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A REVIEW OF FOOTWEAR FOR COLD/WET SCENARIOS PART 2: SOCKS, LINERS, AND INSOLES (U)

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL NOTE 93-28

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ABSTRACT

Presented herein is the second of a proposed multi-part review on footwear. This report deals mostly with the materials and their properties making up the layer or layers of footwear between the skin and the boot, i.e. socks and removable insoles and liners. Aspects of these elements of footwear are related to various military requirements, and as in the first part of the review, attention is drawn to the fact that in meeting these requirements, solutions conflict. A discussion on possible compromises follows, leading to the recommendation that in order to develop proper footwear for the military, a very carefully written statement of requirement is necessary.

RÉSUMÉ

On trouve ci-après le deuxième volet d'un examen portant sur les chaussures, prévu en plusieurs étapes. Le présent rapport porte surtout sur les matériaux (et leurs propriétés) qui forment les couches se trouvant entre le pied et la chaussure (ou la botte), par exemple les bas et les semelles et coiffes amovibles. Ces éléments sont analysés en fonction de différents paramètres militaires, comme dans le cas de la première étude. Par contre, dans la présente étude, on souligne que les solutions qui répondent à ces besoins militaires soulèvent des préoccupations. On présente une discussion sur les compromis possibles et formule la recommandation suivante : si l'on veut développer des chaussures adéquates pour les militaires, il faudra rédiger un énoncé de besoins très précis.

EXECUTIVE SUMMARY

This report deals mostly with the properties of the layer or layers of footwear between the skin and the boot, i.e. socks and removable insoles and liners. It is assumed that cold (-10°C to +10°C) and wet conditions are currently perceived as those against which protection should be improved in the near future. This review has summarized a number of representative studies that have been done on this subject in trying, at least in part, to meet the lengthy list of footwear requirements.

Because the sock, liner and insole are each worn inside the boot, many of the requirements dealing with protection of the foot from the external environment are not applicable. It is suggested that the major requirements of socks are insulation, blister protection, and moisture transport. The requirements of insoles are insulation and shock absorption, and the requirements of liners are insulation protection and in the case of the mukluk, more insulation. With the proper choice of materials, and/or design, and/or construction, there do not appear to be too many conflicting solutions. Within the confines of a boot, design options are very limited, but even here there is room for some compromise. Because the sock is right next to the skin on the weight bearing foot, even small compromises to its composition or design may make large differences in mobility.

Compared to the boot, not much research and development has been done on the subject of socks and removable insoles and liners. Because there are so many scientific and technological aspects to protecting the foot, an ongoing research and development program on footwear is required, to provide advice to the soldier with respect to what footwear will perform best in the many different scenarios he or she may face world wide.

With respect to the development of new footwear, priorities are required. It is recommended that the Canadian Forces requirements and/or deficiencies in army footwear be critically reviewed, and a new set of requirements be written. Essential and desirable aspects of footwear must be separated, and ranked in order of importance. This document would then form the basis of the ongoing research and/or development program set up to address these concerns.

1.0 INTRODUCTION

"Maurice, Count de Saxe (1696-1750), Marshall General of the Armies of France, said: 'the Germans who make their infantry wear woollen stockings, have always great numbers crippled, from blisters ulcers and all sorts of inflammatory humours in their feet and legs, and wool is venomous to the skin; besides they soon break on the toes, and remaining wet upon the feet, presently rot away'.

It is doubtful whether the above remarks, would be treated with any seriousness today. Nevertheless, in our own short experience, we have seen soldiers feet which would probably have been better off without the socks they were wearing. Speaking generally, footwear research tends to neglect the sock at the expense of the boot. It is a matter of some concern that the cost of the army issue sock, is considered by many servicemen to be so prohibitive, that they turn to the civilian market for cheaper socks, whose quality may be so inferior as to nullify the issue of a good boot."

These words were first submitted in 1954 and later published in 1960 (1), and still seem to be as true today as they were then. Many authors and researchers and developers working in the field, suggest a list of footwear requirements important to a particular scenario, and then attempt to meet those requirements, for the most part, with the design of a boot alone, without further addressing the problem of the design of appropriate socks to go with the boot. This is evidenced by the vast literature available on boots, and many fewer references dealing with socks.

It is believed that within the Canadian Armed Forces, the standard issue grey wool sock dates back to the second World War in design and make up. Today, newer materials, newer blends of fibres, and newer designs and construction techniques can go a long way to meeting more modern requirements. Maybe it is time to take a new look at the sockwear philosophy.

This report deals mostly with the properties of the layer or layers of footwear between the skin and the boot, i.e. socks and removable insoles and liners. It is assumed that cold (-10°C to +10°C) and wet conditions are currently perceived as those against which protection should be improved in the near future. Aspects of the elements of footwear mentioned above are related to various stated military requirements, and attention is drawn to the fact that in meeting these requirements, solutions conflict, and compromises are in order.

2.0 THE REQUIREMENT

The previous review in this series of footwear concentrating on the boot (2) listed a collection of requirements for military footwear for cold/wet scenarios. The items were prepared for the most part from US, UK, and Canadian sources. In order to facilitate easier comparisons and discussions, the list is repeated here.

