Human Factors and Ergonomics in Sport and Outdoor Recreation: From individuals and their equipment to complex sociotechnical systems and their frailties

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Editorial

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Introduction

The benefits of sport and outdoor recreation are well known. These include positive impacts on our physical and psychological health and wellbeing as well as a range of broader community, societal and economic benefits. On the contrary, when sport and outdoor recreation systems fail, the consequences can be catastrophic and can include multiple fatalities, large-scale financial losses, and significant trauma to individuals and society. Such impacts can be seen in recent events such as the United States gymnastics sexual abuse scandal, the Mangatepopo Gorge Walking tragedy, the Jules Bianchi Formula One crash, and the FIFA corruption scandal.

As a discipline that is concerned with optimising system performance and human well-being, the important role that Human Factors and Ergonomics (HFE) can play in understanding and optimising sport and outdoor recreation has long been recognised (e.g. Reilly, 1984; Reilly & Ussher, 1988). As a result, a significant body of HFE work has been undertaken to date, and there are various researchers and practitioners currently working in the sport and outdoor recreation context (see Salmon & Macquet, 2017).

Broadly, the work of HFE practitioners in sport and outdoor recreation focusses on either optimising performance (athlete, worker, team, organisation, or system performance) or on preventing accidents and injuries. As the discipline of HFE has matured and advanced, the role that HFE plays in sport and outdoor recreation systems has grown. In the area of sport, for example, early applications focussed on individual athletes (Macquet & Skalej, 2015) and sports equipment design (Reilly & Lees, 1984), however, theoretical and methodological advances have seen HFE applications expand to incorporate sports teams (Neville et al., 2017), sports organisations, and overall sports systems (Hulme et al., 2017). This has seen the focus of HFE work extend from physical ergonomics (e.g. anthropometrics, physiology, injury, disabilities) to cognitive ergonomics (e.g. situation awareness, decision making) and now to systems ergonomics (e.g. injury causation and prevention).

Alongside this, sport and outdoor recreation systems are becoming more complex, more technology centric, and in the case of sport, more competitive and more financially driven. As a result, the appetite for HFE research and practice is increasing. In addition, there is a growing recognition that the problems faced in sport and outdoor recreation settings are similar to those being tackled in more traditional HFE application areas such as transportation, defence, and process control (Salmon, 2017). Researchers and practitioners are recognising the benefits of applying HFE theory and methods, developed in other areas, in sport and outdoor recreation (e.g. Kermarrec and Bossard, 2014; Macquet and Stanton, 2014; Mclean et al., 2017). In turn, the potential to inform safety critical system design and the development of HFE theory and methods through sport and outdoor recreation applications is being realised (e.g. Goode et al., 2018; Neville et al., 2017).

This special issue on *Human Factors and Ergonomics in Sport and Outdoor Recreation* was proposed by the authors in response to this exciting new dawn for HFE in sport, as well as the recent emergence of HFE applications in the area of outdoor recreation (Dallat et al., 2017; 2018; Goode et al., 2016; 2018; Salmon et al., 2010; 2014; 2017a). The proposal was developed alongside the creation of a *Human Factors and Ergonomics in Sport and Outdoor Recreation* conference as part of the Applied Human Factors and Ergonomics (AHFE) conference in Las Vegas in 2015 (see Salmon & Macquet, 2017). The aim of both the special issue and the conference was to provide a platform for communicating contemporary sport and outdoor recreation HFE research, to showcase some of the key issues currently being tackled, and to inspire the HFE community to pursue further applications in sport and outdoor recreation. This special issue also provides an opportunity to reflect on our disciplines contribution as well as its potential role in future sports and outdoor recreation research and practice.

The seven articles included in the special issue each describe recent HFE applications within either sport or outdoor recreation systems. Following a brief overview of the history of HFE in sport and outdoor recreation, a summary of each contribution is provided. The main findings from each contribution are then brought together to articulate the key take home messages. In closing, we discuss the implications for future sport and outdoor recreation HFE research and practice.

