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**Applying systems ergonomics methods in sport: A systematic review**

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**Abstract**

Introduction: As sports systems become increasingly more complex, competitive, and technologically-centric, there is a greater need for systems ergonomics methods to consider the performance, health, and safety of athletes in context with the wider settings in which they operate. Therefore, the purpose of this systematic review was to identify and critically evaluate studies which have applied a systems ergonomics research approach in the context of sports performance and injury management.

Material and methods: Five databases (PubMed, Scopus, ScienceDirect, Web of Science, and SPORTDiscus) were searched for the dates 01 January 1990 to 01 August 2017, inclusive, for original peer-reviewed journal articles and conference papers. Reported analyses were underpinned by a recognised systems ergonomics method, and study aims were related to the optimisation of sports performance (e.g. communication, playing style, technique, tactics, or equipment), and/or the management of sports injury (i.e. identification, prevention, or treatment).

Results: A total of seven articles were identified. Two articles were focussed on understanding and optimising sports performance, whereas five examined sports injury management. The methods used were the Event Analysis of Systemic Teamwork, Cognitive Work Analysis (the Work Domain Analysis Abstraction Hierarchy), Rasmussen’s Risk Management Framework, and the Systems Theoretic Accident Model and Processes method. The individual sport application was distance running, whereas the team sports contexts examined were cycling, football, Australian Football League, and rugby union.

Conclusions: The included systems ergonomics applications were highly flexible, covering both amateur and elite sports contexts. The studies were rated as valuable, providing descriptions of injury controls and causation, the factors influencing injury management, the allocation of responsibilities for injury prevention, as well as the factors and their interactions underpinning sports performance. Implications and future directions for research are described.

**1.0 Introduction**

Sport and physical activity, either through direct involvement or spectatorship, plays a key role in the health and overall wellbeing of many global societies. Accordingly, much scientific work has attempted to optimise sports performance and facilitate participant health and safety. Epidemiological and clinical research-based applications have identified and emphasised the importance of biomedical and behavioural factors underpinning sports performance (Shrier, 2004, Liu et al., 2008, Ganio et al., 2009, Fradkin et al., 2010, Malcata and Hopkins 2014), and have tested the efficacy of various injury prevention interventions (McBain et al., 2012a, b, Lauersen et al., 2014, Leppänen et al., 2014). Notwithstanding the ongoing need for traditional sports science research, there appears to have been a paucity of work directed at better understanding sports contexts more broadly, including the full range of determinants that influence the beliefs, decisions, and behaviours of individual players, teams, and sports organisations (Finch and Donaldson, 2010, McGlashan and Finch, 2010, Donaldson et al., 2012, 2015, Hulme and Finch, 2015, Mooney et al., 2017, Seifert et al., 2017). As such, the utility of systems theory and systems ergonomics methods for optimising sports performance and managing injury in ‘complex sports systems’ has been recently promoted (Salmon, 2017), and requires further exploration.

Ergonomics researchers and practitioners work to optimise systems and enhance human wellbeing (International Ergonomics Association, 2016). Accordingly, the value of ergonomics for the enhancement of sports performance has long been recognised (Reilly and Lees, 1984, Reilly and Ussher, 1988, Shephard, 1988). Following initial applications in the late 1980s, the field of sports ergonomics research has grown considerably and now addresses a diverse set of issues across numerous sporting domains (Atkinson and Reilly, 2009). This research can be broadly divided into three distinct areas of specialisation: (i) physical; (ii) cognitive; and, (iii) systems ergonomics (International Ergonomics Association, 2016, Salmon, 2017). The former, physical ergonomics, is concerned with how the individual’s anatomy, physiology, anthropometry, and biomechanics functionally interact with the design of physical products, objects, and structures (i.e. ‘fitting the human to the system’). From a sports perspective, optimising human-artefact and human-machine interactions can help to facilitate desired performances and attenuate maladaptive physical processes during play (e.g. the design of sports equipment and clothing, or studying a cyclist’s riding position) (Lake, 2000, Born et al., 2013, Balasubramanian et al., 2014, Hsiao et al., 2015). The second, cognitive ergonomics, aims to understand how a range of mental constructs pertaining to memory, general reasoning, and/or motor response, can potentially support or inhibit effective operational decisions within an individual’s immediate environment. Cognitive sports-related applications have largely centred on decision making (McNeese et al., 2015, Macquet and Fleurance, 2007), and situation awareness in relation to communication, team dynamics, and coaching practices (Macquet and Stanton, 2014, Macquet et al., 2015, Neville and Salmon, 2016, Neville et al., 2016). The third specialisation, systems ergonomics – which is the focus of this paper – is concerned with understanding and optimising the functioning of sports systems, including their organisational structures, policies, and processes (International Ergonomics Association, 2016). From a sports performance and injury management perspective, the systems ergonomics discipline operates from an ecological point of reference, and attempts to consider the whole sports system (or interacting multiple elements of it) as the primary unit of analysis.

