Chittenden *Fash Text (2017) 4:22*
DOI 10.1186/s40691-017-0107-z

Fashion and Textiles

RESEARCH PAPER Open Access

Skin in the game: the use of sensing smart fabrics in tennis costume as a means of analyzing performance

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Abstract

Underlying the surface decoration and cut of contemporary tennis costume is a fabric that enacts its own performance and studies the athlete who wears it. Whilst designers such as Teddy Tinling created tennis costumes that brought glamour and theatrical flair to the player's performance, modern sports companies are increasingly using costume to approach human performance from a big data perspective. In the late nineteenth century, women playing tennis wore corsets and long skirts which impeded movement; today, the top players utilize fabric science that enables costume to control and record the temperature, sweat and muscle movement of the performer, whilst also presenting a vehicle to showcase their personality through their aesthetic choices. Smart fabrics allow for greater and more precise control over how our bodies perform, and they similarly alter our understanding of materiality and bodily presence with regards to fashion. The use of smart fabrics in sports, where the patterns of data collected by the costume visually and numerically display the conditions of the player/performance, holds potential for the ways in which we interrogate the interrelationship of clothing and performance across a range of arenas. For fashion research this means it is now possible not just to look at a costume but to look through it, via biometric capture, to a performance realized in data space. It is this duality of costume both in and as performance space that provokes this article to raise questions about the changeable nature of smart clothing and its relationship to the sporting body.

Keywords: Tennis, Smart fabric, Fashion wearables, Sportswear, Data space

Introduction

Each June, Wimbledon Centre Court becomes the focal point for the performances of the world's leading tennis players. Matches showcase pure theatre—the drama, the sweat, the joy and tears, not to mention the physique of the players and the contortions of their bodies as they move around the court. In 2011, Bethanie Mattek-Sands arrived on court at Wimbledon in a costume designed by Alex Noble, who creates costumes for Lady Gaga; this featured a tight dress, knee socks, a jacket decorated with a mass of white tennis balls and black paint under her eyes (see Fig. 1). Mattek-Sands' outfit,

Fig. 1 Bethanie Mattek-Sands in an outfit by Alex Noble, Wimbledon 2011. Photograph: The Associated Press/Mark Baker (reproduced in Lynch 2013)

following Maria Sharapova's all-in-one tuxedo[1] in 2008 and Anne White's controversial white spandex catsuit[2] in 1985, highlights the role sportswear plays as both fashion and an integral part of a player's sporting performance. In this context "sportswear" refers to items worn in the activity of sport that elsewhere might be termed "athletic apparel," as opposed to couture or high street fashion items. To describe sportswear as "costume," as this article does, serves as a reminder of the public spectacle context of the clothing in sporting performance.

For decades, women playing tennis wore corsets and long skirts which impeded movement and added significant weight to the fabric being carried around; the colour white was favoured to hide sweat patches (Poirier 2003). The costumes worn by the top male and female tennis players have evolved beyond the practical need for freedom of movement to utilize the science of fabric technology which helps to control temperature and support muscles whilst also providing a vehicle for players to express their personality and sense of style. Underlying the surface decoration, cut and construction of contemporary tennis costume is a fabric that enhances the wearer's performance. In 2017, fitness is at the fore of professional tennis as players openly discuss their training and diet regimes, pushing their boundaries to increase levels of fitness, stamina and power (Djokovic 2014; Mitchell 2014). Physical endurance is evident in the game of the leading players. With this elite athleticism comes a new role for sportswear that integrates different forms of wearable technology.

Advances in fabric science mean it is now possible not just to look at a costume, but to look through it, via biometric capture, to a performance realized within data space. For

[1] Sharapova's tuxedo can be seen here: https://www.forbes.com/pictures/heeg45hlh/marias-tux/#6679da278da7.

[2] White's catsuit can be seen here: https://www.forbes.com/pictures/heeg45hlh/anne-whites-catsuit/#6235fa171058.

Pailes-Friedman, "what makes smart fabrics revolutionary is that they have the ability to do many things that traditional fabrics cannot, including communicate, transform, conduct energy and even grow" (Gaddis 2014, p. 2). New biocompatible technologies, responsive to physiological and environmental variations, have transformed the role of the tennis costume into an array of interactive interfaces and spaces. Manning (2007, p. 61) writes that "there is no unified body. There are skins, receptive surfaces, gestural movements". Smart fabrics bring a potential for live and digital gestures to communicate in the moment of performance via a player's costume as a receptive surface. Such fabrics position costume as a temporal-spatial performative event that continues to exist as an analyzable data space beyond the actions of the wearer, creating what Kelly (2012) terms an "exo-self".[3] It is this duality of costume both in and as performance space that this article explores to raise questions about the changeable nature of sportswear and its relationship to the sporting body. In so doing the text offers a new perspective on tennis clothing by overlaying some potential implications of more advanced textiles and technologies which allow physical performance to be investigated in new ways. This is timely and groundbreaking as the possibilities for wearable technology advance alongside a growing practical and academic interest in the quantifiable self (Swan 2013).

