Evaluating a Wearable Display Jersey for Augmenting Team Sports Awareness

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Abstract. This paper introduces a user-centered design process and case study evaluation of a novel wearable visualization system for team sports, coined *TeamAwear*. TeamAwear consists of three basketball jerseys that are equipped with electroluminescent wires and surfaces. Each jersey can be wirelessly controlled to represent game-related information on the player in real-time, such as the amount of individual fouls, scores and time alerts. A participatory user-centered approach guided the development process towards a more meaningful, ethically and ergonomically valid design. The system aims to enhance the awareness and understanding of game-related public information for all stakeholders, including players, referees, coaches and audience members. We initially hypothesized that such increased awareness would positively influence in-game decisions by players, resulting in a more interesting and enjoyable game play experience for all participants. Instead, the case study evaluation demonstrated TeamAwear's perceived usefulness particularly for non-playing stakeholders, such as the audience, referees and coaches, supporting more accurate coaching assessments, better understanding of in-game situations and increased enjoyment for spectators. The high amount of game-related cognitive load on the players during game-play seems to hinder its influence on in-game decisions.

Keywords: wearable computing, visualization, design, evaluation.

1 Introduction

Wearable visualization focuses on the design of small computers than can be continuously worn on the human body and enable the representation of abstract data, either to the wearer themselves, or to other people in the wearer's vicinity. It differs from more common visual applications on mobile devices in that *wearables* are specifically designed to be unobtrusively integrated within the user's clothing. By merging visualization with fashion, clothing is considered as a sort of public display that is meant to 'signal' an interpretable meaning [1]. By representing specific information, and thus making people 'aware' of aspects that were normally hidden from view, a wearable display can potentially alter the experience of persons present in its immediate vicinity, including that of its wearer. Accordingly, could a wearable display, worn in a sports context, alter the subjective experience of its typical stakeholders, such as the athletes, coaches, referees, and spectators involved? Would athletes change their game-play when they have access to more relevant game-related information in real-time?

TeamAwear (so named for Team Sports Awareness Wearable Display) is a wearable display in the form of an electronically augmented sports jersey. It is capable of representing game-related information sources in real-time via a small micro-electronic board that controls a series of light-emitting display panels. Its intended application setting is within a team sports environment, where it is simultaneously worn by multiple athletes during the game itself. By perceiving the worn displays, it is expected that the different sports stakeholders become more consciously 'aware' of otherwise hidden or fast-changing crucial game-play related information in the periphery of their attention, hereby positively influencing their sports experience. This approach addresses the relative lack of information that sports stakeholders (especially athletes) receive during fast-paced live games, as opposed to remote television spectators.

We hypothesized that an increased awareness of game-related information would allow athletes to make improved in-game decisions, leading to more interesting game-play. Athletes could exploit opportunities to benefit the individually displayed information in a natural way. For instance, poorer players might be inclined to always pass to top scorers, hereby shifting the collaborative team efforts. Opposing players may deliberately target only those with a high degree of fouls. This is a familiar problem in computer supported collaborative work, as highlighted by the 'work versus benefit' paradigm [2]. Although we found that players did not operate in this way, a different evaluation approach involving a greater number of wearable display jerseys, might still uncover aspects of this kind of intentional exploitation.

In addition, we anticipated that the system could support more accurate coaching assessments, lead to a better understanding of game situations and an increased enjoyment of the game for spectators. We have chosen basketball as our initial application domain for its relatively rapid pace, high amount of relevant information, and high reliance on team-based strategies. Although TeamAwear's technical implementation is not as complex as most other (sensor-embedded and thus input-oriented) wearable computing systems, its main contributions instead focus on a participatory development process within a sports context, and its usage of wearable computing as a intuitive output medium of useful and real-time information.

The development, implementation and use of technology in the sports domain inherently encounters several ethical considerations, which depend on their purpose and potential influence on the sport experience itself [3]. For instance, access to technology should be equal, to ensure no team has a perceived advantage. Technological aids that potentially enhance sports performance historically have received a very slow acceptance, or none at all. Accordingly, although the Australian Basketball Association has permitted this research, no real future commitment for allowing awareness-enhancing jerseys has been made. Even so, the TeamAwear system research is significant in its potential use as a training device for both team and individual sports, as an aid for physically disabled or auditory impaired athletic game-play or as awareness-enhancing clothing outside of the sports domain, such as during team-oriented high-demanding collaborative tasks or emergency situations.

2 Related Work

A *wearable display* extends the fields of *visualization* and *wearable computing,* both of which play significant roles in the sports area. Graphical visualization has already been used in a sports context, in general to enhance the spectator experience. For instance, the *TennisViewer* system allows spectators to explore and understand the vast amounts of data occurring during a competitive tennis match [4]. Visualizations can also facilitate more accurate judgments by referees. The *Piero* graphics analysis tool allows athletes and their actions to be virtually tracked and analyzed by referee officials during a rugby match [5]. Only few visualization examples exist that aim to inform the athletes themselves. The *Cyclops Auto Serve Line Detector* uses sound cues to convey judgmental information to athletes during a tennis match [6]. Similarly, *TeamAwear* conveys relevant game information to support the activities and understanding of common team sports stakeholders.