Ergonomics in sport and outdoor recreation

As mentioned above, there is a significant body of HFE work covering a diverse set of issues in different sporting contexts. This body of work can broadly be decomposed into physical HFE, cognitive HFE, and systems HFE research (Salmon, 2017). Physical HFE research has examined issues ranging from sports equipment and clothing design (e.g., Lake, 2000; McGhee et al., 2013; Reilly & Lees, 1984) to sports injury (e.g., Theberge, 2011), and biomechanics (e.g., Lees et al., 2000). Cognitive HFE research has focussed on various cognitive issues associated with individuals and teams, ranging from decision-making (e.g., Macquet & Fleurance, 2007) and cognition (McNeese et al., 2015) to situation awareness (e.g., Macquet & Stanton, 2014; Neville & Salmon, 2016), sensemaking (e.g., Macquet & Kragba, 2015), and teamwork (e.g. McLean et al., 2018). More recently, systems HFE applications have begun to explore wider sport and outdoor recreation system issues such as accident and injury prevention (Clacy et al., 2017; Hulme et al., 2017), coaching (Macquet et al., 2015), performance analysis (Mclean et al., 2017), and spectators and crowds (Filingeri et al., 2017; Sun et al., 2016).

HFE has received less attention in the area of outdoor recreation; however, there is a growing set of applications occurring in the areas of outdoor recreation and adventure tourism. These emerged more recently; however, they also cover a diverse set of HFE issues including injury (Bentley et al., 2007), accident analysis and prevention (Salmon et al., 2010; 2012; 2014; 2017a), decision making (Trotter et al., 2018), the design and evaluation of ergonomic methods (Goode et al., 2016; 2018), risk assessment (Dallat et al., 2018) and regulatory frameworks (Carden et al., this issue).

Special issue contributions

Hulme et al (*Applying systems ergonomics methods in sport*) open up the special issue with a focus on the burgeoning area of sports systems ergonomics. They present the findings from a systematic review of systems ergonomics applications in sport, the aim of which was to critically evaluate studies that have applied systems ergonomics methods in sports performance analysis and injury management. Hulme et al reviewed five databases to identify sport studies that employed one of the following systems ergonomics methods: Hierarchical Task Analysis (HTA; Stanton, 2006), Cognitive Work Analysis (CWA; Vicente, 1999), the Event Analysis of Systemic Teamwork (EAST; Stanton et al. 2013), the Functional Resonance Analysis Method (FRAM; Hollnagel 2012), the Macro Ergonomic Analysis and Design method (MEAD; Kleiner 2006), Rasmussen's Risk Management Framework (Rasmussen 1997), or the Systems Theoretic Accident Model and Processes (STAMP; Leveson 2004).

Only seven articles were identified, two of which focussed on optimising sports performance, and five of which focussed on sports injury management. The studies identified covered cycling, football, Australian Rules Football, and rugby union and involved applications of EAST, Work Domain Analysis (the first phase of CWA), Rasmussen's Risk Management Framework, and STAMP. Hulme et al use the Critical Appraisal Skills Programme (CASP; Program, 2017) to assess study quality. In addition, they assess the extent to which each application considered the overall sports system as described

Rasmussen's framework (as opposed to considering only components of it, such as athletes or equipment only). According to Hulme et al, the quality of the studies is high; however, there is a need for researchers to provide more information on the methodology adopted and to provide clearer descriptions of study findings. Hulme et al also discuss the reliability and validity of systems ergonomics methods in sport, and argue that further work is required to formally evaluate this in the sports context. Finally, Hulme et al argue that there is a need for researchers and practitioners to gather evidence regarding the impact of sports ergonomics research in practice.