1. Footwear must maintain and enhance mobility and thus:
   a. have good traction on a variety of surfaces (i.e. from loose sand to slippery rocks) over long distances;
   b. be light weight and not bulky;
   c. be flexible and yet have good support while carrying heavy loads over irregular surfaces;
   d. have a sole design to which foreign matter does not adhere;
   e. be properly sized;
   f. be balanced; and
   g. not present or intensify existing hazards (i.e. be non-toxic and not cause dermatitis or complications to wounds or burns or cause blisters).

2. In cold climates footwear must
   a. be insulated and protect insulation in case of puncture;
   b. be waterproof;
   c. be able to absorb and transmit sweat vapour (sweat accumulation is to be avoided in cold weather);
   d. be water vapour permeable or adequately ventilated; and
   e. dry and/or drain rapidly.

3. Footwear must protect against
   a. ballistics;
   b. flame/heat;
   c. flora and fauna;
   d. terrain irregularities;
   e. falling objects;
   f. NBC (nuclear, biological, chemical) threat e.g. protect against all CW (chemical warfare) agents for up to 24 hours, be easily and reliably decontaminated, resist adhesion of radioactive dust, and protect against thermal radiation levels up to 15 $cal/cm^2/sec$;
   g. antifreeze;
   h. POL (Petroleum, Oil, Lubricant);
   j. battery acid;
   k. spikes;
   l. wind;
   m. degradation by sea water, human sweat, or microbiological agents;
   n. blast; and
   o. in some cases, static electricity buildup.

4. Footwear must be well constructed and thus
   a. have reliable closures;
   b. be strong, i.e. not come apart (strong seams and adhesives);
   c. be durable to resist abrasions and bruises from rocky outcroppings (wear resistant);
   d. be repairable;
   e. have a long shelf life without deterioration in any environment;
   f. be undetectable either by visual (camouflage) or IR surveillance;
   g. be shrink resistant;
   h. form a safe seal between the boot and the trouser; and
   j. be easy to don/doff even while wearing heavy gloves.

5. Footwear design must consider personal hygiene i.e. the layer next to skin must be easy to remove and wash.

6. Footwear must be compatible with operation of land/sea/air vehicles and equipment.

7. Footwear must be compatible (integrate) with other combat clothing.

8. Footwear must be easily made (capable of mass production).

9. Footwear must be silent in use.

10. Footwear must be affordable.

Although the requirements are in some cases directed mainly at the outermost layer of footwear (the boot), it should be noted that a fairly large number of the requirements can equally apply to the layer(s) of footwear between the foot and the boot.

With very few exceptions, protecting the feet against cold and wet scenarios is cited as being the most important requirement for maintaining mobility in the military because of the serious cold injuries which can result from the lack of this protection. In Part 1 of this series of reviews on footwear (2), some statistics dealing with military cold injuries (trench foot, frostbite, etc.) are presented, showing a high loss of days of active duty due to these injuries, even as late as the Falklands War in 1982.

The current review of the layers of footwear between the foot and the boot, will be discussed under the headings of socks, removable insoles, and removable liners.

3.0 SOCKS

3.1 General

In reviewing the outermost layer of footwear or boot, it was difficult to discuss without considering the sock as an integral part of a footwear system. Boots were never trialled or tested without socks. To discuss the sock completely apart from the boot is equally difficult; they really are two vital parts of the footwear system.

The sock has two very important functions. It provides insulation to the foot and at the same time protects it from the shear stresses and friction existing on the inner surfaces of the boot. It must also transfer moisture away from the skin, usually to the boot where it can move outward if the boot is not impermeable. It may also be required to prevent the ingress of external moisture in order to maintain the integrity of the insulation. Socks should be strong enough to stand up to lengthy marches, and be constructed in such a way as to minimize pressure spots or ridges, such as seams and noticeable changes in density. They should fit well and be shrink resistant, allowing for feet swelling during extended activities without cutting off already low blood circulation in the extremities. With so many characteristics required of a sock, it has been difficult to find one sock that will do all of the above, and often these tasks are accomplished with more than one layer of socks.

In a multi-layered sock system, the primary function of one layer could be passive insulation, while the function of a second layer could meet other requirements. A polypropylene sock may be worn under a wool sock not only to protect the foot from blisters, but also to protect the skin from an allergic reaction to wool. The material make up of a sock may be important in an effort to reduce static electricity build up, and in a warm/hot scenario, a specially designed sock may be the ideal solution to cool an individual.

3.2 Insulation

Although metabolic heat production and heat storage are two processes which do occur in the foot, they are minimal compared to the heat delivered to the foot by the arterial blood supply. Though the blood supply is the greatest source of heat to the feet, it does not amount to very much i.e. ≈30 W in warm surroundings or during exercise, and <3 W when reduced by cold surroundings (3). This reduction in heat supply is believed to be the result of blood cooling by a reduction in leg temperature, countercurrent heat exchange, and closing the arteriovenous anastomoses (AVA) (1,3).