The merging of wearable visualization and fashion design is a recent trend in which clothing becomes electronically enhanced to reveal information about wearers, or their surrounding environment. Several projects have investigated different technical means to convey sensor data publicly through electronic fashion. These approaches tend to experiment beyond the use of simple LCD or pixel-based displays, and have utilized LED lights [7], [8], so-called 'e-textiles' [9], electroluminescent wire (e.g. [10]), thermo-chromatic inks, shape-changing materials such as shape memory alloys (e.g. [11]), inflatables (e.g. [12]), and so on. In contrast, the TeamAwear system aims to communicate information in an efficient and immediately understandable way.

Wearable visualization in a sports context can be used to convey information to athletes and other stakeholders in a variety of ways. For instance, wearable devices can be used to provide critical information about athletes to referees. The *SensorHogu* force-sensing vest for martial arts improves the accurate detection of contact between athletes, allowing for more fairly judgments [13]. A number of wearable-sensor based devices aim to provide information to improve coaching, such as pressure sensors for high impact sports [14], and accelerometers for movement-oriented sports such as skiing [15]. Similarly, wearable GPS modules, named *FitSense*, are fitted to professional athletes during football competitions to track and visualize their movements during game-play [16]. It is well documented, that when feedback is provided in an appropriate manner, sport athlete performance tends to increase [17]. A tactile display embedded within a vest, named *TACT*, improves the athlete's performance in sports such as ice skating, by communicating relevant real-time information to athletes via minor vibrations targeting their upper body [18]. The *Houston* wearable mobile display shares a person's physical activity data to encourage them to physically exercise outside of the competitive sports context [19]. Athletic wearable devices for the everyday individual have become fashionable and socially acceptable, and form the focus of new commercial ventures, such as the *Running Computer* from *Polar* and *Adidas* [20], and the *Nike + iPod Sport Kit*, consisting of an embedded foot sensor developed by *Nike* and *Apple* [21]. In contrast to most approaches, TeamAwear communicates relevant sports information in a team focused way, and considers all surrounding stakeholders, as opposed to just a coach or referee. The *PingPongPlus* 'athletic-tangible interface' digitally augments the inbuilt dynamics of a Ping Pong game by providing feedback in the form of a visual and auditory visualization, which encourages athletes to keep playing while still maintaining the competitive nature of the sports game [22]. Similarly, the TeamAwear jerseys respond to the intrinsic performances of the players and teams, which can ultimately persuade and increase in these performances.

In general, technology in sports must adhere to a few basic guidelines, in particular safety and fairness. Any technology which attempts to generate risk to stakeholders, or provide an unfair advantage to any one team or athlete will not be accepted by the sports community [23]. This aspect has been addressed during development of TeamAwear, which included extensive investigation into user needs and requirements specifically for the team sports context.

3 User-Centered Design

Because of the relative novelty of wearable computing, and wearable visualization for sports in particular, a user-centered design approach was chosen. By incorporating insights and comments from relevant stakeholders, it was expected that the system's usefulness would increase, as the design process would inevitably encounter critical ethical, ergonomic and usability issues that required insight from experienced users. The design process consisted of three consecutive stages: Evaluative Ethnography, User-centered Discussion and User-centered Participatory Design.

3.1 Evaluative Ethnography

Evaluative ethnography is a fieldwork-based approach that aims to detect relevant information in order to establish the 'work-ability' of a proposed design system [24]. The observations can be facilitated with the aid of specific documentation tools, such as written field notes and proxemic diagrams. An evaluative ethnography study was carried out over a period of approximately eight weeks to examine the intended users during their normal 'sporting state', observed during scheduled training sessions and competitive basketball games. As a result, several primary system design tasks were discerned, such as regarding the environmental parameters (e.g. the typical amount of light, noise and distances on a sports court), the cognitive load on human senses, the understanding of each stakeholder's role during game-play and their typical actions. Accordingly, these insights allowed us to make several preliminary design decisions regarding the choice of technical parts, including the wireless communication, power supply and display media materials. This research also revealed the relatively high demands and constraints on the potential design of the wearable device, in the context of its physical design (i.e. relatively high amount of physical contact between players, so that even falling is not uncommon), its efficiency of information display (i.e. rapidly changing game development), perceptual abilities (i.e. players dedicate full cognitive attention to game-play), game-related restrictions (i.e. devices are not allowed to protrude or advantage any team or team member) and environmental parameters (i.e. bright and loud physical setting).

