Exploring Opportunities for Flexible Wearables to Support Physical Training

KATARZYNA STAWARZ, Cardiff University, Wales, UK
ALUNA EVERITT, University of Canterbury, New Zealand
JUDY BOWEN, The University of Waikato, New Zealand

Advances in digital fabrication with flexible and conductive materials are enabling new opportunities for customisable wearables that enhance physical training across various sports through on-body posture and movement monitoring. However, before developing new wearable devices, it is crucial to understand the unique challenges and opportunities of real-world use and the diverse needs of stakeholders such as athletes, trainers, and sports enthusiasts. In this paper, we report results of two co-design workshops conducted with 11 participants representing a range of sports backgrounds and interests to identify challenges and opportunities for flexible wearables. The participants' designs and prototypes highlight the importance of supporting personalised wearable design, addressing varying contexts, and accommodating different skill levels. We propose design considerations for wearable devices that prioritise flexibility, both in their materiality to support a wide range of movement and in their adaptability to accommodate changing conditions and user progression across skill levels.

CCS Concepts: • **Human-centered computing** → **HCI theory, concepts and models**; *Interaction design theory, concepts and paradigms*; **Human computer interaction (HCI)**; **Ubiquitous and mobile computing**; • **Applied computing** → *Health informatics.*

Additional Key Words and Phrases: Sport, Wearables, Co-design, Personalisation

ACM Reference Format:
Katarzyna Stawarz, Aluna Everitt, and Judy Bowen. 2025. Exploring Opportunities for Flexible Wearables to Support Physical Training. In . ACM, New York, NY, USA, 22 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

Emerging wearable technologies are opening up new opportunities for supporting users during sports activities through real-time on-body tracking and feedback capabilities. Advancements in digital fabrication with flexible and conductive materials [16, 41] are also enabling new levels of customisation for wearables to be realised. These lightweight devices that can collect real-time body movement data and provide instant feedback to the user are helping in expanding the current design space for wearables [63]. However, there is still a lack of knowledge on how this interactive technology could support performance optimisation, and how we could design real-time bodily performance analysis systems to provide feedback and aid coach and athlete's sense-making [14]. Additionally, there is limited understanding of how to design interactive technologies for various parties involved in sports activities [14]. By engaging a range of stakeholders in collaborative exploratory workshops, we bridge these knowledge gaps through qualitative insights from potential users.

At present, wearables for sports applications cater for either elite professional athletes at high cost or everyday casual users (e.g. wrist-worn wearables). High-cost systems designed for professional athletes include examples such as the VALD Performance devices [48] (starting at $329 USD per arm band), and Inertial Measurement Unit (IMU) wearables, like the IMeasureU [27] multi-limb movement platform, which involves a starting cost of $5,500 USD per year for the device and data service subscription. Moreover, some of these high-end systems are designed for controlled environments and may not perform well in real-world settings [36].

2025. Manuscript submitted to ACM

In contrast, wrist-worn wearables such as FitBit, Whoop, and Samsung or Apple smartwatches are more accessible to casual users. However, these devices are for more general use and are limited in their ability to monitor a wide range of body movements [24]. They generally adopt a one-size-fits-all approach and may not accommodate various body shapes, sizes, or abilities [58]. They typically focus on parameters like heart rate (using pulse oximeters) or steps (using pedometers), and are optimised for cardio exercises like running, walking, or swimming, often using GPS, which does not account for the full range of body motion [3]. However, the ongoing miniaturisation of components and advances in fabrication could address these limitations by enabling the development of customisable wearables suitable for various contexts. For example, the flexibility of Thermoplastic Polyurethane (TPU) 3D printing and the ability to embed multiple sensors and actuators (e.g., [16]) suggest the potential for creating wearables that better match individual body shapes and needs, including those often overlooked in technology research [57].

Our research explores opportunities for the use of flexible wearables in supporting athletes and sports professionals, as well as more casual sports enthusiasts. We organised two co-design workshops with personal trainers, coaches, sport science researchers and sports enthusiasts (N=11) to better understand challenges that arise during physical training (e.g., related to bad posture and form), the severity of these issues (e.g., when 'bad' posture risks injury) and common errors that can negatively affect training and performance. We also wanted to learn about participants' attitudes towards using technology as part of training, including issues such technology could introduce or exacerbate, and identify a range of situations where it would be helpful and add value to the user. Our participants developed multiple ideas demonstrating how physical training could be supported and enhanced through flexible wearables attached to their body, and highlighting the importance of personalisation across a wide range of levels and conditions: for different sports, different activities within a specific sport, differences in individual bodies, and different contexts of use.

Our work makes two contributions. First, we extend the sports wearables design space, which is described by Turmo Vidal et al. [63] across the dimensions of sport and fitness practice, technology, wearability, and wearable use in practice. Our work additionally considers the temporal adaptations (see Figure 1; more details in Section 4.3) to the dimensions of users and use (see Table 1 in Section 2.1), thus highlighting opportunities for flexible wearables that meet the needs of different stakeholder groups. It also shows that these needs change over time and vary across different levels of expertise that influence interactions with sport technologies: knowledge and expertise about the specific sport, knowledge about human body and physiology related to physical activity, and experience with technology. This is reflected in design considerations we propose. Second, given the importance of different levels of personalisation, we identify opportunities for personal fabrication for sports wearables that support training and performance as well as potential for rehabilitation and recovery. This focuses on the intersection of the possibilities offered by personal fabrication and the personalisation needs of different users and use cases across the dimensions described.

2 RELATED WORK

2.1 Wearables for Sport and Posture Monitoring

There is a growing interest in Sports HCI [14], in particular in the adoption and design of wearables to support sport and physical activity in general [63]. Research tends to focus on developing and evaluating wearable devices that aim to help improve user performance, often aimed at 'average' athletes [44]. This echoes the commercial trends, with wearable sports applications aimed at both professional athletes and casual users designed to help them get better at their chosen discipline.

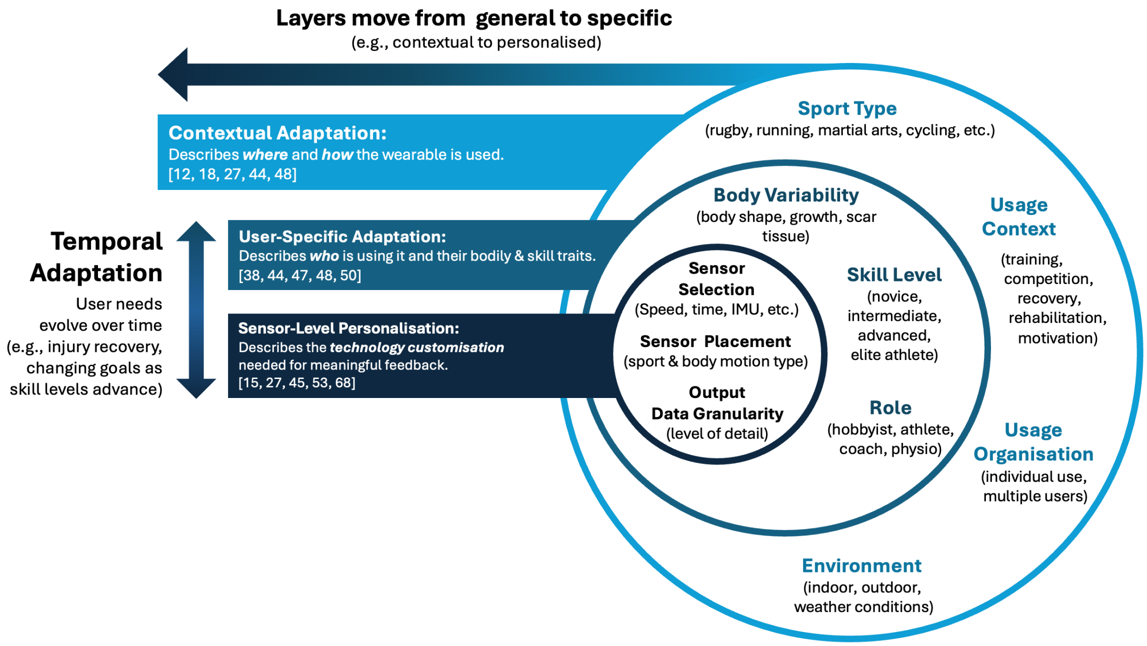

Fig. 1. Our design space for personalised wearable sensing in sports. The outer context layer situates the wearable, highlighting potential necessary contextual adaptations. The middle layer centres on the users' physical and skill-related traits, focusing on user-specific adaptations. The inner layer focuses on the sensing technology. This structure supports identifying and tailoring flexible wearables across a continuum of personalisation needs that can change over time (temporal adaptations), e.g. due to injury, recovery or changing goals.

To support this ongoing improvement, sports wearables tend to focus on sensing and often track metrics like heart rate, pace, distance, temperature, pressure [15, 38, 68], and bio-mechanics to help inform athletes' training and achieve peak performance metrics [45, 69]. This data can be used to design personalised training plans and monitor progress over time. For example, a pressure sensitive insole can be used to monitor the posture of athletes during weightlifting training [15]. Wearables can also provide real-time feedback (e.g., during training), helping athletes adjust their strategy based on live streaming data; one example are AR Goggles for swimmers [18]. Similarly, wearables can aid post-hoc analysis, e.g. after a race or a match, or tactical planning in team sports. For example, the New Zealand rugby team uses smart vests to track its players [7], and similar vests are widely used among football teams, e.g. by Arsenal FC [5].