The heat in the foot is lost by conduction, evaporation, and radiation. Conduction is the main mode of heat loss from the foot to the outer surface of the boot. The other two routes of heat loss are from the evaporation of the sweat produced by the foot and the radiation of heat from the surface of the boot (brought there by conduction).

Thermal insulation is generally obtained via layers of materials, which trap the maximum amount of air within and between the layers. The main source of thermal insulation in footwear is the sock. Although many materials can be used in socks, only a few are usually chosen for military use. These fibres are listed with some of their properties in Table 1.

Material	Characteristics
Wool	good insulator, absorbent, resilient, and able to take dye well
Cotton	cool and lightweight, very absorbent, becomes stronger as it gets wet
Polypropylene	lightweight, resists moisture, oils, and solvents, and easily sterilized
Acrylic (Orlon)	strong, durable, springy, and lightweight
Spandex (Lycra)	good stretch and recovery, resistant to oxidation, and better flexlife
Nylon	strong, durable, and resistant to moisture and mildew
Polyester	resilient and shrink resistant, and insulates and wicks moisture without appreciable absorption

Table 1. List of fibres commonly used in socks.

Wool holds an important place in today's textile trade because of its properties of insulation, absorbency, resilience, and ability to take dye well. Wool fibre is composed of helical chains of amino acids, cross-linked to one another. Because the chains are coiled, they stretch when the wool is pulled, and then recoil back into shape. Wool also possesses a natural crimp which adds to its resilience. Wool fibres are processed to fabric by one of three basic systems: worsted, woolen, and felting. The worsted system requires long, sound wool, which is combed to remove short fibres. The longer fibres are arranged more or less parallel before spinning. The wool is then woven or knitted. Worsted yarn is smooth, strong, and is lighter and less bulky than woolens, and is favoured in hosiery. The woolen system uses short wool, or that containing both long and short fibres. No combing is done. The woven cloth, known as a woolen fabric, has a rougher appearance than that of worsted, and has little shine or sheen. This wool is more often used in blankets and sometimes in work or outdoor socks. The felting system depends on the movement and entanglement of fibres as they are padded in a warm, soapy solution. One product of this type of wool is removable insoles. When wool is heated in boiling water for long periods, it becomes weak and stiff, and when exposed to drying temperatures above 130°C, it slowly decomposes and turns yellow.

Cotton is a natural fibre which chemically absorbs water making it traditionally cool and comfortable to wear. Thick knitted cotton socks can absorb large amounts of water which is why cotton socks are considered to be a superior athletic and work sock. Because cotton is stronger when wet than when dry, cotton socks launder well with very little breakdown of the fibre by hot water or detergents.

Nylon was the first of the "miracle" yarns made entirely from chemical ingredients through the process of polymerization. Nylon is the strongest textile fibre, and the most resistant to abrasion, even when knitted into the sheerest of fabrics. It can be washed and dried quickly. Because of its strength, durability, and resistance to moisture and mildew, nylon became essential in military applications during World War II. The elasticity of nylon-textured yarn permitted the development of new forms of apparel, like hosiery that could stretch to fit several foot sizes. For textile use, nylon fibre is cold-drawn, or stretched, in a process that quadruples its length and reorients the material's molecules parallel to one another to produce a strong, elastic filament.

Polypropylene fibres, a polymer of propylene, are synthetic, lightweight plastic fibres. It is less dense than water and resists moisture, oils, and solvents. Polypropylene is reputed to move moisture away from the body thus keeping the skin dry. Because it has a high chemical resistance, polypropylene can be easily chemically sterilized.

Another example of a synthetic textile fibre which can be designed to meet specific needs is acrylic (e.g. Orlon by Dupont). It is strong, durable, springy, and lightweight, and can be produced as very fine or very bulky fibres. The finer fibres feel soft and luxurious, whereas the thicker fibres feel like heavy wool. Woolly acrylic fibres are used for sweaters and socks. These fibres cannot be subjected to boiling water, because the combination of heat and moisture results in excessive shrinking.

Polyester can be produced as a "normal fibre" (15μ) or a "microfibre" (5μ). Terylene is a normal polyester fibre and is usually used in blends. Its strong attributes include resilience and shrink resistance. Usually, though, normal polyester is not used in socks, but the microfibres of polyester are. Polyester microfibres are specifically engineered to have different cross sections for different purposes. Their prime advantages are that they can insulate and wick moisture without appreciable absorption. They have been used to produce water and wind resistant fabrics that are also vapour permeable i.e. they allow evaporated sweat to pass through. They are available under such trade names as Thermax, Solarmax, and Coolmax. Terylene is also made of a polyester fibre, and is usually used in blends. Its strong attributes include resiliance and shrink resistance.

Spandex (Lycra is a Dupont example) is a manufactured fibre and the fibre-forming substance is a long chain synthetic polymer of which at least 85% is a segmented polyurethane. It provides good stretch and recovery, and is used extensively to keep socks up without binding. Spandex outperforms rubber in sock tops with twice the elastic power per kilogram of yarn, better resistance to oxidation, three times better flexlife, and better looks. Spandex keeps socks in shape, after many launderings.

