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Axillary odour build-up in knit fabrics following multiple use cycles

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Abstract

Purpose – Fibre content can influence the intensity of odour that develops within clothing fabrics. However, little is known about how effective laundering is at removing malodours in clothing which differ by fibre type. The purpose of this paper is to investigate whether a selected cotton fabric differed in odour intensity following multiple wear and wash cycles compared to a polyester fabric.

Design/methodology/approach – Eight (male and female) participants wore bisymmetrical cotton/polyester t-shirts during 20 exercise sessions over a ten-week trial period. Odour was evaluated via a sensory panel, bacterial populations were counted and selected odorous volatile organic compounds were measured with comprehensive two-dimensional gas chromatography and time-of-flight mass spectrometry detection. Analysis occurred both before and after the final (20th) wash cycle.

Findings – Findings showed that laundering was effective in reducing overall odour intensity ($p \leqslant 0.001$) and bacterial populations ($p \leqslant 0.001$) in both cotton and polyester fabrics. Odour was most intense on polyester fabrics following wear, not just before, but also after washing ($p \leqslant 0.001$); although, no differences in bacterial counts were found between fibre types ($p > 0.05$). Chemical analysis found C4-C8 chained carboxylic acids on both types of unwashed fabrics, although they were more prevalent on polyester.

Originality/value – The findings suggest that the build-up of odour in polyester fabrics may be cumulative as important odorants such as the carboxylic acids were not as effectively removed from polyester compared to cotton.

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Paper type Research paper

Introduction

Odours arising from various sources (e.g. body odour, tobacco, food aromas) can develop and be retained within clothing. Due to the close proximity of some clothing items next to the skin, the development of body odours within fabrics is common and generally perceived to be unpleasant. The main source of unwanted body odour from healthy individuals comes from the axillary region, arising from the bacterial metabolism of apocrine sweat (Senol and Fireman, 1999; Shelley *et al.*, 1953). Odour build-up in apparel fabrics occurs through: first, the transfer of bacteria and sweat to the textile where odour is then generated within the fabric itself; and second, the transfer of odorous compounds, first produced on the body, are absorbed/adsorbed by the textile fibres to be later desorbed into the environment. Depending on fibre content, presence of antimicrobials and other fabric finishing treatments the odour produced in the axillary region can differ in intensity and quality from that transferred or generated within fabrics (Dravnieks *et al.*, 1968; McQueen *et al.*, 2007).

A number of different methods may be used to control malodour within textiles themselves. Such as controlling the microorganisms responsible for the development of the malodour (Mao and Murphy, 2001; Obendorf *et al.*, 2007; Payne and Kudner, 1996), absorption/adsorption of odorous volatiles through sorptive materials such as activated carbon (Eza *et al.*, 2012; Ohge *et al.*, 2005) or cyclodextrins (Buschmann *et al.*, 2001); and masking malodour through adding fragrance to the textiles (Martel *et al.*, 2002; Wang and Chen, 2005; Liu *et al.*, 2008). Laundering to remove body odours is another method of controlling malodour build-up. But, malodour may still be perceived in clothing despite laundering (Munk *et al.*, 2000; Takeuchi *et al.*, 2012). This odour may be a result of bacteria which survived the laundry process continuing to metabolize organic soils not effectively removed from the fibres during washing. For example, in a recent study examining the interaction between triglycerides, *Staphylococcus epidermidis* and malodour formation on cotton fabrics, despite some reduction, many microorganisms still remained on the fabric following laundering with detergent only (Chung and Seok, 2012). Although, most of the malodorous volatiles identified in this study were more effectively removed than the bacteria (Chung and Seok, 2012), many odorous compounds continue to remain in fabrics following laundering attributing to odour retention (Munk *et al.*, 2001).

As well as controlling malodour through finishing treatments, consumers could still make purchasing choices based on the generic fibre content when concerned about body odour. This is because the inherent fibre type from which clothing is made can influence the intensity of odour following wear against the body, as clothing made from different fibre types (e.g. natural vs synthetic) can differ in the intensity of odour that develops within the fabric and is subsequently released into the surrounding environment to be perceived by the human nose. For example, McQueen *et al.* (2007, 2008) found that clothing made from polyester was more odorous following wear against the axillary region than clothing made from either cotton or wool. Munk *et al.* (2000) mentioned that cotton fabrics needed to be worn twice and polyester only once in order to get sufficient odour intensity onto the fabrics for analysis of body odorants. Prada *et al.* (2011) also found considerable differences in the chemical groups of volatiles emitted from human hands, which was highly dependent on fibre type, as carboxylic acids were more prevalent on polyester fabrics compared with cotton, wool or rayon. Nonetheless, despite evidence that natural fibres are generally preferable over synthetics for emitting lower odour following wear, there has been little investigation into the build-up of odour over multiple uses, and particularly, whether intensity of odour differs between different fibre types after they have been laundered.

One study that did investigate axillary odour development on fabrics composed of different fibres after laundering, found that odours emitted from "wet" cotton fabrics following washing were perceived to be higher in intensity than "wet" polyester fabrics assessed both one and five days following washing (Munk *et al.*, 2001). Through gas chromatography-olfactometry measurements of extracted compounds, polyester fabrics were found to have a more complex odour profile with a greater array of high-impact odorants than cotton fabrics. The cotton fabrics had one particularly pungent "faecal" type of odorant, 3-methylindole (or "skatole") which the authors suggested likely contributed to the higher odour intensity ratings obtained from cotton fabrics (Munk *et al.*, 2001). However, the same study also reported that other major sweat odorants directly applied to fabric swatches were more effectively removed from cotton than polyester with washing (Munk *et al.*, 2001). The work carried out by Munk and colleagues provided valuable information about the key odorants implicated in the retention of axillary odour on cotton and polyester fabrics following washing. Although, the problem of malodour development due to slow drying has been identified as an important concern (Takeuchi *et al.*, 2012; Nagoh *et al.*, 2005; Munk *et al.*, 2001), the conditions of slow drying, and therefore subsequent odour evaluations of wet fabrics in Munk *et al.*'s study, may represent an extreme circumstance. In many (preferable) situations, people would wash their soiled clothing and dry it promptly after laundering either by machine or by line in a dry environment.

