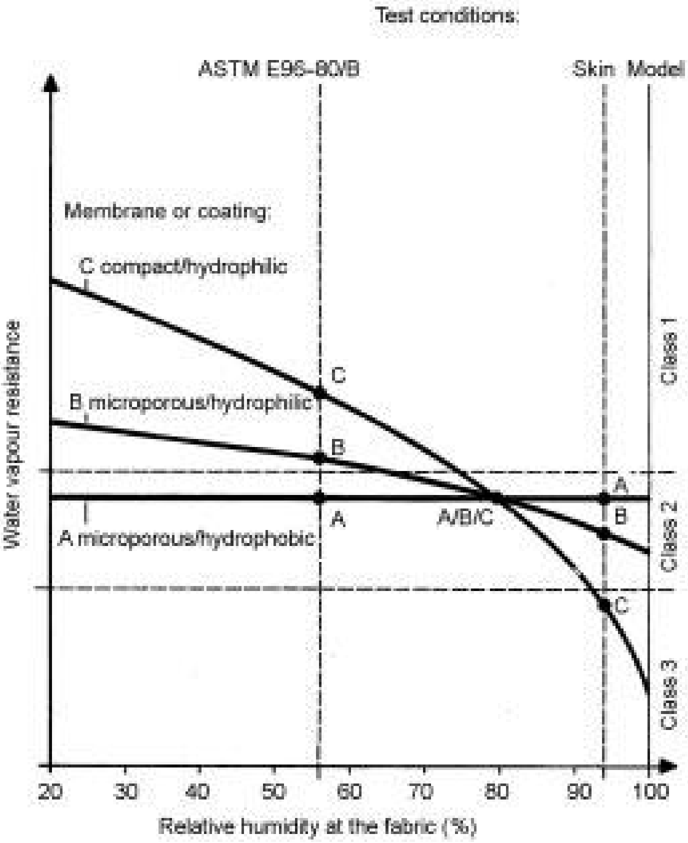
In contrast to thermal insulation, for which the single thermal resistances sum up to the overall thermal insulation, the total water vapour resistance of a combination of textiles is not always equal to the sum of single resistances. In particular, the inclusion of hydrophilic components complicates the picture, as the water vapour resistance of these materials depends on the relative humidity at the membrane (Osczevski and Dolhan, 1989; Farnworth *et al.*, 1990; Bartels and Umbach, 2003a). The lower the relative humidity, the higher (and thus poorer) the water vapour resistance. A schematic drawing of the principles in microporous, hydrophilic and combined microporous/hydrophilic membranes or coatings is given in Fig. 9.9.

The dependency of the water vapour resistance on the relative humidity leads to an increase in the overall water vapour resistance of textile combinations. In standard test methods (ISO 11092, EN 31092) as well as in real wear situations, the ambient air is often drier than the skin or the simulated skin. For instance, within Skin Model tests the relative humidity at the measuring unit is nearly 100%, i.e. saturation with water vapour. On the other hand, in the ambient climatic cabinet a relative humidity of 40% is kept constantly. Hence, the end points of the water vapour partial pressure gradient always correspond to 100% and 40%, respectively.

If a single laminate is measured by means of the Skin Model, the membrane is quite near to the measuring unit and, thus, at a comparatively high value of relative humidity. Hence, according to Fig. 9.9 the water vapour resistance of the hydrophilic component is quite low. If, now, an additional textile layer, e.g. an underwear material, is placed between the laminate and the measuring unit, some of the water vapour concentration gradient drops off over the underwear. Consequently, the relative humidity at the membrane is lower than in the case of the single laminate. Thus, the water vapour resistance of the hydrophilic membrane is higher in combination than alone.

This principle of a worsening water vapour resistance in clothing systems applies to all membranes and coatings with hydrophilic components, but its magnitude differs. In other words, the material improves with increased sweating, implying that maximum breathability can be achieved when it is needed most.

Now, one could think that it would be possible to derive the increase of a laminate's water vapour resistance from the underwear's R_{et}. But to complicate the situation even further, it has recently been found that different underwear



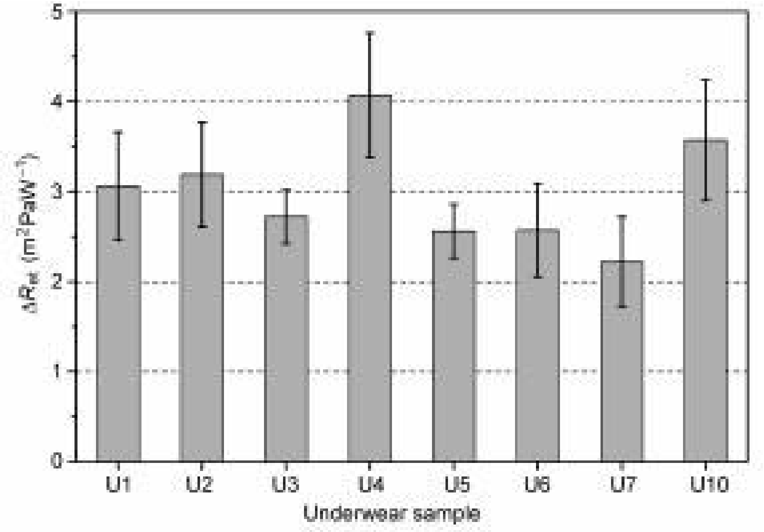
9.9 Schematic drawing of the water vapour resistance of a hydrophilic (C), a microporous (A), and a microporous/hydrophilic (B) membrane or coating as a function of the relative humidity (Bartels and Umbach, 2003a).

materials lead to different increases in the water vapour resistance of combinations, even if their R_{et} values are comparable (Bartels, 2003a).

In Fig. 9.10 the increase of the water vapour resistance ΔR_{et} of textile combinations is given. ΔR_{et} is calculated as the difference between the water vapour resistance of the textile combination $R_{\mathrm{et\,tot}}$ and the sum of the single component's values $R_{\mathrm{et}\,i}$:

$$\Delta R_{\mathrm{et}} = R_{\mathrm{et\,tot}} - \sum_{i=1}^{N} R_{\mathrm{et}\,i} \qquad [9.5]$$

For these investigations the underwear materials described in Table 9.5 were used. As an upper layer, a laminate with a microporous/hydrophilic membrane was taken, which is described in Table 9.6. However, results are comparable for the laminates O1 and O2 given in Table 9.3 (for details see Bartels, 2003a).



9.10 Increase of the water vapour resistance ΔR_{et} according to equation 9.5 of combinations of different underwear materials and the foul weather protective textile O3.

First of all it is obvious from Fig. 9.10 that the worsening of the water vapour resistance differs depending on the underwear material. This result is remarkable as it means that the water vapour resistance of the laminate and its relative humidity dependency is directly influenced by the underwear.

Usually, those underwear materials with a low R_{et} value also have a small ΔR_{et}. This can be understood in theory because in this case the water vapour concentration gradient drops less over the underwear, hence the relative humidity at the membrane is higher. But sample U7 leads to the lowest increase in water vapour resistance of all underwear materials, although it does not have the smallest R_{et}. This result is confirmed in tests in combination with the other laminates O1 and O2, hence it is not accidental.

This positive influence of U7 can only be understood if this sample leads to a locally high relative humidity at the laminate. U7 does take up a little amount of water vapour, which could explain this result. But its vapour uptake is far lower

Table 9.6 Foul weather protective textile used for the investigation of the increase of the water vapour resistance of textile combinations. The water vapour resistance R_{et} was determined according to ISO 11092, EN 31092

No.	Description	R_{et} m^2 Pa/W
O3	3-layer laminate, 137 g/m^2, microporous/hydrophilic PTFE/PU membrane, inside: PA, outside: PA	4.9 ± 0.3

than those of samples U1 and U2 with cotton outside, leading to larger ΔR_{et} values. Hence, it is also not only the amount of moisture taken up by an underwear sample.

It seems as if the influence of the underwear on the worsening of the water vapour resistance of laminates in clothing combinations can only be understood on a microscopic scale. But to clarify this, further research is required.

9.5 Conclusions

The importance of the physiological wear comfort of sportswear was described. It was shown how the wear comfort can be measured effectively by clothing physiological laboratory test apparatus. Sport apparel applications were discussed with the examples of elastic knitwear, biofunctional textiles, foul weather protective laminates and their combinations with functional underwear. For each application, guidelines for the improvement of the thermophysiological or the skin sensorial wear comfort were given.