Injury prevention and rehabilitation is also an inherent part of engaging with sports, especially on a professional level [25, 59]. Issues with posture and body mechanics, flexibility and strength, as well as fatigue, inexperience and previous injuries are some of the factors that can contribute towards a sport injury [65]. As such, wearable devices can be helpful in preventing injuries caused by bad form [3]. They can allow athletes, their trainers and physiotherapists to analyse and refine technique to spot potential issues that could arise. Examples include wearables that support running gait analysis [42] or golf swing analysis [11, 55], which can reduce chances of injury. If an injury does take place, wearable devices can be used to support rehabilitation through monitoring various physiological parameters, such as range of motion, join rotation, speed and stance during walking, breathing parameters or fatigue, to help keep

Users	Use	When Reported	Measurements
Amateur [47]	Training [48]	Real-time [62]	Distance [27]
Professional [50]	Performance [18]	Post hoc [48]	Speed [27]
Coach [48]	Recovery [27]	Long term [48]	Acceleration[27]
Physiotherapist [38]	Rehabilitation [12]		Biomechanics [15]
Tech enthusiast [44]	Motivation [44]		Muscle activity [45]
			Fatigue [53]
			Time [68]
			Posture [15]

Table 1. Sports Wearables: Dimensions of Users and Use

track of the progress [12]. Finally, sleep tracking features in wearables, such as Readiband [17], can aid in recovery and optimise sleep hygiene and are used by professional athletes.

As the above shows, a wide variety of devices is available to support a wide range of sports and use cases within those sports (see Table 1 for a summary). While they can collect several different metrics that could be used in different contexts, limitations and challenges remain. First, most of these devices rely on a constant stream of data to enable predictions, and therefore are vulnerable to hardware or software issues with the sensors reliability and interpretability of the data, which often depends on the quality of underlying machine learning models [68]. Second, there are technical issues related to accuracy, especially outside of controlled environments or when engaging with higher intensity sports or activities that require varied movements [3, 68], which can influence whether people trust the device and therefore raise concerns regarding continuous use. Third, there are issues related to user experience, including the design, comfort and ease of use [34, 39], all of which influence perceived benefits of using wearable devices, which may differ depending on users' needs and goals. Therefore, when designing sports wearables, we need to know more about the unique needs of the athletes (both professionals and enthusiasts), their coaches, and other stakeholders such as physiotherapists.

2.2 Different Dimensions of Sports Wearables: Stakeholders, Data and Unique Requirements

As discussed in the section above, sports wearables are able to capture a wide range of measurements and be used in different contexts (see Table 1). How they are used, however, depends on the users – and different stakeholder groups have unique, often conflicting, needs. The range of current options in this space is wide. While we may differentiate between commercial-grade solutions (where accuracy and improved data analytics are traded off for affordability) and solutions for the keen amateur or home user (typically more affordable but often less accurate), even within those two sub-categories there are big differences in purposes of the available options. This in turn impacts the amount and nature of data collected, how it is analysed and the ability to fine-tune and specialise both metrics and measures. For simplicity, the dimensions given in Table 1 are high level and encompass this range of solutions; each of them could in turn be expanded upon to consider this deeper nuance. For example, even amateur users may adopt high-end solutions if price is not a barrier and their interest in performance improvement demands it. In addition, most of the prior work in the area focuses on athletes of different ability levels (from hobbyists to elite athletes) [44], with less focus on other stakeholders such as coaches, trainers or sports scientists and researchers – all of whom may be relying on the data captured by the sports wearables. In fact, the need to focus on coaches is one of the Grand Challenges in SportsHCI [14], although it is framed around the athlete-coach relationship. While we know that elite athletes and coaches tend to share the data [50], there are limited examples of research addressing specific needs of personal trainers or coaches, with recent studies focused on supporting trainers leading classes [62], understanding needs of tennis coaches [23] or supporting junior ice skaters [31]. In the latter example, Jones et al. [31] discuss the use of IMU sensors for amateur and junior ice skaters, and the different roles they play for coaches, skaters and parents. One key finding relates to how data should be presented to ensure it is not misinterpreted or misused by the different stakeholders. The coaches interviewed by Jones et al. had concerns that the data reported might lead skaters to over-train. There was also potential for conflict with parents of skaters over training regimes based on (mis)interpretation of IMU data. It is also evident in this work that where data is collected by a third party (e.g. a coach), there are important data ownership and privacy issues that need to be considered, particularly in cases where data is gathered from minors. Similar concerns are outlined by Karkazis and Fishman [33] who identify that wearable technology in professional sports is used within a power dynamic that has the potential to erode trust between players and coaches, and coaches and team owners. They argue that such data collection and use need clearer regulations to preserve safety and privacy, and their arguments echo those coming from the industry [56].

Related to the use of data collected from wearable devices is how resulting information is fed back to the wearer, and this depends on who will be using this information and for what purpose. Real-time feedback during use requires understanding not only how this can be provided (which is strongly related to context of use), but also the effect of such feedback during an activity. For example, Mencarini et al. [43] investigated this in the context of wearable devices for rock climbers. They experimented with vibro-tactile feedback to understand where best to locate the vibration actuators on the climbers body, levels of vibration and how climbers could understand the meaning of vibration 'messages' sent by climbing coaches. What was not considered in this work was the potential for distraction from such vibration and what effect this might have on the climber.

Even when we consider personalised wearables for individual use, issues around data ownership and privacy remain [60, 68], especially when that data is collected by commercial devices and stored on third-party servers. As soon as data is transmitted from the wearable device for analysis and visualisation, the question of where that happens, who has access, and ultimately who owns the data become pertinent. Research into the use of wearable devices in hazardous work environments hypothesised that in these cases building bespoke hardware (including for data aggregation and analysis) was preferable to integrating commercial solutions due to these data privacy concerns [8]. This takes us a step further towards users creating their own personalised bespoke wearable devices and into a wider consideration of how they could utilise these to store and provide data over time without compromising personal data security and sovereignty. This is where 3D printing using flexible materials could aid the development of novel wearables.

2.3 Supporting Sports Monitoring and Feedback through Flexible Materials and Advances in Fabrication

Increasing interest and adoption of personal fabrication [6, 46] has enabled 3D printing to become more widely accessible as an approach for developing wearables as 3D printers are commonly found within maker-spaces, public libraries, and even some households. In recent years, researchers have started exploring more flexible and malleable materials. For example, Rivera et al. [51] illustrate how 3D printing and textiles can complement each other, creating textile-embedded 3D-printed objects that are flexible and stretchable. Wong and Hernandez [67] review current additive manufacturing processes for 3D printing, showing their benefits in rapid prototyping that would benefit a range of application areas. Finally, Schumacher et al. [52] present a method to characterise the mechanical behaviour of structured sheet materials allowing users to capture deformation behavior under stretching and bending. With their approach users can explore various structures and design/create materials with specific desired micro mechanical properties. Ultimately, their work allows people to define and fabricate structures with a variety of desired material properties, particularly for bending and stretching. Similarly, Metamaterial mechanisms [29], which can be designed using Computer-Aided Design (CAD) software and fabricated with standard 3D printers, also enable the creation of objects with controlled directional movement and flexibility embedded during the design process. Materials like Polydimethylsiloxane (PDMS) have also been used to create flexible devices. Stretchis [66] demonstrates how to embed stretchable touch and proximity sensors can be used with PDMS to develop thin stretchable wearable interfaces.

Silicon-based fabrication techniques can be used to develop deformable wearables, such as Electrodermis [41], which introduces a range of stretchable and highly customisable electronic bandages. Everitt et al. [16] proposed a design approach utilising multi-material 3D printing to create flexible wearables with integrated input and output capabilities. A co-design workshop they organised identified potential applications for wearables in sports and rehabilitation. Recent reviews further expand on the emerging trends and applications of soft wearables in sports, as well as the social considerations of on-body placement for wearable technology [70, 71]. In addition, research on the design space of soft and garment wearables [19, 20] offers valuable insights into the potential of flexible wearables for physical activity. It highlights design opportunities to enhance both individual and social exercise experiences through visualising feedback on the body for the user and others to see. Similarly, soft wearables could be applied in the area of sports performance, where unobtrusive feedback through texture changes shows promising potential [22]. Therefore, our work explores how we could enhance athletes' experiences through flexible wearables for monitoring and feedback. While flexible materials present an opportunity to develop novel wearable devices, first we need to better understand the needs of different user groups, desirable and useful form factors, and the types of support such wearables could provide.

3 DESIGN WORKSHOPS

To identify challenges related to using wearables to support and monitor physical training, and to explore a wide range of potential opportunities for using novel flexible materials, we conducted two exploratory design workshops at two universities in New Zealand. The study received ethical approval from both institutions.

3.1 Methods

3.1.1 Participants and recruitment. Through mailing lists and personal contacts we recruited 11 participants. Five participants (three women and two men) attended the first workshop held at University of Canterbury, and six (four women and two men) attended the second workshop at The University of Waikato. All participants had varying backgrounds (including sport enthusiasts, athletes, sport and rehabilitation researchers, sport analysts, etc.), and had professional expertise and/or personal interest and experience in a wide range of different sports. Table 2 summarises participant information.

3.1.2 Procedures. The two workshops followed a similar structure. Each lasted 2 hours and was conducted by two researchers: one researcher facilitated the session, while the other was responsible for note-taking and who joined the discussions to ask additional questions. At the beginning of each session, after taking participants' consent, we introduced the project and its objectives, and presented an overview of the session. The workshop activities were divided into two parts: group discussions and design activities. The first part (discussions) focused on exploring participants' experience, related interests and expertise, their current use of technology, and concerns related to using novel technologies to support sports and physical training.

During the second part, we presented a short overview of existing wearable technologies for sport and physical activity, including commercial devices such as a smart insole, smart trainers or smart swimming goggles [18], as well as

Table 2. Participant details, including their professional background, sport-related expertise (for sport professionals and researchers) and/or sports they were interested in on a personal level.