There appears to be no research evaluating the build-up of malodour in clothing made from common textile fibres worn during active leisure pursuits that have been subjected to multiple use and laundering cycles. If odour is retained in a garment and detected even after it has been laundered, the clothing could potentially be discarded well before other signs of degradation became noticeable. As strict fibre content labelling laws apply in several countries, consumers can easily make purchasing decisions based upon disclosed fibre content. Therefore, studies are needed to understand how fibre content influences odour build-up in different types of clothing over time.

The purpose of the current study was to investigate whether a selected cotton fabric differed in odour intensity following multiple wear and wash cycles compared to a polyester fabric. Evaluations were made of soiled apparel fabrics prior to the final laundering cycle (unwashed fabrics) and then following the final laundering and drying cycle (washed fabrics). A holistic approach to odour evaluation was taken where odour was assessed via a sensory panel, bacterial counts were measured and selected odorous volatile organic compounds (VOCs) were also measured.

Materials and methods

Fabrics and fabric preparation

In the global apparel market, cotton is by far the most common natural fibre surpassed only by polyester which is the most common synthetic fibre (Sirichayaporn, 2012). For sportswear, polyester tends to dominate over cotton textiles, while, cotton is still a common fibre of choice to be worn next to the skin in underwear and t-shirts. Accordingly, cotton (COT) and polyester (POL) were chosen as the fibre types for comparison. Both fabrics were constructed as single jersey knit structures and prepared by Cotton Incorporated (Cary, NC). COT comprised of 95 per cent cotton/5 per cent spandex (mass: 184 g/m^2; thickness: 0.57 mm) and POL 95 per cent polyester/5 per cent spandex (mass: 220 g/m^2; thickness: 0.80 mm). Both fabrics had softening agents applied to them (COT: 10 g/L silicone softener, 30 g/L cationic softener, non-silicone, 10 g/L polyethylene softener; POL: 10 g/L polyethylene softener, 50 g/L Milease-T softener for polyester). Polyester fabrics were composed of filament yarns as the majority of polyester sportswear on the market is made from filament yarns rather than staple. It was considered more appropriate to select fabrics based on the types likely to be encountered in the retail marketplace rather than matching the yarn characteristics of the two fabrics. The addition of 5 per cent spandex gave fabrics sufficient stretch to make form fitting t-shirts, suitable for carrying out exercise.

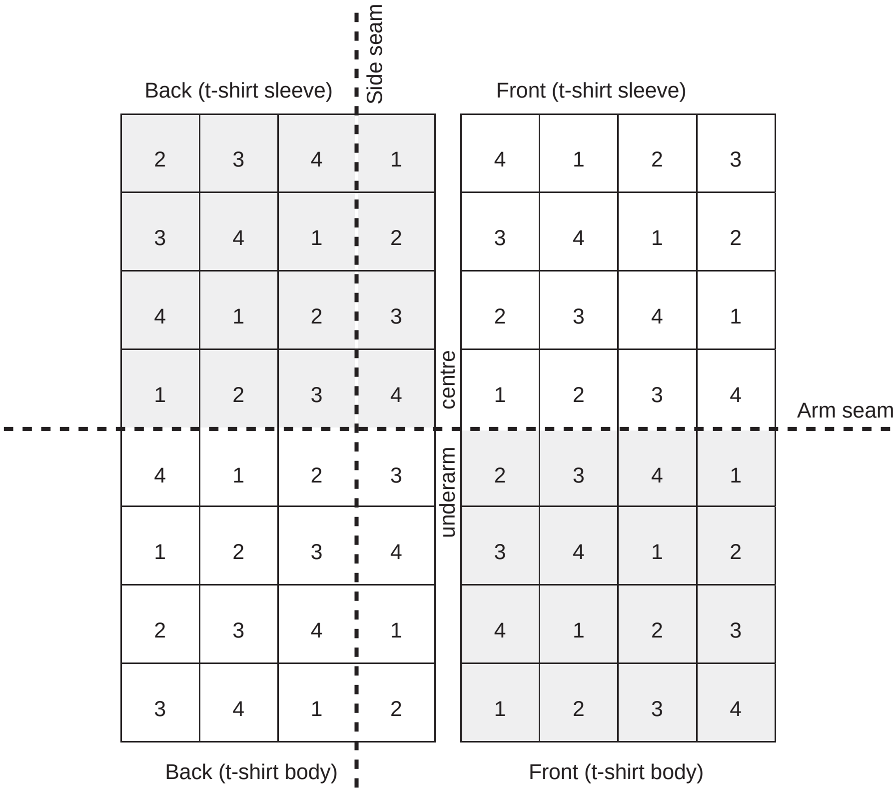
Experimental t-shirts comprised a COT fabric on one side of the body (e.g. left side) and POL fabric on the opposite side of the body (e.g. right side). Prior to garment construction, the COT fabric was laundered once, in order to compensate for the difference in dimensional stability between the two different fabric types.