9.6 Future trends

As comfort is the most important factor in clothing and especially for sportswear, producers who are able to convince the end user of their product's comfort benefits, in particular directly at the point of sale, have an advantage. Therefore, nearly all sport apparel comes with swing tags claiming extraordinary wear comfort. In the shop, the consumer, however, is not able to distinguish between real benefits and solely marketing gimmicks. However, once a consumer has been disappointed, it is difficult to convince him to buy expensive high-tech sports clothing again.

Thus, from both the consumer's and the high quality producer's point of view, there is a need for independent testing of the clothing's physiological properties. This would be comparable to the situation in the field of protective clothing: many of these garments have to be certified by EU notified bodies, in order to guarantee the end user a certain level of protection and comfort.

However, at present there is no European standardisation for sportswear. Nevertheless, producers of high quality textiles and clothing may wish to show that their product is independently tested, especially for wear comfort. An option is shown in Fig. 9.11: the Hohenstein Institutes' label 'Tested Quality'. By this, apart from other properties such as windproofness or watertightness, the product's physiological properties such as the wear comfort vote or the breathability, can be advertised. This label may also be used by textile producers to show the benefits of their materials to their direct customers such as garment producers.

TESTED
QUALITY
HOHENSTEIN
INSTITUTES
SAMPLE TESTED FOR:
✓ WEAR COMFORT VOTE
1.2
(VERY GOOD)
TEST-NO.: FI 03.4.XXXX

9.11 Example for advertising wear comfort at the point of sale by means of the Hohenstein Institutes' label 'Tested Quality'.

9.7 Further information and reading

All research results presented here are taken from technical reports (Bartels, 2003a,b,c). Readers who are interested in details and additional data may obtain these reports, which are written in German, from the author. Also the references cited below may contain useful information. A comprehensive introduction to the science of clothing physiology is given in Mecheels (1998).

9.8 Acknowledgement

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10

Elastic textiles

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10.1 Introduction

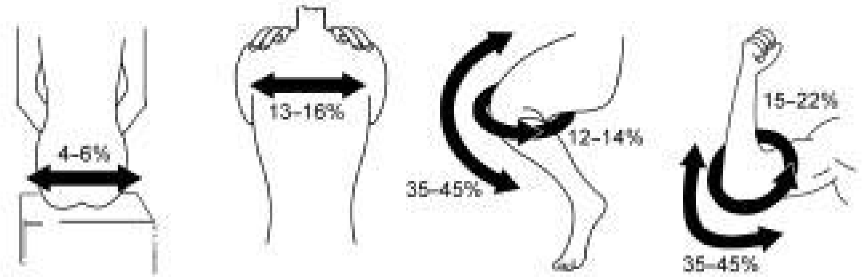
People must be able to move in the clothing that they wear. If clothing restrains movement, discomfort may result due to the pressure exerted on the body by the garment and the clothing may fail. Minimizing a garment's resistance to the body's demands in movement can be achieved through increased fabric fullness in the pattern or through fabric stretch. Increasing the fabric's stretch means garments can be cut to achieve a more streamlined appearance and can conform better to the body, while still maintaining comfort for the wearer in motion.

Simple body movements such as bending the elbows or knees stretches the skin by as much as 50% (see Fig. 10.1).[1] Strenuous movements involved in active sports require even more stretch. The dramatic difference between the skin's elasticity and the lack of elasticity in conventional fabrics results in restriction of movement to the wearer and loss of shape, and consequent performance, of garments. Elastane, even in small amounts, provides the necessary elasticity for a garment to respond to every movement of the body and return to its original size and shape.

Stretch fibres have been credited with opening the way to more comfortable clothing. Market research shows that sports participants who were interviewed (in 10 countries), considered comfort the most important characteristic of clothing for sports or fitness activities (internal research data; see Table 10.1).

Today's stretch garments for sports and outdoor wear play an important role in optimizing an athlete's performance by providing freedom of movement, maximizing comfort, minimizing the risk of injury or muscle fatigue and reducing friction or drag. The major applications are:

- Garments where comfort and fit are most important, including aerobics/exercise wear, golf jackets, ski pants, sports bras and swimsuits.
- Compression garments where stretch garments play an important part in improving several aspects of an athlete's performance (speed, stamina and strength), including cycle shorts, foundation garments, swimsuits and sports bras.



10.1 Key stretch points on the body.

Table 10.1 Most important characteristic of clothing for sports or fitness activities

Rank	Clothing characteristic
1	Comfort
2	Freedom of movement
3	Breathability
4	Machine washable
5	Durability
6	Fit
7	Lightweight

10.2 Freedom of movement

10.2.1 Stretch fabrics

Fabric stretch can be created by many different methods:

- Fibre – elongation characteristics derived from its molecular chain geometry, as is the case with rubber and synthetic elastomers.
- Polymer spinning – bi-component polymer spinning can create fibres with a helical crimp.
- Yarn processing – yarn crimping via thermal or chemical means, as in the twist–heat-set–untwist method of yarn texturing.
- Fabric structures – such as circular knits.
- Finishing – through modifications of fabric structures by compacting slack finishing, slack mercerizing, adding stretch silicone treatment or application of stretch laminates.

The technology is constantly advancing even to the extent of new man-made fibres being developed that warrant new generic sub-fibre status. However, to date the method that gives the greatest stretch and recovery properties are elastic fibres. Recovery of a fabric after stretching is as important as stretching. Good recovery means sportswear garments can provide lasting fit, maintain their shape throughout rigorous wear and regular washings, thus maintaining a garment's body-hugging form which will eliminate chafing and reduce drag.

The first real elastic textiles were created in the 1920s when the US Rubber Company produced a yarn of covered rubber filaments. In practice, however, rubber-based filaments proved unsuitable for many textile applications because garments were heavy and hot because fine yarns could not be produced. Additionally, the garments were prone to suffer rapid degradation of the rubber, being then non-elastic.

A major leap in the evolution of elastic textiles occurred in 1958 when DuPont invented Lycra®, initially known as Fiber K. Developed by the chemist Jo Shivers from petroleum-based raw materials, Fiber K was unlike any other man-made material, possessing exceptional properties of stretch and recovery, stretching by four to seven times its initial length, yet springing back to its original length after the stretching force was released.

DuPont's new product overcame many of the deficiencies in rubber yarn. Lycra® had two to three times the power of the same weight of fabric made from conventional rubber-based elastics and much finer filaments could be produced. Thus softer, lighter, sheerer garments could be made utilizing all textile processing routes. Additionally, it was less susceptible to deterioration by chemicals (chlorine and body oils), light or abrasion, and garments containing Lycra® were easier to care for (machine washable and dry cleanable). Lycra® retained its stretch properties for a longer period of time than rubber yarns.

A new generic fibre classification known as elastane (spandex in the US and Canada) was established for all man-made elastic fibres. Lycra® was the first man-made elastomeric yarn and is now the best known with 92% of females aged 18–49, globally, aware of the brand (men and teens have slightly lower awareness levels) (internal research data), but not every elastane is Lycra®. Lycra® is produced only by DuPont (now Invista™), and the company constantly monitors quality and performance standards. In order to be identified as containing Lycra®, a garment must conform to set quality standards.

There is not one Lycra® but many variants, each carefully engineered for process capability to provide the precise combination of thickness, texture, brightness, stretch performance, fibre chemistry and other characteristics that apply to the fabric or garment end use.

A good example of this is in swimwear. All elastanes are sensitive to chlorinated water, which is why many swimwear garments start bagging after time. DuPont developed special Lycra® types for swimwear with superior chlorine resistance so garments maintain their comfort, support and appearance over a longer time. This has become increasingly important with today's focus on fitness, where swimming in chlorinated pools has become a regular fitness activity rather than a holiday one.

The first elastane yarns were used in waistbands in the 1960s, moving into warp knits for intimate apparel and swimwear in the 1970s, legwear and circular knits for intimate apparel, sportswear and ready-to-wear in the 1980s, wovens for ready-to-wear (trousers, skirts, and jackets), socks, shoes and knitwear in the 1990s, and now moving into home textiles, technical textiles and non-wovens.

Elastane yarns contribute significant elastic properties to all types of fabric: circular knits, warp knits, flat knits, wovens, non-wovens, lace and narrow fabrics. Their main function is to provide controlled stretch and recovery characteristics that enhance all fabrics and garments, adding easy comfort and freedom of movement, and lasting shape retention.

The type of fabric and its end use determine the degree and direction of elasticity required. This then determines the amount and type of elastane required, ensuring optimum performance and aesthetics. As little as 2% elastane is enough to improve a fabric's movement and shape retention, while high-performance garments such as swimwear and active sportswear may contain as much as 30% elastane.