As sports systems become increasingly more complex, competitive, and technology-centric (e.g. Rettner, 2013, Andreasson and Johansson, 2014, Piwek et al., 2016), there is a greater need for systems ergonomics methods to consider the performance, health, and safety of athletes in context with the wider settings in which they operate. Moreover, the problems faced in sports and physical activity settings are intrinsically comparable to those which have featured in traditional systems ergonomics application areas (e.g. defence, process control healthcare, industrial, engineering, and transportation systems) (Walker et al., 2008, Holden, 2009, Davis et al., 2014, Wilson 2014). Therefore, to optimise sports performance and manage injury, it is necessary to address how athletes operate relative to a diverse set of interrelated physical, cognitive, psychosocial, environmental, and wider systemic influences (Marras and Hancock, 2014). Essentially, the key aspect of systems ergonomics research is a focus on the interactions between those elements, as opposed to simply the behaviour of the individual components in isolation (e.g. athletes and coaches). Given that this need has been noted, and applications have been recently encouraged (Salmon, 2017), it is timely to review the current state of research in this emerging area. In addition, and as a growing area of research, it is important to ensure that sports systems ergonomics applications are of sufficient quality to support the translation of findings in practice.

The purpose of this systematic literature review is to identify and critically evaluate studies which have applied a systems ergonomics research approach in the context of sports performance and injury management. Specifically, it is necessary to comment on the focus of the research undertaken, including the study purpose, contexts, and outcomes, as well as to examine the quality of the identified articles from a standpoint of methodological rigour. Closely inspecting the applied methods will also indicate the extent to which they have considered the whole sports system as the unit of analysis, including the interactions between elements, as opposed to focussing only on discrete system levels and/or components in isolation. Addressing these aims is important as it will provide insight into the current knowledge base, and will highlight how and where to improve study quality moving forwards.

**2.0 Methods**

2.1 Electronic search

Five databases (PubMed, Scopus, ScienceDirect, Web of Science, and SPORTDiscus) were searched by the first author for published articles during the dates 01 January 1990 to 01 August 2017, inclusive. Citation software (EndNote for Windows 6.0.1) facilitated the searching process. When searching databases, certain filters and limiters were applied. For example, the search aimed to retrieve articles from 1990 onwards, as this predates the development of the methods to be included (see section 2.2.1). Likewise, database limits were imposed on both the published language and selection of journals so as to maintain a manageable and highly relevant search strategy (i.e. the search in the ‘ScienceDirect’ database did not include journals outside of the wider ergonomics literature). The complete search strategy for each database, including Medical Subject Heading (MeSH) terms, can be viewed in Table 1.

2.2 Eligibility criteria

Studies had to be specifically focussed on understanding a given sports context with a recognised systems ergonomics method (as defined in section 2.2.1 below). Applications involving only physical or cognitive ergonomics methods (e.g. analyses of concurrent verbal protocols, self-confrontation interviews, or video footage) were not eligible.

2.2.1 Inclusion criteria

To be eligible for inclusion, the studies had to comply with the following criteria:

1. Reported analyses were underpinned by a recognised systems ergonomics method that had the capacity to analyse sociotechnical systems and their behaviours (Stanton et al., 2013, Salmon et al., 2017a). These included Cognitive Work Analysis (CWA) (Vicente, 1999), Event Analysis of Systemic Teamwork (EAST) (Stanton et al., 2005), the Functional Resonance Analysis Method (FRAM) (Hollnagel, 2012), Hierarchical Task Analysis (HTA) (Annett and Duncan, 1967), the Macro Ergonomic Analysis and Design method (MEAD) (Kleiner, 2006), Rasmussen’s Risk Management Framework (RMF) (Rasmussen, 1997), and the Systems Theoretic Accident Model and Processes (STAMP) method (Leveson, 2004).
2. Study aims were related to the optimisation of sports performance (e.g. communication, playing style, technique, tactics, or equipment), and/or the management of sports injury (i.e. identification, prevention, or treatment).
3. Information sources included peer-reviewed journal articles or academic peer-reviewed conference papers published in English.