ID	Gender	Background	Expertise and Interests	Workshop
P1	Man	Sport enthusiast	Long distance running	W1
P2	Woman	Sport team leader, Coach	Strength conditioning, rugby, volleyball	W1
P3	Woman	Sport analyst, Massage therapist	Multisport, adventure racing, ultra running	W1
P4	Woman	Sport enthusiast	Pole dancing, gym, yoga, cycling	W1
P5	Man	Sport enthusiast	Strength training, mobility	W1
P6	Woman	Health researcher	Human performance, brain activity; football	W2
P7	Woman	Health researcher	Rehabilitation; hockey	W2
P8	Woman	MSc student, Health	Physiotherapy, rehabilitation; badminton	W2
P9	Man	Sport enthusiast	Powerlifting, Strongman competitions	W2
P10	Woman	Health researcher	Pilates	W2
P11	Man	Sport enthusiast	Mountain biking	W2

the latest advances in research and novel approaches with no current application in sports (e.g. stretchable 3D-printed materials or interactive tattoos [16, 32, 66]). This was used as a starting point and an inspiration for the design activities. Participants were given flipchart paper and A4 sheets, and a set of pens, pencils and markers, and encouraged to design new wearable devices for the sports they were involved in. To help participants with the task, we also provided a short presentation on sketching that included an introduction to low-fidelity prototyping and example rough sketches of different types of technologies; the aim was to make it clear that participants were not expected to make art, but only use sketches to help explain their ideas. Participants worked individually on their ideas.

During Workshop 2, building on the results of the first workshop, we expanded the low-fidelity prototyping presentation to also cover turning sketches into simple cardboard prototypes. As a result, after completing and briefly describing their sketches, participants were asked to turn their ideas into tangible prototypes using cardboard, play dough, stickers and other materials that were available. The tangible nature of the prototypes allowed us not only to focus on functionality included in the ideas, but also to discuss practicalities of wearing the devices participants designed. Both workshops ended with a short presentation of each participant's final idea(s) and a general discussion about sports wearables, including any issues or concerns not mentioned earlier. As per ethical guidelines for this type of study at both institutions, participants did not receive any incentives, although tea and coffee was available during Workshop 1.

3.1.3 Analysis. Both workshops were audio recorded to aid the analysis. The recordings were automatically transcribed using a transcription software, and were later reviewed by the researchers present in each workshop who corrected errors in transcription. Sketches and cardboard prototypes were photographed, and were used as additional information sources for the analysis, mainly to provide context to the discussions in the transcripts.

As we were interested in identifying a wide range of possible opportunities and challenges, the transcripts were analysed thematically [9] following an inductive approach. Each transcript was read and independently coded by the two researchers who attended that workshop. The preliminary codes focused on what participants talked about (e.g. 'adapting the workout', 'correct form', 'movement assessment', 'training with someone') and were also used to identify discussions about specific activities (e.g. 'cycling', 'physiotherapy', 'weights', 'warm-up'). All codes and their content were then discussed with the rest of the research team during regular meetings, which led to the collaborative development of initial themes; we used the Atlas.ti software during the analysis. Given that writing can be part of the analysis [10], the themes were further updated, merged and re-framed while working on this manuscript. In the end, we created four key themes centred around personalisation; they are discussed in the next section.

3.2 Results

The key themes fall under the wider umbrella of "personalisation" and highlight a set of challenges and opportunities for using wearables to support sport activities at different levels and in different contexts: sport-specific, activity-specific, context-specific and body-specific. In this section, we first describe the participants' design ideas, and discuss the main use cases and key features participants were interested in. Some of the workshop outputs are shown in Figure 2. These ideas provide background for the key personalisation-related themes that are reported in later sections, and a set of archetypal users and use cases that we report at the end as a way of summarising the key findings.

3.2.1 Overview of produced design ideas. Our participants reported engaging with and having an interest in a wide range of physical activities ranging from running and weightlifting to hockey, pilates and pole dancing/fitness (see Table 2). However, there were common interests spanning across these different activities. In general, participants were interested in measuring posture and ensuring it is correct, which was also related to monitoring the use of the core muscles and measuring alignment. They were also worried about potential overtraining, and therefore were interested in measuring the levels of lactic acid using EMGs to identify weak points and see which muscles are firing efficiently and which ones are under- or over-used. Participants also highlighted the importance of supporting correct breathing, which is relevant to different sports. In particular, they mentioned weightlifting where incorrect breathing or holding one's breath can lead to collapse and injury when lifting heavy weights.

As the workshop focused on wearable devices, most of the ideas were centred around devices that could be worn, such as trousers, insoles or a bra (see Figure 2). Participants provided several ideas of how the wearables could work and what types of features should be available to make them effective. In particular, they were interested in monitoring and feedback. For example, the participant who designed wearables for pole dancers (Figure 2a) explained that a smart hairband or earrings could help to monitor the tilt of the head to ensure the athlete is not extending their neck during more straining positions, which can lead to injuries. A participant interested in running designed a smart belt (Figure 2b) and a participant interested in mountain biking designed smart trousers (Figure 2c,d) – the aim of both was to monitor posture and joint positions, and to provide feedback where a change in posture would be required. Another participant, who was interested in specific muscle activation during weightlifting, designed a set of stickers with electrodes for flat areas like the back (see Figure 2i and 2j) which could provide detailed, real-time feedback. In general, participants were interested in being notified when to rest or check their posture, ideally through audio-visual cues. Several ideas utilised different colours to convey information, such as visualising fatigue based on brain waves or changing colours based on heart rate or body temperature (headband, Figure 2g). The smart mirror idea also used colours to convey whether user's posture is correct (green) or deviates from the ideal range (red), as shown in Figure 2f.

The main thread linking all these designs and participants' ideas, and underlying all key themes we identified, was personalisation: the need to ensure the wearables are suitable for specific sports, sub-activities within these sports, as well as individuals engaging with these activities and their specific needs that may change due to context. Even though *personalisation* refers to specific design decisions or automatic changes in response to users' actions and data, while *customisation* refers to changes made directly by the user [26], our participants seemed to conflate these two definitions and consistently referred to "personalisation" when talking about different types of necessary adaptations, regardless of

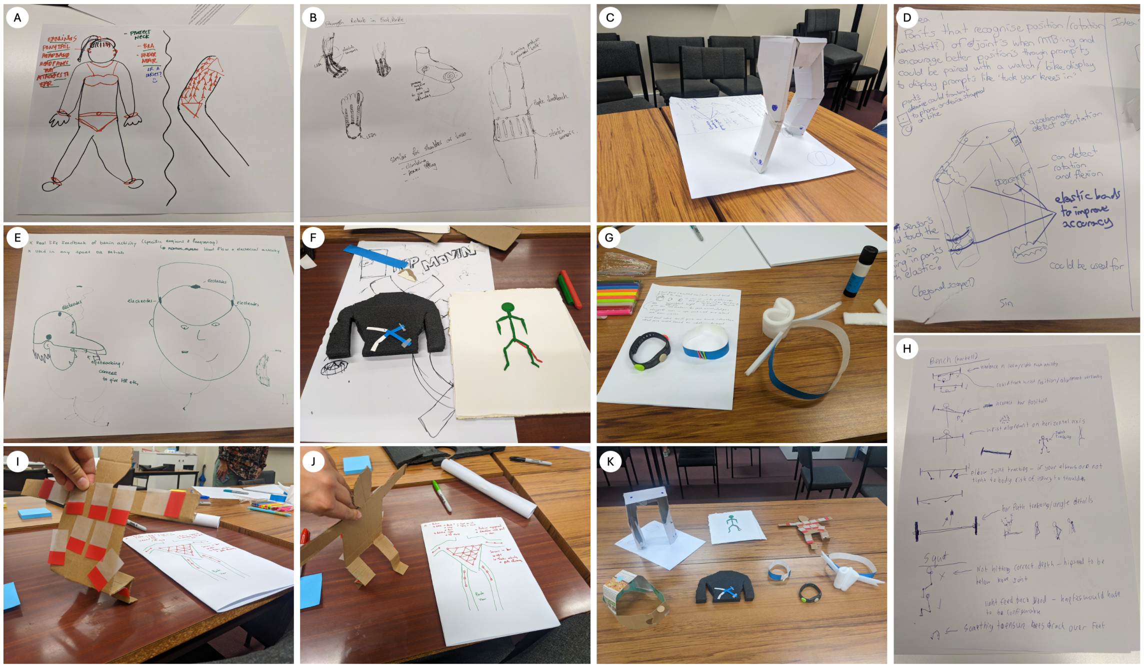

Fig. 2. Overview of participants' sketches and prototypes: A) Left: a smart bra and smart accessories (earrings, hairband, headphones); right: an interactive tattoo for pole dancers. B) Left: strength sensors with LED feedback lights and smart insoles for foot rehabilitation; right: smart belt for posture monitoring for runners. C) and D) Smart trousers for mountain biking that track and recognise joint positions and can detect rotation and flexion. E) A smart cap with electrodes for detecting brain activity to support rehabilitation and sport training. F) Left: a set of electrodes that could be attached to the back to record movement; right: a mirror that shows the posture and highlights any deviations in red. G) A headband with sensors to monitor mood and fatigue. H) A set of sensors to be attached to a barbell to monitor posture for different types of lifts. I) and J) A set of smart stickers that recognise muscle activation for posture monitoring for weightlifters. K) Overview of all prototypes from W2.

their source. We use their terminology in the results, but discuss this in more detail in the Discussion. The need for personalisation and customisation at different levels was reflected in discussions about practical considerations and real world limitations, and differed depending on the level of expertise of participants (sport enthusiasts vs. experts). In the following sections, we use the different levels of personalisation (sport, activity, context, person) to discuss our findings in more detail.