As Tesla Studios launched sales of their Tesla Suit—a Virtual Reality, wireless, full body suit that uses electro muscle simulation technology to capture motion and simulate diverse experiences via the skin, "from a warm summer breeze to the impact of a sudden bullet" (Heinrich 2016, p. 2)—such innovation for clothing in gaming and sports communities is only likely to grow and to become more sophisticated. With this growth comes the possibility to enact experimental methodologies in connection with the sensing and computational nature of intelligent fabrics and demonstrate the extent to which a performance can be made and researched through fashion. The potential exists for clothing across all areas of fashion and performance to exploit big data and the wearable dimensions of new technology. New York Fashion Week "has been a leader in wearable tech, with brands like DVF, Rebecca Minkoff and Tory Burch showing covetable pieces which marry fashion and technology" (Wright 2015, p. 5). One implication of the research reported in this article is an encouragement to blend trends between sports use, fashion use and the quantified self movement to the degree that these wearables extend into the projection of an individual's self through their personal fashion choices. The research demonstrates that it is not just about designing in the technology to the fashion item, but importantly suggests the advantages to those who understand and design for the data space in parallel; this article begins to suggest how the two spaces could work together by drawing on the context of tennis.

Professional tennis players become skilled at highly specific forms of movement such as the serve, volley, and slice, and the manipulation of racket against ball. To deploy such skills, individuals must develop a spectrum of sensory intelligence and use that intelligence about their body to execute skillful, practical shots on court. The design of new forms of smart fabric, responsive to bodily and environmental variations, has implications for how players design and assess their training regimes alongside their match day performances.

[3] The exo-self is the manifestation of an individual's remote data body, complete with exo-senses, assembled from that individual's combined wearable technology data streams. This notion is revisited later in the article.

Following this introduction and a brief interlude into the research design, the next section portrays the lived experience of the tennis costume in performance, including restrictions to movement and what might be deemed as acceptable court attire. Proceeding to introduce smart fabrics demonstrates the potential to foster costumes that sustain tennis performance and operate as a second skin to support muscles and collect biodata. Conceiving of costume as an interactive skin that senses and reacts to body shape, texture and heat suggests the possibilities for new patterns of embodied communication where the patterns of data collected by clothing can visually and numerically infer the internal and external conditions of the player during any particular performance. Sensing happens not only in or through the body, but also in and through a smart fabric that captures the player's "data exhaust"—the side product of the individual's actions on court. The aim of this article is to promote research that engages with new practical and academic methodologies and tools for decoding sportswear as a materiality of movement—and in ways beyond the motion capture body suits now familiar in the film industry. Body and gesture monitoring of professional players will improve tennis performance as machine and coach co-diagnose the movements of the player. Gerrard believes the ultimate goal is to combine data from wearables with other data sets, such as tactical analysis of previous games and opponents' playing styles (Smith 2016).

In the current marketplace, 'many of the technical specifications are painfully complicated. Circuits, sensors, connectors and batteries have yet to be designed to fit on the human body, creating an opportunity for innovation' (Wright 2015, p. 10). Key areas that need innovative improvements include (i) materials that are more flexible in order to align with the dynamic shapes of the body; and (ii) contextually-driven and adaptive interfaces which will become more intuitive with the actions of the body and eventually begin to disappear. Examples of both in this article may prompt further test cases or prototypes. A potential future of sensing and communicating tennis fashion that can express individuals' personalities, whilst capturing and augmenting their physiological performance, highlights the act of wearing a costume as one of wearing and generating a data space. This article contributes to the research of such a future and the formation and analysis of big data from smart clothes. In so doing it intends insights into the wider societal quantification of the body and its actions, thus informing the design of future wearable technologies and tools for their analysis.

Method

The descriptive research design behind this article is based on a secondary data analysis model that uses an organized method of locating, assembling, and evaluating a body of sources on a particular topic within a set of specific criteria, and drawing on snowball and purposive sampling methods (Hanington and Martin 2012). Descriptive research designs help provide answers to the questions of who, what, when, where, and how to obtain information concerning the current status of the phenomena and to describe "what exists" with respect to a situation (Brennen 2017). This makes it an ideal approach to study a nascent field and how wearable technology influences ideas across disciplines—in this instance: fashion, sport, performance, data analytics and material science. Arguably, wearable technology is gaining most widespread traction in sport, where tennis and fashion have a long standing and enduring relationship. Therefore, wearables in tennis costume seemed the most constructive parameters within which to explore the interrelationship of data, drama, fashion and fabric.

One fundamental limitation to this research may be seen as not having direct access to a prototype or its live data-feed for empirical analysis, yet that would have been a very different study, one that focused on mathematics and measurement. Instead, the intention of this wider and more qualitative approach is to spur readers to pose more interdisciplinary and conceptual challenges of wearable technology and its uses. The key to secondary data analysis is to apply theoretical knowledge and conceptual skills to utilize existing data and resources to address the area of study. In the case of this research an in-depth literature review of areas of interest was conducted examining the previous and current works of leading academic and commentators in the field of wearable technology, performance studies, sports fashion and sports data. The Internet has led to vast amounts of data (including research papers, technical reports, articles and blogs) being collected and curated and easily accessible for research. University pages, journal publisher websites and platforms such as Academia.edu and ResearchGate provide a source for academic papers, whilst sites such as Forbes, TechCrunch and online news portals give access to business and technological reports and information. I systematically trawled these sources using keyword search (inc. "smart fabrics"; "tennis fashion"; "textiles technology"; "sports wearables") and followed links through to other sources and authors. The intention in reading across fields was to understand what the blending of theoretical insights from fashion, data analytics and the body performing in space might mean for future design and ideas. It is beneficial to have multiple sources to bolster confidence and nuance in findings.