After an initial search, the first author inspected the titles and abstracts of all retrieved articles against the inclusion criteria. For the remaining eligible articles, two authors (AH and PS) independently conducted the screening of abstracts and, in cases of insufficient detail, the full-texts. Eligibility disagreements were resolved during discussions involving three authors (AH, GR, PS).

2.3 Data extraction and study interpretation

The following study information was extracted from eligible articles: (i) authors and date; (ii) purpose; (iii) focus; (iv) context; (v) method(s); (vi) procedure(s); and, (vii) data sources.

2.4 Quality evaluation

A critical assessment of the included studies was required to evaluate methodological quality. The Critical Appraisal Skills Programme (CASP; Oxford, England) checklist was selected as a means to appraise study quality (Critical Appraisal Skills Program, 2017). Developed by the Public Health Resource Unit of the National Health Service, the CASP checklist elicits yes/no responses designed to evaluate the quality and potential contribution of qualitative research more broadly. It includes 10 items covering topics such as purpose, context, setting, research design, data collection and analysis, researcher bias, ethics, and overall research value and impact (Table 2). Two authors (JT and KP) who had not contributed to any of the studies included in this review, independently assessed the quality of each article, and awarded each item a positive (+) or negative (-) score (i.e. corresponding to yes/no). The results of the quality assessment process were discussed in a formal meeting with three authors (AH, JT and KP). These discussions helped to explain more specifically why a given item received a positive or negative score, and also served to resolve any potential inter-rater discrepancies.

|  |  |
| --- | --- |
| **Database** | **Search terms and applied filters** |
| PubMed | Search ((((ergonomics[Title]) OR systems[Title]) OR systems theory[MeSH Terms]) OR "systems thinking"[Title/Abstract]) AND sport[Title] Filters: Publication date from 1990/01/01 to 2017/08/01 |
| Scopus | (TITLE(ergonomics) OR TITLE(systems) OR TITLE-ABS-KEY("systems thinking") AND TITLE(sport)) AND PUBYEAR > 1989 AND PUBYEAR < 2018 AND ( LIMIT-TO ( LANGUAGE,"English" ) ) |
| ScienceDirect | (systems AND ergonomics AND sport) Filters limited to *Journal*: Applied Ergonomics; Journal of Science and Medicine in Sport; Safety Science; 1990 to “present”) |
| Web of Science | (systems AND ergonomics AND sport (TITLE)) Filters: 1990 to 2017 |
| SPORTDiscus | (TI ergonomics OR systems AND sport) Published Date: 1990/01/01-2017/08/31; Language: English; Publication Type: Academic Journal, Conference Paper, Conference Proceeding |

**Table 1: Key words, Medical Subject Heading (MESH) terms, and applied filters associated with each of the five databases**

**Table 2: The Critical Appraisal Skills Programme (CASP) checklist that was used to assess the quality of the included articles**

|  |
| --- |
| **Question\*** |
| 1. Was there a clear statement of the research aims? |
| 2. Was a qualitative methodology appropriate? |
| 3. Was the research design appropriate to address the aims of the research? |
| 4. Was the recruitment strategy appropriate to the aims of the research? |
| 5. Were the data collected in a way that addressed the research issue? |
| 6. Has researcher-participant relationships been adequately considered? |
| 7. Have ethical issues been taken into consideration? |
| 8. Was the data analysis sufficiently rigorous? |
| 9. Was there a clear statement of research findings? |
| 10. Was the research valuable? |

\*A more detailed explanation elaborating on each item can be found in Electronic Supplementary Material Table A1

**3.0 Results**

3.1 Full-text selection

After searching five databases, a total of 1,506 articles were identified. After removing 80 duplicates and examining 1,426 titles and abstracts, 539 potentially relevant articles were retained. The decision to exclude 887 articles was based on whether the study had a sports focus. Closer examination of the abstracts and, if required the associated full texts, led to the exclusion of a further 535 articles (reasons disclosed). Articles not identified through the systematic searching process were later added based on the authors’ knowledge of the domain (n=3) (the addition of these three articles in the searching process was primarily attributable to issues around journal indexing, as well as the fact that two studies were recently published as conference papers). Overall, this process resulted in a total of 7 articles for inclusion (Figure 1).