Récopé et al. (*A study of the individual activity of professional volleyball players*) describe two case studies in which they used observation and self-confrontation interviews to assess behaviour and situation assessment in defensive scenarios. In the first study, two national teams were observed during three competitive matches occurring during an international men's volleyball tournament. In the second study, 12 players from the original study took part in self-confrontation interviews designed to elicit information on the salient features used by players during the scenarios. Players were grouped into two populations based on the defensive behaviours exhibited. According to Récopé et al., the findings show important differences between the two populations. For example, the players in population A were found to distinguish between game situations based on the perceived danger of losing the rally (termed 'anxious vigilance'), whereas the players in population B did so according to whether they perceived it to be their responsibility or a teammates to intervene in order to win the point. Récopé et al. conclude that there are differences in behaviour and situation assessment even when players are part of the same national team and are expected to apply the same game system. Récopé et al. close their article with a useful discussion of how their findings can be used in practice by coaches. In particular, they suggest that training can be optimised by incorporating sensemaking.

Rochat et al. (*Enactments and the design of trail running equipment*) describe two studies undertaken to investigate trail runners' perceptions and use of trail running carrying and hydration systems to inform and optimise carrying and hydration system design. The overall aim is to demonstrate how data on end-user use and experiences can be extracted and analysed to inform design. Rochat et al. argue that sports equipment designers have traditionally focussed on engineering principles rather than human movement science, and that end-users should be involved in a co-creation based design process. The first study involved an analysis of the information posted by trail runners in the 'equipment and products' category in an online running forum, whereas the second study involved an analysis of runners' activity whilst using five different carrying and hydration systems.

In the first study, messages were coded and analysed using inductive content analysis. Two meaningful themes were identified: 'Choosing the most convenient system before buying it', and 'enacting specific issues of the carrying systems while running'. The former related to runners attempting to match design features to race characteristics, and the latter related to specific issues encountered, such as discomfort through noise and bouncing, usability and adjustment issues, and difficulties in accessing pockets. In the second study, a field test was undertaken whereby nine runners ran a pre-defined trail running loop five times using five carrying and hydration systems that were selected based on the most discussed items in the first study. At the end of the trial, runners participated in a self-confrontation interview, with a particular emphasis on the runners' interactions with the carrying and hydration systems. Finally, runners were asked for their preferences on the different carrying and hydration systems used. Four enactments with the carrying and hydration systems were identified: exploring and adjusting the carrying system; reducing permanent perturbations caused by carrying system when running; dealing with environmental constraints; and analysing enactments with the carrying system. Runners' rankings of the carrying systems showed that some were perceived to be more efficient than others, and highlighted the strengths and weaknesses of each model. In particular, systems with water bladders and rigid bottles were perceived to be the least comfortable. Rochat et al. conclude that designers should attempt to minimise or remove disturbing elements (e.g. weight, bounce, noise) and make them as transparent as possible. Moreover, they argue that future test protocols should be designed to ensure that different performance contexts are considered and that user trials with self-confrontation interviews be used during the design process.

Varadarajura & Srinivasan (*Design of clothing for hot environments*) focus on the design of sports clothing to optimise thermal comfort. They present a study comparing physiological thermal comfort when running and during post-running rest periods when wearing 3 'body mapping'-based shirts versus a conventional running shirt design. Body mapping-based designs map fabric properties such as weave and knit structure to the sweat and heat production characteristics of different parts of the body. For example, Varadarajura & Srinivasan describe how female athletes have higher sweat rates than male athletes on their upper arms, lateral lower back, and upper central back. Further, both male and female athletes sweat the most along the spine and upper back, with the sweat rate being lowest on the upper arm.

Participants performed a running activity on a treadmill, and various data was recorded including skin temperature, heart rate, skin micro climate as well as subjective ratings of skin temperature, skin moisture, and overall comfort. At the end of each trial, participants rested for 10 minutes and the same measurements were taken. Each of the four shirts was subjected to twenty trials. According to Varadarajura & Srinivasan the analysis identified key differences between the shirts in terms of objective and subjective ratings of thermal comfort. They conclude that, during running, more thermal physiological benefit is achieved when wearing body mapping-based shirts versus conventionally designed shirts. They argue that wearing a body mapping-based shirt enables a more consistent skin temperature, micro skin climate, and heart beat when compared to the conventional design.