One advantage of this approach is the breadth of information available and the ability to apply learning from adjacent fields, but limitations arise through lack of control over the original data collected or questions addressed in these diverse sources; neither is it possible to examine the entire population of sources. The type and genre of sources to be studied have been identified as the research progresses leading to a need to move beyond academic papers to industry news reports and blogs and wider media reporting on latest trends and products, and resulting in an exploratory approach which mirrors the exploratory nature of wearable technology itself.

Results and discussion

Tennis costume in performance

In the late Nineteenth century, tennis decorum required men to wear a suit and tie (Fig. 2) and women a cumbersome dress with a corset and long sleeves. Figure 3 shows the extent of fabric carried by female tennis players at that time, including a high neck, long sleeves, draped apron and bustle that quickly caused the body to overheat. Contemporary fashions made it difficult to find a practical alternative to the restrictive clothes of the period; elegance took precedence over performance, much to the frustration of players unable to move as well as they might or showcase their skills effectively (Delanoë 2014). As a data space, these costumes function largely, via written and photographic record, as a statement on fashion trends and uses of apparel in different periods. The actual bodily performance within such a costume is largely surmised. In 1919, *American Lawn Tennis* advised women that a corset was "a requisite component of the correct togs

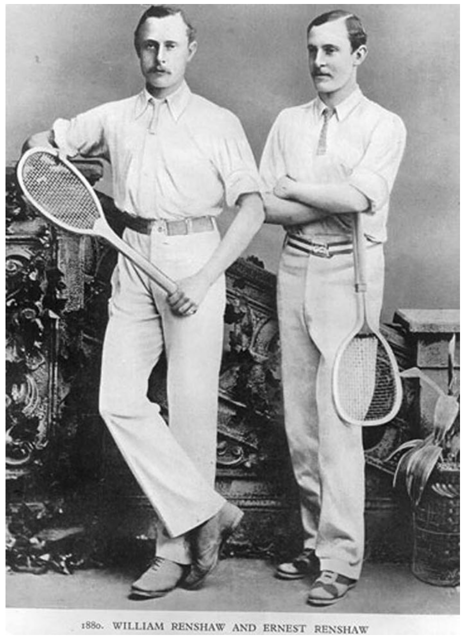

Fig. 2 Male tennis clothing, 1880 (Wimbledon winners William and Ernest Renshaw). Photograph: Don Lope (Wikipedia public domain)

Fig. 3 Tennis Dress c.1885. The Los Angeles County Museum of Art

for tennis" (Cassel 1919, p. 30). Cassel provides early evidence of a costume that supported and controlled the body but which hampered performance; contrast this, nearly one hundred years later, with twenty-first century compression fabrics that still act to support and control the body but this time in order to enhance physical performance. Fabric technologies, and in particular breathable fabrics, have slowly revolutionized sportswear (So 2015).

One of the dominant forces in the design of female tennis players' costumes was Teddy Tinling. A tennis player himself at the age of 21, Tinling decided on dressmaking as a profession and set out to bring a touch of glamour and individuality to women's tennis clothes. His drive to bring a sense of drama through costume took little account of the effects of fabric choice on sweat or physical performance and included a three-piece ensemble in black velvet for Rosie Casals and a shimmering opalescent cellophane dress for Billie Jean King's "battle of the sexes" match against Bobby Riggs in 1973. King, however, never wore the now lost dress which she found too "scratchy and abrasive" next to her skin (Leibowitz 2003) and opted instead for a crystal studded back-up dress (Fig. 4).

Tinling's designs were controversial and, in 1948, his dress for champion Betty Hilton's Wightman Cup match "so outraged Hazel Wightman she threatened to ban colour—if not Tinling—from future Wimbledon games" (Blausen 2016, p. 4). Tinling correctly predicted that an all-white rule would prevail at Wimbledon and, in 1949, he designed a dress for Gussie Moran in white satin-trimmed rayon, which shimmered and included the now infamous lace trimmed shorts:[4] "Tinling was accused of introducing sin and vulgarity to a gentleman's game and was banned from Wimbledon for the next 33 years" (Blausen 2016, p. 5). Despite this his clothes were not banned, and they continued to bring a sense of flair and glamour to Centre Court performances. Blausen (2016, p. 6) notes that "Tinling had an easy rapport with the stars of the game. He designed to suit the playing style and personality of the players he came to know so well, matching fabric, trim, and cut to the individual". By doing so Tinling found ways to subvert the all-white restrictions, which he felt led to costumes that lacked spectator appeal and did nothing to showcase a player's individuality. From 1971 to 1978 Tinling was the official designer for the Virginia Slims circuit, where he would design some 100 dresses per season, each unique to the player (Blausen 2016).

The period following Tinling largely saw costumes become more uniform in cut and aesthetic and within the narrow design scope of commercial brands. Until very recently, costumes worn by leading players at Grand Slam events were dominated by the symbols of an exclusive group of brands, for instance the Nike swoosh, Adidas' three stripes and Lacoste's crocodile. In the men's game, led by Djokovic (Uniqlo) and Andy Murray (Under Armour), there has been a shift towards brands that place an emphasis on fabric technologies and data. The founding principle of Under Armour was to "make athletes better," and to achieve that the company uses its clothing to "approach human performance as a big data problem". In so doing, Pierce (2016, p. 5) contends "Under Armour isn't a clothing company, but a tech company. That's where this entire industry is heading. The days of wristbands and straps are numbered".[5] As an artistic expression, costume enacts a dialogue between the body's proportions and movement and the shape, volume and materiality of the fabric. However, with the current focus on a fabric's computational and data collection capacity, the potential exists to disregard the importance of a costume's theatrical effect in the quest to acquire big data.