3.2 Participative Design Study

A set of user discussion sessions were organized for which representatives for each of the typical basketball stakeholders (i.e. athlete, coach, referee and spectator) were invited. The goal of these sessions was to identify potential usage scenarios as well as critical design requirements. The initial recruitment occurred via distributed flyers and handouts. We specifically appealed for female basketball players, due to an assumed reduced amount of physical aggression during game-play, and less risk of potentially harming the device or its wearer. The recruitment resulted in a limited but sufficient response due to the relative scarcity of female basketball players, the technological character of the device, and the fact that the subjects did not receive any reward for their significant time investment. The numbers of volunteer users was based on the relative importance of their roles to the intended application: each of the sessions involved at least 6 semi-professional athletes, 1 coach and 1 referee, and 3 spectators.

The initial design discussions were intentionally left open-ended, 'allowing' the concept of a sports-related wearable display to be discovered and developed by the focus group itself. During the sessions, it became clear that there was a genuine interest for real-time information access during game-play. However, no participant wanted to display personal physiological or environmental data (e.g. stress level, heartbeat, amount run) to the outside world, for potentially risking unfair tactics by opposing teams. Instead, it was agreed to display 'publicly available data', related to the actual game itself. Several game-related information sources, normally hidden from view, were identified that were considered as useful during a typical competitive basketball game, listed in Table 1.

Table 1. Game-related information sources selected to be displayed by the jersey

Information	Stakeholder	Rationale
Time Limits	*athlete* *coach* *referee*	Athlete: a reminder to hasten teams actions to take a shot (shot clock), or before end of game Coach: strategic decisions depending on game clock Referee: identify time clock related errors more effectively
Individual Fouls	*athlete* *coach* *spectator*	Defensive Athlete: in-game decisions and playing style, i.e. provoke offensive faults. Offensive Athlete: in-game decisions and playing style, i.e. attempts to provoke defensive faults. Coach: reminder of team members with fouls (for both teams), i.e. determining exchange of players, game strategies to protect players with high amount of fouls, or influence competing strategy. Spectator: increased awareness of influencing factors, 'catch up' when part of the game has been missed
Individual Score	*athlete* *coach* *spectator*	Defensive Athlete: in-game decisions and playing style, i.e. more attention and status to top scorers. Offensive Athlete: affects in-game decisions and playing style, i.e. more passes to actual top scorer. Coach: choice of strategies and exchange of players. Spectator: focus on top versus poorly performing players
Winning versus Losing Team	*spectator* *athlete*	Athlete: increased awareness, especially in a tight competition. Spectator: increased engagement in game

Fig. 1. Group design proposal sketching (left); determining appropriate positioning of wearable computing box (middle); hands-on physical design to determine display locations (right)

Participants were divided into small groups containing a variety of each stakeholder type. Following a typical constructivist studio-based approach, each group creatively designed a set of proposals, which were presented, critiqued and refined by the whole group. These design sessions revealed a general consensus on the relative importance of specific information sources, a wish for continuous unobstructed visibility of the display, and a desire to make the jerseys fashionable and aesthetically appealing. These user participation sessions also determined the ergonomic position of the wearable computing box (see Figure 1), which was chosen to be attached below the lower chest or waist. Female participants preferred the waist location, whereas males preferred the lower chest. The participants also decided on the physical design of the system (also see Figure 1), including the material, color and positioning of the displays themselves.

3.3 Prototype Development

After the participative design sessions, three fully working jersey prototypes were implemented. These allowed for the evaluation of different solutions for attaching the displays, and tested the wearability of the jersey during extensive use. The following game-related information sources were selected to be displayed (see Figure 2).

- **Time Limits.** Consisting of the ‘game clock’ on the upper left chest (shown when only 1 minute of game-play remains for a particular round), and the ‘shot clock’ on the upper right chest (shown when only 10 seconds remain for an athlete to make a goal attempt). This information was considered important by the participants as it acts as an urgent warning signal to take action, which is often neglected or inefficiently communicated verbally. For this reason, the displays were placed on the upper chest for maximum visibility towards own team members**.** The displays have contrasting colors (i.e. violet and yellow) so they are easily distinguishable.
- **Fouls.** The foul displays operate symmetrically on the shoulders from the inside out, according to the accumulation of fouls by the respective player. As the maximum amount of fouls is five, only four wires are shown. The foul displays were placed on the shoulder area, so the wearer themselves could more easily refer to and even peripherally detect their own number of fouls.
- **Individual Points.** Embedded symmetrically on each side of the jersey, are three panels representing the player’s individually scored points. These displays are

illuminated sequentially upwards as more points are scored over the entire period of game-play, in gradations of 10 points. In this way, all participants can perceive who the game's top scorers are. These displays were placed along the sides to maximize visibility, especially during passing/shooting scenarios at which an athlete's arms are often raised.