Sports-related concussion is a major injury issue in fast-paced contact sports such as rugby, football, and ice hockey. Worryingly, research has demonstrated that athlete concussions are often undiagnosed or mismanaged. Clacy et al (A systems approach to understanding the identification and treatment of sport-related concussion in community rugby union) report on a study of concussion management in community rugby union which aimed, first, to identify which actors are responsible for concussion management and, second, to gather their perceptions on their own specific concussion management roles and responsibilities. 118 members of the community rugby system in Queensland, Australia completed a questionnaire regarding their concussion management-related roles and responsibilities. The sample included players, coaches, parents, medics, administration personnel, volunteers, and referees. The findings were mapped onto Rasmussen's risk management framework (Rasmussen, 1997) to identify where in the community rugby union system the actors and associated responsibilities reside. The findings show that there is currently a heavy reliance on medical personnel to diagnose player concussions; however, medics are often not available at community rugby games. Clacy et al conclude that appropriate concussion diagnoses may not be occurring in community rugby, and that work is required to remove the reliance from medics onto other actors in the system (e.g. players, coaches). The findings also show that standardised concussion assessment tools are not being used, with less than a fifth of the medics reporting that they currently use them. Finally, Clacy et al report that less than 1% of the players involved in the study felt that they had role to play in concussion management, along with only 25% of the coaches and parents. Clacy et al conclude that future work should focus on rectifying this by clarifying the responsibilities of different actors across the system.

The Ergonomics of sports shoes has been a prominent focus of HFE research in sport (Frederick, 1984; van der Putten & Snijders, 2001), with inappropriate sports shoe design being previously identified as a key contributory factor in sports injuries. Herbaut et al. (*Determination of optimal shoe fitting for children tennis players*) investigated the optimal inner-shoe volume for children tennis players by asking participants aged between 8 to 12 years old to assess the comfort of 6 different tennis shoes. The shoes differed in terms of last (thin, medium, wide) and upper construction (flexible or stiff). In addition to the subjective ratings, they examined the influence of shoe last and upper construction on the pressure applied on participants feet, hypothesising that shoe last plays a more important role in the level of pressure exerted than upper construction elasticity. This was tested via participants wearing a sock equipped with sensors to measure the pressure applied on their feet by each shoe. Herbuat et al. report that the widest shoes produced the lowest pressure and were perceived to be the most comfortable. They conclude that simply scaling down adult tennis shoes for children does not offer optimal comfort. In particular, they recommend that footwear manufacturers should design wider sports shoes for children than for adults.

Regulation, or lack of it, has been identified as a key contributory factor in various fatal incidents that have occurred during led outdoor activities (Goode et al., 2018). The final article from Carden et al (Sociotechnical systems as a framework for regulatory system design and evaluation) shifts the focus of the special issue onto the design and analysis of safety regulation in led outdoor activity systems. Pointing to the lack of formal methods for evaluating regulatory systems, Carden et al argue that HFE methods, in particular those associated with systems thinking and sociotechnical systems theory, provide a useful framework for describing and evaluating regulatory systems. They demonstrate this by presenting the findings from a study in which Work Domain Analysis, the first phase of Cognitive Work Analysis (CWA; Vicente, 1999), was used to evaluate the recently introduced New Zealand Adventure Activity Regulations (NZAAR). Specifically, the abstraction hierarchy method was used to describe the regulatory system in terms of its functional purposes, values and priority measures, purpose-related functions, object-related processes and cognitive objects. Based on this, Carden et al identified some of the constraints that will likely impact how well the regulatory system works following implementation. According to Carden et al the findings suggest the regulatory systems functional purpose of ensuring safe outdoor recreation is not fully supported by the functions and physical objects available. Carden et al also concluded that WDA provides a suitable framework for evaluating regulatory systems generally, and recommends that be used for this purpose in other safety critical systems. A final interesting feature of Carden et al.'s analysis is the inclusion of cognitive objects as well as physical objects at the lowest level of the abstraction hierarchy. Carden et al. describe cognitive objects as tools for thinking, such as ideas, beliefs, ideologies and belief systems. This is an extension to the abstraction hierarchy method and one that has interesting ramifications of CWA applications in other areas.