Elastane is never used alone but is combined with, and adds stretch to, any fibre blend (man-made or natural), taking on the appearance and hand of the host material. The appearance, care label instructions, and thermal characteristics of a fabric are dependent on the dominant fibres in the fabric. An example of this is the silk Lycra® second skin garments which sprinters wear. These reduce wind resistance and can cut up to a tenth of a second off their race times which could be the difference between winning and coming second.

To maximize comfort and performance – primary concerns for participants in active sports – the most important fabric properties are:

- Stretch – to ensure your clothing doesn't restrict body movement and performance.
- Moisture management – to ensure skin stays dry, thus minimizing:
  (a) evaporation from the skin which results in rapid heat and energy loss;
  (b) friction between clothing and the body and therefore reduced irritation.
- Waterproofness and breathability – for protection from the elements while maintaining a comfortable personal microclimate.
- Temperature control – buffering against temperature swings between periods of activity and rest.
- Light weight – to enhance performance and conserve energy as less weight is carried.
- High strength and durability – to protect the wearer and their clothes.

It is possible to combine any number of these properties in a fabric with good stretch and recovery. To produce a fabric with good elasticity that will make a good sportswear fabric it is important to take account of the interdependency of fibre, yarn construction, fabric structure and finish. Therefore, in practice, in order to achieve optimum performance, most high-tech fabrics aimed at the performance apparel markets feature two or more of these properties in combination. The two most important properties in creating a fabric for comfort (the most important characteristic of clothing for sports or fitness activities) are stretch and breathability.

10.2.2 Breathablility

The human body strives to keep its core temperature at 37 ºC. During physical activity, extra body heat is produced causing the nervous system to react by sweating. Sweat glands pump perspiration through pores, body heat is transferred to the sweat, causing it to evaporate and cool the body.

If a garment cannot ‘breathe’, i.e. transport moisture from the skin to the surrounding area, perspiration, in the form of water vapour, and excess heat from the body cannot escape. The wearer will experience clamminess as water vapour condenses on the inside of the fabric and body heat may be lost as wet fabric clings to the skin. This may cause discomfort and, in cold weather, chilling.

Using fabrics with better moisture transport means less energy is wasted trying to cool the body and the heart rate remains lower. This leaves more energy available for increased performance and endurance. This is an important consideration for all layers of clothing.

10.2.3 Breathable stretch

Coolmax® Lycra® is one of the best fibre combinations for next-to-the-skin sportswear, uniquely engineered to keep users dry and comfortable. Research conducted at Eastern Carolina University in 1999 substantiates the findings from a 1998 Brazilian study. Coolmax® is proven to dry faster than any other fabric and to thermoregulate the body. This is due to:

- its uniquely engineered cross-section that moves moisture quickly to the outer surface of the fabric
- the larger surface area of the fibre which allows faster evaporation to occur
- the more open fabric yarn structure which provides outstanding breathability
- the fact that the enhanced performance is ‘built into’ the fibre (rather than being a chemical finish) so it does not wash out over time.
- the Coolmax® fibre which absorbs significantly less moisture than cotton and other fibres.

Coolmax® fabrics keeps the wearer drier, cooler and better hydrated so the body does not have to work as hard on thermoregulation and heart rate remains lower, leaving more energy for enhanced performance.

- Coolmax® pulls moisture away from the skin and disperses it throughout the fabric and then dries that moisture faster than any other fabric. Unlike cotton, fabrics do not saturate or stay wet on the body, which helps prevent skin irritation, rashes or chaffing.

- Coolmax® is proven to help the body with thermoregulation. It cools the body by drawing heat generated moisture away from the skin. Infrared images of athletes show that the average temperature of athletes wearing Coolmax® is lower than when wearing garments made of other fabrics.
- Coolmax® improves hydration status during exercise. This is because Coolmax® keeps athletes drier and cooler than equivalent competitive fabrics and as a result the body does not have to sweat as much in an effort to cool itself naturally.

Coolmax® Lycra® is used in all types of next-to-the-skin clothing for activewear.

- In high-performance athletic apparel, top sports brands use engineered fabric constructions and garment constructions with breathable stretch fibres to maximize performance for top athletes. For example, mesh ventilation panels are incorporated in garments in critical locations to prevent the body overheating.
- Coolmax® is also increasingly used in gentler mind and body conditioning pursuits such as yoga.

10.2.4 Breathable waterproof stretch

Waterproof breathable technologies play a crucial role in maintaining wearer comfort during outdoor pursuits. Traditional waterproof garments are high on performance but make concessions to comfort and design. This is because waterproof garment design is constrained by the need to stop all water penetration, seams have to be taped, and flaps are required to cover exposed areas such as zips, pockets, hoods and elasticized cuffs. Waterproof breathable fabrics involve a trade-off between waterproofing and breathability.

Microporous coatings or laminates have individual pores that are bigger than the diameter of perspiration molecules but are smaller than those of raindrops. Water vapour can pass though the fabric but rain cannot. The membrane largely determines the performance of the fabric but the porosity of the outer and inner layers and the thickness of the adhesive also affect the breathability. The larger the pores of the coating, the more breathable the fabric but the less waterproof. The most important considerations are the application for which it will be used and the activity level.

Athletes' increasing demand for clothing with function, durability, fashionability, freedom of movement, quick drying and weather protection led to the creation of soft shell technology. Initially it was introduced in European Alpine skiing garments but it is now in broader, general outdoor markets such as hiking and climbing. The soft shell concept is based on balancing the conflicting goals of breathablity and weather protection with durability, to provide greater comfort for normal rather than extreme weather conditions. The definition of a soft shell varies from company to company but the common performance parameters include breathability, water repellency, wind resistance, abrasion resistance and the ability to stretch. While they are not waterproof, they have a high level of water and wind repellency. In addition, they can be equipped with further functions. Tests have shown that forgoing waterproofing, the moisture transport of the soft shell fabric proves considerably better and increases the feeling of well-being. This can be measured by lower skin temperature during active and rest phases and in the moisture absorbed by the fabric.

The soft shell effectively does away with the traditional layering system that utilizes fleece insulation and a heavy waterproof/breathable outer layer. Consequently, it reduces the weight needed to insulate and protect against the elements. It can combine three fabrics in one: an abrasion-resistant outer layer (often with a dirt-resistant finish), a middle layer that repels water without interfering with perspiration transport, and a soft inner layer of high volume for winter warmth or mesh for summer cooling dispensing with the need for additional lining.

In 1976 W L Gore and Associates introduced Gore-Tex, a waterproof breathable technology, which uses a microporous film of eFTFE finish that transformed the market for outdoor clothing. Today there are two main technologies for achieving waterproof breathable fabrics:

- Microporous coating or laminates in which individual pores are bigger than the diameter of perspiration molecules but are smaller than those of raindrops.
- Hydrophilic (non-porous), water-loving/moisture-drawing coatings or laminates are capable of absorbing water vapour from the inside of the fabric. The heat generated by the body inside the fabric creates molecular movement to drive water vapour down the polymer chains in the coating to the external face of the fabric. Fabrics with a non-porous membrane typically have three layers: an abrasion-resistant outer layer, a microporous membrane and a soft inner layer.

To make water-repellant breathable fabrics with stretch and recovery requires a base fabric with stretch and recovery and either:

- membranes with inherent stretch and recovery characteristics (typically hydrophilic), e.g. Aquator® which provides multi-directional stretch and recovery; or
- an advanced lamination technique that concertinas a non-stretch membrane up onto the base fabric giving the membrane mechanical stretch. This is generally one-way stretch only.

10.2.5 Bi-component stretch as an alternative to elastanes

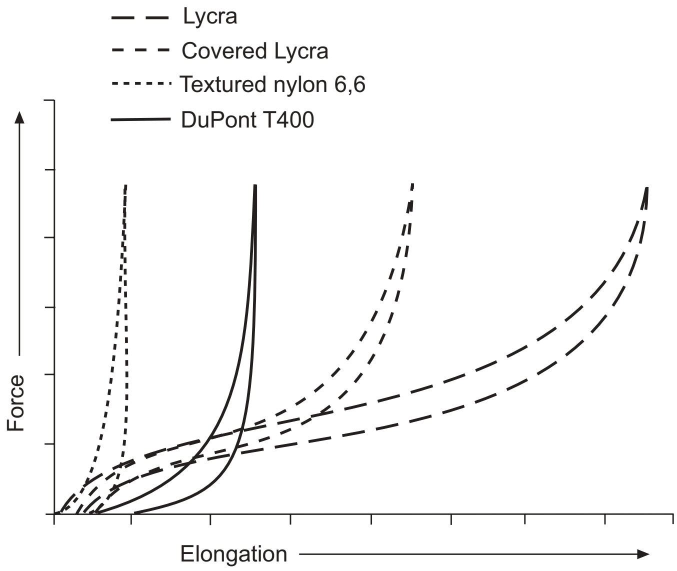
High-temperature dyeing or lamination can damage the stretch and recovery properties of some stretch fibres. Therefore in soft-shell outerwear where there is only a need for moderate comfort stretch, the new generation of bi-component stretch fibres can be considered.

