

# Wool in Human Health and Well-Being

Raechel Laing and Paul Swan

**Abstract** This paper reviews published and unpublished literature on the role of wool in human health and well-being. Human-based investigations, or those involving human simulations (manikins) were the focus. The principal parameters in the review were skin health, physical contact between textiles/garments and human skin (tactile acceptability—prickle, friction, allergies), thermal and moisture properties, human body odour, and sleep (bed clothes/sleepwear, bedding).

**Keywords** Wool fibre • Skin health • Perceptual characteristics

## Introduction

The objective of the review was to identify and critically review published and unpublished literature on the role of wool in human health and well-being, where possible, accounting for inconsistencies in evidence in that literature. Several exclusions were applied i.e. wool in very specialised applications such as high-level human performance, and medical interventions; burning behaviour/flammability; wool in the built environment; and wool in animal health. Findings from investigations on most of these topics have been well published.

Evidence of the role of wool in human health and well-being was obtained by reviewing published peer-reviewed literature, unpublished reports, and personal communications. More than 240 documents were examined. The focus was evidence based on human studies (or those from human manikins), rather than laboratory reports of fabric properties, although the latter were sometimes also considered. The principal parameters identified for the review were (i) skin health,

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R. Laing (✉)

University of Otago, Dunedin, New Zealand  
e-mail: raechel.laing@otago.ac.nz

P. Swan

Australian Wool Innovation, Sydney, Australia

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(ii) physical contact between textiles/garments and human skin (including tactile acceptability—prickle, friction, allergies), (iii) thermal and moisture properties, (iv) human body odour, and (v) sleep—bed clothes, sleepwear, bedding. Some methodological and data issues also warranted comment with regard to interpretation of findings.

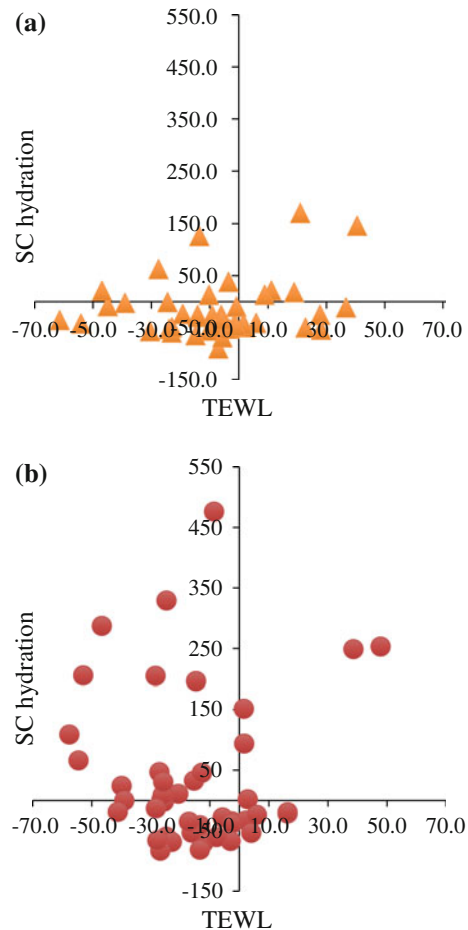
## Skin Health

Skin is the human body barrier to the external environment, attributable to its physical structure and properties. Indicators of skin health include pH, water content of the stratum corneum (SC), transepidermal water loss (TEWL), skin elasticity. Skin pH is typically acid, ranging from 4.0 to 7.0 pH: skin with <5.0 pH is considered more desirable than that with >5.0 pH (Lambers et al. 2006); superficial layers of skin are typically 4.0–4.5 pH (Darlenski et al. 2009; Schmid-Wendtner and Korting 2006). Water content of the SC (SC hydration) reflects the skin response to changing environmental conditions, and when not functioning correctly, SC is typically ‘dry’ (Rawlings and Harding 2004). Transepidermal water loss also reflects the skin response to changing conditions and is another effective indicator of skin barrier function (Elkeeb et al. 2010), with small changes detectable (Fluhr et al. 2006). Water content of the skin is related to elasticity and linked to age (Potts et al. 1984).