- **Winning/Losing.** A simple on/off display is embedded in the back of the jersey to indicate which team is winning ('on' for winning, 'off' for losing). This display is visible at quite far distances from the court, such as for spectators who might have missed parts of the match. The athletes themselves thought that it would be useful to be reminded of who was winning when moving between goal areas, a time when often only the athletes' backs are visible.

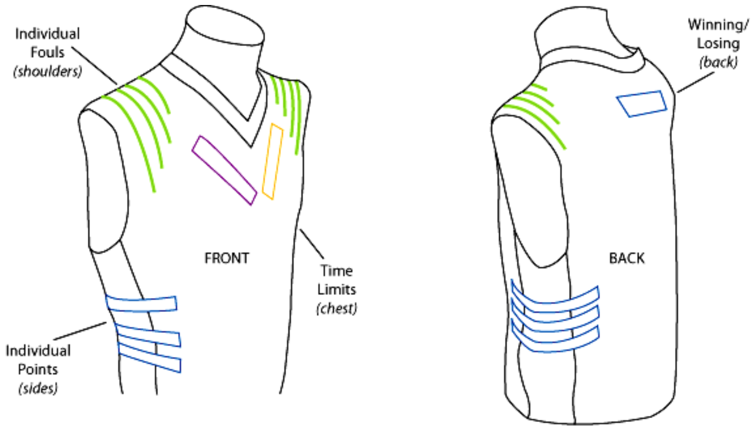

Fig. 2. Diagram showing the exact display locations and their specified meanings

One should note that the display layout of the jerseys shown in Figure 2 is a product of a creative design process, and depends on its intended application. It has been tailored specifically for use in basketball play, where display elements are positioned in visible areas not restricting the traditional basketball jersey format. While its intentions would remain the same, the display layout (and information content) of such a jersey within other team-based sports would unquestionably differ.

3.4 Technical Development

The technical development was mostly determined by safety and usability considerations. Safety is of the utmost importance for any sports-related activity, and the most important reason why technology is not readily accepted in a sports context. Typical safety risks include physical contact with electricity-conducting elements, accidentally hitting or being caught in protruding parts, or falling on top of the wearable device. Inevitable technical failure was considered by deliberately including 'weak spots' that allow quick and safe detachment instead of uncontrollable breakage.

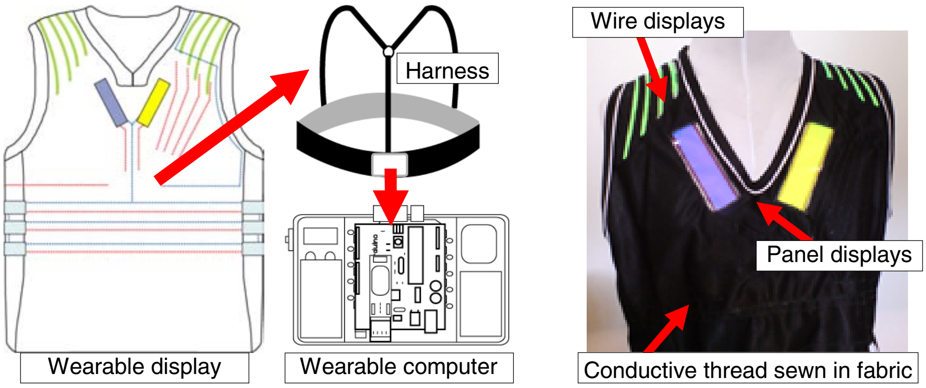

Fig. 3. Diagram of system parts including wearable display jersey (dotted blue and red lines represent conductive thread circuit), harness, and wearable computer (left); Final prototype TeamAwear jersey (right)

In addition, the jerseys were designed so that they do not disturb the normal physical activity of the players. Adverse influences range from simple long-term tiredness due to the extra weight, to subtle alterations in physical movements potentially affecting the player's overall sports performance. Lastly, due to the heavy perspiration during sports, all parts were protected against moisture and allowed for easy washing.

The TeamAwear system consists of three separate parts which conveniently link together during use, as illustrated in Figure 3:

- **Wearable Display Jersey.** Each jersey is equipped with nine detachable light illuminating display panels (5 x 1 inch) and eight wires (1/8 inch diameter). Both displays are made from *electroluminescent* (EL) material, containing a phosphor-based substance that emits light in response to a high-frequency AC electrical signal. The panels and wires are flexible, allowing for an unobtrusive connection to textile fabric. All displays are sealed within transparent vinyl pockets sewn beneath the jersey surface, so they can be easily removed if the jersey needs to be washed. Each jersey contains an additional fabric mesh layer sewn inside, adding an extra protective layer between the electronic components and the wearer's body.
- **Conductive Thread.** An electrical circuit is sewn into the jersey fabric with *conductive thread*, a type of silver-coated synthetic fiber able to pass current with little resistance (<0.2 Ohms). The thread is used to sew a precise pattern that creates a complete circuit onto the jersey itself, as it acts as a power conduit to each display. The jersey circuit includes both positive and negative (ground) threads. Each conductive thread is sealed using washable fabric gel to avoid direct contact and short-circuiting. Conductive press studs allow the jersey to be easily (dis-) connected with the EL displays so the jersey can be washed (Figure 4, right).
- **Wearable Computer.** A micro-electronic board controls each of the displays based on the instructions it receives via a wireless connection with a central computer. The wireless communication is accomplished via a Class 1 Bluetooth serial module, which was selected for its fast communication speed and far