Lycra® T400 is a new bi-component-filament yarn from Invista™ with stretch and recovery properties which position it between elastane and standard mechanically textured yarns.

It is created from polymers with different rates of shrinkage that are combined to give self-crimping, long-lasting stretch and recovery properties, unlike textured yarns that require an additional process to develop their crimp. The distinctive performance qualities of this new fibre have led the US Federal Trade Commission to grant the fibre a new generic sub-class elasterell-p. Similar registration of the new generic fibre in Europe is now proceeding.

This polyester-based yarn has the advantage that it is chlorine proof and can withstand bleaching and washing techniques which could not normally be used on stretch fabrics and still stretch after laminating (see Fig. 10.2).

Due to its flat stress strain curve, Lycra® T400 provides a fit that is more relaxed than traditional Lycra® elastane. Wearers feel less compressive force fighting against their movements in garments made of cotton Lycra® T400 blends than wearing the same garment made with lower stretch textured yarns. Garments have lasting stretch and recovery for ease of movement.



10.2 Stretch and recovery curves for bi-component yarns.

Lycra® T400 is used in higher percentages than elastane products, bringing a unique feel and enhanced performance (lower shrinkage, easy care and improved durability) to garments.

10.2.6 Coarse gauge knitwear

Consumer research confirmed that more than half the respondents from 14 countries wear the clothes they purchase for general fitness for other occasions besides sporting activities (internal research data). Many activewear brands are focusing on this crossover trend of sportswear as leisurewear, improving the fashion element and everyday performance of ranges to create clothing that transitions from the gym to relaxing at home. Knitwear has expanded beyond the traditional cricket, tennis or golf sweater to become an integral part of many of these ranges as a new, more fashionable cover-up than the fleece. Knitwear has also evolved, offering improved performance.

Knitwear of any fibre with the added ingredient of elastane provides ease of movement, resists bagging and keeps its shape, so garments retain their appearance even after repeated washing and wearing.

Further easycare benefits can be achieved using new man-made yarns such as Supplex® with Lycra®. It has the look and feel of cotton with a remarkably soft hand that withstands repeated wash cycles. Compared with cotton, Supplex® knitwear is more durable, lightweight and easy to care for (fast drying 40% quicker than cotton).

For extreme sports, where market research shows us that 64% of consumers look for outdoor clothes that offer protection benefits (internal research data), new fibres such as Cordura® are being introduced to knitwear. Combined with just 15% of new bi-component polyester stretch fibres, such as Lycra® T400, they offer new levels of lightweight durability and protection with comfort, freedom of movement, lasting shape retention, and dimensional stability.

Knitwear with elastic fibres for outdoor pursuits such as golf or tennis can easily be treated with Teflon® to repel water and resist dirt and staining.

10.2.7 Maternity active wear

Research suggests that women who continue to exercise throughout their pregnancy have easier pregnancies, and shorter and less complicated deliveries. This has motivated women to continue or even start exercise regimes during pregnancy. Potential profits in this sector have prompted a number of major activewear brands to enter the maternity activewear market. The best sellers have been the activewear garments that can be worn as workout wear and casual wear.

Traditional styling has changed with the trend towards body consciousness – the consumer is not covering up her pregnancy. She wants the same design elements and performance as before she was expecting, along with extra features for enhanced comfort, fit and support in clothes that will grow with them. Innovation in stretch fabrics has been especially important in delivering different types of stretch for fit and support in all the right places without unwanted constriction.

10.2.8 Leather with Lycra®

Skintight leather can be uncomfortable to wear because it does not stretch with your body. Some skins are softer than others and stretch naturally but they have no memory and after a while they all lose their shape, permanently bagging after multiple wearings.

Taking the core attributes of Lycra® (recoverable stretch) and working with tanneries, Invista™ has applied these benefits to leather, creating Leather with Lycra®. The tanning process and formulation are modified to create skins with considerably more of their natural stretch intact. A laminating process is then used to fuse a lightweight woven fabric with Lycra® content to the back of the leather skins. This processing means that the Leather with Lycra® can be made extremely lightweight. The Leather with Lycra® maintains the natural stretch of the leather and relies on the Lycra® in the backing fabric to provide the memory to ensure the garments or shoes keep their shape.

Garments made of Leather with Lycra® retain the characteristic look and feel of leather yet are better fitting, significantly more comfortable, washable at 30 °C and retain their original shape even after repeated wearing and washing.

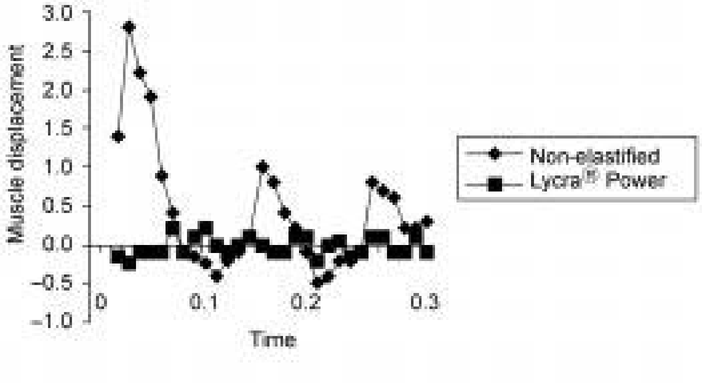
In sportswear, Leather with Lycra® is desirable because it can be moulded rather than requiring seams or gathers which can cause friction points. Additionally it does not sweat like synthetic alternatives and, because it does not sweat, it causes less friction and less irritation and more comfort. Commercial programmes exist in golfing gloves that mould around your hand, giving you a better grip, trainers for climbers and cyclists where the foot flexes a great deal, ballet shoes to produce a smooth point without leather gathered up under the sole, and in curved bicycle saddles and cycle shorts.

10.3 Enhanced performance

10.3.1 Lycra® Power[2]

The Lycra® Power concept originates from an understanding of the relationship between garment compression and muscle performance.[3,4]

A five-year research programme, conducted by exercise physiologist Dr William Kraemer and co-workers at the Center for Sports Medicine at Penn State University and sponsored by DuPont from 1991 to 1995, showed that all types of fatigue (strength, endurance and power) can be significantly reduced by



10.3 Diagram showing magnitude of muscle oscillation during exercising for Lycra® Power shorts vs. non-elastified fabrics.

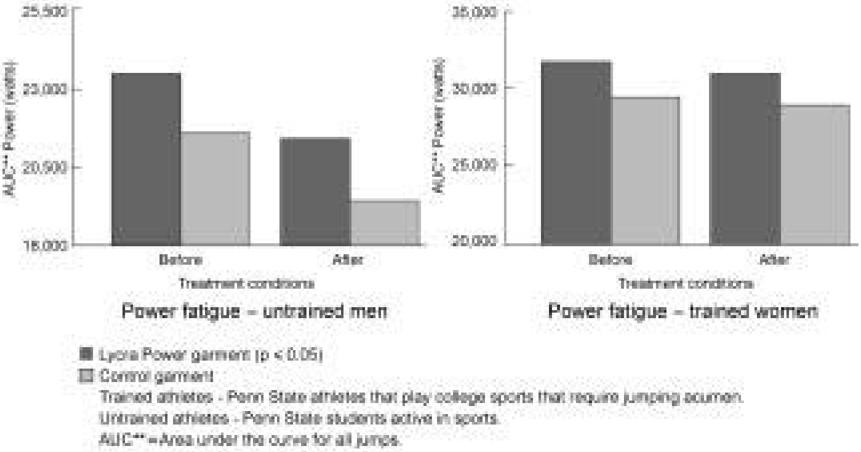
means of reducing degree of muscle oscillation as a consequence of wearing Lycra® Power garments (as seen in the example in Fig. 10.3). The findings also showed that an athlete's force and power production when wearing a compression garment were an average of 12% higher than with a loose fitting garment and that 73% of the athletes tested increased the accuracy of their movements (proprioception) or body positioning. Improvement in any of these areas can have a significant effect on overall athletic performance.

Kraemer and his colleagues tested dozens of college age men and women of different fitness levels, including athletes and non-athletes. The goal was to determine whether compression shorts, which are worn from the waist to just above the knee do more than make you feel and look good.