(1,506 articles)

PubMed 25

Scopus 180

ScienceDirect 415

Web of Science 470

SPORTDiscus 416

80 duplicate articles excluded based on a non-sporting focus

1,426 articles

887 articles excluded after title/abstract screen based on a non-sports focus

539 articles

4 articles

7 articles included in literature review

535 sports-focussed articles excluded after abstract/full text screen

Inappropriate study design/method 379

Literature review/commentary 84

Physical ergonomics study 57

Sports psychology 15

3 further articles added

**Figure 1: A visualisation of the systematic searching process**

3.2 Study characteristics

In summarising key study information (Table 3), two articles focussed on understanding and optimising sports performance whereas five examined sports injury management. The methods used in the seven articles included EAST (Stanton et al., 2005), CWA (the Work Domain Analysis Abstraction Hierarchy; WDA-AH) (Vicente, 1999), Rasmussen’s RMF (Rasmussen, 1997), and STAMP (Leveson, 2004). No systems ergonomics studies using FRAM (Hollnagel, 2012), HTA (Annett and Duncan, 1967), or MEAD (Kleiner, 2006) were identified. The individual sport application was distance running (Hulme et al., 2017a, b), whereas the team sports contexts examined were cycling (Salmon et al., 2017b), football (Mclean et al., 2017), Australian Football League (AFL) (Dawson et al., 2017), and rugby union (Clacy et al., 2016, 2017). The study procedures and sources of data underpinning the development or validation of methods and models varied across the studies.

3.3 General overview of the included methods

3.3.1 Event Analysis of Systemic Teamwork

EAST provides an integrated suite of ergonomics methods for analysing the performance of complex sociotechnical systems. Underpinning the method is a ‘network of networks’ approach, in which three mutually inclusive network-based representations (or models) are used for analysing performance-related activity (Salmon et al., 2014). Firstly, a task network is used to provide an overview of the main goals and tasks to be performed within the system. Secondly, a social network explicates how the system is organised, including the nature of the communications that are found between both people and objects. Thirdly, a situation awareness network is used to describe how key information and knowledge are shared and integrated across the system to support decision-making (Salmon et al., 2014). Recent applications of the framework have adopted a composite network analysis approach whereby the three networks are integrated to show the relationships between tasks, social interactions, and information (Stanton 2014a).

3.3.2 Cognitive Work Analysis

CWA was developed to model complex sociotechnical work systems (Vicente, 1999). Unlike many other ergonomics methods that aim to describe how work, activity, teamwork, and/or performance are conducted and achieved, the CWA approach focusses on the constraints that are imposed by the purposes, functional properties, activities, individual roles, and cognitive strategies within a given system. This means that, for example, to optimise system performance and facilitate work-related processes, it is necessary to model the existing system, and subsequently develop recommendations for improvement and (re)design (Vicente, 1999). There are five different phases associated with CWA, each of which has a specific objective. As it is the only CWA phase to have been formally applied in sport, the WDA-AH is described below.

The WDA-AH provides an in-depth description of the constraints that govern the purposes, values and functions of the system under analysis. The abstraction hierarchy component of the analysis is represented as a model containing five levels. The top three levels consider the overall purposes, values and priorities, and functions of the system, whereas the bottom two levels concentrate on the physical components and their affordances, showing how components are exploited to undertake the functions required to achieve the systems overall purposes. Developing the WDA-AH involves understanding the objectives of the system (i.e. working from the top-down), as well as identifying the system’s physical capabilities (i.e. working from the bottom-up). Through a series of ‘means-ends links’, the system’s purposes, priorities and values, functions, and physical objects are modelled to demonstrate the integration of, and influence between, individual system components.

3.3.3 Rasmussen’s Risk Management Framework

Rasmussen’s (1997) RMF is arguably one of the most popular, contemporary systems-based models that is used to support the causal analyses of unintentional large-scale critical incidents and injury (Le Coze, 2017, Leveson, 2017, Salmon et al., 2017c, Waterson et al., 2017). The RMF is predicated on the following ideas: (i) systems comprise various hierarchical levels (e.g. government, regulators, company, company management, staff, and work), each of which contain actors (individuals, organisations, or technologies) who share responsibility for production and safety; (ii) decisions and actions occurring at all levels of the system interact to shape system performance, meaning that organisational safety and health are influenced by all actors, not just front-line workers; and, (iii) critical incidents and injury are caused by multiple contributing factors, not just one bad decision. The framework also highlights the concept of migration, whereby behaviours shift towards and away from safety and performance boundaries due to various financial constraints and organisational pressures.