3.2.2 Personalisation for different sports. As our participants reported engaging with a wide range of different sports (often at the same time; see Table 2), they all had slightly different needs and expectations, which were often communicated through discussions about barriers to use and concerns. As such, there is a need to develop different functionalities and form factors to allow for dynamic personalisation to cater to needs of specific sports and variations within them without the need to develop custom devices for each. For example, correct positioning of sensors depends on what the person is doing: what works for powerlifting (and could be worn on the back or integrated in the belt) may not necessarily work for runners as the device could move around as the body moves or not be recognised correctly. There was also a clear distinction between strength and cardio exercises, with the latter seen as generating more sweat which could potentially dislocate any wearable devices and interfere with the functioning of the device:

> *"I'm pretty certain sweat is somewhat conductive so even if you start sweating with* [the muscle stickers; Figure 2j] *on, then it might start screwing up the readings because it might be reading different muscles because all that sweat is connecting it all together."* – P9, W2

Participants also mentioned issues with lack of reliability if the devices were not designed with practicalities of a specific sport in mind. In other words, the lack of personalisation to reflect specific behaviours could affect their credibility. For example, one participant, a sport team leader, mentioned smart mouthguards for rugby players that monitor head movement and notify the coach when they suspect a concussion. However, the sensors are very sensitive and tend to generate a large amount of false positives, e.g. when the player abruptly looks around, which can result in them incorrectly being asked to leave the field for safety concerns. The participant had concerns that such an unreliable device that doesn't account for players' full range of behaviours would not be welcomed by the players:

> *"If I said to the girls at training tomorrow 'You're gonna wear mouth guard at the Centre and if it goes over 7 you're off the field for the rest of the game' they'd be like 'WHAT!?' They'd lose their sh*t."* – P2, W1

The need for personalisation was also mentioned when discussing sports that involve a set of different skills and would therefore require different metrics. Pole dancing is an example of such a discipline. It was an interesting case study because the athletes' clothes further complicate the requirements for any wearable devices: for safety reasons no jewellery or watches can be worn, and exposed skin is necessary to ensure better grip. However, as pole dancing is a highly technical discipline that requires both strength and flexibility, standard wearable trackers such as wristbands or smart watches would not be suitable even if they could be worn. One participant suggested potentially integrating sensors in the bra as it would allow for heart rate measurements, but that would not be good enough for posture monitoring as neck is the key area that needs to be protected to prevent injuries:

> *"I was thinking, because with pole dancing, what else can you actually wear but just the underwear? [laughs] And also I was thinking of, like a* [sensor in the] *ponytail that you can just kind of like forget. So with pole dancing we really want to protect our necks. So it's that before you do a move, a specific move, there is that point that you have to make sure that you are tucking your chin."* – P4, W1

Overall, the discussions showed that while similar factors could be relevant for different sports (e.g. posture monitoring), the differences between the disciplines and movements they require meant that, on a fundamental level, wearables would have to be adapted and personalised to match the requirements for each sport. However, that would be only the first step as further personalisation would be necessary within each discipline.

3.2.3 Personalisation for specific activities. Participants argued that even within a specific sport the needs and utility of a wearable device may differ, depending on a specific activity. For example, there are different requirements between the two main types of lifting: the more static powerlifting and Olympic weightlifting that involves more dynamic movements such as snatch and clean & jerk. Any monitoring or feedback functionality available in a wearable device would have to be adjusted for the specific version of lifting. However, there could be issues even within the same discipline. When discussing the idea of back stickers (Figure 2i), the participant who proposed it pointed out that while the stickers could work for deadlifts or squats, they would not necessarily work for a bench press (the third from the set of powerlifting lifts) as the user would be lying on their back, which could damage or displace the sensors.

> *"Some people wear like the weightlifting belts as well that could potentially interfere* [with the stickers]. *Yeah, even on the upper back it's like if you have your squat bar, even for bench press just lying down on it..."* – P9, W2

Participants also mentioned rehabilitation, physiotherapy and dealing with injuries, as well as injury prevention, as relevant. These were seen as inherently linked with any type of physical activity, because even if injury is not sport-related, it will have impact on what the person can do once they return to training and what types of exercises can be included as part of their recovery. Therefore, any device designed for athletes would have to support rehabilitation and recovery, and therefore take into account athletes' reduced range of motion or any other movement-specific modifications. However, it must focus on relevant movements. The participants argued that rehabilitation is often presented as related to the general area of body (e.g. upper limb rehabilitation, lower body rehabilitation), but the specific types of movements heavily depend on the types of activities the athletes are engaging in, and these can vary within the same sport, depending on context and the strength and flexibility of other areas. If the aim is to prevent injury and support rehabilitation, understanding how that specific part links with the rest of the body matters.

> *"You know, cyclists.* [Say,] *they're having this persistent ankle injury. So where is it coming from and how long have they had it? And is it an overuse injury? If it is an acute injury then that's in the realm of physiotherapy. But for us it's sort of, and for me as well, it's sort of looking at the whole body: how does the whole body work?* [...] *In the realm of physio, they can only treat the part that's injured and I think it's really limiting, and it's totally dumb idea because you know we're not separate pieces."* – P3, W1

Finally, participants also highlighted issues with lack of knowledge or understanding among athletes as they have impact on how people engage with different activities and therefore would have to be accounted for in the design of a wearable. Even within the same area, such as weightlifting, people may not necessarily understand the best practice or correct posture for each type of lift. Similarly, participants highlighted misconceptions about training that could lead to overtraining and potential injury, and argued that such lack of knowledge would affect how people interpret – and misinterpret – data collected by the wearables. This could raise concerns related to reliability of the data or reduce trust. One example participants provided was a warm-up and lack of understanding of its purpose and what it entails. Many people confuse warm-up with static stretches that are best suited as a cool down exercise after a workout, while the warm-up should lead to the increase of body temperature to prepare it for the upcoming activity. Participants wondered if sports wearables could help in situations where people neglect warming up:

> *"One thing I find with multisport, because you're doing 3 to sometimes 4 different disciplines, there's very little warm up. There's very little, there's limited attention to actually caring for your body and taking notice before you train, because you're having to train so much and 3-4 different disciplines, so you just get out, go do your training, finish, run, kayaking. And it's such a busy schedule and professional athletes will be so busy.* [...] *So, most people have Garmin watches and they look at just their heart rate, distance metrics, and that's it.* [...] *Lot's of tech doesn't take into account body temperature, and it would be useful because with outdoor sports you're often in environments, like rugby in the winter, and the summer. Yeah, temperature regulation, humidity, precipitation – having those metrics would be good."* – P2, W1

Overall, participants were clear that different activities require different approaches – and therefore would benefit from different types of technological support. Therefore, it is important that any sports wearables are not just designed with a specific sport and its main activities in mind, but can also be personalised to account for complementary activities such as warm-up or recovery.

3.2.4 Personalisation for individual bodies. Over and over, the discussions kept returning to individual differences and understanding one's body. It was clear to the participants that any device, even if designed with a specific sport or activity in mind, would have to also take into account each individual's characteristics. Furthermore, bodies change. What is considered "normal" or "correct" form is in practice different for different people, and any injuries and life experiences can lead over time to changes in range of movement, muscle activation or general mobility. As such, participants argued that it was important to treat body as a whole that undergoes continuous changes.

> P2: *"When we're looking at, you know, the lateral knee and ankle injuries, you need to look at the gait. You need to look at the structure. Is it a woman with, you know, wider hips?"*
> P5: *"Yeah, you tend to get the injuries crisscrossing the body in a lot of strength training as well. So you would overcompensate with one side and then that can lead to an injury over here, so then you overcompensate, you know, it kind of crisscrosses the whole body."*
> P2: *"Yeah. And any old injuries have changed in structure. Yeah, they come back to bite you later. Like, you know, if you've torn something, it's not gonna be muscle tissue repaired, it's gonna be scar tissue."*

Addressing these issues would require highly personalised devices. However, extensive personalisation could increase the complexity and cost of a device, and participants raised several concerns related to accessibility and reliability. In particular, they had concerns related to users' difficulties with knowing how to use such devices and being able to analyse the data and relate it to their own experiences. There was also a concern that extensive personalisation and continued real-time monitoring could increase dependency on the device and lead to overthinking and second-guessing oneself, which could have a negative effect on the performance.

> *"They have watches and they're kind of for golf. And so it gives instant feedback about the swing that you do. And so* [participant's colleague] *was actually quite keen to get those and see whether that instant feedback is generating overload. Are we overthinking our movements? Are we getting dependent on it?"* – P7, W2

3.2.5 Personalisation for activities in different contexts. All the above points need to also be considered within different contexts of use. As our participants had different backgrounds (sport researchers, sport analysts and coaches, and athletes with various levels of expertise), they highlighted different ways of using the wearable devices. The main difference was the distinction between designing something for users to track themselves vs. designing for sport professionals working with athletes: who is the data for and how would it be used? What type of information should actually be tracked and with what level of details?

> *"Like, for rugby,* [we] *don't wanna be like overloaded with information.* [...] *For instance, on the GPS you can have about 250 different types of data. So like at the end of the day, as a practitioner, we probably only take five out of the 250.* [...] *Because those are the five ones there within a group of 30 girls that we're gonna be able* [to explain] *to. Because we're not gonna be sitting in class for a whole semester teaching them about all the metrics and how to use them and whatnot."* – P2, W1

There was also the issue of the target group and location, where additional environmental and contextual factors would need to be considered (weather, terrain, etc.). Such factors were seen as potential sources of barriers to use, as devices designed for one context or one user group may not be easily transferable to others, e.g. due to the use of medical terms or understanding what is being measured, why and how it should be interpreted, or simply practicalities of use and the constraints introduced by the activity itself:

> *"I think, with those kind of devices like eye tracking* [...] *I think the biggest thing that I realized is that people like, if you talk to athletes, they're like, oh, when would I use this? When would I put this on? When*

> *are you measuring me? And I'm kind of like, well, during a game would be ideal because that's the situation when everything happens, right? But they quite often say, yeah, but we can't go on the field with something on. So yeah, I think that's my biggest issue – that you almost have to use* [it] *in a lab or during training, but that's not the real life circumstances."* – P7, W2

In addition, there was the issue of public vs. personal spaces: a device designed to support sports research or professional athletes would have different requirements than one designed to be used by amateurs in public, where it could potentially be seen as invading one's privacy or annoying/interfering with the training of others present in the same location or the athletes themselves. Participants mentioned the common practice of athletes using video to assess their form, posture and progress (e.g. for weightlifting and pole dancing), which can also capture others who are around. In terms of wearables, they pointed out that feedback and support provided by the device could be distracting to others (especially audio or visual feedback). Haptic feedback could be more discreet, but it could potentially backfire:

> *"Something visual* [as feedback] *could be good but you don't want it super obtrusive and you need to actually be able to see it without it negatively affecting your form. So, like, sometimes you'll see people checking their squat depth. Whereas if benching or something, if you've got something on your breast, you can see it very easily, but also having some haptic feedback* [would be useful, but would have to be] *configurable per person because some people need quite a lot to be able to feel it. Some people will get a jolt with it and obviously you don't wanna jolt it if you're lifting 100 kilos over here because* [during a bench press] *then that's decapitation time!"* – P5, W1

3.3 Archetypal Users and Use Cases

As the themes discussed above show, there are several levels of personalisation that need to be taken into account when considering sports wearables. Based on these results and building on the dimensions of users and sports wearables use extracted from the literature (see Table 1), we created a set of archetypes that represent a range of users and use cases relevant to the results described above. The archetypes are shown in Figure 3. While they do not represent a fully comprehensive overview, they allow us to focus on the specific themes that emerged from our data and the literature.