Following the field trial (described below) fabric specimens were cut out of the t-shirts following wear but prior to laundering (unwashed), and following laundering and drying of the t-shirt (washed). The sampling plan for preparing specimens is shown in Figure 1. The laundering and drying procedure used for the final wash was similar to that described by the participant (i.e. top-load or front-load washer; machine or line dry). The centre of the sampling plan was located on the t-shirt to correspond to the position of the centre of the underarm. Diagonally opposite squares at least 72 mm $\times$ 72 mm were cut out of each unwashed t-shirt and then cut into smaller 18 mm $\times$ 18 mm specimens. The smaller specimens were sorted into groups as indicated by their number on the grid. The pooled specimens were randomly assigned to either: sensory analysis (16 specimens), microbiological analysis (eight specimens) or chemical analysis (four specimens). For sensory analysis, two groups were combined (e.g. eight specimens numbered "2" plus eight specimens numbered "4") to make up a test sample of 16 specimens in total. For the microbiological analysis, only one group of eight specimens was required (e.g. specimens numbered "1"). For chemical analysis where only four specimens were required, the specimens closest to the underarm seam were used (e.g. half of specimens numbered "3"). None of the fabric specimens contained any part of a seam (i.e. fabric specimens were cut adjacent to but not including the seams). The same sampling procedure was carried out on the washed t-shirts cutting out specimens from the remaining fabric in the underarm region of the t-shirt.

Field study

Prior to any research being carried out involving human participants, all research protocols were approved by the relevant Human Research Ethics Board at the University of Alberta.

The development of body odour in clothing is a highly complex process which involves the physical transfer of odorants, precursors to odour (i.e. apocrine sweat), and bacteria from the body into the adjacent fabric. The semi-occluded environment of the axillary region is humid and warm (35.5-37 °C) (Sund-Levander *et al.*, 2002) and not only facilitates the growth of microbes, but enhances the absorption of odorous compounds into the fibre structure of some fibre types (e.g. hydrophilic). Therefore, a wear trial involving human participants repeatedly exercising in clothing over



Note: Specimens were pooled by number from diagonally opposite squares (e.g. shaded matched with shaded)

Figure 1.
Sampling plan of t-shirt in order to prepare groups of 18 mm × 18 mm specimens for sensory, microbiological and chemical analysis

a defined length of time was the most effective way to collect odour which represented real-life use. A field trial, in particular, was considered to be the most appropriate approach for collecting this information, rather than a more tightly controlled wear study, as people will naturally vary in their activities, diets, laundry practices, and therefore the results from this study would better reflect the natural variability occurring in the general population.

Ten healthy participants (five females and five males) participated in the field trial. The participants had been screened prior to selection to ensure they generated sufficiently high post-exercise odour intensity. The screening procedure involved participants wearing t-shirts which had polyester fabric swatches sewn into the underarm for 1 hr of exercise. Following wear, the fabric swatches were removed from the t-shirts and assessed for odour intensity.

Each participant in the field trial was provided with two t-shirts, one marked t-shirt A and the other marked t-shirt B. For t-shirt A, cotton was in the left side and polyester was in the right side of the t-shirt; and for t-shirt B, cotton was in the right side and polyester was in the left side. This was to control for factors such as a left/right imbalance that an individual may have.

All participants were provided with a perfume-free and dye-free laundry detergent (Tide® Free & Gentle, Proctor & Gamble) to use for the duration of the study. Participants were asked to wear each t-shirt on average two times per week for at least 1 hr of exercise over a ten-week period so that each t-shirt was worn 20 times in total. Participants were responsible for laundering their own t-shirts for the duration of the study, until the final wear cycle (20th wear) where they returned the unwashed t-shirts to the study personnel. Participants were asked to record their activities (e.g. type and length of exercise, length of time t-shirt worn in total, handling procedure between wear and wash, assessing odour on left and right side of t-shirt) in a log-book. Also, participants were asked to report whether they used a top-load or front-load washer, and whether they machine or line dried their t-shirts. Participants were also asked not to wear perfumed products or deodorants in the underarm region before they exercised in the t-shirts. No other restrictions were requested of them.

Procedure for sensory analysis

Totally, 17 assessors (13 females and four males) ages ranging between 18 and 59 years (median age range 18-29) participated on the sensory panel. All assessors were recruited from the University of Alberta campus. Assessors were screened and trained to assess odour intensity following the guidelines in Section 7 "Assessor Selection and Training" of ASTM E1207-09 (American Society for Testing and Materials, 2009).

A test sample comprised 16 specimens (18 mm $\times$ 18 mm) of the "like" fabric which had been worn by one individual (e.g. participant F1 or participant F2) and obtained from the same t-shirt (t-shirt A or t-shirt B). Fabric specimens were placed in standard conditions (20 ± 2°C and 65 ± 5 per cent R.H.) for 12-14 hrs before sensory analysis. Following this conditioning period, specimens were placed in an amber wide-mouth bottle (60 mL in volume) which then had the lid screwed on to prevent loss of compounds. A reference sample was included in sensory analysis, which was also comprised of 16 specimens in a 60 mL bottle. The reference sample was obtained from polyester fabric which had been sewn into the underarm region of a t-shirt and worn by one male participant. The bottles with the test and reference samples were placed in a 36-38°C water bath for sensory evaluation.

Assessors rated odour intensity of test samples on two consecutive test days: unwashed samples on the first day and washed samples on the second day. During each test session, assessors sniffed nine samples. The reference sample was always presented as the first sample for each assessor, and the remaining eight test samples were ordered according to an 8-treatment Williams' Latin square design (MacFie *et al.*, 1989) to prevent order effects. Results for the reference samples were not included in the analysis. Sensory analysis was performed in standard sensory testing rooms (International Organization for Standardization, 2007) at 21 ± 2°C.

Intensity of odour was rated on a 150 mm line scale with extremely low labelled on the left of the scale and extremely high labelled on the right. Assessors were asked to take three small sniffs at the mouth of the bottle, make a decision, and mark the intensity on the line scale with a vertical mark. They were asked to allow 30 sec between each sample and to refresh the nose by sniffing the glass of distilled water supplied in the sensory booth. All nine scales were printed on the same response form and the samples were labelled with a random three-digit code number. Scores were converted to a number by measuring from the left of the line to the vertical line marked by the assessor. Measurements were taken to the nearest 0.5 mm.