Because the skin may be in direct contact with wool/wool products, evidence of skin health and changes in this after such contact is of interest. There is a dearth of publications on skin health and its relationship with fabrics manufactured from either wool or other fibre types. Effects of dry and wet fabric samples ( $n = 16$  different fibres and structures, including wool) on the forearm of females ( $n = 35$ ) for 75 min showed little effect on SC hydration when dry, but an increase when wet with both wool and cotton fabrics (Schneider et al. 1996). Effects of fibre content of socks on health of the skin on human feet has also been investigated (Laing et al. 2015). Dress socks in different fibre/yarn types (100 % acrylic, 100 % wool 24.5  $\mu\text{m}$ , 100 % wool 20.5  $\mu\text{m}$ , 100 % cotton) were worn (with standard boots) for a minimum of 8 h per day over an 8-week period. Each participant ( $n = 16$  males) was his own control with % change in indicators analysed. Differences in the effect of sock types, wool and cotton, at the heel were observed: although effects on SC were not significant, the order of mean values was wool 20.5  $\mu\text{m}$ , wool 24.5  $\mu\text{m}$ , both positive; cotton, acrylic, both negative. Improved barrier function, indicated by a decrease in TEWL and an elevated SC, was evident at the heel (Fig. 1).

No other completed investigation of skin health related to fibre content of skin coverings made from wool has been identified. Preliminary findings from an investigation on effects of wool fabrics against the skin of those predisposed to atopic dermatitis seem promising (Swan 2014, personal communication).

**Fig. 1** Percentage change from baseline TEWL and from baseline SC hydration at the heel **a** cotton sock, **b** wool sock 20.5  $\mu\text{m}$  (reproduced from Textile Research Journal 2015 85(17) 1849–1863 doi: [10.1177/0040517515573413](https://doi.org/10.1177/0040517515573413) with permission)



## Physical Contact Between Textiles/Garments and Human Skin

An aversion to next-to-skin wool garments has been attributed to discomfort or a sensation of prickle, and beliefs and experiences with wool in childhood can influence future use (Sneddon et al. 2012a, b). Prickle is understood to be mechanical irritation of the skin by coarse fibre ends indenting the skin and activating nerve endings (Garnsworthy et al. 1988; Naylor 1992; Naylor et al. 1997). Fibre, top, yarn, and fabric factors can influence the tendency of a fabric to exhibit prickle (Naylor 1997; Naylor et al. 1997) e.g. length of fibre protruding from the fabric surface, presence of coarse fibre ends (Naebe et al. 2015). Methods for overcoming prickle effects include enzyme treatments (Bishop et al. 1998; Das and

Ramaswamy 2006), and yarn structural modification (wrap yarn reductions of 1, 3 and 3  $\mu\text{m}$  for 25, 29 and 31  $\mu\text{m}$  diameter wool fibre respectively (Miao et al. 2005)).