physical range, good reliability, and easy hardware availability. However, this choice especially suffered in terms of power supply demands, as Bluetooth was originally developed for high-bandwidth communication streams. The system is capable of transmitting data from a central location to up to 10 different jerseys simultaneously, which can receive this data up to a distance of over 94 feet, the standard length of a basketball court (see Figure 5). The electronic board is based on *Arduino* [25], a community-driven physical computing platform that aims to reduce the technical complexity for the enthusiastic interaction designer. The setup is powered by a single standard 9 Volt battery. The computing components are embedded in a non-breakable plastic box measuring about 4.7x3x1 inch, shown in Figure 4 (left). The box features a safety switch to disconnect the electrical power in case of emergency. The resulting setup weighs approximately 8.8oz, similar to an average mobile phone.

- **Harness.** Each system includes a unisex harness to which the wearable computer is attached, worn underneath the jersey (Figure 4, left). It assures that the device is fixated even during brisk movements, and can cause minimal physical harm to the wearer's body after unintentional contact. It has a Y-shape front for female athletes and can be worn in the reverse for male athletes. It is made from an elastic ribbon, and can be adjusted for any body size or preferred wearing position.

Fig. 4. The wearable computer box attached to athlete's body by harness under the jersey (left); wearable display jersey during use (middle); attachment of displays beneath jersey surface using conductive thread and conductive quick-snap studs for easy detachment (right)

The application software is based on Processing [26], a community-driven Java-based platform that can easily communicate to Arduino boards. The application sends real-time instructions from a laptop computer to each of the jerseys via a standard Class 1 'cable-replacement' Bluetooth USB adapter (range: 300 feet). The interface can be used by a game official at the bench, and is shown in Figure 5 (right).

4 Evaluation

The case study evaluation took place in a normal basketball hall on our university campus, within the context of a socially competitive match. Plays were limited to a half court, to ensure all stakeholders were in close viewable distance from one another. All participants were informed beforehand as to the meaning of each display on the jersey. The evaluation consisted of two stages: an *awareness* investigation involving pairs of game-like scenarios, with and without wearing the TeamAwear system; and a *game-pla*y simulation during which the TeamAwear system was worn by athletes during a socially competitive basketball game, followed by questionnaires and interviews.

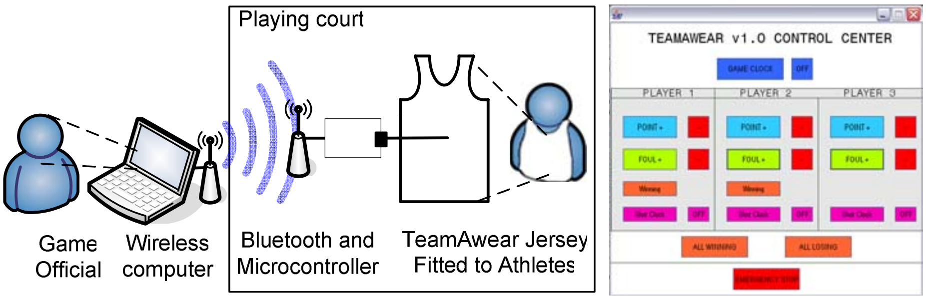

Fig. 5. When data is registered during game-play, instructions are sent in real-time to all connected TeamAwear jerseys via Bluetooth (left); Control interface running on a laptop computer during game-play maintains wireless connections with all TeamAwear jerseys (right)

4.1 Participants

The case study evaluation focused on all team sports stakeholders, including athletes, coaches, referees and spectators. The evaluation participants were recruited using flyers and handouts, which were distributed in sports halls and handed out after basketball games. Eleven participants took part, including: five athletes (female: four; age range 19-25), one referee (age 42), one coach (age 23), and four spectators (age range 16 to 55). All athletes had amateur to semi-professional basketball experience, and spectators indicated beginner to amateur basketball knowledge. One should note that as the subjects were aware of the system's purpose beforehand from the content on recruitment flyers and received no incentive for their participation, their attitude might be positively biased towards the use of technology in sports. The athlete category in particular initially seemed very enthusiastic, some stating they considered it to be completely acceptable *"for people of their generation to … be fitted with small computers*". Before the evaluation, players were allowed to wear the jerseys for 5 minutes during training to become accustomed and learn its visual use.