The tests centred on vertical jump performance as measured by jumping repeatedly on a force plate linked to a computer monitor. The intense laboratory study involved long-term subject familiarization, subject jump practice (without the certified garments), subject achievement of high test–jump/retest–jump reliability, and highly controlled laboratory conditions were used to uncover the benefits of the Lycra® Power apparel. A series of tests were administered that represented the span of fatigue types experienced by an athlete when involved in sport or recreational activities. Before and after creating the fatigue, the athlete's ability to produce power was examined.

Power fatigue

Power fatigue was tested by analysing repetitive jumping performance from ten consecutive maximal jumps on a force platform both before and after the subjects had performed ten sets of ten maximal jumps with thirty seconds' rest between sets. When the athletes wore Lycra® Power apparel, power loss related to fatigue dropped off significantly (see Fig. 10.4). Those wearing compression



10.4 Change in power fatigue for subjects wearing Lycra® Power shorts vs. non-elastified garments.

shorts had enhanced mean power output – 12% more on average, as much as 30% more in some cases. They had more stamina and were able to jump with more force and power.

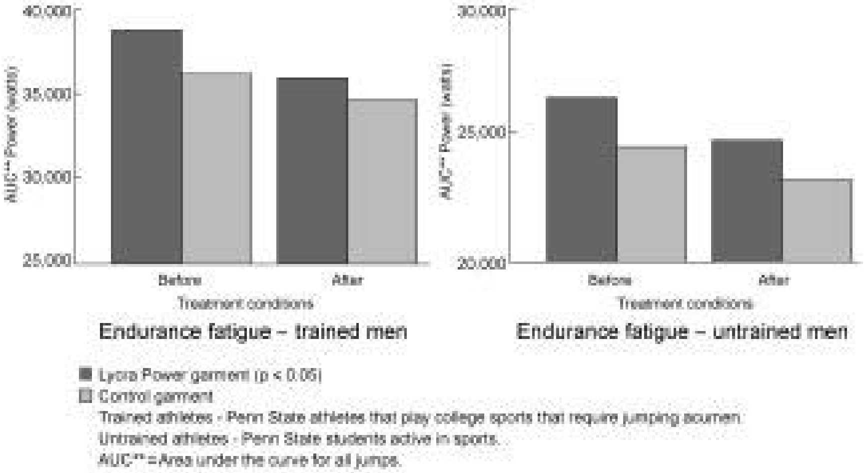
This has important performance implications for repetitive, intermittent, explosive sports such as American football, volleyball, basketball and soccer, where production must remain high in conditions of fatigue. The results were even more dramatic in the untrained than in the trained subjects. This offers interesting applications for performance enhancement with the beginner.

Endurance fatigue

Endurance fatigue was produced by a thirty-minute run at 70% maximum heart rate on a treadmill set at 2% incline. The effects of the Lycra® Power garment were determined by comparing the results of the laboratory jump analysis of ten consecutive maximal jumps on a force platform before and after the run. In both the trained and the untrained subjects endurance fatigue was reduced and there was significantly greater performance in those wearing the Lycra® Power apparel than those who did not (see Fig. 10.5).

Strength fatigue

Strength fatigue was produced by having the subject perform a strength task consisting of four sets of maximal weight, lifted for ten repetitions with one-minute recovery, on a supine leg press. The effects of the garment were determined by comparing results of the laboratory jump analysis before and after



10.5 Change in endurance fatigue for subjects wearing Lycra® Power shorts vs. non-elastified garments.

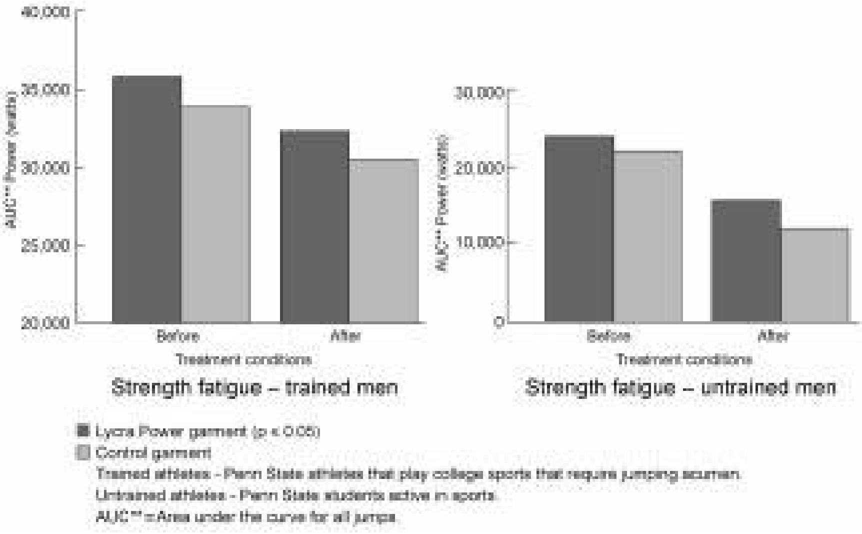
the strength task. The results, once again, revealed that the group wearing Lycra® Power garments showed significantly greater power production (Fig. 10.6).

Lycra® Power: conclusion

Whether you are a trained professional or work out on weekends, male or female, Lycra® Power apparel can improve your performance by as much as 30%, no matter what the sport or activity. Compression garments incorporating Lycra® Power have been shown to reduce muscle fatigue and boost athletic performance and the staying power of muscles by means of enhanced proprioceptive ability (the ability to sense change in position and physical tension in the muscles) and reduced muscle oscillation.

The support provided by the compression shorts reduces muscle vibration (oscillation or unwanted movement), by fortifying the thigh muscle against the shock waves and vibrations caused upon landing impact by such activities as running and jumping. Muscle vibration is a major cause of muscle fatigue which limits performance by causing a reduced efficiency in the nerve-firing ability to control the muscle. The most visible effect is it interferes with the body's proprioceptive ability.

Compression shorts help your kinesthetic sense, the sense of where you are and how your body is moving and positioned in space. The fabric does this by exerting subtle pressure on the nerve receptors in the skin, muscles and joints. This heightened proprioceptive awareness enables athletes to perform better, especially when they are tired, because they are better able to maintain proper



10.6 Change in strength fatigue for subjects wearing Lycra® Power shorts vs. non-elastified garments.

form and technique and thus move the body more efficiently. In the study, compression shorts helped 70% of subjects increase the accuracy of their body movements and positioning.

The study concluded that the fabric and design characteristics of the different garments tested appear to produce a similar outcome in the test performance of the wearer. Therefore a range of fabrics and garment styles may afford similar biological/psychological mechanisms for enhanced repetitive performance. But not every compression garment will enhance performance. The type of compression and the amount of Lycra® can affect the quality of the response. To obtain Lycra® Power certification, garments must follow certain guidelines. This ensures garments have enough compression to enhance performance while retaining enough stretch not to compromise mobility. The guidelines cover materials, construction and garment usage.

Lycra® Power compressive shorts are being used extensively in the world of sports in basketball, volleyball, football and cycling.

10.3.2 Garment engineering[5]

More recently, Invista™ launched a garment engineering programme specifically focused on providing the answers to comfortable fit that market research consistently shows to be a top priority for consumers. The programme aims at combining effective human sizing knowledge with shaping and comfort research and utilizing Invista's latest Lycra® developments in order to achieve optimal garment solutions.

To fully understand the body's interaction with clothing, metrics need to be defined that can be quantified. Comfort[6] is easiest to quantify using metrics based on forces. Traditionally the response of garments to stretching and body movement has been characterized by a stress/strain curve of a component yarn or resultant fabric. Measuring the real force exerted by the garment on the body is difficult because different garment shapes can exert very different forces, and the exact values depend on the consumer size and shape. Additionally, comfort and performance are functions of movement and local body position.

> In the absence of motion many garments can appear to be equally comfortable; but as soon as movement is involved, the differences can be significant. Therefore force needs to be measured over the course of the movements that the garment will be typically used for.
>
> During movement, different parts of the body stretch very differently; and the amount of stretch can be very different in each direction. An example of this is the draping around the knee when the knee is bent since the high stretch area along the leg is near a low stretch area around the leg. A comfortable garment must dynamically follow this non-uniform stretch field during movement.

In collaboration with leading institutes, Invista™ has developed highly sensitive dynamic force sensors. Placed between the garment and the wearer at particular points on the body, they can directly measure the forces exerted by garments on the body. A schematic diagram of this device is shown in Fig. 10.7. The sensors can detect a wide range of forces with excellent resolution and report the results in real time allowing for dynamic measurements.