Perceptions of wearers have been linked to prickle (McGregor et al. 2013; Stanton et al. 2014). A British-based wear trial on next-to-skin/thermal underwear in which 21  $\mu\text{m}$  diameter wool was used, reported approximately 30 % of the male participants indicated garments were 'scratchy' and that same percentage of participants indicated the garments were thermally unacceptable (Harnett 1984a). In a subsequent wear trial using 19  $\mu\text{m}$  diameter wool, no participant perceived the garments as itchy or scratchy (Harnett 1984b). Fabric 'pleasantness' has been reported to decrease as temperature and relative humidity increase (Gwosdow et al. 1986), so it is likely participants who perceived the garments too warm were those who perceived the garments as scratchy. Two Australian studies are pertinent. In one, wool fabrics manufactured from 19  $\mu\text{m}$  fibres were reported to have no greater prickle value than cotton fabrics when assessed in a controlled, non-standard atmosphere ( $22 \pm 1^\circ\text{C}$ ,  $65 \pm 5\% \text{RH}$ ) ( $n = 60$  volunteers) (Naylor et al. 1992). In a second, fabrics manufactured in a next-to-skin long-sleeved, fitted garment composed of fine wool (16.5  $\mu\text{m}$ ) were ranked as most preferred by adult females ( $n = 39$  Australian,  $n = 47$  USA) over comparable garments manufactured from 18.5  $\mu\text{m}$  and 20.5  $\mu\text{m}$  wool. Garments were handled as if purchasing, so both tactile and visual cues were present (Sneddon et al. 2012b). What is not always clear in these studies is whether all manufacturing parameters (yarn, fabric structure, fabric mass per unit area) other than fibre type, were identical, and whether test conditions were also identical. Skin temperature and relative humidity are known to affect the sensation of prickle of products worn against the skin (Gwosdow et al. 1986), and when sweating begins, wool garments may become less comfortable (Wang et al. 2003). The perception of skin wetness in turn is influenced by interactions between thermal and mechanical stimuli (Filingeri et al. 2014), with warm temperatures suppressing the perception of skin wetness and coldness seeming to dominate (Filingeri et al. 2015).

How the human skin responds to movement of fabric across its surface (friction between fabrics and skin) is of interest in applications such as next-to-skin garments. A first response may be redness of the skin, an indicator of irritation. Several studies on fabric type and blood flow and/or skin temperature have been undertaken (Gan et al. 2010; Hatch et al. 1990), although most do not include wool fabrics. The study by Gan et al. (2010) measured fabrics for just five minutes on the forearm of one participant. Hatch et al. (1990) observed skin redness in some participants, suggesting increased blood flow to that area was caused by contact between fabric and skin, although blood flow at the site was not measured.

In relation to foot coverings, the three important parameters are how textiles respond in the presence of moisture, friction between the skin surface and the sock fabric, and compression and compressional resistance/recovery of the sock fabric. Reports of the superiority in sock performance of one fibre type over another, particularly through the 1980s and 1990s, included comparisons of acrylic with cotton or wool socks (Brooks et al. 1990; Euler 1985; Herring and Richie 1990, 1993; Morris et al. 1984). Some years later, sock fabrics manufactured from

mid-micron and fine wool were reported to have a lower coefficient of static friction than fabrics composed of acrylic in both dry and damp conditions when measured against a synthetic skin (van Amber et al. 2015b). Fibre type, yarn structure, and fabric structure are all controllable manufacturing variables, thus their relative effects on frictional properties also controllable. Fabrics in this study were prepared for a factorial experimental design (100 % mid-micron wool (26  $\mu\text{m}$ ), 100 % fine wool (19  $\mu\text{m}$ ), 100 % acrylic (19  $\mu\text{m}$ ); yarn high twist, low twist, single; single jersey, full terry, half terry). The lowest coefficient of static and dynamic friction was evident with the single jersey. With respect to damp fabrics, that made from fine wool exhibited the lowest coefficient of static friction and acrylic the highest.

Compression/compressional resilience of socks, including wool socks has been reported. Wool cushioned socks have been shown to have a greater shock-attenuating effect than walking barefoot (Howarth and Rome 1996), and wool socks were also associated with an increased time to peak force, and decreased propulsive force than when the participant(s) was walking bare footed (Blackmore et al. 2011), unsurprising in both cases. Differences detected were attributed to differences in sock thickness (i.e. fabric structure and sock construction had a more important shock-attenuating effect than the type of fibre (Blackmore et al. 2011). Similarly, fibre type was not a significant factor in the percentage of thickness retained under compression (van Amber et al. 2015a), but was relevant in compression: recovery ratios, the acrylic fabrics being superior to the two wool fabrics when fabrics were damp. The authors did caution against potential misinterpretation, as the fabrics held different amounts of moisture (van Amber et al. 2015a).