[4] Moran's outfit can be viewed here, alongside other designs by Tinling: http://tennis-buzz.com/ted-tinling-tennis-fashion-designer/.

[5] A recent partnership between Under Armour, technology company HTC and developers MyFitnessPal, MapMyFitness and Endomundo, might result in a new trend in tracking in professional sports events.

Fig. 4 Billie Jean King's dress by Ted Tinling 1973. The National Museum of American History

The importance of a costume's aesthetic performance is as key for many leading players as its technical sports capabilities; how the fabric and cut of the sportswear perform under conditions of movement and light, body-shape distortion of patterns and cut, and especially colour when chosen to contrast with the vibrant orange of clay courts or bright blue of hard courts. A costume's aesthetic image is arguably more prominent for female players, though one should not forget Agassi's denim shorts[6] or Federer's study in monogrammed elegance.[7] Costume helps to shape the image projected by the player and to transform them in their performance; to stand out from the crowd of players wearing similarly-branded outfits. In this sense, as Tinling recognized, a theatrical costume becomes part of the player's personality and helps him or her to manage and shape a performance persona.

In 2017, the shapes and expressions made by tennis players mean that any costume is put through demanding paces by the performing body as shown by Novak Djokovic in Figs. 5 and 6. Costume can take the brunt of the player's frustration with their performance and this is illustrated by Fig. 6, with Djokovic provoking comparison with the Incredible Hulk (Parry 2015) yet being unable to rip his Uniqlo shirt.

Manzini et al. (1989) noted that the identity of materials can generally be defined both in terms of their physical and cultural performances. As smart fabrics facilitate the integration of electronics with textiles, there should be little reason why flamboyant and spectacular designs cannot also be of physiological calibre or feature a variety of

[6] Images of Agassi's denim shorts can be viewed here: http://www.modearea.com/andre-agassi-competed-at-the-u-s-open-in-tiny-jean-shorts/.

[7] Federer's tennis outfits can be viewed here: http://tennisfashion101.blogspot.co.uk/2011/10/roger-federer-swiss-style-icon.html.

Fig. 5 Novak Djokovic (reproduced in Robson 2015)

Fig. 6 Novak Djokovic, Wimbledon 2015. Photograph: Mike Frey

thermochromic or LED effects that change in accordance with the body's performance.[8] Whilst smart fabrics allow us greater and more precise control over how our bodies perform sports skills, they similarly alter our understanding of materiality and bodily presence in terms of fashion more widely.

Fabric science and smart sportswear

The introduction of responsive materials and computing technology in textile structures offers an opportunity to develop smart sportswear with a new type of behaviour and functionality. Opportunities for smart clothing to drive research around use and utility arise as these textiles collect different kinds of data and use it in new and combined ways. For Berzowska (2007), smart fabrics are not only about combining textiles and electronics but about the conception of an entirely new medium which has to be tested, transformed and re-invented. The previous section of this article considers costume in performance at the surface of the body, where players respond to the feel and form of their costume and viewers to its visual properties and appeal. The remainder of the article posits costume as performance by exploring the interaction of fabric and technology in the ultimate generation of "living" fabrics and data spaces.

Smart textiles are possible through three developments: "(i) new types of textile fibres and structures such as conductive material; (ii) miniaturisation of electronics; and (iii) wireless tech that enables technology to be wearable and communicating at the same

[8] Already being used by fashion companies such as The Unseen, a London-based company fusing the worlds of science and design, founded by Lauren Bowker, who refers to herself as a material alchemist. Clothing and accessories are based on the idea of colours that alter via user interaction or their environment. http://seetheunseen.co.uk/enter/.

time" (Berglin 2013, p. 7). The five main functions of smart fabrics are: sensors, data processing, actuators, storage and communication. The extent of a fabric's intelligence can be divided into three subgroups: "passive smart," "active smart" and "very smart". Passive smart fabrics can only sense the environment, active smart fabrics sense stimuli from the environment and react to them, and finally very smart fabrics adapt their behaviour to external circumstances (Das and Chowdhury 2014, p. 2).

The current wearable technology market consists mostly of sports and activity trackers (Rogers 2013). Nike and Apple introduced fitness tracking wearables in a 2006 collaboration to allow users to track their movements with iPods. In 2009 the first FitBit was released as a clip-on device that counted steps by means of an accelerometer (Paulson 2014). The first wave of "Fitness Trackers" including FitBit, Jawbone and Nike + FuelBand were essentially glorified pedometers. A second wave of devices appeared as fashion brands including Swarovski and Gucci teamed up with Intel, Google, and Samsung to create aesthetic and fashion-driven ways to wear data devices. Aside from aesthetics, devices also demonstrated technological advances, including "biosensing," the collection of personal data related to health such as heart rate, hydration, and muscle fibre activation (Yang 2014).

In 2008, Adidas purchased Textronics®, a team of experts in the fields of textiles and electronics to design sportswear using the latest fabric technologies. Their designs since have utilized soft textile sensors to capture the electrical activity or the mechanical movements of the body. Elastic yarns are used as "building block fibres" to weave or knit conductive or optical fabric structures and elastomeric polymers exhibit changes in electrical conductivity as the material is stretched. These polymers, with variable resistance properties, can behave as strain gauges, switches and sensors to track and capture a materiality of movement. Wallace et al. at the University of Wollongong developed a sports bra that changes its properties in response to breast movement; the fabric alters its elasticity in response to information about how much strain it is under. This smart bra is capable of instantly tightening and loosening its straps or stiffening cups when it detects excessive movement (Pitt 2014). The tennis player's body can increasingly be considered a functional platform in sportswear design since it causes property change in the textile surface—referring not just to the live presence of a player within a match, but also to their role as an agent in activating the costume.