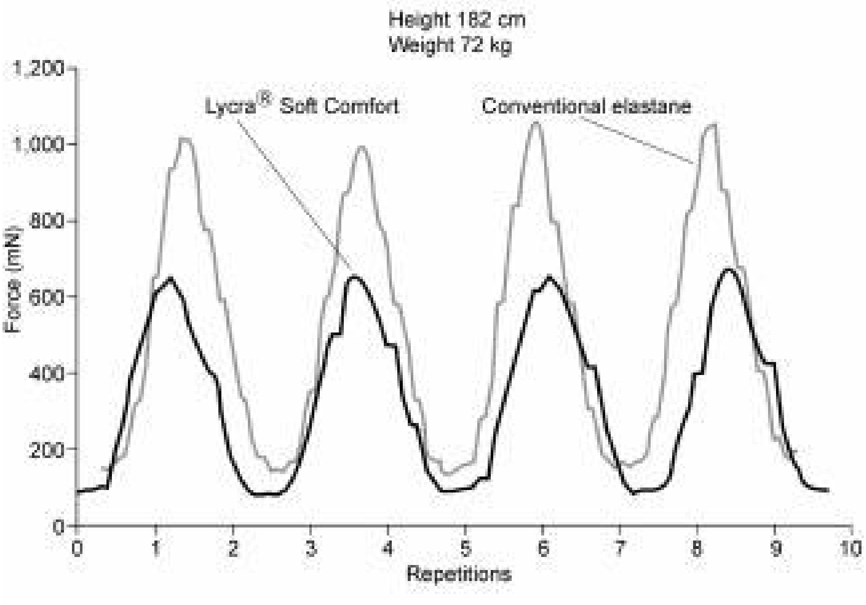
The sensors can chart the pressure range acting across the total muscle area to highlight pressure hot spots. And you can take an average of the pressures measured by all the sensors at each point in time to give a dynamic assessment of the comfort during different exercises.

Figure 10.8 provides an example of the force response for cycling shorts when the wearer is bending. In this case the wearer experiences lower force or resistance when a garment containing Lycra® Soft Comfort is stretched beyond the wear elongation. This results in a garment which yields or 'gives' more easily when required to stretch with the body during movement, hence providing a greater freedom of movement compared with the same garment containing a conventional elastane yarn.

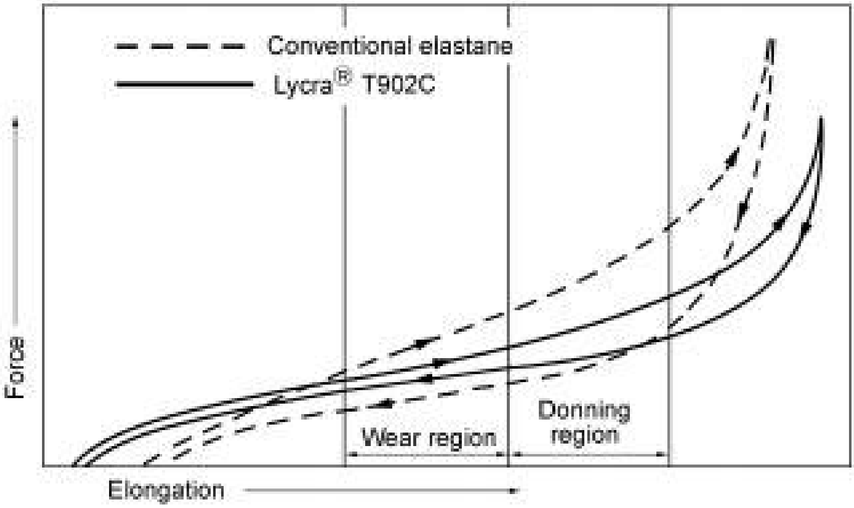
Lycra® Soft Comfort

The Lycra® Soft Comfort family of yarns with 'soft stretch' has been specially designed to reduce resistance to movement compared with traditional elastanes while at the same time providing support and fit. Lycra® Soft Comfort yarns are especially suited to garment applications requiring comfort with controlled contouring or shaping.

10.7 Schematic diagram of the dynamic force measurement device with sensors (Source: DuPont).



10.8 Dynamic force comparison of cycle shorts with conventional elastane and Lycra® Soft Comfort. Peaks indicate garment force or resistance during bending.



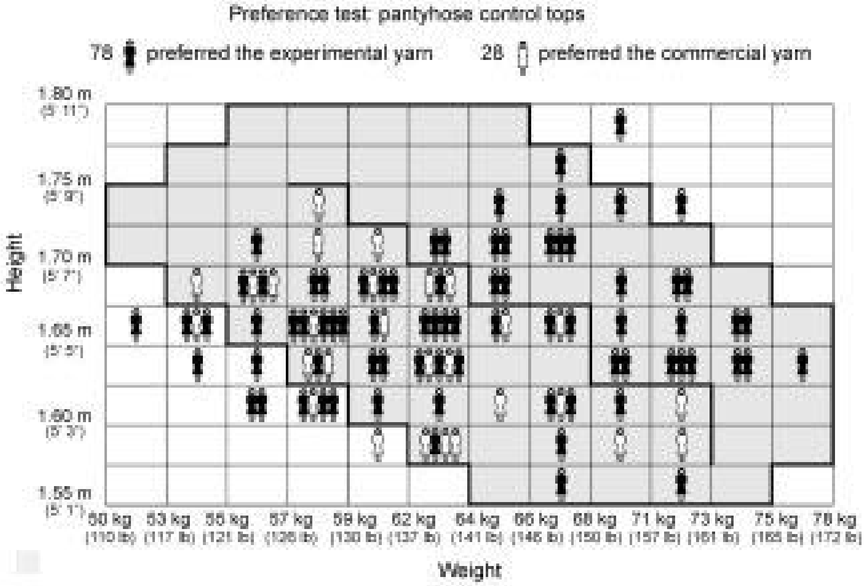
10.9 Stress/strain curves for a Lycra® Soft Comfort yarn and conventional elastane.

The traditional stress/strain curve (Fig. 10.9) shows that less force is required to stretch Lycra® Soft Comfort yarns than conventional elastane; however, the recovery power of Lycra® Soft Comfort is greater than conventional elastane throughout the wear and donning regions. For consumers, this means that Lycra® Soft Comfort garments should be easier to stretch during body movement but garments also fit and shape firmly. The overall flatness of the Lycra® Soft Comfort stress/strain curve should give rise to a more consistent fit across size ranges.

Numerous wear tests with Lycra® Soft Comfort yarns have been carried out to investigate whether the lower resistance to movement leads to added comfort perceivable to the wearer.

Results from a 108 consumer preference test are shown in Fig. 10.10. In this test, Lycra® Soft Comfort yarns have been used in the pant part of the garment. The figure shows that there is an overall marked preference (ca. 3:1) for the garments containing Lycra® Soft Comfort, indicating that the added comfort and stretchability of these garments is being felt by the wearer. One further conclusion from this test is that preference appears stronger at the extremes of the size range thus indicating that these garments are better fitting across the breadth of the size ranges.

Further wear test studies have shown that during exercise a garment with Lycra® Soft Comfort demonstrates a dramatic decrease in pressure on the body, in contrast to the limitations of generic elastane. Additionally, these tests have shown that the degree of preference is dependent on the decitex of yarns used and overall level of shaping or compression of the garments in question.



10.10 Results of preference wear test for garments containing Lycra® Soft Comfort and conventional elastane.

Shaping

Shaping is harder to quantify because it lacks exact definition or metrics. Additionally, to quantify a 3-D object, 3-D tools are needed. Ibrahim *et al.* did pioneering work on the relationship between fabric stretch to anthropometric requirements and garment performance in the early 1960s.[1] He measured shaping at the critical strain areas of the body by drawing a series of lines on the skin at regular intervals and measuring the changes in skin dimensions that took place with critical body movements. Today, DuPont is able to use Laser technology in a 3-D body scanner to acquire anthropometric data for shaping research. With the scanner's 2 mm resolution in each direction it is possible to assess and quantify the exact changes of body shape, comfort and fit during any variety of movements. The shaping differences between garments can be visually illustrated and quantitatively measured so that individual needs can be addressed in an optimal manner.

Garment engineering conclusion

Utilizing the information from the 3-D body scanner, the dynamic pressure sensors and the newest concepts in fibre and construction it is possible to deliver superior comfort and performance in athletic apparel. The garment engineering methodology can be applied to all types of garment, both close to and away from the body.

10.3.3 In footwear

Consumer market research has demonstrated comprehensively that consumers are ready for Lycra® in their shoes – over 40% already believe that shoes with Lycra® will be better.