3.3.4 Systems Theoretic Accident Model and Processes

STAMP (Leveson, 2004) takes the view that unintentional incidents and injury result from the inadequate control or enforcement of safety-related constraints – when disturbances, failures, and/or dysfunctional interactions between components are not handled by control mechanisms. As such, STAMP considers safety as a ‘control issue’ that is managed through a ‘control structure’, with the primary goal of enforcing constraints on actors (i.e. people and organisations) from across the system. Various forms of control are factored into STAMP analyses, including managerial, organisational, operational, and manufacturing-based controls (Leveson, 2009). That is, overall system behaviour is dictated not only by appropriately designed and engineered systems, but also by policies, procedures, shared values, and other aspects of the surrounding organisational and social culture. The STAMP approach has various methods associated with it, including an accident analysis method (Causal Analysis based on STAMP; CAST) and a risk assessment method (Systems Theoretic Process Analysis: STPA), both with their own purposes and objectives. Applying both CAST and STPA involves developing a control structure for the system under analysis showing the relevant actors, controls, and feedback mechanisms across five hierarchical levels (similar to those associated with Rasmussen’s (1997) RMF). The control and feedback loops are included to show what control mechanisms are enacted down the hierarchy, as well as what information about the status of the system is sent back up.

**Table 3: An overview of extracted key information associated with the seven included articles**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Author** | **Purpose** | **Focus** | **Context** | **Method(s)** | **Procedure(s)** | **Data sources** |
| Salmon et al. (2017b) | Examine distributed situation awareness, decision making, and teamwork dynamics in a National Road Series cycling peloton | Elite, performance | Competitive cycling, Australia | EAST | Naturalistic study, video/audio recordings, interviews | Cycling team (5 riders, 1 director sportif, 1 mechanic) |
| Mclean et al. (2017) | Develop a model of the football match system to better understand performance analysis requirements | Elite, performance | Competitive football (soccer), International | First phase CWA | WDA-AH, workshops | 8 SMEs, soccer coaching experiences covering Europe, Asia, and Australia |
| Dawson et al. (2017) | Examine the factors influencing player, coach, and medics’ decisions to remove concussed athletes from play | Amateur, injury | Competitive AFL | Rasmussen’s RMF | CDM, semi-structured interviews | 15 members of an amateur AFL club (9 players, 2 coaches, 4 medical staff) |
| Hulme et al. (2017a) | Validate a prototype model of the distance running system | Amateur, injury | Recreational distance running, Australia | STAMP | Online surveys, modified Delphi | 24 SMEs (16 runners, 8 systems thinking researchers) |
| Hulme et al. (2017b) | Develop a prototype control structure systems model of the Australian distance running system | Amateur, injury | Recreational distance running, Australia | STAMP | Expert-informed group consensus, workshops | Scholarly and non-traditional literature (e.g. media, government reports) |
| Clacy et al. (2017) | Explore the perceived responsibilities for identifying and treating sports-related concussion across a range of actors (e.g. players, medics) | Amateur, injury | Competitive rugby union, Australia | Rasmussen’s RMF | Online surveys, thematic analysis (Nvivo software) | 118 SMEs (50 players, 17 coaches, 18 parents, 2 management, 17 medics, 5 admins, 3 volunteers, 6 referees) |
| Clacy et al. (2016) | Examine how sports-related concussion is managed (i.e. prevented, identified, and treated) | Amateur, injury | Competitive rugby union, Australia | Rasmussen’s RMF | As per Clacy et al (2017) | |

Australian Football League (AFL); Critical Decision Method (CDM); Cognitive Work Analysis (CWA);Event Analysis of Systemic Teamwork (EAST); Risk Management Framework (RMF); Subject Matter Expert (SME); Systems Theoretic Accident Model and Processes Model (STAMP); Work Domain Analysis Abstraction Hierarchy (WDA-AH)