At present, smart shirts often still need some data storage capacity as the fabric in itself does not have computing power. Pieces of hardware are still necessary, but they are now available in miniaturized and flexible forms. One of the most important issues for sportswear is that the garment should be washable and the electrical components insulated to prevent water/detergent damage; thus, many designs opt for a removable black box that is only attached during the period of data capture. In one example, Canadian-based OMsignal worked with Ralph Lauren to create the Polo Tech shirt.

Ralph Lauren, designer of the uniforms for the Wimbledon umpires, line judges and ball boys/girls, has embraced the big data possibilities of fabric technology through the Polo Tech shirt (Fig. 7). This product is "a compression shirt with biometric sensors that act like an extremely sophisticated fitness band without having anything around your wrist" (Kooser 2014, p. 1). The nylon shirt is infused with conductive silver-coated fibres which act as sensors to track distance, calories burned, heart rate, stress rate and

Fig. 7 Ralph Lauren Polo Tech shirt. Photograph: Courtesy of Ralph Lauren

intensity of movement. The information is collected by a black-box data module and fed into an iOS app that then streams this data in real time to a smartphone. An athlete can adjust training by breathing more deeply, increasing exertion to hit a target heart rate, or focusing on reducing stress in competitive situations (Kooser 2014). The shirts were trialled by some of the ball boys at the 2014 US Open. The data from the shirt can be analysed using algorithms that pick out the key biometrics and psychometrics that the athlete and their coach choose to monitor (Collins 2014).

Although wearable technology has quickly infiltrated the fitness industry, the literature shows that there is a large gap where higher-level performance is concerned. The notion that wearable technology has the capacity to extend human capabilities, shape behaviour, and amplify social and behavioural responses (Joinson and Piwek 2013) invites investigation of the complex nature of micro-level motion capture in tennis and attracts brands such as Under Armour to view the big data potential in their textiles.

A number of companies, including Heddoko,[9] Mico,[10] and Cityzen Sciences,[11] are exploring ways to utilize a fabric's intelligence to improve players' abilities on the court. Others are pursuing the integration of technological components and capacities to the point of disappearance, where the technology becomes an undetectable part of the clothing save for a data exhaust streaming off the textile. Vigano observes, "we are in a convergence zone… Imagine if a plasticky glorified pedometer could be injected into what people decide to wear. We think wearable computing will become transparent and the devices will disappear to the eye" (Stables 2015, p. 5). The convergence between the miniaturisation of electronic components, intelligent textile production, advances in biotechnology and the growth of wireless and cloud computing locates wearable technology at the intersection of ubiquitous computing and functional clothing design.

Despite an extensive research effort over the last ten years only a few smart textiles are on the market. Whilst smart garments have clear use cases in sport, medicine and the

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9 http://www.heddoko.com/.

10 http://www.innovationintextiles.com/dryarn-and-mico-sportswear-collection/; http://www.mico.it.

11 http://www.smartsensing.fr/en/.

military—and the origin of many smart fabrics came from military innovations—critical issues concerning the real need for smart textiles and the ethical issues of being monitored remain. Big data brings together large amounts of data and allows for the intersection of multiple types of data that previously would not have been considered together, the results of which may be utilized by insurance companies or advertisers. Health institutions are required to protect the privacy of health data but individuals are free to share their own data and post it publicly, and increasingly individuals are choosing so to do. Boundaries between public and private space are blurring and one of the major challenges of smart fabrics that generate this type of data is preserving individuals' privacy, including how far data is captured beyond the fabric surface, the security of data use and storage.[12] Despite this, wearable technology is gaining traction alongside advances including the Internet of Things (IoT), 3D printing and Augmented Reality (AR) glass tech (Hololens, Magic Leap).

We are arguably at a pivotal moment for what is possible in terms of integrating data collection and communication power into our clothing and surrounding paraphernalia; with this comes an opportunity to reinvent how we think about the relationship between technology and our clothing/objects and their related data streams. The Quantified Self (QS) movement is a response to self-tracking behaviours, described as "an advanced user community of people who have begun to explore and experiment with novel uses for personal data" (Watson 2013, p. 1). Consumers have access to a growing number of gadgets designed to gather real-time signals from their bodies, convert this information into digital data and expose it to algorithms programmed to reveal insights and inform future behaviour. Kelly (2012), a QS community founder, contends that the current moment of self-quantification is merely an intermediary step toward "the future self"—one that Swan (2013, p. 95) describes as "spatially expanded with a broad suite of exosenses". The body becomes a "knowable, calculable and administrable object" (Viseu and Suchman 2010, p. 162). Whilst this is an emerging trend for wearable technology in society, in sports smart fabrics are already materialising the data body for scrutiny. Wolf (2010) proposes that such data serves as a new kind of "digital mirror" in which to see and learn new things about ourselves.