Although it is possible to produce socks made entirely of one fibre, it is more common that socks are made from a combination of two and sometimes more of these fibres, taking advantage of each of their various positive characteristics. A quick survey of socks was taken from four outdoor clothing catalogues. Sock information was extracted and grouped with respect to percentage content of materials in table 1. The result is shown in figure 1. Blends make up the large majority of socks (44 out of 51), and wool still seems to be the most popular fibre (34 out of 51). Because the acrylic, nylon, and polypropylene socks are advertised as liners and not as good insulators, the popularity of wool as an insulator jumps to 34 out of 42.

3.3 Vapour Permeability

Water and insulation are not compatible. Whether entering the boot from the outside, or produced from within, water soaks the insulation, displacing the air, reducing its effectiveness. Protecting the insulation from external wetting is typically achieved by careful design of the boot (2), or a boot liner (discussed later). Sweat is the always present contaminating agent from within.

Sweating from the feet differs from the rest of the body, because it is, to a large extent independent of the external temperature (4). There is a high incidence of sweat glands on the soles of the feet and their secretion is increased by exertion or emotional stress. Estimates for the total amount of sweat produced by the foot of an inactive person is in the order of 5 g/H/foot,

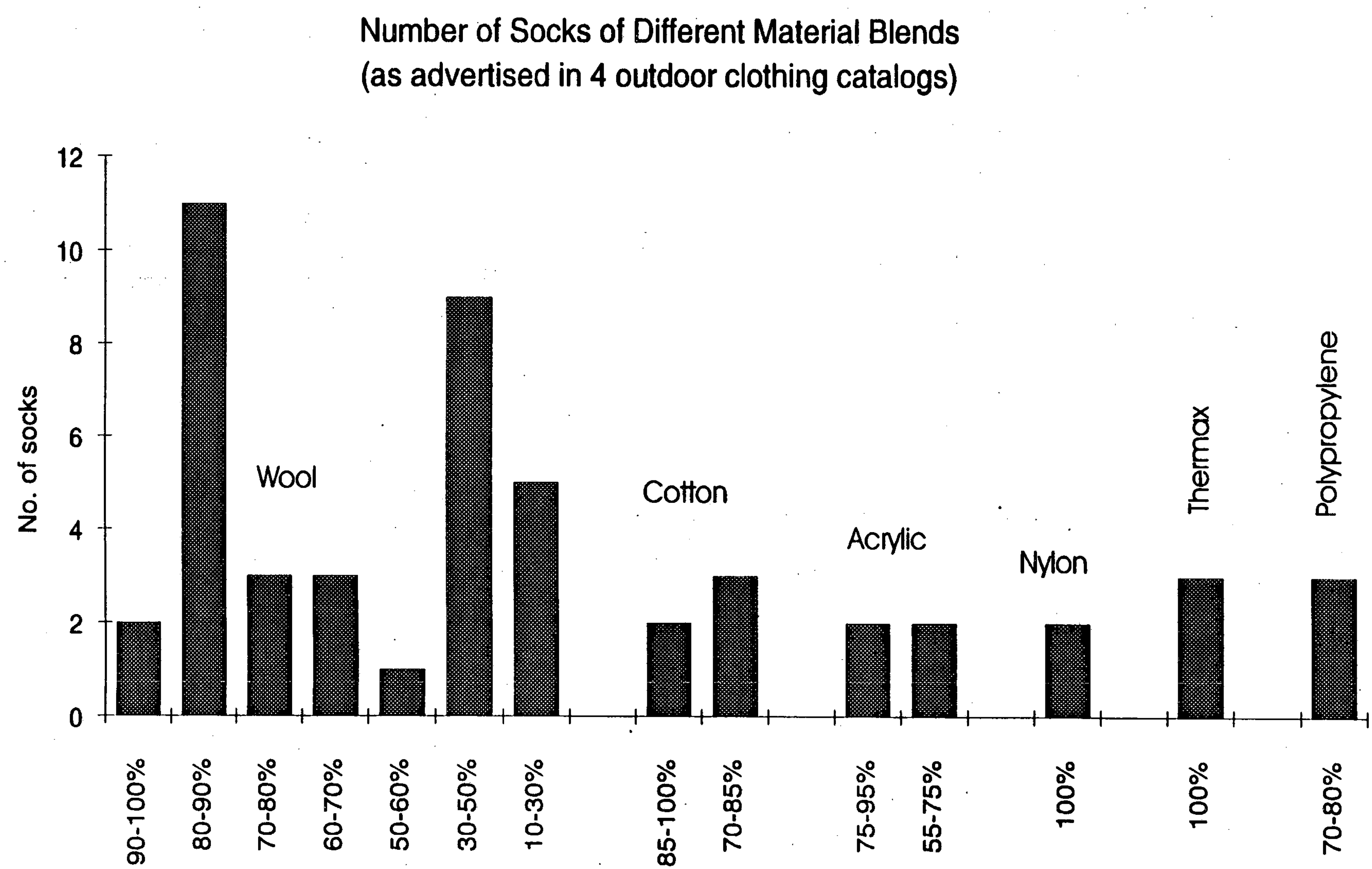

Figure 1. Distribution of materials used in sock manufacturing.

whereas the total amount of sweat produced by the foot of an active person is in the order of 50 g/H/foot.