4.2 Awareness Evaluation

This evaluation was designed to test the ability of the jerseys to increase the stakeholders' awareness of game-related information sources. Players followed four different game-play scenarios, first without, and then while wearing the TeamAwear jerseys. Each scenario simulated a change in one of the game-related information sources represented by the displays. For instance, a scenario could consist of assigning fouls to a random number of athletes, or observing their individual scores. At the conclusion of each scenario, a survey queried each stakeholder about their in-game awareness in regard to the information source changed. In the cases which used the TeamAwear system, all displays would be completely switched off immediately after the play so users could not see them at the time of answering.

The results of the surveys showed a slight increase in awareness for the players, of which approximately average 4 out of 5 could correctly recall game-play data with jerseys, average 3 out of 5 without. For the non-playing stakeholders viewing the game from the court side, the difference was more significant (average 4 out of 4 versus 2 out of 4). This result seems to suggest a difference in use between the in-game experience and non-player experience of the display. Due to the fast-paced nature of a typical basketball game-play, with its need to focus on the ball, competitors and teammates, a player can only rely on quick glances. Therefore, the error rate was slightly more pronounced (1 out of 5 versus 2 out of 5) with the wire displays on the shoulders, due to a lower visual perceptibility. No errors were recorded in regard to the winning versus losing team scenario (all participants responded correctly), as players have an already intrinsic strong interest in this information. Non-playing stakeholders tended to have less cognitive effort to observe the jerseys, becoming more aware of the information communicated on the displays.

4.3 Game-Play Evaluation

A 15 minute social competitive basketball game was carried out and recorded on video, with two players in each team and one team continuously wearing the jerseys. Small teams naturally limit any 'strategic' influences, but are considered sufficient for the goals of this prototype case study, which focused on detecting the fundamental usefulness and usability of this highly technological intervention. The game was followed by a referee, a coach and an audience. An *experience questionnaire* was issued directly after the game, querying issues of wearability, visibility, and user experience via both binary and open-end questions.

- **Wearability.** The issue of wearability was only applied to the athletes, who felt that the jersey and wearable computer were comfortable to wear and did not restrict their normal physical movements during game-play ("*I actually forgot I was wearing it*"). The flexible and user-adaptable harness assured that the ergonomic influence of the system was minimized. A small number of players (2 out of 5) were bothered by the heat emission from the wearable computer box, and noted that the jersey made them feel slightly hotter than usual. However, some condensation did build up underneath the plastic surfaces protecting the displays, which not only limits the natural dissipation of sweat, but ultimately might become a security risk in terms of short-circuiting the electrical parts on a long-term basis.
- **Visual Display.** All participants reported that they could clearly perceive the displays during use, and were able to understand and remember what each display represented. Several responses referred to display arrangement as "*intuitive*" and "*easy to understand*". All participants agreed that the displays were not overwhelming or distracting, even when multiple displays were activated. All players agreed that the panel displays were significantly easier to perceive than the glowing wires, which were sometimes confusing as the difference between multiple active wires was not easily discernable. The athletes revealed that they

were not able to perceive their own displays, but instead often relied on other jerseys for general game-related information. Players sometimes deliberately stretched the shoulder part of the jersey in front of their face to double-check its actual state, an undesirable action that is possibly related to self-assurance and not trusting the technology: "*I wanted to be sure my fouls were represented correctly*".

- **Game Experience.** In terms of the overall game experience, it was found that the athletes might benefit the least from the TeamAwear system. Spectators claimed the game was "*more interesting to watch*" and "*easier to follow*" as a result of the wearable displays. In particular, the spectators with only a rudimentary knowledge of basketball indicated they were able to "*understand the play better*" and that this "*made the experience richer*". All participants unanimously agreed that there exists a definite use for this technology in the future.

Because of the fast-paced nature of team sports, it is often difficult for players to remember their mental considerations for specific game-play related actions. Therefore, the participants were shown a video recording of their game-play on a television screen, and then *retrospectively interviewed* as a group. This approach aimed to allow the participants, specifically the athletes, to perceive their actions from a third-person viewpoint and 'recall' eventual in-game reasoning, and possible influences caused by the TeamAwear system, similar to a *post think-aloud* session.