> Darren, 'The Hobbyist' is an **amateur** who uses technology for **motivation**. He is most interested in **post-hoc** data and measures attributes such as **biomechanics, muscle activity, distance and time**. Findings within the themes of *personalisation for different sports and individual bodies* are most relevant for this archetype.

> Eddie, 'The Amateur' is also an **amateur** but uses technology for **training and measuring performance**. He uses the data in **real time** while cycling and also **post-hoc** for analysis and **long-term** to measure improvements. He is interested in all possible measurements that can assist with his cycling performance and recovery. Findings within the theme of *personalisation for specific activities* are most relevant for this archetype.

> Arlo, 'The Professional' is a **professional** athlete. She uses technology to support **training, performance and recovery** (in conjunction with her coaches). **Real time** data supports her training sessions while **post hoc and long term** data are used in conjunction with her coaches to measure performance and improvement. This includes **all possible measurements** as well as **specialist** measures (such as stroke and kick analysis in the water). Findings withing the themes of *personalisation for specific activities and in different contexts* are most

relevant for this archetype.

AJ, 'The Coach' is a Coach who uses technology to measure and monitor his American football teams both on and off the field. He uses technology and data analytics to support players and the rest of the coaching team with **training, performance, recovery and rehabilitation**. Data is gathered and analysed **real-time and post hoc** and subsequently re-analysed **long term** to understand gains and improvements of longer term fitness and skill strategies. **All possible measurements** are gathered, including **specialist measures** such as player impact and collisions on the field. Findings within the themes of *personalisation for specific activities, for individual bodies and in different contexts* are most relevant for this archetype.

Allie, 'The Gadgeteer' is an **amateur**. She is mostly interested in **technology itself**. She mostly uses **real-time data** in the moment, e.g. to capture her daily steps or sleep patterns, but the measurements she is interested in change as the technology she has access to evolves over time. Findings withing the themes of *personalisation for different sports and activities and in different contexts* are most relevant for this archetype.

Caira, 'The Physio' is a **physiotherapist** using technology for **rehabilitation** with her patients. She uses technology in **real time** with her patients to demonstrate things like muscle activations, technique and body position. She also uses patient data **post hoc and long term** to measure progress and recovery. She is mostly interested in measuring **muscle activity and biomechanics**. Findings withing the themes of *personalisation for individual bodies and in different contexts* are most relevant for this archetype.

The archetypes illustrate how different user groups' needs could affect the design and functionality of sports wearables. We refer to them in the next section when discussing the opportunities for flexible wearables and personal fabrication more broadly.

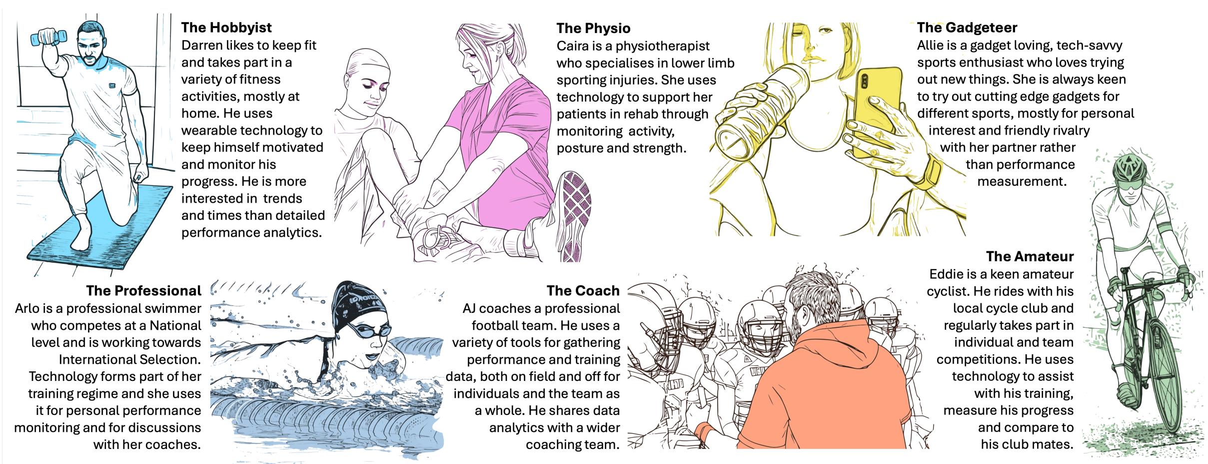

Fig. 3. Archetypal Users illustrating a wide range of use cases of sports wearables informed by the literature and our findings. Images created by the authors based on photos from pexels.com, royalty free.

4 DISCUSSION

Our aim was to explore the opportunities for the use of flexible wearables to support physical training. To that end, we conducted two exploratory design workshops with a total of 11 participants (sport enthusiasts, sport professionals and researchers) who designed and prototyped a wide range of potential flexible wearable devices they would like to use as part of their own training or to support others. They also highlighted the role of rehabilitation, physiotherapy, injury prevention and recovery as inherent parts of physical training. While we were interested in a wide range of opportunities, our participants mainly focused on sensing and feedback, without mentioning actuation, possibly because most people are not aware of this possibility and current commercial wearables do not support actuation. As such, they focused on more mainstream features, such as sensing and basic feedback via modalities such as visual or audio or haptics. Overall, our key findings are centred around different levels of personalisation (that also includes the need for customisation), highlighting several opportunities for using flexible wearables to support sport in different contexts, as well as challenges that need to be addressed. In particular, the results highlight the opportunities for personal fabrication as a potential approach to ensuring the varying and evolving needs of different stakeholders are met.

4.1 Different Levels of Personalisation

While both personalisation and customisation refer to adaptations that make devices more useful and acceptable to users [13, 40], the source of these adaptations differs [26, 30]. Our results show that the participants were interested in both: the design of sports wearables should from the start take into account different needs and contexts of use (*personalisation*) and such devices should include features that would enable the users to further adapt them to their needs (*customisation*). There has been limited focus on personalisation in the context of sports wearables beyond supporting personalised training [14] as research tends to focus on other aspects of this design space (see [14, 44, 63]). A notable exception is research by Jarusriboonchai and Häkkilä [30], although their focus was on customisation. They analysed 129 commercial wearable devices (mostly different types of fitness trackers) to identify available customisation options, and found that most customisation practices focused on functional features, interaction techniques, locations on the body, and the appearance [30]. Our work highlights the need to take it further and consider different personalisation levels, which could be achieved with flexible wearables that also allow for further customisation. The results suggest that this flexibility could be two-fold: on the one hand, the device itself could be flexible, made of flexible materials that can change shape [35], and adapt (or manually be adapted) to different shapes and bodies; on the other hand, the changing context of physical training, linked to skill progression, potential injury, and need to accommodate recovery, calls for versatile, adaptable devices that could be used in different contexts. We expand on this later in Section 4.2.

Furthermore, the different levels of personalisation reflected by our archetypal users (Figure 3) suggest a need to distinguish between novice and expert users, regardless of which user group they belong to – and that expertise should be considered across different dimensions. Engaging with sport requires some degree of background knowledge and experience, and therefore that distinction should cover several levels that influence interactions with sport technologies: 1) knowledge and expertise about the specific sport, 2) knowledge about human body and physiology related to physical activity, and 3) experience with technology. For example, an amateur cyclist (such as Eddie, The Amateur archetype), may be a tech-savvy expert, but know very little about physiology beyond what he thinks is necessary to properly warm up and recover after a ride. In contrast, within a rugby team, the coach (similar to AJ, our coach archetype) may have a high expertise in this sport and good knowledge of physiology, but limited technical skills, while his team's physiotherapist (such as the archetype Caira) may be an expert in her field, be pretty technical and interested

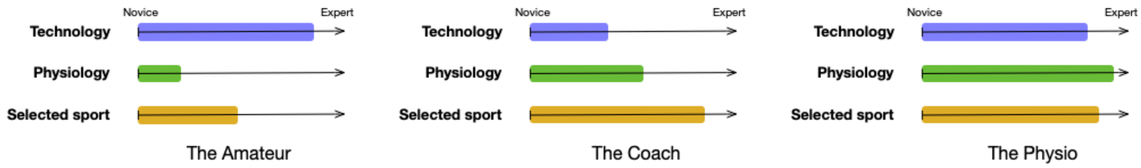

Fig. 4. Examples of how the different dimensions of expertise (knowledge of technology, physiology and a specific sport) may differ for different user types.

in technology, and on top of this may know a lot about rugby as she used to play in the past for her local team (see Figure 4 for comparison); as such, all these archetypal users would use the data from wearables in a different way and expect different level of detail. In addition, as effects of wearables on athletes can change depending on their experience [44], **the levels of expertise across all three dimensions change over time** – and that continuous progression needs to be accounted for during the design process. This, in turn, opens up opportunities for personal fabrication.