Designed by Sabine Seymour, SoftSpot is a "plug + play" sensor system for clothing that monitors biometric and environmental data and automatically connects with the Internet of Things: "its proprietary technology leads the way from wearables to 'disappearables'. It is invisible, soft, washable, flexible, and wireless" (Seymour 2015, p. 3). Seymour (2010, p. 13) describes "fashionable wearables" as the intermediary "between the human body and the spaces we navigate… our clothing, accessories and jewellery are the epidermal interfaces with which we can experience the world". As fabrics assume "epidermal properties"—either as a material that mimics the functions of human skin or as the intimate layer between a body and its environment—there is potential for intelligent fabrics to act as an epidermal portal between flesh and data performance spaces. In this case a tennis player's costume would act simultaneously as the layer between his/her body and the world and as the intermediary between his/her body and a remote

[12] Such concerns will be exacerbated as more big technology players stitch together their various data acquisitions and within legal frameworks such as the General Data Protection Rules (GDPR), due to come into effect May 2018. https://ico.org.uk/for-organisations/data-protection-reform/overview-of-the-gdpr/.

data world, as a portal to a parallel performance dimension. Smart costume captures the time-matter which constitutes a performance, and yet because the costume is also the process of generating the data space from biometric and biomechanical impulses it frames the body in terms of its “sensorial architecture” (Tomas 1989).

The performativity of human and fabric skin has led to a keen interest in developing energy-related fabrics. This new class of materials focuses on circulation, muscle recovery and blood flow to enhance energy and wellness. Labelling itself “a different kind of performance technology”, Hologenix’s Celliant consists of “minerals embedded in a synthetic polymer that interact with the body’s electromagnetic emissions to induce increased oxygenation and blood flow… the technology modifies visible and infrared light, recycling them into energy that the body can use more effectively” (Schwarz 2011, p. 3). Powered by the body’s own metabolism, Celliant claims to be “more hybrid engine than textile. It recycles and converts radiant body heat into something that gives the body a measurable boost—infrared energy” (“What is Celliant?” 2016, p. 1). As fabric science explores how costume can measure heart rates and respond to temperature, capture the nuanced movement of muscle and also utilize the power of the wearer’s own metabolism to generate energy, one has to consider the extent to which our costumes are becoming a second skin.

Skin in the game?

Skin-tight fabrics such as elastic and Lycra-spandex have long been integral to the costumes of athletes engaged in activities ranging from swimming and running to speed skating and skiing. For the most effective data capture the fabric needs to fit as flexibly and comfortably close to the skin as possible, mirroring the body’s own contours. Stretchable sensors combine electronic components, energy supply and actuators on a stretchable substrate with stretchable conductors. To assimilate flexible printed circuit boards with fabric, the components need to be arranged to avoid body “flex zones” where excessive bending might damage sensitive components, yet in tennis it is these areas with the greatest variation of bend or movement that generate the most valuable data. A method for direct screen-printing of biological sensors onto clothing has been demonstrated by the University of California San Diego’s Laboratory for Nanobioelectronics. By printing the sensors onto an elastic fabric they are able to maintain tight contact with the skin (Yang et al. 2010); this also means that the shape of the costume evolves as the player gains and loses muscle.

Although the advantages of tight compression fabrics for physical performance have been well established of late (Marqués-Jiméneza et al. 2016), for women in particular there are still aesthetic concerns about revealing such a fit. Despite players such as Serena Williams wearing body-hugging catsuits,[13] women are more often criticised for body shape and weight in ways that leave them potentially more vulnerable in public performance situations to hecklers, social media and Press comments.[14] Increasingly we are seeing players wearing compression and skin-tight garments underneath looser

[13] During the 2002 US Open, Williams wore a black Puma catsuit, shown here: http://www.telegraph.co.uk/sport/picturegalleries/8268556/Venus-and-Serena-Williams-in-pictures-their-outrageous-tennis-outfits-through-the-years.html?image=10.

[14] This is a vast theoretical field of study to which there is not scope to detour in this article. Interested readers might find valuable sources in Varnesa et al. (2013), Mulgrew and Tiggemann (2016) and Gauntlett (2008).

items, such as men wearing shorts under shorts. This presents a situation in which the data capture element is separated from the aesthetics of a public presence.

The Tesla VR Suit uses tiny electric pulses which stimulate the skin surface, muscles and nerve endings to create tactile feedback and to simulate diverse sensory experiences. So, whilst smart fabric in sportswear captures data from the skin and transmits it to a data space, the Tesla Suit also operates in reverse to feed information from a data space to the skin. There is potential for sportswear to adapt this approach and assist training by feeding remote pressure data back to the skin and, in particular, to support resistance training of subtle muscle combinations. Integration of wearable electronics introduces new challenges for thermal management by adding the heat produced by certain electronic components to that produced by the body. In addition, plastic or resin components forming an impermeable barrier too close to the body can hold in heat and moisture hereby reducing comfort.

As an expansion of the concept of a second-skin, MIT's Tangible Media Group is experimenting with a more literal "bio-skin," a "living material" that responds to perspiration and body heat (Stinson 2015). As the person wearing the bio-skin becomes warm and begins to sweat, the material peels away to reveal breathable holes in the clothing. One of the researchers, Chin-Yi Cheng explained: "we are trying to create an interactive feedback loop between the human body, biofilm and the environment" (McGoogan 2015). The bio-skin fabric is made from natto cells, which expand and contract in response to atmospheric moisture. This material is traditionally used in a soybean-based breakfast dish in Japan and more recently has been tested in melt-resistant ice cream. The MIT team, led by Hiroshi Ishii and Lining Yao, grew natto cells and bio-printed them into scale-like shapes (see Fig. 8a, b).