Applying the principles of dynamic garment engineering to feet and shoes, supported by wear tests and market research, Invista™ has developed technologies to ensure that the enhanced fit, comfort and freedom of movement benefits of Lycra® are also available in footwear. In particular, Invista™ has developed a set of principles relating to shoe upper material selection (applicable for fabrics, leather and synthetic leather), as well as shoe construction.

Fundamentally, the patented technology is built on an appreciation of foot dynamics. Through careful material selection and slightly adjusted standard shoemaking techniques, shoe uppers can be made to adapt to changes in volume experienced by the foot. Volume changes occur during movement, and feet tend to swell throughout the day. Excessive pressure is at best uncomfortable, at worst debilitating and, for people with certain illnesses, potentially life-threatening. Insufficient support, especially in a sports shoe, leads to a sense of insecurity, a lack of foot stability and, in the worst case, injury. Defining the upper and lower limits of force over a typical elongation/volume change range has allowed Invista™ to develop the Comfort Zone for shoes. This relatively simple concept is helping tanneries, synthetic leather makers and fabric weavers and knitters achieve better engineered materials which, when applied with the right shoemaking techniques, result in better performing shoes.

10.3.4 In football

In football, Kappa introduced the ‘Kombat 2002’ for the Italian football team shirts for the 2002 World Cup. The stretch jersey Nylon Lycra® top was designed to prevent players being stopped by shirt pulling. The elastic performance of the shirt allows the players an extra 50 cm of movement to help them to complete their action even when held by an opponent, as well as allowing the referee to clearly spot infringements.

Adidas launched its Dynamic Layering Concept (DLC) for football kit for the World Cup in 2002. The DLC uses Lycra® Power in ultra-lightweight, second skin apparel with moisture management. The apparel in the range is separated into two integrated layers: a skin layer and a protective layer. The skin layer consists of the skin jersey, power short and power sock. The protective layer comprises an Outside jersey, the Protection Short and the Team Protection Sock. The Power Short uses Climalite, for moisture management, with Lycra® Power for all the benefits which have already been highlighted in Kraemer *et al.*’s study (section 10.3.2). The short’s protection layer is also treated with Teflon® for an anti-soil and anti-stain function.

10.3.5 In rugby

The Rugby World Cup in 2003 saw the traditional rugby top replaced by various skintight shirts with elastane. The new shirts were designed to keep the players cool in heat and humidity: they were lightweight, using a fibre with moisture management properties to draw the sweat away from the body and mesh ventilation panels to prevent overheating. To make players harder to grasp in a tackle the traditional collar was replaced by a loop neck construction and the whole shirt was made skintight by the incorporation of elastane. Nike went a step further for the England top using a woven rip stop construction that would be harder to grip than a skintight stretch jersey construction. The power of Lycra® used in the construction caused it to snap back when grabbed by the opposition.

The hooker, props and the second row who need to get hold of their own team mates in the scrum and lineout had different shirts from the other players. The All Blacks therefore did not make their forwards' tops as close fitting to help binding; England had specially designed gripper print panels placed at the front, side and shoulders to provide extra friction in scrums and lineouts.

10.3.6 Hydrodynamics in swimming

Top swimwear brands have taken the benefits of Lycra® Power and the new generations of Lycra® that deliver enhanced chlorine resistance, comfort and durability, and have gone further, incorporating hydrodynamic ergonomics into fabric constructions and garment engineering. Through these techniques, brands aim to find materials for full bodysuits that are faster than skin by reducing surface resistance. Some of the new suits claim to have the potential to enable athletes to improve their times by up to 3%, which could be the difference between a gold medal and fourth place. It is worth noting that it is tricky for a coach to get as little as 1% improvement from a top athlete.

Speedo holds the dominant position in the competitive swimwear market. It claims that more than 80% of major championship medals have been won in recent years by competitors wearing its products. Speedo developed its S2000 Fastsuit for the 1992 Barcelona Olympics, designed to reduce surface resistance by up to 15%. Various competitors wearing it broke four world records and won seven gold medals. The suit was superseded at the 1996 Atlanta Olympics by the Aquablade fastsuit which had a striped surface to create spiraling vortexes, increasing the water flow next to the body, reducing resistance and improving glide time speed. For Sydney in 2000, Speedo took inspiration from sharks to design the fabric for its new suit FastSkin. Like humans, sharks are not naturally hydrodynamic. But microscopic tooth-like scales on their skin enable them to swim quickly by channelling the flow of water and producing miniature eddies around the shark, reducing friction and drag as it moves though the water.

Speedo has recreated this effect in a swimsuit with vertical resin stripes, containing V-shaped grooves, superimposed on it. The grooves effectively suck water close to the body and hence reduce drag by up to 7.5%. For Athens, Speedo have launched the FastSkin II. This mimics the shark's varying denticles by using different fabric on different parts of the body, where the first FastSkin used one fabric throughout. Seams have been moved for added comfort and variations have been developed for men and women, as well as stroke-specific suits.

Adidas took a different approach to swimwear using its Jet Concept silicone riblet technology to minimize drag. This technology is based on the aerodynamics of producing lift from a moving contoured surface, panels extending from the underarm to the lower back channel water smoothly over the body to reduce the dead water that sits upon the swimmers back. Swimmers believe this raises legs higher and achieves a body position closer to the horizontal.

10.3.7 Aerodynamics for track and field and cycling

The Sydney Olympics in 2000 also saw the introduction of Nike's Project Swifts, and Swift Suit to track and field, with Cathy Freeman winning gold in the 400 metres. Then, in 2002 for the Winter Olympics in Salt Lake City, the Swift Skin was introduced to speed skating and the Swift Spin bike suit was introduced for the Tour de France. Like the swimsuits, they were all stretch body suits designed to help maximize performance using the principles of muscle compression and aerodynamics.

Nike tested over fifty fabrics for wind resistance, elasticity, warmth and breathablity to choose the final six fabrics that it used in the Swift Skin for the speed skating. The six fabrics used in various places on the suits are coated stretch fabric, textured stretch fabric, stretch-vent fabric, textured mesh fabric, stretch tricot fabric and silver speed fabric. The fabrics for the Swift Skin and the Swift Spin both act in a similar manner to the dimples on a golf ball by speeding the air flow over the surface.

The same process is applied, in each case. The best performing fabrics were combined using Nike Zoned Aerodynamic Technology – an advanced form of body mapping. This is a process that scientifically determines where on the body to place different fabrics for the maximum benefit, and where they work strategically and harmoniously with the athlete's natural motion in relation to air flow. Direction and placement of necessary seams that cannot be eliminated are critical. They are positioned in line with the air flow direction or completely out of the way to improve the aerodynamics and to reduce creasing, therefore minimizing the amount of trapped air which would slow the athlete. Additionally, items such as gloves and shoe/skate covers would be worn with the Swift Spin, Swift Skin and Swift Suit to improve aerodynamics.

10.4 Performance, recovery and well-being

10.4.1 Enhance performance and prevent injury

Wacoal Sports Science has a range of anatomically correct performance apparel called CW-X Performance Conditioning Wear. The range has been designed for high-energy outdoor sports using built-in compression panels of bi-stretch Coolmax® Lycra® to support key muscle groups and joints during physical activity.

The range was developed after extensive research on kinesiology (the study of human form and movement, particularly how the body moves and how points of pressure and support aid that movement) at the Wacoal Human Science Center in Japan. Researchers found that of all sports-related injuries, the knee was the most commonly affected. Based on this understanding, they developed CW-X to support the muscles that support the body, aiding muscle movement and lessening fatigue.

CW-X's patented Conditioning Web acts as a built-in taping system to deliver precise, targeted support, binding muscles and ligaments together. It supports joints and muscles at critical points to enhance performance and help prevent injury. The web consists of engineered support panels sewn into the garment to create gentle pressure around the knee joints, quadriceps, hamstring and calf muscles to protect them from strain and improve athletic performance from warm-up to recovery.

With this support, joints and muscles work in unison and are therefore more efficient. They are less prone to injury or the effects of muscle vibration. Energy and circulation increase.

Pulse frequencies of the muscles were measured electromyographically. Unsupported and partly supported legs both show frequency decrease during exercise – indications of fatigue. Legs supported by CW-X showed negligible frequency decrease. Athletes were tested doing power exercises. Those wearing CW-X showed significantly lower fatigue through all phases of exercise, from warming up to cooling down.

The range is particularly beneficial for quadriceps intense sports such as skiing, snowboarding, cycling and running.