- **Influencing Decisions.** The feedback provided by athletes during the video playback reflected only subtle changes in some aspects of their playing style. Most players described that during the majority of the game, the jerseys did not influence their in-game decisions. One athlete mentioned that when she saw her team mate had a high points score, "*it made me want to pass to her more, as she had a 'hot hand*". The players indicated that they mainly glanced to the jerseys during time periods when the pace of game-play naturally slowed or stopped, such as after a goal was scored or a foul was called, "*whenever the ball was reset, I would take the time to look at the displays before starting the play again*". The athletes reported that the time display had the most influence: "*I played harder [more aggressively] when I saw the game had little time left*", and "*I noticed the game-clock, and I yelled this to my team mates*". Some players indicated that even when they perceived some useful information, such as the foul amount of their competitors, such knowledge inherently would not change their game-play anyway. These results suggest that the intensity of the game itself supersedes any consideration of perceiving and interpreting the display: the players were not able to pay enough attention to the displays as they were too preoccupied with the game situation itself, and even when they perceived the displays during calmer moments, they did not consider (or forgot) this knowledge when making in-game decisions.
- **Confidence.** An awareness of one's own and the team's performance during game-play seemed to boost a personal feeling of self-belief. When one player noticed her particularly high score indicated by the displays on the side, "*being reminded of my high score gave … a general feeling of confidence*". Also, athletes felt more confident in their own actions during game-play, as one athlete stated that "*I felt more comfortable passing to a team member I could see had scored more points than myself*". This feeling relieved some pressure placed on

athletes during game-play, with one athlete exclaiming that when she could see her team was winning "*it made me feel more relaxed*". Although the jerseys were originally intended to enhance the athlete experience indirectly through improved decisions and actions, it seemed they especially boosted self-assurance and morale, as scores are represented on an individual level, not on an anonymous scoreboard.

- **Non-Player Comments.** Although initially not intended, spectators seemed to benefit the most. The interview responses indicated they were able to follow the game more closely and accurately. One spectator who was inexperienced with the rules and plays of basketball said "*I didn't have to think a great deal to know what was going on*". Another novice spectator indicated that the jerseys "*did enhance the experience for me*" as she could see and understand when a player received a foul. This opinion was also reflected by other novice spectators, one saying the jerseys "*gave me the basic information I otherwise wouldn't have known*". Overall this contributed to a more enjoyable experience for spectators who were able to better understand game-play, even finding it *"more interesting than normal"*. The coach indicated she had a better overview over the game flow, as *"you can keep track of your players and more easily make decisions of which players to keep on and which to take off"*, "*you can tell your players which opponents to 'double-up on' based on observing their fouls or points*". This knowledge can normally only be accessed by a dedicated person scouting the players, or by verbally requesting information from the official bench. The referee indicated "*it could really speed up the game from the referee's perspective, having to consult the bench less*", as much of the useful information is literally represented 'on' the player themselves.

Fig. 6. User evaluation study during a social competitive match. From Left to Right: high scoring athlete (blue horizontal strips) clearly identifiable by all stakeholders, a high foul athlete (green shoulder wire displays), a high and low scoring athlete in close proximity, and the wireless laptop computer steering the wearable display jerseys (foreground).

4.4 Key Design Requirements for Wearable Visualization Devices in Sports

Based on the experiences and outcomes encountered during the development of the TeamAwear system, a number of design requirements became apparent.

Ethical Considerations
This study revealed several ethical considerations for a wearable visualization application in the sports domain. Firstly, there is the aspect of potential injury of the wearer: any additional object worn by a player might directly or indirectly inflict personal harm, or cause a deficiency in sporting performance. Naturally, one needs to consider whether the advantage of being more aware of information weights up against wearing a less comfortable jersey or an extra weight on the chest. For instance, the Human Ethics Committee had difficulty to assess this project's true risk due to its perceived technological novelty and its high-risk 'competitive' sports application domain. Secondly, one needs to consider the potential change in competitiveness when only a portion of the players allow their information to be exposed to the competing team. From a moral perspective, either all or no players should wear a potentially performance deteriorating device. Wearing externally controlled information on one's body necessarily results in giving up the right for self-expression: the wearer has no direct control to what information is shown, in what context and during what time. More particularly for our display, the top players, but also the least productive ones, become rapidly visible. This may be seen as a clear benefit for non-expert players who could use the display to make decisions for improving their game-play, yet may also represent a disadvantage as expert players might already make exactly the same decisions without the aid of such display. This immediate visual disclosure to external critique might not be desirable, depending on the wearer's self-confidence level. This aspect might also explain why no participant agreed on displaying individual physiological data, such as heartbeat, stress level, tiredness or energy usage. Participants were quick to point out early in the design stage that any display of such personal data would be damaging to the individual athlete's and team's performance. It could easily result in players losing motivation, as well as opposing teams taking advantage of one's obvious weak points. However, this issue was approved by spectators, who agreed this would contribute to a more interesting and intriguing spectator experience. This raises the question whether the athletes should wear such revealing display solely for the sake of the spectators? One should also note that some typical game-related aspects considered of high value in a basketball game are not explicitly shown on the jerseys, such as shot accuracy, defense actions, steals, rebounds or assist passes. Consequently, by highlighting only a subset of information, the wrong emphasis might be created towards players, coaches and spectators, to what a good 'basketball performance' really is about. Lastly, there is the issue of inherently 'relying' on technology, especially in this application where there was no technology required before. For instance, what happens if the system breaks, causing players, coaches or referees to rely their actions on wrong information: should the match be halted, the end results altered, or should the jerseys only be treated as non-essential and non-trustworthy gadgets?