When sweat occurs and accumulates in the material immediately surrounding the foot, an unpleasant feeling is described by many. During 100 chamber trials, Brooks et al (5) asked the subjects what they felt were the most important attributes that socks can possess. After reviewing the answers to a combination of questions, it became evident that a perception of less dampness and less slippery feel, are the main factors linked with a sock preference. Therefore, it would be advantageous to remove as much moisture as possible from the area immediately surrounding the feet, and to maintain the integrity of the insulation. This moisture should be transmitted to, and through the boot. Other work done by Farnworth et al (6) to understand the mechanism of action of heat and moisture transport in footwear, has also led to the conclusion that not only absorption is important, but also transmission.

Of additional note, after performing certain tests, Brooks (5) suggests that wetting socks with water does not always mimic the results of wetting socks with sweat, and recommends using synthetic sweat in moisture transport experiments. This may yet lead to better correlation between laboratory and field tests.

Stokes describes an experiment comparing three materials (wool, nylon, and polyester) used in socks issued in the Canal Zone (1). Although there were no subjective differences in comfort, or deleterious effects due to these socks, there were significant differences in sweat retention of the footwear. The socks showed the following relationship in sweat retention:

Wool > Nylon > Polyester

The respective boots exhibited the reverse relationship. The sock plus boot combinations, though, followed the same relationship as that of the socks.

Besides simply choosing materials which possess a high vapour permeability and an ability to pull sweat away from the skin, work has also been carried out on new finishes for these materials which would reduce their water retention (7).

3.4 Material Testing

Although socks were included in all of the many trials done on boots, there is not nearly as much work done to compare various sock systems.

Test criteria are not always similar enough to assist in the determination of the best overall sock for a soldier. Gilling et al (8) compared a polyester sock, an Arctic Sock (heavy wool), and a polyester/nylon sock combination in the cold, and found little difference between them with respect to toe temperatures. Similar results are reported by Stokes (1) in comparing the G.S worsted wool sock and the heavy wool sock. Swain et al (9) compared a wool/cotton/nylon (50/30/20) sock with a nylon (100%) sock and a nylon/cotton (60/40) sock in a warm climate, and found the nylon sock superior to the nylon/cotton sock, which was preferred over the wool sock. Here the best sock was the lightest, absorbed the least amount of water, and was the easiest to dry. Using a sweating hot plate, Ng (10) compared a polypropylene (hydrophobic) sock, a light grey wool(hydrophobic but hygroscopic) sock, and a dark grey wool (hydrophillic) sock. Since the sweating hot plate was used to monitor the response of a material to wetting, conclusions were drawn from the best insulation values of the wet socks. Not much difference was noted between the wool socks, but both of them provided better insulation than the polypropylene, dry or wet. Brooks (5) also tested wool socks against polypropylene socks, and also against cotton and Orlon socks. Instead of a hot plate though, test subjects were used, who also gave subjective preferences. Wool was clearly preferred over cotton and acrylic, but wool and polypropylene had about equal preference. The imbibed sweat content of the subjects' socks was found to increase in the order wool, polypropylene, acrylic, and cotton. The low retained sweat levels in the wool and polypropylene socks could explain their being so close in comparisons.

Hock et al (11) investigated the "chilling effect" of moist fabrics. Thirty-six fabrics of various weights and thicknesses, for the most part wool, cotton, and wool/cotton blends, were moistened and compared. Fabrics which made good contact with the skin and which caused a drop in skin temperature, were also those which caused the greatest chilling effect. Since cotton fibres have much higher skin contact than wool, it was found that a progressive improvement with respect to chilling occurred as the wool content increased.

3.5 Socks and Blisters

Although cold injuries to the foot are a serious threat in a cold-wet scenario, the most common overall injury in the military, induced by footwear, is blisters (1,3,12,13). Friction is essential for locomotion, and skin damage to the foot is the consequence. Under normal conditions, this damage is hardly noticeable and easily repaired. Under prolonged activity, however, blisters and erosions are the result. For the soldier, this can be completely disabling and under combat conditions, potentially hazardous.

It has been concluded (12) that blisters are caused by frictional shearing forces that lead to mechanical breakdown in the epidermal cells, and by damaging effects of increased tissue temperature. The epidermis splits as a result of loss of cell to cell connections, fills up with fluid, and the result is a blister. Moist, as opposed to wet, skin appears to encourage blister formation by increasing friction and macerating the foot surface. It has been suggested (13,14) that in addition to this, prolonged activity also causes feet to swell, amplifying the effects of friction in ill fitting boots. Reynolds (14), in studies to determine the types of injuries occurring during long marches carrying various loads at different speeds, found blisters to be the most common injury, and most often occurred at the heaviest loads at medium to fast speeds.