4.2 Opportunities for Personal Fabrication

The growing popularity of digital fabrication technologies, particularly desktop 3D printers, has given rise to personal fabrication [6, 46]. This represents the early opportunities for democratising manufacturing, giving rise to a new class of creators and makers. Mota [46] emphasises that increased public access to digital fabrication tools, software, and blueprint databases has fuelled a tech-driven Do-It-Yourself (DIY) movement reflecting a growing desire among individuals to shape and personalise the products they consume. Personal 3D printers have become increasingly accessible due to their compact size, affordability, and ease of use for individuals with limited technical skills, enabling wider audience to engage in DIY fabrication. Furthermore, platforms like Instructables [28] and Thingiverse [61] provide users with easy access to a database of virtual models and projects that can be downloaded and customised. These communities are constantly growing, with numerous contributors sharing designs that can be modified, remixed, and adapted to fit individual needs. This approach brings opportunities for fabricating wearables for sports and physical exercise, allowing primary designs to be adjusted to fit the user's unique body shape and size. Using CAD tools, users can also further personalise these designs to meet their specific needs and requirements before 3D printing.

With the increasing integration of LiDAR technology in mobile devices, such as the latest iPad Pro and iPhone Pro [2], users can now also 3D scan their body parts with their phones and import these into CAD software to 3D print custom modules tailored to their exact body shape. This approach would allow for personalised adjustments based on individual needs, skill progression, and the diverse and evolving physical forms of users. It underscores the need for flexibility in both the material properties of wearables, to accommodate a range of movements, and in their adaptability to changing contexts and scenarios. The materials used during fabrication must be durable to withstand long-term use and comfortable to ensure a positive user experience. Specialised flexible materials, like thermoplastic polyurethane (TPU), play a critical role in meeting these requirements. For example, Chinchilla™ flexible 3D printer filament from NinjaTek is skin-safe and certified for medical applications, such as prosthetic socket liners. As a result it could be suitable for sports applications: its soft-touch properties support comfort, making it well-suited for prolonged contact with the skin during physical activity.

Wearables designed with this level of flexibility also offer the potential to move away from the 'single-use device' model and its negative impact on the environment. Rather than discarding devices as the athlete outgrows them (physically, or by reaching the next stage in their skill development or becoming interested in other parts of their performance), users could modify their flexible wearables to extend their lifespan and utility, and to meet the evolving demands of higher expertise. The device could (and perhaps should) be flexible enough to adapt to both physical changes and skill advancements, or even contextual shifts. Such adaptable design could allow athletes to use one device across multiple stages, rather than relying on several different devices that would eventually be discarded.

Finally, an important consideration in moving towards more user-designed and controlled wearables is how the data that is collected can be analysed and visualised. Recent research has focused on developing tools and libraries for this, for example, the Wearables for Health Toolkit (W4H Toolkit) offers a comprehensive platform for managing, analysing, and visualising data from various wearable devices [21]. Similarly, RAPIDS provides a reproducible pipeline for standardising the pre-processing, analysis, and visualisation of mobile sensor data [64]. For Android devices, middleware has been developed to analyse wearable data and provide personalised recommendations [1]. All of these initiatives support user control by enabling not only wearable devices themselves to be personalised, but also the analysis and presentation of the data. As such, they could help to better adapt the wearables to different users and their varied needs.

4.3 Design Considerations for Flexible Wearables

While prior research focused on specific sports or types of activity (e.g. [11, 23, 31, 43]), different types of functionality (e.g. different approaches to visualising physical activity data [15, 20] or providing feedback [22, 37]), or synthesising the literature to identify the wider research trends [12, 14, 30, 44, 63, 68], **our work expands the design space for personalised sensing in sports by taking into the account the dimensions of users and use, their different levels of knowledge and experience, and the change over time.** As shown in Figure 1, the design of flexible sports wearables not only needs to consider the technical aspects (e.g. type of sensors, their placement on the body, data granularity) in relation to the characteristics of specific sports, but also in relation to users' physical and skill-related traits (body variability, skill level, level of engagement with a given sport) and the wider context in which the physical activity takes place (specific context of use, number of users involved, environment). However, these different layers of adaptations are not static as users' needs evolve over time, e.g. due to injury, recovery or changing training goals. All of this determines how flexible wearables should look and behave, and what types of personalisation and customisation would be necessary for different user groups. Given the opportunities discussed above, we bring forward the following design considerations informed by different types of adaptations identified through our work:

4.3.1 User-Specific Adaptations: Account for changing bodies and different shapes. Participation in sports changes one's body, regardless of whether one trains casually or on a professional level. Each person's shape and size is unique and changes in response to training, sport specific adaptations, and changes brought by injuries [25]. Sports wearables should therefore be made of flexible, stretchable materials that would ensure that they remain comfortable and unobtrusive as the body changes. This could be achieved using flexible materials such as Electrodermis [41] to create shape-changing, self-adjusting designs, which could be inspired by shape-change in nature [49]. The software that powers such devices should also take these changes into the account, for example by regularly re-establishing new baselines as the athlete reaches new milestones or their training routine changes.

4.3.2 Contextual Adaptations: Allow for customisation and personalisation of metrics and data presentation for diverse user needs. Following from the point above, sports wearables should give people control over the types of metrics and data they collect, what level of detail is available, and how it is presented. For example, novices may not understand what VO_2Max is, but that can be an important information for experienced athletes and their coaches. Furthermore, the level of control also depends on whether one wants to share that data with others, e.g. a coach [50], as this may vary depending on the context (e.g. regular training vs. preparation for a competition) and therefore may involve different metrics and different level of granularity of data. In addition, personal fabrication means that users could select specific sensors to be included in the device and customise the way their data is visualised.

4.3.3 Temporal Adaptations: Design to accommodate change over time. Finally, sports wearables should be designed with change in mind: as athletes are developing their skills and their performance improves, their priorities and goals change. For example, a novice pole dancer may need to prioritise upper body strength at first, but as they get stronger, they will have to focus more on flexibility, which reduces injury risk and is needed for more advanced poses. A smart flexible wearable would ideally enable tracking and measuring both. Furthermore, professional athletes may train for big sporting events which happen less regularly (e.g. the Olympic Games or Football World Cup, which take place every 4 years), which may have impact on the intensity of the training. As such, the devices need to accommodate such rare events without invalidating 'regular' data and metrics. Similarly, any breaks or changes in the training routine, e.g. due to injury or life events, need to be accounted for. In particular, the device needs to support reduced intensity and frequency of training linked to rehabilitation, return after injury, or simply changing seasons. Such adaptability should apply to both software and the hardware. For example, after an injury, the physical design could temporarily change (or be changed by the user) so that it can be worn in a different way or attached to a different body part.

4.4 Future Research Directions for Personalised Sports Wearables

Our work also points towards future research directions. In particular, there is potential for the use of flexible wearables to support rehabilitation and physiotherapy, given how prevalent injuries are in sport. On a related note, there is an opportunity to actively focus on injury prevention. For example, weightlifting, or engaging with strength training as a companion activity to any other sport, can become dangerous when performed with incorrect posture, especially when working with heavier weights or without supervision [54]. Flexible wearables could not only monitor the posture, but also notify the users when their form deviates from the optimal range. How this could be done in practice and what feedback modalities would be best for different environments is a topic for future research.

Introducing devices that provide advice, specially in the context of injury prevention, requires a careful understanding of what constitutes the 'right' posture and how far one can deviate from it without increasing the chances for injury. In other words, how good is 'good enough'? And, by extension, how accurate would the wearable devices need to be? There is an opportunity for future research to explore this in more detail. However, given that end users who engage with sports may have different levels of expertise (as illustrated in Figure 4), simply communicating that their posture or form are incorrect is not enough – the message needs to be presented in a way that the user can understand and respond to it. This covers both real-time feedback provided by the device itself as well as visualisations of the data collected by the device. How this could be done effectively by a wearable device (and without distracting the athletes) differs depending on the sport and expertise of the user, and is therefore another interesting line of research.

There is also potential for integration of smart decision-support systems within flexible wearables. As the athlete is improving their skills and becoming more experienced, they build a better understanding of what type of conditioning would be most helpful or what muscle groups they should be focusing on. If a personal trainer or another sport professional gets involved as a result of that progression, they may also point out areas for improvement or behaviours to avoid – all of which may require different data. If the smart wearable was equipped with a machine learning algorithm, it could automatically detect changes in performance and adapt the information that is presented. How to do this efficiently and how to present that data to all parties involved is another exciting research avenue.

Finally, future research should explore the side effects of using flexible and customisable wearables, and focus on potential unintended consequences [4]. For example, there are tensions that arise when considering personal and customisable wearables: flexibility vs. usefulness, usability, reliability. Furthermore, while personal fabrication could enable a full control over the design of the device and its features, our participants also highlighted the issue with complexity it could introduce and potential for harm. If we want to enable people to develop devices for themselves, how should we safeguard them? This links with the different levels of expertise discussed earlier: different people may customise a device in different ways, but they may not be knowledgeable enough to know when their customisations could increase the risk of injury. There is a need to identify a default set of algorithms/features that are reliable and provide a good baseline; perhaps the customisation should be limited or some features should be off-limits. More research is needed to explore these potential consequences and to identify suitable mitigation strategies.

4.5 Limitations and Future Work

Our research involved two design workshops with a total of 11 participants. While one could argue that this is not a representative sample, it is adequate for qualitative research of this nature (e.g. [20, 37, 43]). Furthermore, as these were exploratory workshops, our aim was not to collect generalisable data, but to generate new ideas. We succeeded in this regard and were able to identify a wide range of sports and ideas that could benefit from flexible wearables, including sports underrepresented in HCI, such as pole dancing.

The workshop presentations included examples of sport technologies that might have biased participants' ideas. While this is possible, the effect of such bias is of a lesser concern here: while the functionality or form factor might have been informed by what the participants saw, we were more interested in their underlying justifications and explanations of *why* they designed their wearables in a specific way and *why* they included specific features. Therefore, our analysis focused on understanding their justifications while using their designs only to illustrate their points, which helped to minimise this bias.