Microbiological procedure

The eight fabric specimens designated for microbiological analysis were placed in sterile 50 mL Corning tubes containing ten to 15 sterile glass beads and left to stand overnight (approximately 12-14 hrs). Prior to extraction, 10 mL of phosphate buffer saline solution amended with 0.05 per cent Triton X-100 was pipetted into each of the tubes which were then vortexed for 1 min. A ten-fold dilution series was made from the vortexed solution with the buffer solution. Aliquots of 20 μL were placed onto each type of culture media in triplicate and then incubated for 48 hrs at 37°C. Two types of culture media were used, the first consisted of a non-selective (NS) media (Taylor *et al.*, 2003) and the second selected for aerobic *Corynebacterium* species subgroup A (ACF) (Austin and Ellis, 2003). Total bacterial populations were counted for each media and viable counts were expressed as colony forming units per millilitre (CFU/mL).

Chemical analysis

The four fabric specimens designated for chemical analysis were placed in a 10 mL crimp-top clear headspace vial (Chromatographic Specialties Inc., Brockville, ON). The odour extraction was performed by solid phase micro-extraction using divinylbenzene/carboxen/polydimethylsiloxane coated fibres (SUPELCO, Bellefonte, PA). Before performing an extraction, the fibre was thermally cleaned for 2 min at 250°C. Extractions were conducted for 21 h at 30°C with sample vials immersed in a temperature-controlled, stirred oil bath. Analytes were desorbed from the fibre in the gas chromatograph injector for 3.5 min.

The fabric samples were analysed by comprehensive two-dimensional gas chromatography (GC × GC) with time-of-flight mass spectrometric detection on a Pegasus 4D system (Leco Instruments, St Joseph, MI) equipped with a liquid nitrogen cryogenic quad-jet modulator. The columns used for the first and second dimensions were a 30 m × 0.25 mm, 1 μm film thickness Rtx-5MS (chromatographic specialties) and a 1.8 m × 0.18 mm, 0.18 μm film thickness DB-Wax (chromatographic specialties), respectively. Helium (Praxair, Edmonton, AB) was used as the carrier at a flow of 1.5 mL/min. The analytes were desorbed in splitless mode using an inlet temperature set at 250°C. The primary oven temperature programme was 35 (held for 3.5 min) – 250°C (held for 10 min) at 4°C/min. Relative to the primary oven, the secondary oven was programmed to have a constant offset of +10°C and the modulator a constant offset of +20°C. A modulation period of 5 s was used. Data were collected from m/z 35-350 at rate of 100 spectra/s. The detector voltage was −1350 V, the ion source temperature was 200°C, and the MS transfer line temperature was 240°C.

Statistical analysis

An analysis of variance (ANOVA) was carried out to determine if there were any differences in odour intensity with four fixed factors (wash level, fabric, participant and assessor). Where there were significant differences found, Tukey's *post hoc* tests were carried out. Additionally, each matched fabric pair for each participant was analysed using paired-sample *t*-tests (SPSS Inc., 2010).

Bacterial counts (CFU/mL) were log transformed for analysis. An ANOVA was carried out on the $\log_{10}$ transformed total aerobic bacteria (NS media) and aerobic corynebacteria (ACF media) counts. The model included three factors all at fixed levels: wash, fabric and participant. Where there were significant differences found, Tukey's *post hoc* tests were carried out (SPSS Inc., 2010).

Results and discussion

Reports from the field trial

Two participants (one female and one male) withdrew part-way through the study; therefore, the results presented were based on eight participants. Overall, the average time a t-shirt was worn for one exercise session was 1 h and 15 min. The average total time that a t-shirt was worn for one trial day was 2 hrs and 24 min. Most participants carried out some type of high-intensity aerobic exercise such as running, cycling or a cardio workout which included aerobics, cardio circuit training or just "cardio". The way in which the t-shirt was handled, following wear and prior to laundering, varied depending on the participant. Most participants (five out of eight) reported that for the majority of the time, their t-shirts were either put into a gym bag or in a laundry pile so they were not aired out prior to laundering. Three participants routinely hung their t-shirts to dry or "air-out" following wear, prior to laundering.

A summary of the participants' own rating of odour intensity for each side of their t-shirts is shown in Table I. Participants sniffed their own t-shirts both prior to washing as well as following laundering. Odour intensity was generally perceived to be more odorous from the polyester side of the unwashed t-shirts with 79.5 per cent of total evaluations rating polyester as the strongest in odour compared with only 13.6 per cent of total rating cotton as stronger. Prior to laundering few "no differences" in odour intensity were detected (6.8 per cent) when participants "sniffed" the two fabrics of their own t-shirts, whereas following laundering 63.5 per cent of the odour intensity ratings were not different. Only one participant reported perceiving higher odour intensity on the cotton side of her unwashed t-shirts the majority of the time (data not shown). For example, for both t-shirt A and B, F3 reported cotton to be more intense 15 times, polyester more intense three times, and only once perceived no difference between the two sides. One limitation of asking participants to rate their own t-shirts is that due to the differences in appearance between the two fabrics (e.g. polyester had more lustre than cotton); it was not possible to blind the participants to the fabric. In another study on odour reduction due to antimicrobial treatment, two fabrics (one placed under each underarm) appeared identical, and participants did not know which fabric had been treated with an antimicrobial agent (Mao and Murphy, 2001).