Various preventative measures have been studied, including correctness of fit and proper break in of the boot (13), using foot powder to reduce friction and frequent sock changes (14), using lubricants and anti-perspirants (12), and wearing two socks per foot (15). Proper fitting does seem to reduce the incidence of blisters, as does using lubricants, but apparently using foot powder and frequent sock changes does not. It has been the experience of many soldiers on a march that wearing two wool socks per foot reduces the occurrence of blisters, and this was further investigated by Thompson et al (15). 357 marines made up three groups, each wearing a different sock system. Group A wore the standard issue wool-cotton-nylon-spandex sock; group B wore the standard sock with a thin polyester inner sock; and group C wore the same inner sock with a prototype outer sock consisting of wool and polypropylene. Group C suffered significantly fewer blisters compared to either of the other two groups.

3.6 Other Developments

Pratt et al (16) calculated that approximately 5 watts of heat would be required to maintain both feet at a temperature of 10°C within an ambient temperature of -40°C, wearing a standard insulated boot. A pair of electrically heated socks powered by batteries was designed and tested, and the results suggested that battery powered electric heat was feasible, and could double the exposure time of an inactive foot soldier at -40°C before the danger of frostbite. Winckless (17,18) also reported on trials of an electrically heated sock, Vacuum Reflex Mk I and II. These socks were rated at 8W, and were tested in combination with both the mukluk and the DMS Boots at -32°C. He concluded that the socks adequately protected the feet in the mukluk, but not in the DMS Boot.

In an attempt to cool the body exposed to heat stress, such as occurs when wearing protective clothing in a hot environment, a cooling sock has been developed (19,20) which circulates cool water through plastic tubes sewn into socks. The system effectively reduced heat stress in individuals wearing chemical protective suits in a 35°C environment. This is mentioned because the author believes a similar system could pump a warm liquid through the same sock to warm the foot and the body.

Koeller (21) suggested a quilted sock filled with desiccant might be useful to adsorb perspiration moisture. The desiccant sock could be worn over a conventional sock to avoid the necessity of laundering the desiccant sock. This sock could be discarded after its usefulness is outlived, or rejuvenated using heat.

With respect to the requirement to protect the man against static buildup, or more important, static discharge, Wilson (22) investigated the feasibility of a spark and the hazard it poses. Since this is a whole body phenomenon, it is hard to separate out the contribution of footwear. Several articles of Canadian military clothing were examined, including footwear (sock, assumed to be the standard army wool sock). Although he concluded that all ensembles tested recorded energies high enough to be considered dangerous (>0.2 mJ), a subsequent review (29) showed they were not sufficient to ignite a fuel-vapour/air mixture whose minimum ignition energy is 0.2 mJ. Pritchard (23) measured the electrical conductivity of five types of socks, and concluded that where conductive shoes are required to be worn, only thin cotton socks or 75-85% cotton reinforced by nylon should be worn. Thick cotton socks, and synthetic (nylon, acrylic) socks fail certain conductivity tests, and it was suggested that they do not belong in ordnance operations where electrostatic discharge is a concern. A recent review by Crow (29) has attempted to put into perspective, the actual hazard static electricity poses to certain military trades. It summarizes some common sense procedures to avoid it, lists the pros and cons of developing materials to minimize its buildup, and suggests, that static electricity may not be quite as hazardous as others have perceived it to be.

4.0 Removable Insoles

4.1 General

The insole is arguably the most important part of footwear, because it acts as an interface between the body (legs) and the ground. Removable insoles are an important part of that system. When marching, a soldier can develop momentary forces five times his body weight during heel strike. Ideally, the insole should therefore be a good shock absorber, should be able to retain its shock absorbing capability, should attenuate the impact loading efficiently, and return the impact energy to the body creating the sensation of springiness. Not only should a removable insole do all the above, but at the same time it should ideally absorb sweat, and act as an insulating layer between the foot and the boot sole, which is in contact with the cold ground. Stokes (1) has observed, that by absorbing sweat, insoles have protected the boot insole from early deterioration. It is certainly easier to replace a removable insole than a boot.

More and more insole materials are coming onto the market. They can be loosely categorized as solid synthetics (such as

Sorbothane), meshes (such as Saran), layers (such as Cambrelle), and felt.

A solid polyurethane insole like Sorbothane (Trademark of Spectrum Sports) is a good shock absorber because it is a visco-elastic polymer that acts like a liquid, absorbing shock in all directions. It distorts easily and recovers, sometimes with a slight delay.

Saran is a manufactured fibre mesh in which the fibre forming substance is any long chain synthetic polymer composed of at least 80% by weight of vinylidene chloride units ($-CH_2-CCl_2-$). It is highly resilient, resists staining and is flame resistant. Saran also resists moisture and mildew, and has good abrasion resistance.

Cambrelle (Trademark of Imperial Chemicals Industries) is a non-woven material made by combining a core layer of polyamide (nylon) with a fibre (polyester) layer. The two fibre layers are bonded together firmly by heating, thus dispensing with needling and chemical binders. These fabrics are characterised by their excellent resistance to abrasion, their absorbency, and their permeability to air and moisture.