Claims of allergic reactions to wool arise from three potential sources: chemical (e.g. lanolin, residues of chemical substances used in processing), physical (irritation from prickle, largely resolved), and allergens (e.g. insects/mites typically associated with carpets/furnishings). In the 1980s, wool fibres had been reported as causing acute and cumulative irritant dermatitis and as aggravating atopic dermatitis (Hatch and Maibach 1985), but by the 1990s, wool as a skin irritant caused by prickle, was better understood (Hatch and Maibach 1995). Prickle or itch is still sometimes misconstrued as a 'wool allergy'. For example, 35–40 % of interviewees who would not consider buying wool garments nominated prickle as the reason, and 7–10 % nominated allergy (Starick 2013). Although some residual misunderstanding remains (Fujimura et al. 2011), atopic dermatitis is not wool allergy.

One possible chemical explanation for wool allergy is related to lanolin on wool rather than the fibre itself. A review of 24,449 patients in Britain from 1982 to 1996 reported a 1.7 % annual rate of sensitivity to lanolin or wool alcohol, a relatively low sensitivity in this sample (Wakelin et al. 2001). During the 1980s Hatch and others sought to identify dermatological problems related to fibre content and dyes (Scheurell et al. 1985), with little published since that time. Whether a causal link exists between chemical substances in textile products and allergic reactions was investigated in a cooperative study in Italy (Associazione Tessile e Salute-Health and Textile Association 2013). The report identified contact dermatitis to be caused mostly by fabric dyes, but also finishing resins and adhesive resins, particularly when these release formaldehyde. Prevalence and sensitisation to formaldehyde

was reportedly decreasing. ‘Emerging allergens’ were noted, attributable to non-European manufacturers (Associazione Tessile e Salute-Health and Textile Association 2013).

An epidemiological study ( $n = 401$  patients, aged 5–84 years) showed fabrics were the cause of contact dermatitis in approximately 70 % of cases, metallic and garment accessories in approximately 17 % of cases, and shoes in approximately 14 % of cases (Associazione Tessile e Salute-Health and Textile Association 2013). Dyes and intermediary agents accounted for 44 % of cases: garments most commonly involved were nylon stockings (8.9 %), underwear (13.4 %), shirts (13.0 %), trousers and skirts (13.8 %), and sportswear (8.1 %) (Associazione Tessile e Salute-Health and Textile Association 2013). Other than nylon (stockings), no mention was made of fibre content. That sweat on the skin under fabric is likely to affect permeability of those fabrics to chemical transfer (i.e. from dyes, finishes) has been long recognised (Raheel 1991), although no wool-related evidence has been identified. Companies manufacturing pure new wool textiles are required to ensure the safety of their products through declaring compliance with Restricted Substance Lists. These restrictions appear specific to members of the European Union.

## Thermal and Moisture Properties

Many advantages of including wool fibres in textiles for human health and well-being derive from the chemical composition and structure of the fibre, particularly those related to thermal and moisture properties. Molecules in the fibre are able to create hydrogen bonds with water, immobilising the water and incorporating it into the fibre, with a small amount of heat released. This is detectable in fabric form (Laing et al. 2007), in garments in use (Laing et al. 2008), and in bedding (Naylor 2014, personal communication). Physical structure of the wool fibre (e.g. crimp, scaled surface) is a major determinant of yarn properties irrespective of whether processed by the woollen or worsted system, and largely irrespective of yarn twist. That wool (i.e. wool products) is considered by end-users to be ‘warm’ is due primarily to fibre bulk and crimp, which lead to bulkier yarns and yield thicker, more thermally resistant fabrics/end products (Harnett 1984a; Leeder 1984), and many papers published during the 20th century show this.