Fig. 8 **a** "Second Skin". Photograph: Tangible Media Group/MIT Media Lab. **b** "Second Skin" (detail)

Aligning the cells in a specific pattern, the team could programme them to behave in a certain way—in this instance to curl open when heated (McGoogan 2015); in addition to a cooling system, this fabric also presents the player with the opportunity to design for deliberate patterns or even sponsor logos, and, of course, has possibilities for fashion away from sportswear—especially theatre where stage lighting has the potential to generate a similar body heat effect. As a source of data, biosensors and GPS technology could capture motion data via the position and micro-condition of these cells/fabric shapes at any one moment.

Barad argues that "matter is not produced and productive, generated and generative. Matter is agentive, not a fixed essence or product of things" (Barad 2007, p. 137). Costumes are "not mere static arrangements in the world, but rather dynamic reconfigurings of the world" (Barad 2003, p. 816). Although my focus is on tennis, there are clear possibilities for advances in smart sports fabrics to inform studies of stage and theatrical as well as couture fashion designs, and vice versa, because wearable technology interfaces increasingly encourage us to use costume to manage and interrogate information and our actions in the world in new ways.

Sportswear as a data space

Although the performance of players wearing smart shirts is predominantly watched on court, it can also be experienced in a virtual space and abstract form by downloading data from the costume. According to Whitlock (2006, p. 85), "in an age of mediated bodies and avatars, the potential of motion capture in performance suggests a new method of character creation as well as new possibilities for recording and re-using human motion". In recent decades, film studios have identified the potential of costume as a tool to translate human movement into data that can then shape the movement of a CGI character. Motion capture costumes for films are typically full body suits with reflective markers at strategic points on the body to plot movement through space. Despite the prevalence of this technology, Pingali et al. (2001, p. 76) observe that, "although there is some effort towards placing active and passive sensors on the players and objects to facilitate real-time motion capture, most sports do not allow such interference". Sheets et al. (2011) note that quantitative kinematic measurements in realistic environments are limited by current motion capture technologies. Increasingly, designers are exploring the potential of integrating these capture techniques into fabrics worn by athletes. A smart sports shirt enables a more holistic capture of not just external points moving through space but also the body's internal movement through muscle, respiration and temperature cycles. The capabilities of such a costume allow the body's performance to be transformed into a cloud of numerical data.

Raw data from the costume builds the performance as a virtual interactive space, open to analysis by player and coach: "once a sporting event is stored in a database in the form of motion trajectories, scores and other domain specific information, a viewer can explore and interact with the virtual version of the real event" (Pingali et al. 2001, p. 77). Hence, the conception of an exo-self and a time-series self as a new entity complicating the unified human body where, for Schüll (2016, p. 26), the "body" is "a data-generating device that must be coupled to data-monitoring systems; together they inform a new episteme that devotees find empowering". It becomes possible to compare a player's style and strategy in one match with his/her performance in other matches; to create situations in which bodies are connected and extended in space as well as in relation to one another. The collected data highlights an indexicality of the costume's relationship to that which it records, but also a shift from this data being primarily the residue of the flow of the live performance to instead being conceived as some kind of ontological force in its own right. In this way, the garment becomes its own event, carrying its own sense of mobility and temporality.

Data captured via a player's costume manifests in a variety of visualizations, from animated 3D characters to line graphs, plot points and charts. Sensors track more than 100 metrics such as distance, speed, acceleration, deceleration, and heart rate. They also assess spatial changes in direction using 3D accelerometers, 3D magnetometers and 3D gyroscopes. For Hannah (2014, p. 20), "within the dilating layers of the body-object-event as objectile, the costume can be interpreted as matter-in-action and action that matters". Figure 9 shows some of the outputs from the Ralph Lauren Polo Tech shirt (see Fig. 7), while Fig. 10 demonstrates dashboards from Sony's Smart Tennis Sensor, a device which fits onto the end of the racket handle. Whilst data capture from intelligent fabrics is still in test mode, this example of performance information captured via the player's racket highlights the variety of data visualizations which could be built into costume capture data space and which focus specifically on tennis performance rather than generic training platforms. According to Harris (2013, p. 242), "as design practitioners challenge perceived notions of textile, substrate, and skin through relatively newfound

Fig. 9 Polo Tech shirt dashboard. Photograph: Courtesy of Ralph Lauren

Fig. 10 An example of tennis data dashboards—Sony's Smart Tennis Sensor. See also: http://www.sony.co.uk/electronics/smart-devices/sse-tn1w

digital contexts, resulting propositions include high-tech interfaces for communication, surface embellishment, and guise". Furthermore, Birringer and Danjoux describe the telepresence possibilities for costume that converts the dynamics of moving design "through algorithmic mappings of the kinetic data into a virtual format where data can be varied infinitely and transmitted between geographically distant wearers" (Birringer and Danjoux 2009, p. 102).

Data capture allows the player to embrace his/her skills in trend and plotted progression. Once captured, the data can be integrated and re-fleshed to fit with bodily performance and training offline. Manning (2012, p. 129) suggests that "it is not movement become form, but movement unforming… the creation of a strange interval through which image and body begin to intertwine" and where costumes are not things, but phenomena—"dynamic topological reconfiguring/entanglements/relationalities/(re)articulations" (Barad 2003, p. 818). Within the data space we might find various single tennis actions de-fleshed—translated into lines, graphs, percentages and ratios by a fabric skin that contributes to the capture of a de-fleshed performance. Via their costumes, players are able to monitor their heart rate during play, measure the resting and peak rates and recovery time, measure calories burnt and track data from multiple performances in comparison. Individuals can map the total number and placement of steps taken during a point or the whole match and this detailed analysis has a tangible influence on how players think about their performance, mentally mapping the data back into performed actions. This example also raises questions about the ways in which motions are read differently when seen on a human form as opposed to data charts on screen. Further, with the rapid advances in the representation of the human body in CGI and the games industry, more sophisticated models for displaying sports data may soon be available.