Felt is described under the heading, Insulation, in the sock section.

4.2 Material Testing

Early work centred on providing insulation via the insole. Stokes (1) measured the temperature gradient across two types of insoles in a cold chamber at -23.3°C, using thermocouples attached to the skin of volunteers and to the insole of the boot. The temperature gradient across a 7-ply plastic mesh insole used in the British Cold-Wet Boot was found to be 17.1°C, while that across the thick felt and plastic insole used in the Mukluk was 36.5°C. Other tests by Coffey et al (24) with two very similar insoles showed similar results. Felt liners were more comfortable and warmer, but absorbed moisture, became uncomfortable, took a long time to dry, and shrank badly. Previous experiments by Larose (25) compared drying times of wool, wool mixed with cattle hair, and wool mixed with goat hair insoles, and found that materials containing goat hair or cattle hair had better drying properties than all wool, but differed little when compared to each other.

More recently, some studies have been done to evaluate several removable insoles on their merits as shock absorbers. Chau (26) tested the shock absorption of footwear with and without the insoles to compare their respective performance. Foam and ventilating insoles offer no improvements in performance. The contribution of a cushion insole to lessening impact pressures in footwear is small, but the polyurethane insole (Sorbothane) offered significant improvement to shock absorption of footwear.

As with socks, electrically heated insoles have also been studied. Winckless (17) describes the RYMAX Mk III, which was tested in the Mukluk and the Boots DMS in a climate of -32°C with minimum wind. The author concluded that the heat produced was adequate, but heat distribution needed improvement, as the toes were kept warm at the expense of the heels. As with the socks (Vacuum Reflex) to which they were compared, adequacy was only achieved in the Mukluk and not in the Boots DMS. Lukyanova (27) also describes an electrically heated insole developed in the Soviet Union. It takes the form of a current-conducting rubber insole sandwiched between two layers of insulating rubber. The current conducting layer is designed to a particular resistance so as to achieve a 12W heater. The insoles were tested in a variety of cold scenarios, and it was concluded that at -25°C and lower, and under windy conditions, these heated insoles should be used.

Although concerns involving fungal growth in footwear are usually reserved for footwear in the warm and humid tropics, there are occasions in cold-wet scenarios, at the upper end of the temperature range in a well insulated boot, when this might also present a problem. Studies have been done (28) on the microbial growth on various combinations of Saran and Cambrelle insoles, which showed that all combinations were susceptible to fungal growth. If this begins to become a problem, all parts of a soldier's footwear should be treated with fungicides.

5.0 Removable Liners

5.1 General

This last category in the footwear system, which is situated between the foot and the boot, includes two subcategories. One is defined as an additional loose-fitting insulation layer such as a duffle sock used in a Mukluk, and the other is defined as a thin impermeable or semi-permeable insulation-protecting layer such as a Gore-Tex sock or a rubber vapour barrier.

5.2 Testing of the Insulation-Protecting Layer

Very thin rubber socks were studied in the US (30) as a possible means of protecting the insulating sock from becoming wet from external moisture. It was also known that this would not allow sweat to escape, and this would lead to soaking the sock from within. In tests where three pairs of socks were worn, with the impermeable layer placed at different positions within the system, it was discovered that "near" (closest to the skin) impermeable layers caused the feet to sweat less than "far" layers. Work progressed toward the development of a double barrier boot, made of an impermeable layer on both sides of the insulation (31). Because this system was only good for static duties, and socks had to be changed frequently, and feet had to be dried frequently, and foot care had to be meticulous to prevent serious problems, this development did not receive broad acceptance.

With the advent of the water resistant, water vapour permeable fabrics, footwear has taken a giant leap forward. Now insulation layers can be kept reasonably dry from external wetting, and still allow an egress for evaporated sweat. Van Roey (34) reviews materials which can accomplish this goal, and although there are many, only a few have been widely marketed. There are generally three types of waterproof/water vapour permeable fabrics: high-density-fabrics, fabrics with coatings, and laminated fabrics. The latter are the best known of these, and are either microporous (Goretex by W.L. Gore/USA), hydrophillic (Sympatex by Enka Glanzstoff/Germany), or a combination of these properties (Thintech by 3M/USA).

Boot liners made of the Goretex material have been developed and trialled in the UK (32) and Canada (33). Tests in the field and in the laboratory have shown a significant improvement in performance in military footwear by keeping the feet warmer and more important, drier. Goretex liners have many desirable features required by boot designers, except that they are expensive.

5.3 Testing of the Insulation Layer

In the Northern or Arctic regions of Canada, under extreme cold dry conditions, the Canadian Forces wear the mukluk. The primary source of insulation of the mukluk is a thick removable liner or duffel sock. It is manufactured with two layers of a wool/viscose (0.93 kg/m^2) duffel cloth with nylon reinforced heel and toe. Because of the loss of the source of supply for this duffel sock material, a new material was tested (35). The new sock was manufactured using the same pattern as the other, but with a different material, wool/nylon (1.1 kg/m^2). The tests were conducted in a cold room at -23°C where subjects walked on a level treadmill at 1.6 m/sec wearing the new sock and the original sock on separate occasions. No difference was noted in their durability, thermal protection (as measured by skin temperature), or comfort (as measured by the sweat absorption). Duffel material appears to be the most often used insulating material in mukluks.