Analysis of odour by the sensory panel

In this study, amber glassware was used to mask the appearance of the fabrics during odour analysis by the sensory panel to avoid bias due to expectation errors. Laundering effectively reduced odour within fabrics, as odour intensity was perceived to be higher prior to laundering than after laundering ($F_{1,762} = 228.91$, $p \leqslant 0.001$). This was true regardless of fibre type, as odour intensity on cotton fabrics was rated as 31.1 ± 13.8 prior to washing and 20.6 ± 7.6 following washing, and polyester fabrics

Table I. Summary of participants' perception of odour intensity on their own t-shirts (number of times and percentage)

		Most intense side of t-shirt		
	n	POL	COT	ND
Unwashed	293	233 79.5%	40 13.6%	20 6.8%
Washed	301	75 24.9%	35 11.6%	191 63.5%

Note: ND, no difference was detected between the left and right side of the t-shirt were rated as 60.2 ± 18.4 prior to washing and 33.5 ± 10.0 following washing (Table II). Odour intensity emitted from fabrics following removal from the human body was strongly dependent on fibre content of the fabric from which the t-shirt is composed, as differences in odour intensity as a result of fibre type were also detected ($F_{1,762} = 326.81$, $p \leqslant 0.001$). Before laundering, polyester fabrics were perceived to be significantly higher in odour intensity (60.2 ± 18.4) than the cotton fabrics they were matched with (31.3 ± 13.8). Following laundering polyester was still perceived to be higher in odour intensity (33.5 ± 10.0) than the washed cotton fabrics (20.6 ± 7.6).

The mean (± standard error of the mean (SEM)) of sensory assessments for matched fabric pairs for individual t-shirts before and after washing is shown in Figure 2(a) and Figure 2(b), respectively. Participant had a significant effect on overall odour intensity emanating from the washed and unwashed fabrics ($F_{7,762} = 26.13$, $p \leqslant 0.001$), with participant M2 having the highest overall odour intensity (t-shirt B POL: $M = 97.00$). In fact, odour perceived on the two cotton fabrics in t-shirts worn by participant M2 were higher than some polyester fabrics worn by other participants (e.g. M1 and M3). This finding was somewhat different from another published study with five male participants, where axillary odour emanating from polyester fabrics were consistently perceived to be more intense than either cotton or wool fabrics, regardless of the participant who wore the fabrics (McQueen *et al.*, 2007).

With the exception of the two t-shirts worn by participant M3, all polyester fabrics were perceived to have significantly higher odour intensity than the matched cotton fabrics prior to washing. That polyester was perceived to have higher odour intensity than cotton was not unexpected, particularly prior to washing. Polyester fabrics were significantly more odorous than either cotton or wool fabrics following wear against the male axilla after t-shirts (with fabrics sewn into the underarm region) were worn for two consecutive days of manual work (McQueen *et al.*, 2007).

Generally, the same trend of significantly higher odour intensity in polyester fabrics than cotton, was apparent following washing as well. This was a new finding as this is the first time a relatively long-term study investigating the build-up of axillary odour in polyester and cotton clothing has been conducted. However, there were some exceptions, as t-shirt A worn by participant F3 cotton was perceived to have higher odour intensity ($t_{14} = -4.870$, $p \leqslant 0.001$). Also, no significant differences were apparent between washed polyester and cotton fabrics for participants' F1 (B), F3 (B), F4 (B) and M3 (A&B).

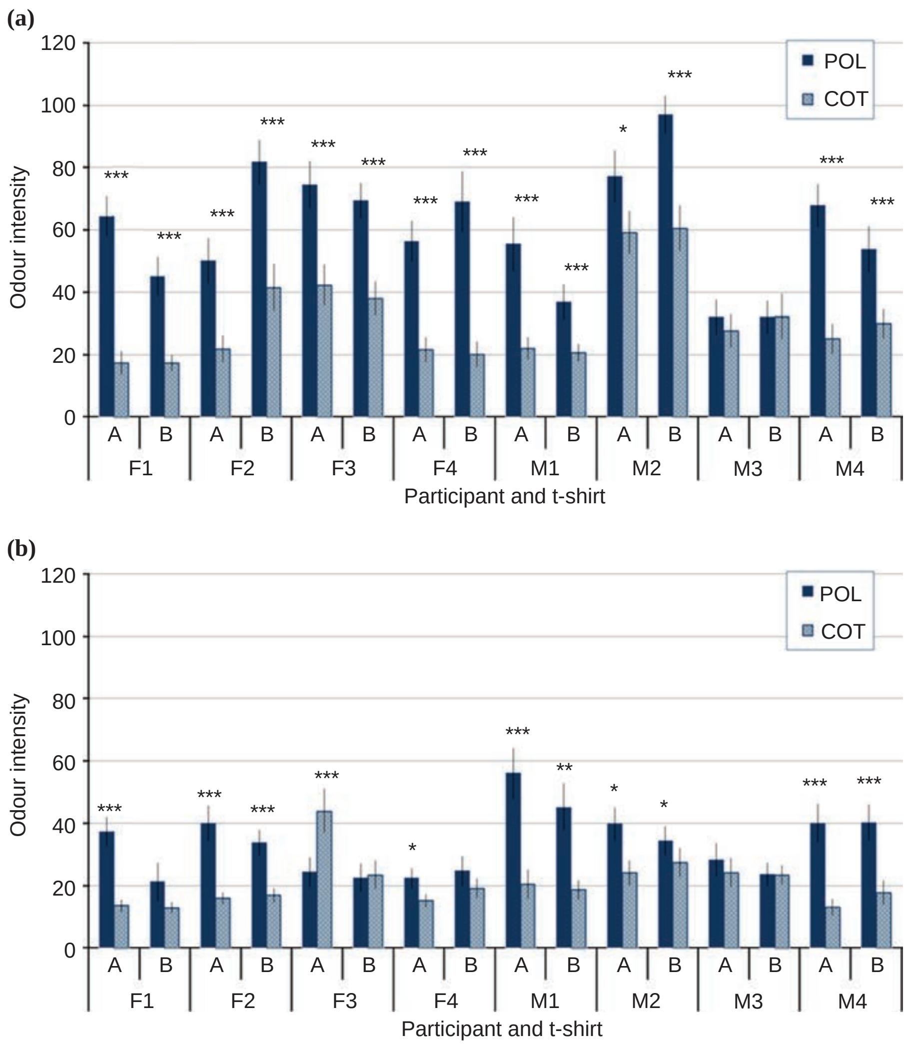
Bacterial counts

The log transformed bacterial counts for all participants and t-shirts combined are shown in Table II. Bacterial counts grouped by participant and t-shirt are shown in Figure 3(a) and (b) for unwashed and washed t-shirts, respectively.