Developers argue that those invested in competitive sports, including engineers, athletes, and stakeholders, will see a revolution in the industry where players' performances, coaches' strategy, and the resulting fans' viewing experience will be enhanced through ubiquitous computing (Springer 2014). The costume and its associated functions can help players to see their bodies through a scientific lens, to see the body as a system, and to think of it in terms of function. It also provides players and coaches with a language for thinking about bodily structures and systems. Thus, as much as fabric science is about possibilities for researching the costume, the costume itself becomes a tool for researching the body beyond as smart fabrics and wearable technology initiate what Balsamo (1995, p. 215) calls "new technologies of corporeality".

Conclusion

In the late nineteenth century, corsets constructed with metal or whalebone constricted the breathing and pierced the flesh of women tennis players. Developments in sportswear design and fabric science have seen the materials of contemporary tennis costume adopt temperature, sweat and muscle control properties, as well as electronic sensors to capture biometric and biomechanical data from the performance. The development of biosensors, nano-transistors and the ability to print electronic circuits directly onto stretchy materials has enabled the development of a dynamic and interactive costume that is responsive to the environmental and physiological variations of its wearer. This functionality, and the possibilities it brings, highlights costume as an active and activating object capable of dynamically intervening between the body and its environment to create a remote space in which the performance can take place. For Whitlock (2006, p. 85), "with motion capture, the human body becomes data and this transformation expands the very idea of the physical body to new limits". In the same way that Howard (2002, p. 87) observes that costumes "become the extension of the actor in space", costumes extend the tennis player in space in multiple ways: from the fashion statements that extend the personality and style of the individual to the literal extension of the body via the contortionism experience on court and, now, with smart fabrics, an extension of the tennis player's body beyond the court into a remote data space.

This article has plotted a change in the relationship between tennis costume and performance, beginning with the effects of costume in a performance space where the costume and form of evolving fashion trends are felt by the player and appreciated by spectators for visual impact. The fabrics that comprise costumes on court are no longer materials with fixed properties; their performativity and the control of their performativity means that costumes become smart objects that can virtually change their states, transforming themselves and acting in accordance with the data of the environment. The ability to capture the performing body in all of its nuances grows greater with advances in Virtual Reality and game simulation programmes. As the closest thing to the player's body in action, there are clear advantages to costume that can access and record motion and biometric data—certainly for sports, but also in areas of performance art, theatre and healthcare.

A "costume-as-big-data" approach could have broader implications for the world of sports. At Grand Slams, the costumed performing body is already seen through a range of modes: live on court; via camera feed to screens within the grounds (e.g. Henman Hill at Wimbledon); to screens beyond the grounds; in online blogs and video clips of matches; and in news/magazine reports. Media channels broadcasting action from

Grand Slam events already augment their coverage of matches with innumerable statistics and graphs plotting ball placement and speed, whilst commentators from screen and print media have been known to pass comment on what a player is wearing. The data captured by smart fabrics may presage a future where players' heart rates or biometric rhythms are reported across key points, leading to a place where costume presents itself as a temporal-spatial layered and multi-dimensional event concerned with both aesthetics and the human condition—as a performative agent rather than a decorative layer. This concept is echoed by Chen Shachar, co-founder and CEO of PlaySight's SmartCourt: "imagine big data-information and video from all over the world—letting you compare your performance with other players, find partners, have remote coaching" (Leybovich 2015, p. 26). As fabric science advances, Walzer (2013, p. 1) predicts: "a shirt that doubles as a personal trainer. A jacket able to take photos with gesture movements… Fabrics that boost energy, reduce cellulite and moisturize your skin". Beyond the technological expertise needed to assemble the hardware and software for real time tennis costume sensing and data capture, there is a need for tools which help players to organize, analyze and integrate the variety of visual and numerical information communicated by their costume. Treating tennis costume as a means to extend players' physical bodies raises questions about the future and the boundaries of sports performance through fashion, design and the practical applications of fabric science technologies.

According to Juniper Research (2014, p. 2), the smart wearables market is expected "to generate $53 billion hardware revenues by 2019, compared to $4.5 billion in 2014". Further, Juniper Research predicts that more advanced technologies will first be created "for the enterprise and healthcare segments, which have clearer use case diane-von-furstenbergs" (2014, p. 2). But Wasik (2013, p. 8) contends that "wearable devices represent a new threshold in aesthetics. The tech companies that mastered design will now need to conquer the entirely different realm of fashion". The wearable technology landscape continues to evolve at speed as more complex sensors and means of data capture from fabric emerge. The utility and appeal of wearable technology makes demands on fashion designers to combine aesthetics with the technical specifications of products. Designers must understand these aspects and their potential analysis to successfully enter the wearables market. The research informing this article contributes to this endeavour in two ways: by suggesting how fashion designers can learn from advances made in sportstech, but also how they might help to return the Ted Tinling flair to current big data sportswear.

Authors' information
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Competing interests
The author declares that she has no competing interests.

Received: 14 February 2017 Accepted: 12 July 2017
Published online: 29 July 2017

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