Thermal properties of a fabric are derived from one or more of four parameters: thickness, thermal conductivity, absorptivity, and heat of absorption. Wool fabrics are regarded as providing superior thermal properties under both damp and wet conditions. The small amount of heat released with absorption of water, and wool fibres/fabrics reported as having a lower thermal conductivity than cotton, polypropylene or acrylic, underscore these advantages (Schneider et al. 1992). Fabrics composed of wool have been reported as absorbing more moisture than matched fabrics composed of synthetic fibres such as nylon, polyester, and acrylic (Collie 2002; Laing et al. 2007; van Amber 2013). Absorption of liquid from the skin results in perception of drier and therefore warmer skin (Laing 2009). Further

evidence confirmed perception of warmth is affected by perception of wetness (Filingeri et al. 2014), with warm temperatures suppressing the perception of wetness (Filingeri et al. 2015). Surface wetness of fabrics in contact with the skin is known to influence more general perceptions of comfort (Hatch et al. 1987).

Garments composed of wool when worn have been reported to lower the relative humidity at the skin surface compared to effects of garments composed of acrylic fibres (Li 2005). Wearing wool garments has also been reported to delay the on-set of sweating and result in smaller changes in core temperature than when wearing matched polyester and wool/polyester plated garments (Laing et al. 2008). Buffering is the probable explanation for these smaller changes in core temperature and smaller increases in heat content in both cold and hot conditions than identical polyester garments. Participants wearing the wool garment had a lower heart rate during all test conditions (Laing et al. 2008). Buffering effects of wool fabrics/garments compared to polyester have also been reported by Li et al. (1992), and wool blankets compared to an acrylic/cotton blend reported by Umbach (1986).

Smooth, lightweight wool fabrics have been shown to be perceived as cooler to the touch (forearm test,  $n = 20$  participants) than comparable woven fabrics of cotton, polyester, and a wool/polyester blend, with an immediate drop of 0.4–0.8 °C observed in skin temperature on the forearm (Cameron et al. 1997). These and other similar findings on lightweight fabrics of the latter part of the 20th century led to new commercial markets for apparel.

The thermal resistance of wool fabrics has also been attributed to improvement in specific aspects of user health. Use of wool undergarments (and bedding) over a six-week period was reported to reduce symptoms and drug use of patients suffering from fibromyalgia (Kiyak 2009). Details on construction, mass per unit area, thickness, and laundering practices were not reported for either the undergarments or the bedding however.

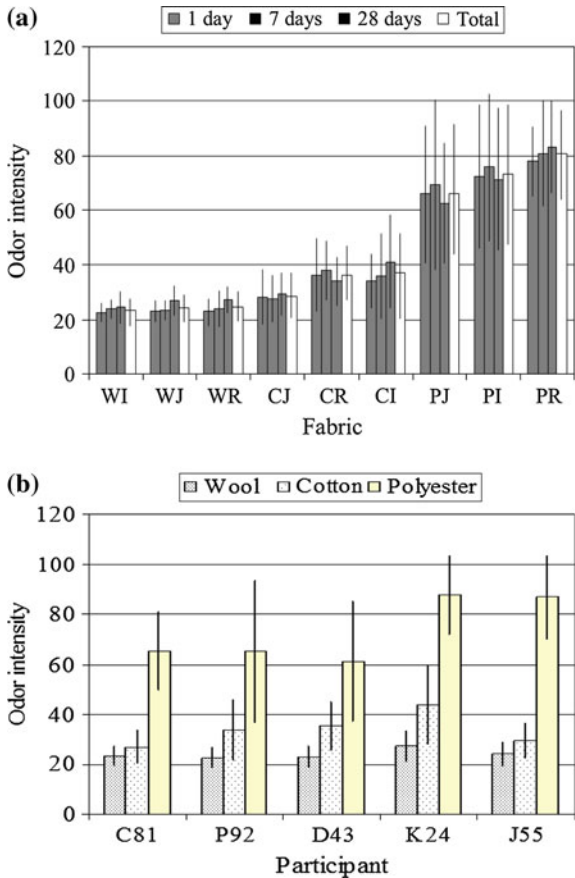
## Human Body Odour—Textiles, Clothing, Footwear