Even though our participants included a mix of athletes, sports professionals and researchers who engage in a wide range of sports, we did not manage to recruit any professional athletes or physiotherapists. However, experiences with professional sports and rehabilitation and recovery were covered in the workshops through comments of participants who work with these groups (e.g. the sport analyst and a coach). Nevertheless, future work should focus on the specific user groups in more detail to better understand their needs. We are also planning to organise more hands-on workshops where we could 3D print the designs proposed by participants using different types of flexible filaments, which would enable them to test and refine their ideas further.

5 CONCLUSIONS

Thanks to advancements in fabrication and flexible materials, it may be possible to develop novel sports wearables for measuring form and performance. Two workshops conducted with a total of 11 participants, including sports enthusiasts, sport professionals and researchers, highlighted the need for personalised wearables that take into account different levels of personalisation to make sure they are suitable for specific sports, activities within these sports, and individuals who will wear them. They should also reflect the changing context, as users' expertise and engagement can change over time. We argue that flexible wearables are well suited to address this. We provided a set of design considerations and suggestions on how wearable devices made of flexible materials and designed to accommodate changing contexts could support physical training.

ACKNOWLEDGMENTS

We would like to thank the participants for their engagement and fruitful discussions. We would also like to thank the School of Computer Science and Informatics at Cardiff University for making this collaboration possible, and for University of Canterbury and The University of Waikato for hosting the workshops.

REFERENCES

[1] Marios C Angelides, Lissette Andrea Cabello Wilson, and Paola Liliana Burneo Echeverría. 2018. Wearable data analysis, visualisation and recommendations on the go using android middleware. *Multimedia Tools and Applications* 77, 20 (2018), 26397–26448.

[2] Apple Inc. 2024. *iPhone 16 Pro spec.* Retrieved September 12, 2024 from https://www.apple.com/uk/iphone-16-pro/specs/

[3] Gobinath Aroganam, Nadarajah Manivannan, and David Harrison. 2019. Review on wearable technology sensors used in consumer sport applications. *Sensors* 19, 9 (2019), 1983.

[4] Chirag Arora and Maryam Razavian. 2021. Ethics of gamification in health and fitness-tracking. *International Journal of Environmental Research and Public Health* 18, 21 (2021), 11052.

[5] Arsenal Media. 2021. *How STATSports can improve your performance.* Retrieved September 2, 2024 from https://www.arsenal.com/news/how-statsports-can-improve-your-performance

[6] Patrick Baudisch, Stefanie Mueller, et al. 2017. Personal fabrication. *Foundations and Trends® in Human–Computer Interaction* 10, 3–4 (2017), 165–293.

[7] Beta Solutions Blog. 2023. *How Legendary All Blacks Utilise Real-time Player Tracking Technology.* Retrieved September 2, 2024 from https://www.betasolutions.co.nz/how-legendary-all-blacks-utilise-real-time-player-tracking-technology

[8] Judy Bowen, Annika Hinze, Christopher Griffiths, Vimal Kumar, and David Bainbridge. 2017. Personal Data Collection in the Workplace: Ethical and Technical Challenges. In *HCI 2017 - Digital make-believe. Proceedings of the 31st International BCS Human Computer Interaction Conference, BCS HCI 2017, University of Sunderland, St Peter's campus, Sunderland, UK, 3-6 July 2017 (Workshops in Computing)*, Lynne E. Hall, Tom Flint, Suzy O'Hara, and Phil Turner (Eds.). BCS. https://doi.org/10.14236/EWIC/HCI2017.57

[9] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology* 3, 2 (2006), 77–101.

[10] Virginia Braun and Victoria Clarke. 2022. *Thematic Analysis. A Practical Guide.* SAGE, London.

[11] Maro Cheon, Batbayar Khuyagbaatar, Jeong-Hwan Yeom, and Yoon Hyuk Kim. 2020. Analysis of swing tempo, swing rhythm, and functional swing plane slope in golf with a wearable inertial measurement unit sensor. *Journal of Mechanical Science and Technology* 34 (2020), 3095–3101.

[12] Roberto De Fazio, Vincenzo Mariano Mastronardi, Massimo De Vittorio, and Paolo Visconti. 2023. Wearable sensors and smart devices to monitor rehabilitation parameters and sports performance: an overview. *Sensors* 23, 4 (2023), 1856.

[13] Alan Dix. 2007. Designing for appropriation. In *Proceedings of HCI 2007 The 21st British HCI Group Annual Conference University of Lancaster, UK.* BCS Learning & Development.

[14] Don Samitha Elvitigala, Armağan Karahanoğlu, Andrii Matviienko, Laia Turmo Vidal, Dees Postma, Michael D Jones, Maria F Montoya, Daniel Harrison, Lars Elbæk, Florian Daiber, et al. 2024. Grand Challenges in SportsHCI. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*. 1–20.

[15] Don Samitha Elvitigala, Denys J.C. Matthies, Löic David, Chamod Weerasinghe, and Suranga Nanayakkara. 2019. GymSoles: Improving Squats and Dead-Lifts by Visualizing the User's Center of Pressure. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300404

[16] Aluna Everitt, Alexander Keith Eady, and Audrey Girouard. 2021. Enabling multi-material 3D printing for designing and rapid prototyping of deformable and interactive wearables. In *Proceedings of the 20th International Conference on Mobile and Ubiquitous Multimedia.* 1–11.

[17] Fatigue Science. 2024. *Readiband.* Retrieved September 2, 2024 from https://fatiguescience.com/applications/elite-athlete-sleep-fatigue-management/

[18] FORM. 2024. *FORM Swim.* Retrieved September 2, 2024 from https://www.formswim.com/

[19] Francine Gemperle, Chris Kasabach, John Stivoric, Malcolm Bauer, and Richard Martin. 1998. Design for wearability. In *Digest of Papers. Second International Symposium on Wearable Computers (cat. No. 98EX215)*. IEEE, 116–122.

[20] Çağlar Genç, Merve Erkaya, Fuat Balcı, and Oğuzhan Özcan. 2018. Exploring Dynamic Expressions on Soft Wearables for Physical Exercises. In *Proceedings of the 2018 ACM Conference Companion Publication on Designing Interactive Systems* (Hong Kong, China) *(DIS '18 Companion)*. Association for Computing Machinery, New York, NY, USA, 147–152. https://doi.org/10.1145/3197391.3205427

[21] Arash Hajisafi, Maria Despoina Siampou, Jize Bi, Luciano Nocera, and Cyrus Shahabi. 2024. Wearables for Health (W4H) Toolkit for Acquisition, Storage, Analysis and Visualization of Data from Various Wearable Devices. *2024 IEEE 40th International Conference on Data Engineering (ICDE)* (2024), 5425–5428.

[22] Hayati Havlucu, Aykut Coşkun, and Oğuzhan Özcan. 2019. Specifying Relevant Textural Properties for Unobtrusive Feedback on Sports Performance. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Tempe, Arizona, USA) *(TEI '19)*. Association for Computing Machinery, New York, NY, USA, 165–171. https://doi.org/10.1145/3294109.3300974

[23] Hayati Havlucu, Aykut Coşkun, and Oğuzhan Özcan. 2019. Designing the next generation of activity trackers for performance sports: Insights from elite tennis coaches. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–7.

[24] André Henriksen, Martin Haugen Mikalsen, Ashenafi Zebene Woldaregay, Miroslav Muzny, Gunnar Hartvigsen, Laila Arnesdatter Hopstock, and Sameline Grimsgaard. 2018. Using fitness trackers and smartwatches to measure physical activity in research: analysis of consumer wrist-worn wearables. *Journal of Medical Internet Research* 20, 3 (2018), e110.

[25] Helmut Hoffmann. 2020. Rehabilitation of Sports Injuries. In *Injury and Health Risk Management in Sports: A Guide to Decision Making*. Springer, 81–90.

[26] Chen-Wei Hsieh and Sherry Y Chen. 2016. A cognitive style perspective to handheld devices: customization vs. personalization. *International Review of Research in Open and Distributed Learning* 17, 1 (2016), 1–22.

[27] IMeasureU. 2024. *IMeasureU*. Retrieved August 16, 2024 from https://imeasureu.com/

[28] Instructables. 2024. *Instructables*. Retrieved September 12, 2024 from https://www.instructables.com/

[29] Alexandra Ion, Johannes Frohnhofen, Ludwig Wall, Robert Kovacs, Mirela Alistar, Jack Lindsay, Pedro Lopes, Hsiang-Ting Chen, and Patrick Baudisch. 2016. Metamaterial mechanisms. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. 529–539.

[30] Pradthana Jarusriboonchai and Jonna Häkkilä. 2019. Customisable wearables: exploring the design space of wearable technology. In *Proceedings of the 18th International Conference on Mobile and Ubiquitous Multimedia*. 1–9.

[31] Michael Jones, Mia Caminita, Elizabeth Klemm, Dustin Bruening, and Sarah Ridge. 2024. Training, children, and parents: Coach perspectives on wearable sensor data in sub-elite figure skating in the United States. *International Journal of Human-Computer Studies* 183 (2024), 103184. https://doi.org/10.1016/j.ijhcs.2023.103184

[32] Hsin-Liu (Cindy) Kao, Paul Johns, Asta Roseway, and Mary Czerwinski. 2016. Tattio: Fabrication of Aesthetic and Functional Temporary Tattoos. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 3699–3702. https://doi.org/10.1145/2851581.2890269

[33] Katrina Karkazis and Jennifer R. Fishman. 2017. Tracking U.S. Professional Athletes: The Ethics of Biometric Technologies. *The American Journal of Bioethics* 17, 1 (2017), 45–60.

[34] Jayden Khakurel, Jari Porras, Helinä Melkas, and Bo Fu. 2020. A comprehensive framework of usability issues related to the wearable devices. *Convergence of ICT and Smart Devices for Emerging Applications* (2020), 21–66.