Table II. Sensory evaluation of odour and bacterial counts from fabrics

	Unwashed		Washed	
	COT	POL	COT	POL
Odour intensity[a]	31.1 ± 13.8	60.2 ± 18.4	20.6 ± 7.6	33.5 ± 10.0
Bacterial counts ($\log_{10}$ CFU/mL)				
NS	3.75 ± 0.90	3.78 ± 0.68	1.57 ± 1.62	1.19 ± 1.10
ACF	3.20 ± 1.10	3.33 ± 0.97	1.35 ± 1.76	1.01 ± 1.17

Note: [a]Odour intensity was rated using a 150 mm line scale



Notes: (a) Unwashed; (b) washed. Odour intensity was rated using a 150mm line scale. $*p<0.05$; $**p<0.01$; $***p<0.001$

Figure 2.
Mean odour intensity ($\pm$SEM) for cotton and polyester fabrics grouped by participant and t-shirt

Washing had an effect on bacterial populations with bacterial counts being significantly lower on washed fabric samples than unwashed fabric samples ($F_{1,32}=257.57$, $p\leqslant 0.001$). Another contributing factor to changes in bacterial populations was the participant who wore the t-shirts ($F_{1,32}=16.46$, $p\leqslant 0.001$). There was no effect on bacterial populations as a result of fabric type ($F_{1,32}=3.14$, $p=0.086$). That bacterial counts obtained from fabrics were not influenced by fibre content was not entirely unexpected, as no differences in bacterial numbers were found among cotton, wool and polyester fabrics only one day after removal of the t-shirt from the body (McQueen *et al.*, 2007). However, in another study where five fabrics made from different fibre types were incubated for 24 hrs with axillary

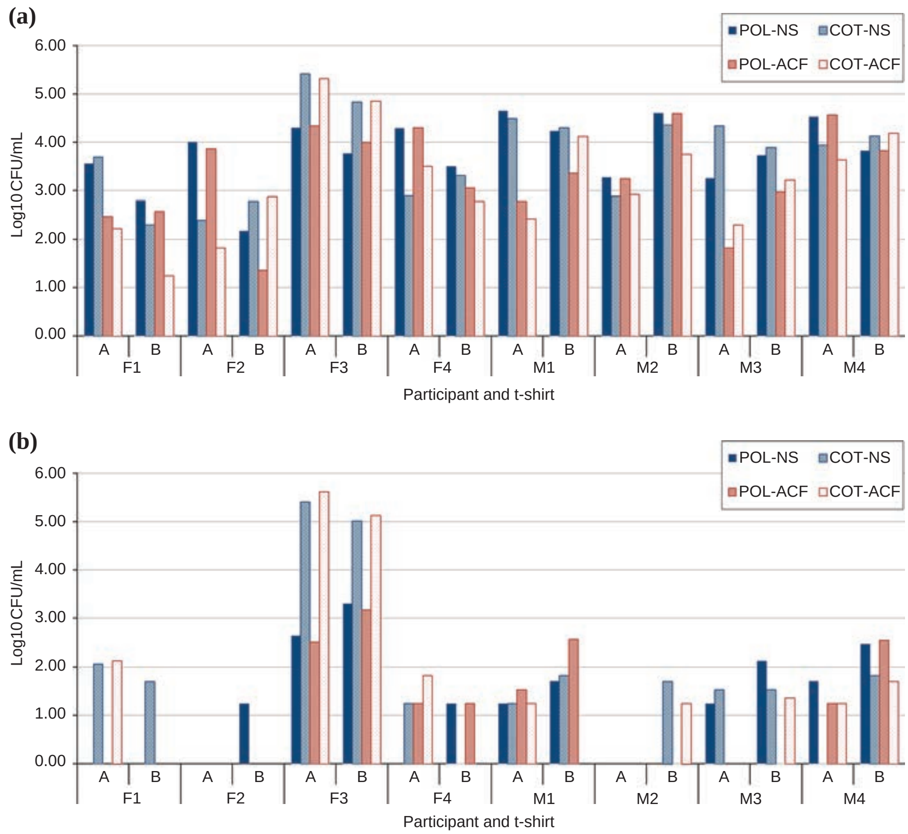


Figure 3.
Bacterial counts (log10 CFU/mL) grown on NS and ACF agar for cotton and polyester fabrics grouped by participant and t-shirt

Notes: (a) Unwashed; (b) washed

sweat, far greater diversity of bacterial taxa was found depending on fibre type (Teufel *et al.*, 2010). For polyester matched with cotton t-shirts there was a significant interaction between fabric and participant ($F_{7,32} = 3.279$, $p \leqslant 0.01$). This significant interaction was associated with t-shirts worn by participant F3 as the bacteria extracted from fabrics she wore remained high even following washing with counts obtained from cotton fabrics being 2-log-fold higher than those obtained from polyester fabrics (Figure 3(b)).