Basic understanding of body odour and several links to clothing have been known since the 1950s (Shelley et al. 1953): human apocrine sweat, a sterile fluid, is acted on by bacteria and other organisms residing on the skin [e.g. *Staphylococcus*, *Micrococcus*, *Bacillus*, *Acinetobacter*, *Klebsiella*, *Enterobacter* and *Streptomyces* (Kloos and Musselwhite 1975)], releasing volatile acids and indoles (e.g. isovaleric, butyric, carbonic). Major sources of body sweat odour are those emitted by the apocrine glands (i.e. fatty acids, steroids, amines). Axillary hair collects sweat and other debris, and in relation to foot odour, similar patterns occur (Ara et al. 2006; Marshall et al. 1987, 1988). Strong foot odour has been linked with greater total population densities of microflora, staphylococci and aerobic coryneforms, rather than an increase in any single type of bacterium (Marshall et al. 1988). Minimising this odour is another measure of ensuring well-being.

In the 1970s, isovaleric acid (the ‘sweat-like’ odour) was identified as one of six main primary odours (Amoore 1977). A study of ten males (aged 25–30 years) (n = 5 strong foot odour, n = 5 low or no odour) showed isovaleric acid identifiable in all participants with foot odour, but not in those without (Kanda et al. 1990). While isovaleric acid is responsible for foot odour (Kanda et al. 1990), propionic acid, isobutyric acid and butyric acid are also contributors (Ara et al. 2006).

Clothing adjacent to the axilla or textiles covering the foot (socks, shoes) are implicated in human body odour, as organisms are able to reside in various fabrics (Shelley et al. 1953) and in footwear. Understanding the interactions among axillary odours, bacterial count and fibre type improved during the early part of the 21st century (McQueen et al. 2007a, b, 2008). McQueen et al. assessed the odour of fabric samples (wool, polyester, cotton; interlock, single jersey, 1 × 1 rib, matched constructions) which had been worn by five males. Polyester fabrics exhibited the strongest and wool fabrics the least intense odour (Fig. 2). No inherent antibacterial properties were evident, with bacterial counts at day 1 similar on all fabrics.

**Fig. 2** Odour intensity ratings of wool, cotton, polyester fabrics (mean ± s.e. m.) **a** stored for different times, **b** five participants, (reproduced from Textile Research Journal 2007 77, 449 doi: [10.1177/0040517507074816](https://doi.org/10.1177/0040517507074816))





Bacterial populations were present on all fabrics for up to 28 days, with numbers remaining relatively stable in wool fabrics, and declining in polyester fabrics (McQueen et al. 2007a). Whether the bacterial count was related to the method of extraction is unknown but is considered unlikely to explain the observed differences in odour intensity.

Intermittent claims are made about wool being naturally antibacterial, but no evidence to support these claims has been identified. McQueen's work (2007) did not show a link between the number of bacteria and odour. Nor has any evidence of anti-fungal properties related to wool been identified. The notion of natural antibacterial/antimicrobial properties may arise from the fact that wool products such as garments do not retain/release odour volatiles during and following wear as do comparable products in other fibre types. Exposure of a matrix of known odour volatiles to wool, cotton, polyester fibres/yarns under controlled conditions provided some explanation of the mechanisms involved (Yao et al. 2015), and this work is continuing.

Treatments to confer antimicrobial properties on textiles have been developed and many reviewed (Gao and Cranston 2008). One method applied to wool and wool products has been inclusion of silver (Li et al. 2010; Tang et al. 2011) although concerns have been expressed about development of bacterial resistance to silver (Percival et al. 2005). Effectiveness of other wool-metal complexes/salts has also been examined (Freddi et al. 2001; Zhao and Sun 2006; Zhu and Sun 2004), as has chitosan as an antimicrobial treatment for woollen fabrics (Hsieh et al. 2004).