Wearability
The inherent characteristics of the sports domain highly restrict technical design possibilities. From miniaturization of all computing elements to the washability of clothing, each design decision is primarily determined by strict wearability and usability requirements.

Perceptibility

The evaluation study made apparent that the display type itself plays a significant role. Athletes revealed that they often made decisions based only on their peripheral vision. For instance, players can immediately decide to pass a ball to others based only on seeing a glance of clothing color, posture, body height or hair color. Therefore, displays with a large surface area are favored, as they are more easily distinguishable from any distance. There also needs to be a substantial contrast between the "visibility of states" that the display embodies [27]. For instance, it was found that the EL-wire displays could be quite deceiving, as they glow bright green when turned on, but still appeared greenish when turned off. In contrast, the panels could be discerned more easily due to their absolute color change (white to bright blue). It is important to keep displays subtle: flashing or fading displays can be confusing or show false information when in an 'intermediate' state. Spacing between displays is crucial, as it was found that displays placed close together were perceived as merged. To assure that no faulty information is provided, the state of the whole system should be visible at all times: for instance, is a display turned 'off' because of the actual data, or because it is broken?

Intuitiveness

Unlike ambient displays and electronic fashion pieces, which are intended to be learnt over time, wearable visualization should be discernable in as little time as possible. Although all participants of this study were briefly informed about the meaning of each display, it was found they did not need to 'think' about what the displays were showing. For instance, the wire displays representing the fouls were intentionally placed on the shoulder to 'warn' players when they had many fouls, similar to the aggressive raising of shoulder blades. Similarly, the displays representing athletes' individual points were arranged in an upward fashion, reminiscent of a music equalizer or data visualization bar chart. An intuitive layout design requires input from end-users, who may be familiar with different representations for concepts such as 'big', 'small', 'good', 'bad', or 'warning'. In this study, the participants seemed to be inspired by alternative sport visualizations, such as on-screen graphics shown during sports broadcasts, and graphical visualizations on video game avatars.

Design Process

This project has demonstrated the advantage of user participation, which provided insights that would be impossible to gather in a different way. User contributions were particularly useful in the system's physical and ergonomic design, which performed successfully during the game-play evaluation. It was also helpful in identifying the most important information sources, and their most suitable positioning on the jersey. The largest problem encountered, however, was recruiting enough suitable and committed people for a technological application that was virtually unknown.

5 Conclusion and Future Work

This paper introduced the design and case study evaluation of a novel wearable display system for team sports, that augments the mutual awareness of game-related information sources in real-time. Although its technological implementation is relatively simple compared to other sensor-based wearable systems, its design was constrained by the complex demands of the high-risk sports application context. Although its technological design proved to be successful, several unforeseen conceptual insights were discovered. The influence of the displays on the players in-game decisions, as originally hypothesized, showed to be very limited due to the fast-pace and highly demanding cognitive load of the game itself. As the information was shown onto the players themselves, the displays rather seemed to influence their self-confidence level. In contrast, referees, coaches and spectators seem to benefit the most of an increased game awareness: to make decisions more effectively and efficiently, to understand the actual game dynamics more profoundly, and to make the game more enjoyable to watch. Therefore, we propose wearable visualization as an effective awareness-enhancing device for non-players, which is conceptually similar to superimposed, explanatory infographics during television broadcasts or webcasts.

We consider our case study evaluation as successful for further investigation in the area of wearable visualization in the sports domain. Even when a similar system would not be accepted by the relevant national sports federations for competitive use, the system can still be used for training, disability sports, collaboration or social competition purposes. For instance, the jerseys can be worn to reflect the player's performance during training, can visually indicate strategic 'plays' (e.g. which player has to move when and where), or communicate strategies from the coach to the players (locally or remotely). A similar system could convey strategic information or increase situational awareness for emergency services during crisis operations. All participants indicated to understand the system's usefulness and even agreed to use it in the future when it would become more user-friendly. Therefore, future research could include fine-tuning the design of the jerseys, evaluating the system during a match with 'real' parameters (i.e. five against five, full time), and the addition of more complex information sources that cannot be easily discerned or remembered by the stakeholders (e.g. shot accuracy and assists, or aggregated data such as defensive and offensive statistics).

The apparent success of TeamAwear among the spectators of a basketball game could be seen as desirable outcome for the highly visual medium of television, inspiring further development as a media application to promote audience interest and enjoyment. Placed on the players themselves, such jerseys might be a more natural solution that also appeals to the players, and not only the audience. It might also overcome the typical performance problems of infographical computer graphics overlays in fast-paced sports.

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