[35] Hyunyoung Kim, Celine Coutrix, and Anne Roudaut. 2018. Morphees+: Studying Everyday Reconfigurable Objects for the Design and Taxonomy of Reconfigurable UIs. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3173574.3174193

[36] Jemma L König, Jascha Penaredondo, Emily McCullagh, Judy Bowen, and Annika Hinze. 2024. Let's Make it Accessible: The Challenges Of Working With Low-cost Commercially Available Wearable Devices. In *Proceedings of the 35th Australian Computer-Human Interaction Conference* (Wellington, New Zealand) *(OzCHI '23)*. Association for Computing Machinery, New York, NY, USA, 493–503. https://doi.org/10.1145/3638380.3638415

[37] Judith Ley-Flores, Laia Turmo Vidal, Elena Márquez Segura, Aneesha Singh, Frederic Bevilacqua, Francisco Cuadrado, Joaquín Roberto Díaz Durán, Omar Valdiviezo-Hernández, Milagrosa Sánchez-Martin, and Ana Tajadura-Jiménez. 2024. Co-Designing Sensory Feedback for Wearables to Support Physical Activity through Body Sensations. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 8, 1, Article 40 (March 2024), 31 pages. https://doi.org/10.1145/3643499

[38] Ryan T Li, Scott R Kling, Michael J Salata, Sean A Cupp, Joseph Sheehan, and James E Voos. 2016. Wearable Performance Devices in Sports Medicine. *Sports Health* 8, 1 (2016), 74–78.

[39] Jun Liang, Deqiang Xian, Xingyu Liu, Jing Fu, Xingting Zhang, Buzhou Tang, Jianbo Lei, et al. 2018. Usability study of mainstream wearable fitness devices: feature analysis and system usability scale evaluation. *JMIR mHealth and uHealth* 6, 11 (2018), e11066.

[40] Sampada Marathe and S Shyam Sundar. 2011. What drives customization? Control or identity?. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 781–790.

[41] Eric Markvicka, Guanyun Wang, Yi-Chin Lee, Gierad Laput, Carmel Majidi, and Lining Yao. 2019. Electrodermis: Fully untethered, stretchable, and highly-customizable electronic bandages. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. 1–10.

[42] Rachel Mason, Liam T Pearson, Gillian Barry, Fraser Young, Oisin Lennon, Alan Godfrey, and Samuel Stuart. 2023. Wearables for running gait analysis: A systematic review. *Sports Medicine* 53, 1 (2023), 241–268.

[43] Eleonora Mencarini, Chiara Leonardi, Alessandro Cappelletti, Davide Giovanelli, Antonella De Angeli, and Massimo Zancanaro. 2019. Co-designing wearable devices for sports: The case study of sport climbing. *International Journal of Human-Computer Studies* 124 (2019), 26–43.

[44] Eleonora Mencarini, Amon Rapp, Lia Tirabeni, and Massimo Zancanaro. 2019. Designing Wearable Systems for Sports: A Review of Trends and Opportunities in Human–Computer Interaction. *IEEE Transactions on Human-Machine Systems* 49, 4 (2019), 314–325. https://doi.org/10.1109/THMS.2019.2919702

[45] Frank Mokaya, Roland Lucas, Hae Young Noh, and Pei Zhang. 2015. Myovibe: Vibration based wearable muscle activation detection in high mobility exercises. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing*. 27–38.

[46] Catarina Mota. 2011. The rise of personal fabrication. In *Proceedings of the 8th ACM Conference on Creativity and Cognition*. 279–288.

[47] Kim Oakes, Katie A. Siek, and Haley MacLeod. 2015. MuscleMemory: Identifying the Scope of Wearable Technology in High Intensity Exercise Communities. In *Proceedings of the 9th International Conference on Pervasive Computing Technologies for Healthcare* (Istanbul, Turkey) *(PervasiveHealth '15)*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), Brussels, BEL, 193–200.

[48] VALD Performance. 2024. *Vald Performance.* Retrieved August 16, 2024 from https://valdperformance.com/sports

[49] Isabel PS Qamar, Katarzyna Stawarz, Simon Robinson, Alix Goguey, Céline Coutrix, and Anne Roudaut. 2020. Morphino: a nature-inspired tool for the design of shape-changing interfaces. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*. 1943–1958.

[50] Amon Rapp and Lia Tirabeni. 2018. Personal Informatics for Sport: Meaning, Body, and Social Relations in Amateur and Elite Athletes. *ACM Trans. Comput.-Hum. Interact.* 25, 3, Article 16 (jun 2018), 30 pages. https://doi.org/10.1145/3196829

[51] Michael L Rivera, Melissa Moukperian, Daniel Ashbrook, Jennifer Mankoff, and Scott E Hudson. 2017. Stretching the bounds of 3D printing with embedded textiles. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 497–508.

[52] Christian Schumacher, Steve Marschner, Markus Gross, and Bernhard Thomaszewski. 2018. Mechanical characterization of structured sheet materials. *ACM Transactions on Graphics (TOG)* 37, 4 (2018), 1–15.

[53] D. R. Seshadri, R. T. Li, J. E. Voos, J. R. Rowbottom, C. M. Alfes, C. A. Zorman, and C. K. Drummond. 2019. Wearable sensors for monitoring the internal and external workload of the athlete. *NPJ Digital Medicine* 2, 71 (2019).

[54] Hamza Shahzad, Hira Jabeen, Hafiz Rana Muhammad Arslan, Muhammad Hashim Ghouri, Subhan Ali, Muhammad Umar Gondal, Muhammad Arif, and Saima Bibi. 2021. Musculoskeletal injuries among weight lifters with or without supervision? a comparative cross sectional study. *Age* 15 (2021), 35.

[55] Skilled Golf. 2022. *11 Best Golf Swing Analyzers in 2024 + Buying Guide.* Retrieved September 2, 2024 from https://skilledgolf.com/gear/training-aids/best-golf-swing-analyzers/

[56] B Socolow and Ieuan Jolly. 2017. Game-changing wearable devices that collect athlete data raise data ownership issues. *World Sports Advocate* 15, 7 (2017), 15–17.

[57] Katta Spiel. 2021. The Bodies of TEI – Investigating Norms and Assumptions in the Design of Embodied Interaction. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction* (Salzburg, Austria) *(TEI '21)*. Association for Computing Machinery, New York, NY, USA, Article 32, 19 pages. https://doi.org/10.1145/3430524.3440651

[58] Katta Spiel, Fares Kayali, Louise Horvath, Michael Penkler, Sabine Harrer, Miguel Sicart, and Jessica Hammer. 2018. Fitter, Happier, More Productive? The Normative Ontology of Fitness Trackers. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI EA '18)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3170427.3188401

[59] Samuel D Stephenson, Joseph W Kocan, Amrit V Vinod, Melissa A Kluczynski, and Leslie J Bisson. 2021. A comprehensive summary of systematic reviews on sports injury prevention strategies. *Orthopaedic Journal of Sports Medicine* 9, 10 (2021), 23259671211035776.

[60] Anthony Studnicka. 2020. The emergence of wearable technology and the legal implications for athletes, teams, leagues and other sports organizations across amateur and professional athletics. *DePaul J. Sports L.* 16 (2020), i.

[61] Thingiverse. 2024. *Thingiverse.* Retrieved September 12, 2024 from https://www.thingiverse.com/

[62] Laia Turmo Vidal, Elena Márquez Segura, and Annika Waern. 2018. Movement Correction in Instructed Fitness Training: Design Recommendations and Opportunities. In *Proceedings of the 2018 Designing Interactive Systems Conference* (Hong Kong, China) *(DIS '18)*. Association for Computing Machinery, New York, NY, USA, 1041–1054. https://doi.org/10.1145/3196709.3196789

[63] Laia Turmo Vidal, Hui Zhu, Annika Waern, and Elena Márquez Segura. 2021. The Design Space of Wearables for Sports and Fitness Practices. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 267, 14 pages. https://doi.org/10.1145/3411764.3445700

[64] Julio Vega, Meng Li, Kwesi Aguillera, Nikunj Goel, Echhit Joshi, Kirtiraj Khandekar, Krina C. Durica, Abhineeth R. Kunta, and Carissa A. Low. 2021. Reproducible Analysis Pipeline for Data Streams: Open-Source Software to Process Data Collected With Mobile Devices. *Frontiers in Digital Health* Volume 3 (2021).

[65] AWS Watson. 1997. Sports injuries: incidence, causes, prevention. *Physical Therapy Reviews* 2, 3 (1997), 135–151.

[66] Michael Wessely, Theophanis Tsandilas, and Wendy E. Mackay. 2016. Stretchis: Fabricating Highly Stretchable User Interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology* (Tokyo, Japan) *(UIST '16)*. Association for Computing Machinery, New York, NY, USA, 697–704. https://doi.org/10.1145/2984511.2984521

[67] Kaufui V Wong and Aldo Hernandez. 2012. A review of additive manufacturing. *International scholarly research notices* 2012, 1 (2012), 208760.

[68] Luyao Yang, Osama Amin, and Basem Shihada. 2024. Intelligent Wearable Systems: Opportunities and Challenges in Health and Sports. *ACM Comput. Surv.* 56, 7, Article 190 (apr 2024), 42 pages. https://doi.org/10.1145/3648469

[69] MR Yeadon and MTG Pain. 2023. Fifty years of performance-related sports biomechanics research. *Journal of Biomechanics* 155 (2023), 111666.

[70] Clint Zeagler. 2017. Where to Wear It: Functional, Technical, and Social Considerations in on-Body Location for Wearable Technology 20 Years of Designing for Wearability. In *Proceedings of the 2017 ACM International Symposium on Wearable Computers* (Maui, Hawaii) *(ISWC '17)*. Association for Computing Machinery, New York, NY, USA, 150–157. https://doi.org/10.1145/3123021.3123042

[71] Mengjia Zhu, Shantonu Biswas, Stejara Iulia Dinulescu, Nikolas Kastor, Elliot Wright Hawkes, and Yon Visell. 2022. Soft, wearable robotics and haptics: Technologies, trends, and emerging applications. *Proc. IEEE* 110, 2 (2022), 246–272.