The effect of footwear on temperature and humidity, and related microbial populations on skin of feet was investigated in the 1960s, but with little information on the footwear, including socks. A study of the socks and shoes of hospital patients with symptoms of *tinea pedis* but not undergoing treatment ( $n = 30$ ) focussed on these items of clothing as carriers of fungal spores (Brown and McLarnon 2007). Although non-significant, there was a trend for participants with *tinea pedis* infections to also have infected footwear (Brown and McLarnon 2007). That fungal spores remain in socks, shoes, and on various surfaces has been assumed given high levels of transmittance and re-infection (Ajello and Getz 1954). Surprisingly, wool socks appear not to have been included in these studies.

## Sleep—Bed Clothes, Sleepwear, Bedding

Clothing worn during sleep (pyjamas, nightdresses, 'stretch-and-grows'/'onesies') has the potential to influence sleep quality, with several variables indicating sleep quality (e.g. time to the on-set of sleep, duration of sleep, duration of wakefulness). Sleep in adult humans becomes disrupted once thermoregulatory mechanisms are elicited (Bach et al. 2002), and information on many aspects of temperature and sleep have been published (REM (Muzet et al. 1983; Okamoto-Mizuno et al. 1999); room temperature, bed temperature, and various body temperature indicators (Muzet et al. 1983; Okamoto-Mizuno et al. 1999); effects of elevated skin

wettedness (Okamoto-Mizuno et al. 1999)). Temperature of the sleep environment is even more important for infants, as temperature has been suggested as one cause of Sudden Infant Death (Muzet et al. 1983; Stanton 1984).

There is some evidence that the quality of sleep can be affected by the type of fabrics in both bedding and clothing worn in bed. Most investigations have not included wool (e.g. pyjamas of cotton/elastane compared with those of polyester/elastane (Yao et al. 2007)). Patterns of sleep of pre-school children ( $n = 101$ , aged 2–5 years) was the focus of an Australian study on effects of bedding, bedroom environment, sleep hygiene. Sleepwear was typically cotton in winter and summer, with cotton/synthetic sleepwear reportedly worn by about half the children. Few children wore sleep clothing made from wool fabrics, just 7 % of children in winter (Richdale 2013). A sleep problem was associated with synthetic bed wear in winter and in summer, and feeling ‘too cold’ during sleep (Richdale 2013).

Effects of sleeping apparel (wool, cotton) and bedding (wool, synthetic) on sleep of 17 participants (adults, aged  $24.6 \pm 6.9$  years;  $n = 10$  males,  $n = 7$  females) over nine nights of sleep have been examined (Shin et al. 2014). Participants were randomly allocated to one of two ambient conditions (17, 22 °C), to the sleeping apparel, and to the bedding types. Wool bed apparel was suggested as promoting sleep through a shorter time to its on-set, and also the total sleep time was of longer duration. Differences were attributed to the general hygroscopicity, high moisture absorption rate, and thermal resistance of the wool textiles. Effects of bedding were less clear.

A pilot study in Britain in the early 1980s reported low birth weight babies gained more weight when nursed on lambswool (either lambswool in an artificial fibre backing or natural lambskins) rather than cotton sheets (Scott et al. 1983). The authors hypothesised that the wool provided a more thermally neutral, ‘less stressful’ environment, although these findings were based on absolute weight gain rather than a percentage of initial body weight (Roberts et al. 1986). The study was repeated with monitored energy intake, and no significance detected (Roberts et al. 1986). During the latter part of the 20th century and early 21st century Wilson and colleagues examined infant sleep arrangements and the links with Sudden Infant Death (Wilson et al. 1994), particularly thermal parameters (Wilson et al. 2000, 2002). Use of a wool under-blanket with a ‘waterproof’ covering had previously been reported as contributing to a lower likelihood of the incidence of Sudden Infant Death (Wilson et al. 1994). These investigations demonstrate the complexity of bedding and its effects.