Key take home messages

The contributions presented in this special issue confirm that sport and outdoor recreation HFE research remains highly relevant. The articles cover applications of systems ergonomics methods in elite sport, volleyball player behaviour and situation assessment, running shirt, sports shoe design and trail running carrying and hydration system design, concussion management, and regulatory system design and evaluation. It is encouraging to see that HFE remains relevant in sport and outdoor recreation and also that the scope of applications appears to be increasing. A notable feature is the increasing adoption of a systems ergonomics approach when attempting to understand and optimise sport and outdoor recreation systems (e.g. Hulme et al., this issue; Clacy et al., this issue; Carden et al., this issue). This reflects a wider trend across HFE whereby systems thinking is increasingly underpinning HFE studies (Salmon et al., 2017b; Walker et al., 2017; Waterson et al. 2017). Further systems thinking applications in sport and outdoor recreation are encouraged as well as physical and cognitive HFE applications.

The articles included in this special issue on 'Human Factors and Ergonomics in Sport and Outdoor Recreation' provide a series of important take-home messages. It is worth noting that many apply to HFE application areas generally, as opposed to only sport and outdoor recreation. The key take home messages can broadly be categorised into messages forsystems ergonomics applications, sports product design, injury management, and regulatory system design.

Sports systems ergonomics applications

- Despite the popularity of systems ergonomics applications in other domains, to date there have been few (seven) systems ergonomics applications in sport;
- Sports systems ergonomics applications are of high quality, however, there is a need for researchers to provide more information on the methodology adopted and to provide clearer descriptions of study findings.
- Testing the reliability of systems ergonomics methods is a critical area of future research, both in sport and outdoor recreation and in other HFE application areas;

Sports product design

- Sports equipment designers should ensure that different performance contexts are considered during design and that user trials are throughout the design process;
- Hydration and carrying systems with water bladders and rigid bottles are perceived by trail runners to be the least comfortable;
- During running, more thermal physiological benefit is achieved when wearing body mapping-based shirts versus conventionally designed shirts;
- Wearing a body mapping-based shirt enables a more consistent skin temperature, micro skin climate, and heart beat when compared to a conventional running shirt design;

- Simply scaling down adult sports shoes for children does not offer optimal comfort; and
- Sports footwear manufacturers should design wider sports shoes for children than for adults.

Injury management

- In community rugby, there is a shared responsibility for concussion management that spans all actors in the system from players, coaches, and medics and to the Australian Rugby Union, the Australian Sports Commission, and the International Rugby Board; and
- In community rugby there is a reliance on medics to diagnose player concussions, however, they are often not present and few use the relevant standardised concussion assessment tool.

Regulatory system design

- Sociotechnical systems methods such as CWA provide a suitable framework for designing and evaluating regulatory systems; and
- Recently introduced adventure activity regulations do not incorporate the tools required to achieve their functional purposes safe activities, legislative compliance, consumer confidence, industry and national reputation, and economic stability.

It is encouraging to see that HFE researchers are exploring a range of issues in sport and outdoor recreation and further that the findings have practical relevance both in sport and outdoor recreation but also in other areas in which HFE professionals work. It is our view that, as sport and outdoor recreation systems continue to evolve, there will be an increasing requirement for input from HFE professionals. The contributions presented in this special issue give an overview of contemporary research in this area; however, there are many other issues to tackle, and likely more will emerge. Just as HFE work has evolved in 30 years from initially considering individual athletes and their equipment to now consider overall sport and outdoor recreation systems and their frailties, it is likely that the next 30 years will see new and exciting developments in this area. In particular, important emerging and future issues that will benefit from HFE inquiry include artificial intelligence and machine learning, new forms of performance analysis, doping, technology insertion, the utilisation of big data, and corruption and racism in sport.

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