Chemical analysis

Chemical profiles of the volatile compounds were incredibly complex. Typically between 1,000 and 2,000 individual compounds were found in the fabric samples, with differences appearing not only between fibre types, but also between male and female participants, and from the right and left sides of the same individual. For the purpose of this paper, only the carboxylic acids will be discussed as they were present in samples from almost all participants and carboxylic acids have been recognized as key contributors to the overall axillary odour bouquet (Munk *et al.*, 2000, 2001; Zeng *et al.*, 1991). As well, acidic compounds have also been identified as major contributors to malodour remaining on fabrics following laundering (Nagoh *et al.*, 2005; Takeuchi *et al.*, 2012). The C4-C8 carboxylic acids were identified in the majority of the samples and are shown in Figure 4. Butanoic acid, hexanoic acid and octanoic acid were all found in at least one fabric sample for every participant regardless of fibre type. Pentanoic acid was detected in at least one fabric sample for all participants. Heptanoic acid was less prevalent in the cotton fabrics, but was detected in at least one t-shirt from the unwashed polyester fabrics for all participants with the exception of M4 where none was detected. In both the polyester and cotton fabrics worn by M2, heptanoic acid was detected.

Laundering tended to remove carboxylic acids from fabrics, but more so for cotton fabrics than polyester fabrics. Unwashed polyester fabrics tended to have the greatest quantity of acids present and many of the acids were still detected following washing. Unwashed cotton also had high quantities of butanoic, hexanoic and octanoic acids; however, following washing far fewer peaks were found. This was particularly notable for octanoic acid which was present in only two washed cotton fabric samples.

For the carboxylic acid compounds, it was clear that there was a strong effect of fibre type. Polyester fabrics tended to exhibit higher total peak values of the carboxylic acids and also retained the acids even following laundering. In contrast, the cotton fabric samples had fewer carboxylic acids present following laundering. It was not unexpected that the carboxylic acids were less effectively removed from polyester fabrics by washing. In "aromatic soiling" of a variety of odorants (i.e. ethylbutanoate, (Z)-4-heptenal, (E)-2-nonenal, 3-methylbutanoic acid, guaiacol and 4-methyloctanoic acid), all compounds were readily removed through washing procedures from cotton fabrics but not so from polyester (Munk *et al.*, 2001). The non-polar compounds in particular were more difficult to remove from polyester with laundering alone. This can be explained by the hydrophobic nature of polyester and the hydrophilic nature of cotton which facilitates the removal of soils and also odorants from cotton (McQueen *et al.*, 2008). It appears likely that there is a cumulative effect with odour building up in polyester over multiple use cycles since the odorous carboxylic acids are not effectively removed due to laundering. Furthermore, it has been suggested that odour continues to develop in polyester fabrics even after it is no longer in contact with the axillary region, based on the observation that volatile compounds likely to be short-chained carboxylic acids were higher in concentration in polyester fabrics seven days after wear compared to one day following wear (McQueen *et al.*, 2008). This did not occur for either the wool or cotton fabrics also assessed in the study (McQueen *et al.*, 2008).

The compound 3-methylindole, identified by Munk *et al.* (2001) on laundered cotton fabrics following soiling with axillary sweat and described as having a "faecal" smell, was not found in the current study. In Munk *et al.* (2001) study, the authors reported measuring odour and volatile compounds following slow drying techniques, where the fabrics were still wet during assessment. In the current study, participants laundered and dried the t-shirts much more quickly, either by machine drying or line drying in a dry indoor environment. Many participants did report that they did not air/dry their t-shirts between wearing and laundering. This could mean that some t-shirts were wet due to sweat for some period of time, and odour similar to that described previously (Munk *et al.*, 2001) could have developed in the cotton fabrics. However, of the eight participants only F3 reported the cotton fabric to be more intense than the matched polyester, both before and after laundering. Yet, the sensory panel rated the polyester fabrics she had worn as more intense than the cotton fabrics prior to washing. They did, however, rate the cotton fabric of t-shirt A as being more odorous following washing, and for t-shirt B there were no differences between the two fabrics. Examination of the carboxylic acids found on the fabric samples of participant F3