Since the classic 1980s investigation by Umbach (1986), understanding the role of bedding is slowly being enhanced. Umbach compared performance of a wool blanket with another from acrylic (matched for thickness, mass per unit area), a comparison based on a skin model, instrumented human manikin (Charlie) dressed in pyjamas, and also humans ( $n = 4$  males in a climate chamber). The wool blanket performed better in terms of thermal insulation, moisture absorption, and moisture buffering. With respect to underlays, investigations during the latter part of the 20th century focussed largely on sheepskins or pile-type constructions. Participants

(n = 10) sleeping on a wool ‘fleecy’ underblanket were observed to have 20 % more periods of immobile sleep and more participants self-reported feeling better in the morning and having improved sleep quality (Dickson 1984). Better understanding of potential effects of fibre/fabric/structure would be possible with detail on both mattress pads (e.g. fibre content, construction, mass, thickness).

Bed covers used on Australian pre-school children (n = 101) (Richdale 2013) in winter were either duvets or blankets (approximately equal numbers of each), and wool (fill) in 26 % of duvets and 28 % of blankets. In summer, the most common cover was a cotton blanket (44 %) and wool just 12 %. Sheets were common in both summer and winter. In terms of underlays, these were cotton for approximately one third of the sample irrespective of season: wool underlays were much less common, with 12 % in winter and 10 % in summer (Richdale 2013). This study involved multiple factors: differences in fabrics/structures, fibre types self-reported, and some categories of variables not mutually exclusive (e.g. the underlay mattress protector (waterproof) may have been used with either a cotton or a wool underlay). However, children who slept in any synthetic bed wear in summer or winter were more likely to be reported as having a sleep problem.

## Conclusions

This review provides evidence of the contribution of wool to human health and well-being. What is known includes

1. Indicators of skin health are measurable, and textiles in close contact with the skin can affect these. Wool fabrics in close contact with the skin can maintain and/or enhance normal moisture levels of the skin.
2. The mechanisms underlying prickle resulting from skin contact with wool fabrics are well understood, and can be ameliorated by manufacturing processes at fibre, yarn, and fabric stages. Perception of wool products remains a barrier to use for some consumers.
3. Effects of fabric structure dominate many performance properties when all variables other than fibre type are controlled. This relates particularly to thermal and moisture relationships.
4. There is no evidence to support claims that wool fibre causes allergic reactions. Allergic reactions may occur as sweat from the human body reacts to dyes and/or finishes on wool fabrics, or fabrics of any other fibre type, which are in contact with the skin surface.
5. Wool in garment form provides benefits during exercise by slowing thermo-physiological responses, thereby allowing adaptation to the changed environment.
6. There is physical and perceptual evidence of smooth, lightweight, woven wool fabrics being cooler to the touch than comparable fabrics in several other fibres/blends.

7. Thermal and moisture transmission through a layered assembly is not the sum of properties of the individual layers and air spaces. Effective cooling of the human body through evaporative heat loss is decrementally affected by layers, up to 80 % reduction in effectiveness.
8. No evidence has been identified which shows wool is intrinsically antibacterial or antimicrobial (and thus wool is biodegradable, an advantage). Wool yarns/fabrics are treated to confer antimicrobial properties, and while of some benefit, consumer concerns have been raised.
9. Wool fabrics (garments) after wear, have less intense odour than matched cotton or polyester fabrics: intensity of odour seems not to correspond with the number of bacteria extracted, and adsorption/release of odour volatiles from wool differs to that from other fibres.
10. There is some evidence that wool blankets perform better than equivalent acrylic/blend blankets from a human thermophysiological perspective. Other than for babies and infants, little is known about effects of underlays on sleep.

Understanding the role of wool in human health and well-being is not straight forward as both investigative approaches and level of detail provided in reports/papers differ widely. Although standard test methods may be followed (e.g. ISO, ASTM, BS), different standard methods purportedly measuring the same parameter may not do so. Description of methods followed and materials used are not always complete. Fibre-based comparisons are often confounded with other manufacturing variables by insufficient control of yarns/fabrics/finishes. Caution in interpretation of findings is therefore required.

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