6.0 DISCUSSION

Because the sock, liner and insole are each worn inside the boot, many of the requirements dealing with protection of the foot from the external environment are not applicable. It is suggested that the major requirements of socks are insulation, blister protection, and moisture transport. The requirements of insoles are insulation and shock absorption, and the requirments of liners are insulation protection, and in the case of the Mukluk, more insulation. With the proper choice of materials, and/or design, and/or construction, there are not many conflicting solutions. The areas where compromises are required are discussed.

In the review of the sock, insole, and liner, (SIL), the military footwear requirements were reviewed and only those which could be met by the SIL were discussed. In Part 1 (2) of this series of reviews dealing with the boot, the work presented, attempted to meet all the requirements with a properly designed boot, which leads to much compromise. It is suggested, that if one considers footwear as an integral system of boot and SIL, and the overall requirements are each delegated to a specific part of the system, the number of compromises facing each part of the system may be reduced. An example might be to relieve the boot entirely of providing insulation and/or waterproofing, and impose these criteria on socks, making selection of materials, design and construction of boots easier.

The biggest SIL compromise is with insulation and space. It has been stated (3,36) that during a long march, the temperature and activity may be high at the start, and low at the finish. Thus, insulation which is adequate for one extreme, may be inadequate for the other. In almost any other part of the body, insulation can be added or subtracted in response to changing environmental conditions, but in the boot which should have been fitted for a particular SIL configuration, an insulating layer cannot be added (no space) or subtracted (creating a risk of blisters). It has been reported by Stokes (1) that adding an extra sock and squeezing the foot into the same boot, does not provide the extra warmth commonly presumed. The initially added insulation is lost when the socks are compressed in the boot. The already low blood supply may also be reduced by the compression. One possible solution to the variable insulation requirement might be the electrically powered socks and insoles, but the practicality of a soldier carrying an electric source of heat is dependent on other factors such as weight and the availability of batteries.

With respect to the US double vapour barrier boot designed to protect the foot against the cold, and the insulation from getting wet, Stokes (1) and Court (31) point out that the heat lost by the foot during exercise or warm weather can not be sufficiently dissipated. The foot becomes overheated and the sweat is not removed. Therefore the boot's upper temperature limit of use is low. Keeping the feet dry has been compromised by keeping the insulation dry.

A proper fit is also an important topic for compromise. It has been reported (1,36) that during prolonged activity such as long marches, the foot swells. The compromise is, therefore, whether the boot, along with the appropriate SIL, should be fitted when the foot is swollen or not. If the footwear is fitted when the foot is unswollen, the insulation may become compressed and the blood supply to the foot may become restricted as the result of swelling due to prolonged activity. If fitted when the foot is swollen, footwear will be looser under normal activities, and unless some way is devised to secure the foot to minimize movement in the boot, friction and the possibility of blisters will be the result. Similarly, Blaber (36) suggests that individuals carry insoles of two thicknesses. At the start of a march, the thicker insole should be used, and later on, as the sock is changed and the feet show signs of swelling, the insole is exchanged for the thinner one.

Waterproof and water vapour permeable liners have certainly come a long way to solving some of the footwear problems of the past. Effective marketing has pushed a few trademarks into the common language. Goretex is a prime example. The material is definitely effective in its claims, but it is also very expensive, and sometimes unaffordable. As Van Roey (34) points out, there are other similar products available, but much less known, and slight compromises in performance characteristics might lead to large reductions in cost.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Compared to the boot, not much research and development has been done on the subject of socks and removable insoles and liners. This review has summarized a number of representative studies that have been done on this subject in trying, at least in part, to meet the lengthy list of footwear requirements. Within the confines of a boot, design options are very limited, however, even here there is room for some compromise. Because the sock is right next to the skin on the weight bearing foot, even small compromises to its composition or design may make large difference in mobility. Because there are so many scientific and technological aspects to protecting the foot, an ongoing research and development program on footwear is required, to provide advice to the soldier with respect to what footwear will perform best in the many different scenarios he or she may face world wide.

Because solutions to the individual requirements of footwear may conflict with one another, priorities are required. It is recommended that the Canadian Forces requirements and/or deficiencies in army footwear be critically reviewed, and a new set of requirements be written. Essential and desirable aspects of footwear must be separated, and ranked in order of importance. This document would then form the basis of the ongoing research and/or development program set up to address these concerns.

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Presented herein is the second of a proposed multi-part review on footwear. This report deals mostly with the materials and their properties making up the layer or layers of footwear between the skin and the boot, i.e. socks and removable insoles and liners. Aspects of these elements of footwear are related to various military requirements, and as in the first part of the review, attention is drawn to the fact that in meeting these requirements, solutions conflict. A discussion on possible compromises follows, leading to the recommendation that in order to develop proper footwear for the military, a very carefully written statement of requirement is necessary.

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