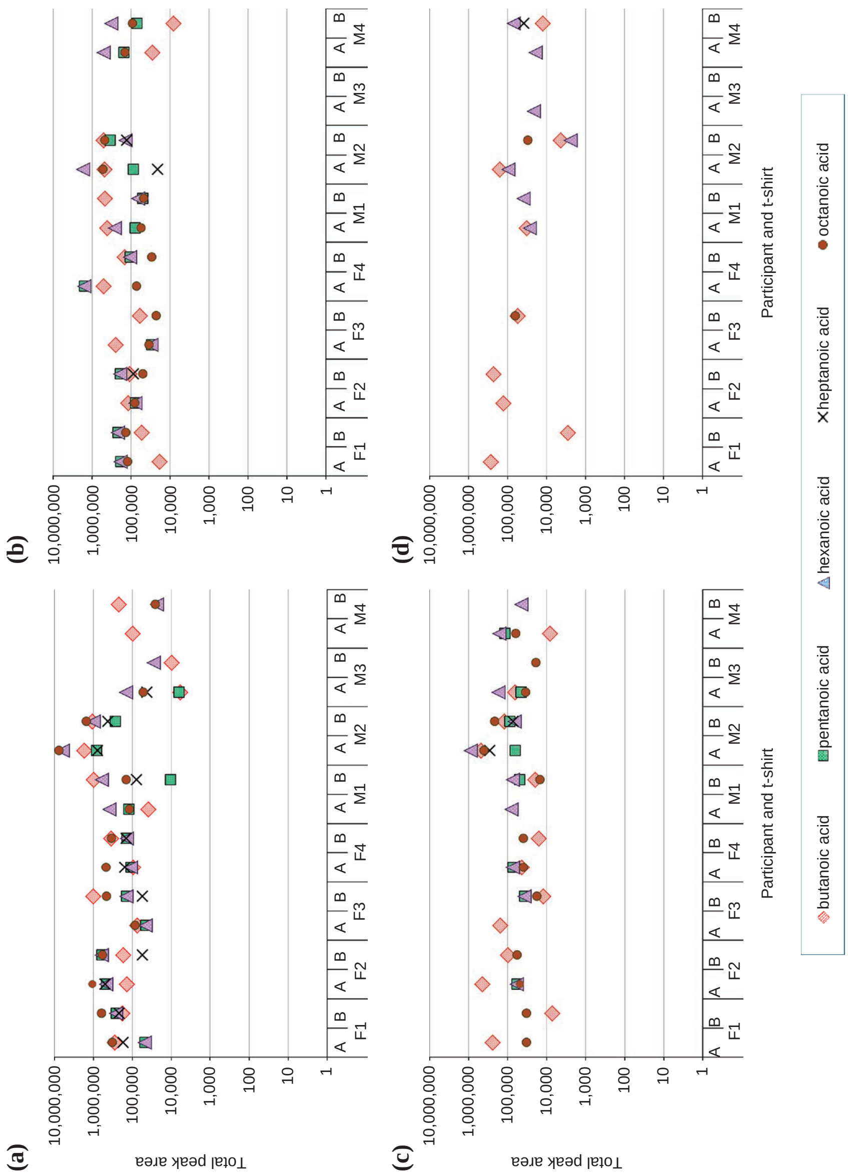


Figure 4.
Total peak areas for C4-C8 carboxylic acids for cotton and polyester fabrics grouped by participants and t-shirt

Notes: (a) Unwashed polyester; (b) washed polyester; (c) unwashed cotton; (d) washed cotton

(Figure 4) showed that more carboxylic acids were present on the polyester fabric for t-shirt A (i.e. butanoic acid, pentanoic acid, hexanoic acid, octanoic acid) and only butanoic acid was found on the cotton side of t-shirt A. This suggests then that other compounds are responsible for the more intense odour perceived on the washed cotton fabric for t-shirt A. Nonetheless, the types of odorants responsible for body odour will be highly dependent on the participant as one participant who was perceived to have the strongest odour by the sensory panel (i.e. M2), had high quantities of all five carboxylic acids identified on the unwashed fabrics, regardless of fibre type.

It is important to mention that differences in fabric properties such as thickness, mass per unit area, as well as the differences in yarn composition (i.e. filament vs staple yarns) may have had a small influence on overall odour intensity emitted from worn fabrics. Yet, these differences will only have had a minor impact on overall results as fabric structural properties have been shown not to influence odour intensity when comparing fabrics that emit high odour intensity (i.e. polyester) compared with those that emit low odour (i.e. cotton and wool) (McQueen *et al.*, 2007). In fact, the lightest weight polyester fabric (128 g/m^2; 0.74 mm) in the study by McQueen *et al.* (2007) was perceived to be significantly higher in odour than the heavier, thicker cotton fabrics (i.e. 166-244 g/m^2; 0.79-1.23 mm). Furthermore, this study was conducted as a field trial to represent real-life use as much as possible, therefore selecting clothing fabrics that better represents common types of clothing found in the market was deemed to be more important than closely matching physical properties.

Future directions

As this study was a field trial which was largely uncontrolled in many factors (e.g. participants' diet, intensity and length of exercise, total wear time, laundering/drying methods), as well individuals naturally vary in many physiological parameters, variation in odour intensity, odorous VOCs and bacterial populations among samples were expected. Yet, the uniqueness of this study is that it does represent real-use situations. This study has been the first to examine build-up of odour over multiple use cycles, specifically addressing odour emitted from cotton and polyester fabrics following laundering; however, it did still only examine odour build-up in garments to 20 wear/wash cycles. During a typical garment's life-time many garments would be worn many more times (e.g. 50 +). An increase in use cycles will likely further intensify odour intensity following laundering although the relationship between cotton and polyester should be expected to remain the same. Nonetheless, further investigation into this is warranted. Also, only relatively short-term wear of the clothing occurred in this study. In many situations clothing would be worn for longer periods of time and at lower intensity exercise (e.g. during a working day or outdoor recreational activities such as hiking). Therefore, as the build-up of odour in fabrics over longer periods of time and for greater duration of activity could be more intense than that examined in the current study, further investigation is warranted.

In the current study, 5 per cent spandex was incorporated into both fabrics. Since spandex was in both fabrics it was not possible to determine what effect spandex itself may have on odour intensity following wear. As spandex is very common in sportswear, understanding its impact on overall odour intensity would be worthwhile for future studies.

Another research direction is assessing the durability of odour control technologies, such as antimicrobial treatments imparted onto fibres/fabrics, during use and laundering. The potential benefits of durable treatments which reduce, or even prevent, the build-up of odour in clothing could result in consumers laundering their clothing less frequently and therefore benefit the environment through reduced energy and water usage.

Conclusion

In this study, the build-up of axillary odour in cotton and polyester fabrics from t-shirts which had been worn during periods of physical activity for 20 wear/wash cycles was examined. A holistic approach was taken to evaluate odour build-up as odour was measured by a sensory panel, bacterial populations counted, and odorous VOCs, particularly the C4-C8 chained carboxylic acids, were identified through chemical analysis.

The polyester fabric was perceived to be significantly higher in odour intensity compared with the cotton fabric evaluated in this study. This increase in odour intensity on polyester fabrics was found both prior to and following washing. This suggests that of the two fabric types compared in this study that cotton would be the preferable fibre choice for many consumers who may be concerned about managing body odour. Based on the results of this study it is possible that cotton could potentially be worn on multiple occasions, even without laundering, as odour builds-up in cotton more slowly than polyester and odour is more effectively removed once it is washed. The findings in this study also suggest that the build-up of odour in polyester fabrics may be cumulative as important odorants such as the carboxylic acids are not as effectively removed from polyester compared to cotton. In fact, these odorants tend to be retained by polyester in greater quantities than in cotton even before washing.

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