10.4.2 Energising Socks

Gradient compression stockings have been used for over fifty years for the treatment of chronic venous insufficiency.

Blood is pumped around the body through arteries, but returns to the heart in the veins. In the lower legs this blood is actually helped back up to the heart and lungs by the calf muscles which act as a pump during exercise, and by one-way valves in the veins, which prevent the blood from dropping back down with gravity. Medical compression hosiery is designed to provide the extra support leg veins need by ensuring the appropriate pressure to return blood to the heart. Typically, the compressive force is greatest at the ankle and diminishes over the calf to a minimum at the top of the thigh.

Studies at Amsterdam University Medical Centre have shown that, over the calf, stockings with low gradient compression have an energizing effect on legs of active healthy people. They are effective in reducing fatigue symptoms – with up to 37% reduction in swelling of the lower leg. These benefits are realized in Lycra® LegCare hosiery and Energizing Socks with Lycra®, both developed in line with Invista's technical guidelines for the required compression profile and elasticity for perfect fit and functionality.

Adidas has combined the benefits of gradient compression and Lycra® Power compression in its Power Sock. It applies graduated muscle compression to exert the maximum level of compression at the ankle and reduce the compression progressively over the calf. This graduated compression is said to improve blood circulation and reduce muscle vibration. And the compression is designed to enhance proprioceptive awareness and reduce muscle fatigue, as well as optimizing oxygen use and shortening recovery time.[7]

10.4.3 Performance and recovery

Skins Ultimate Body Technology was developed by sports physicians in Australia following the Penn State study specifically to assist athletes to recover faster from strenuous exercise.

The brand claims to have a range of garments that include and go one step further than the static compression benefits highlighted in the Penn State study. The body-moulded garments made from microfibre nylon and Lycra® are designed to give mild graduated compression to the muscles of the lower body and are engineered to provide support and alignment to those muscles. This enhances circulation and blood oxygenation; improved oxygen levels will provide you with more energy. These garments will continue to work on the body after activity has stopped, aiding the athlete's recovery.

All sports involve the expenditure of energy and the subsequent build-up of lactic acid (which causes soreness/fatigue) in the operative muscles. This is why cooling down after exercise is such an important part of the post-exercise regime. The ability to maintain adequate circulation plays an important part in the recovery phase by enhancing the elimination of built-up lactic acid.

Additionally, as muscles get tired they become less disciplined and lose their alignment, increasing the risk of injury. The support and gentle compression helps keep muscles in line and at optimum position to reduce the risk of injury during exercise.

10.4.4 Textronics

Stretch fabrics enable comfortable second skin garments to be made. This type of clothing, in intimate contact with the body, can be used to incorporate textronics to monitor the technique and form of athletes.

Textronics combines textile technology with electronics. A clear example of this today can be found in Australia, where an intelligent knee sleeve has been developed to help prevent sporting injuries by actually telling athletes when they have landed in the wrong way. But the possibility of creating conductive fibres and yarns is not too far off. Garments made from conductive fabrics in intimate contact with the body could be used to monitor the athletes and improve their form in training and also enable coaches to monitor players' fatigue and injuries from the side lines.

10.4.5 Well-being through clothing

Elastane allows garments to move with the body in a way that enhances delivery of body care benefits. Research conducted in the US and Europe in 2003 shows a universal interest in the concept of deriving well-being benefits through clothing. Benefits of greatest interest are freshness and a massaging effect (internal market research).

To enhance the sense of well-being, nothing comes close to the importance of freshness. Physically, freshness is about controlling bacteria, moisture and body oils that can cause malodour. Emotionally, freshness is about how one smells, looks and feels. Freshness is often ranked first or second by both men and women as a benefit that they would seek and be willing to pay more for. With intimate contact it is possible to deliver freshness benefits in clothing through specially engineered yarns or textile finishing treatments.

A massaging effect can be created by going one step further than graduated compression. Using powerful elastanes on seamless machines, constructions with pronounced dimples or ribs can be created in specific locations on the body. These dimples/ribs create a massaging action. The energizing effect can be enhanced by the addition of vitamins and minerals to the fabric such as sea kelp which is known to stimulate circulation at the skin's surface while imparting nearly thirty minerals that nourish the glands and help balance the body's metabolism.

10.5 Conclusion

Technological advances in fibre and fabric innovation are moving faster today than ever before and leading the way is sportswear. The competitive nature of sport has bred a competitive apparel market with brands competing for new innovations that will enhance an athlete's performance and become the latest consumer trend.

10.5.1 Elastification

Elastic textiles using elastane enable the delivery of much more to sportswear than stretch and recovery.

Combining the efforts of fibre, fabric and garment engineering enables the creation of compression garments that deliver performance improvements. This was first proven by the Kraemer study at the Center for Sports Medicine at Penn State University in the US, with athletes wearing Lycra® Power garments showing performance improvements of as much as 30%. Wacoal Human Science CW-X Performance Conditioning Wear subsequently offered further evidence of the benefits of compression supporting the muscles to enhance performance, lessen fatigue and even help prevent injury.

In addition to its role in compression garments, elastane is essential for the creation of second skin garments that move with the body. Garments that maintain intimate contact with the body can be used to deliver well-being benefits such as freshness or could incorporate textronics to monitor technique and form.

10.5.2 Driving demand

There are several key factors that are driving demand for elastification and the advance of technology in sportswear. The first of these is demand from the athletes themselves. Depending on which sport is practised, athletes look for sportswear that offers function, durability, fashion, comfort and freedom of movement.

The second key driver is the rise of sportswear's cultural significance and fashion identity. This has been affected by a variety of factors: football fans who have not only adopted football wear but also golf clothes and tennis shoes; the marketing and intensive visibility of sport; the ever increasing global reach and interest in events such as the Football World Cup; the increase in the number of women who follow sport, and finally the position of sport in street culture.

10.5.3 Growth segments

The activewear business is continuing to grow, but price deflation is present, although not as bad as in apparel overall. Because of the price deflation a number of brands are focusing on licensed sportswear and high-performance apparel. Three segments showing the best growth are licensed sportswear and the two consumer groups that have been participating more in sports in the past decade: women (who are especially keen on aerobic and fitness activities but whose participation in outdoor activities has risen sharply) and the higher age groups.

Women purchase more than 80% of all fitness clothing, buying 93% of women's, 89% children's and 55% men's fitness clothing. They account for about 45% of sports apparel sales value for their own use, versus men who account for only 36% and children with 19%. Women's sports have more participants than ever before, and this trend is forecast to continue. The female consumer is demanding crossfunctionality, with clothes that can be worn to the gym, for yoga, walking or shopping. Women have an established positive attitude to stretch and Lycra®: 66% think they look/feel better in clothes with Lycra®, 61% think it is worth paying more for clothes with Lycra®, 68% of females globally associate Lycra® with performance, 71% associate Lycra® with high quality and 89% associate Lycra® with comfort (internal research data).

Men are more likely to buy apparel for most team sports, particularly football. Men's awareness levels of Lycra® is only slightly lower than women's but preference levels have trailed substantially. However, significant for the future of elastification, research shows that 50% of men globally now agree that stretch makes clothing more comfortable. Combine this fact with global research that found that 20% of consumers own a jersey or strip that is a replica of their favourite sports team or athlete's kit, and it is apparent that this licensed clothing is a significant growth area. The advent of more form-fitting shirts in rugby and football should very quickly filter down to become the norm for sports fans, growing elastification.

No consumer purchasing analysis can ignore the older consumer market today. As the number of people aged 45 plus continues to increase, their purchasing power and impact on the sportswear market is growing. This group is likely to be more conscious about health and have the time and money to participate in fitness and outdoor activities. US statistics have found that the number of people aged 55 plus who are members of health clubs has increased by 158% and three in ten Americans aged over 55 exercise regularly; this is proportionally higher than that of any other age group. Research also shows that this group favours comfort in fitness clothing above all else. Good news for elastification, with 71% of women and 57% of men over 50 considering stretch makes clothing more comfortable.

10.5.4 Future market growth

The promotion of and desire for a healthy lifestyle is a cultural trend that is here to stay, and sports apparel will continue to benefit from this. Sport is an early adopter of high-tech fabrics, and because of its cultural significance today these fabrics will filter down to the broader apparel market. Elastification plays an important role in many technological developments and therefore demand will remain high as this cycle continues to drive the sportswear industry.

Developing new technologies and products for fitness clothing benefits the market for elastification in two ways. Firstly, consumer demand is maintained because they want to wear the latest gear, and will purchase better performing clothing even though their existing clothing may still be serviceable. Secondly, most new technologies come with a premium price, which helps drive up the market.

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10.7 Notes and references

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