3.4 Quality assessment

One article was excluded from this evaluation as it did not draw upon the knowledge, expertise, or experiences of participants for the purpose of developing or validating its contained systems ergonomics model (Hulme et al., 2017b). After the exclusion of this study, six studies were eligible for a methodological quality assessment (Table 4). The inter-rater reliability between the two analysts who conducted the quality assessment process was found to be ‘fair’ (Landis and Koch, 1977), Kappa statistic (*k*) = 0.321 (*p =* 0.009), 95% CI (0.017 to 0.625). Following the resolution of inter-rater discrepancies, items two, three, four, six, seven, and 10 were unanimously scored positive. The lowest scores were awarded to items eight and nine, which corresponded to whether data analyses were sufficiently rigorous, or if a clear statement of the research findings had been presented, respectively. Producing a composite score for each study for the purpose of conducting an overall comparison was not performed, as this did not provide a meaningful reflection of the quality of the research. Rather, the CASP checklist was used as a means of highlighting potential methodological strengths and limitations for the purpose of suggesting how future studies might be improved from a quality-related standpoint.

**Table 4: The Critical Appraisal Skills Programme (CASP) quality assessment scores for six of the included studies**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Criteria for assessing methodological quality\*** | | | | | | | | | |
| **Study** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Hulme et al. (2017a) | + | + | + | + | + | + | + | + | + | + |
| Mclean et al. (2017) | + | + | + | + | + | + | + | + | + | + |
| Salmon et al. (2017b) | + | + | + | + | + | + | + | - | + | + |
| Dawson et al. (2017) | - | + | + | + | + | + | + | + | - | + |
| Clacy et al. (2017) | + | + | + | + | - | + | + | - | + | + |
| Clacy et al. (2016) | + | + | + | + | + | + | + | - | - | + |

\*The quality assessment criteria were as follows: (1) there was a clear statement of the research aims; (2) a qualitative methodology is appropriate; (3) the research design was appropriate to address the research aims; (4) the recruitment strategy was appropriate in relation to the research aims; (5) Data were collected in line with the research issue(s); (6) the researcher-participant relationship was considered; (7) ethical issues were taken into consideration during the study; (8) data analysis was sufficiently rigorous; (9) a clear statement of findings was reported; and, (10) the research was valuable. Negative score = (-), positive score = (+).

3.5 System levels and factor interactions analysed

One aim of this review was to evaluate the extent to which the included methods had considered the whole sports system as the unit of analysis, as opposed to focussing only on individual components in isolation. Accordingly, when mapped onto a recognised key systems ergonomics framework (Salmon et al., 2017a, c) (Figure 2), the studies that applied EAST (cycling) (Salmon et al., 2017b), and the WDA-AH (football) (McLean et al. 2017), involved analyses covering the work, staff, and management levels (i.e. the system levels that the analysis covered were identified by the type of information collected and the elements that were presented). Three sports injury studies using Rasmussen’s (1997) RMF (AFL) (Dawson et al., 2017), and Leveson’s STAMP method (distance running) (Hulme et al., 2017a, b), considered the whole system, including the regulatory and government levels. Two sports injury studies covered four system levels, from the equipment and environment level, to the regulatory bodies and associations level (Clacy et al., 2016, Clacy et al., 2017).

In terms of the interactions between and across a range of system elements (e.g. factors, actors, and/or organisations), the cycling (Salmon et al., 2017b), football (McLean et al., 2017), and distance running-related injury studies (Hulme et al., 2017a, b) applied methods and models that accounted for relationships across the sports system. However, the distance running STAMP model was relatively abstract, and did not, unlike in the EAST (Salmon et al., 2017b) and WDA-AH (McLean et al., 2017) applications, illustrate one-to-one relationships linking individual system elements (Hulme et al., 2017a). In other words, and from a conceptual standpoint, the EAST (Salmon et al., 2017b) and WDA-AH (McLean et al., 2017) applications offered a high level of detail with regard to the specific relationships modelled between discrete system elements. Three studies applying Rasmussen’s (1997) RMF did not account for any relationships or feedback between or across individual elements and/or system levels (Dawson et al., 2017, Clacy et al., 2016, Clacy et al., 2017).



**Figure 2: The levels and interactions examined in each of the systems ergonomics studies**

3.6 Sports performance applications

This section describes the findings associated with the reviewed articles, and provides a general critique of the study quality.

3.6.1 Teamwork in cycling

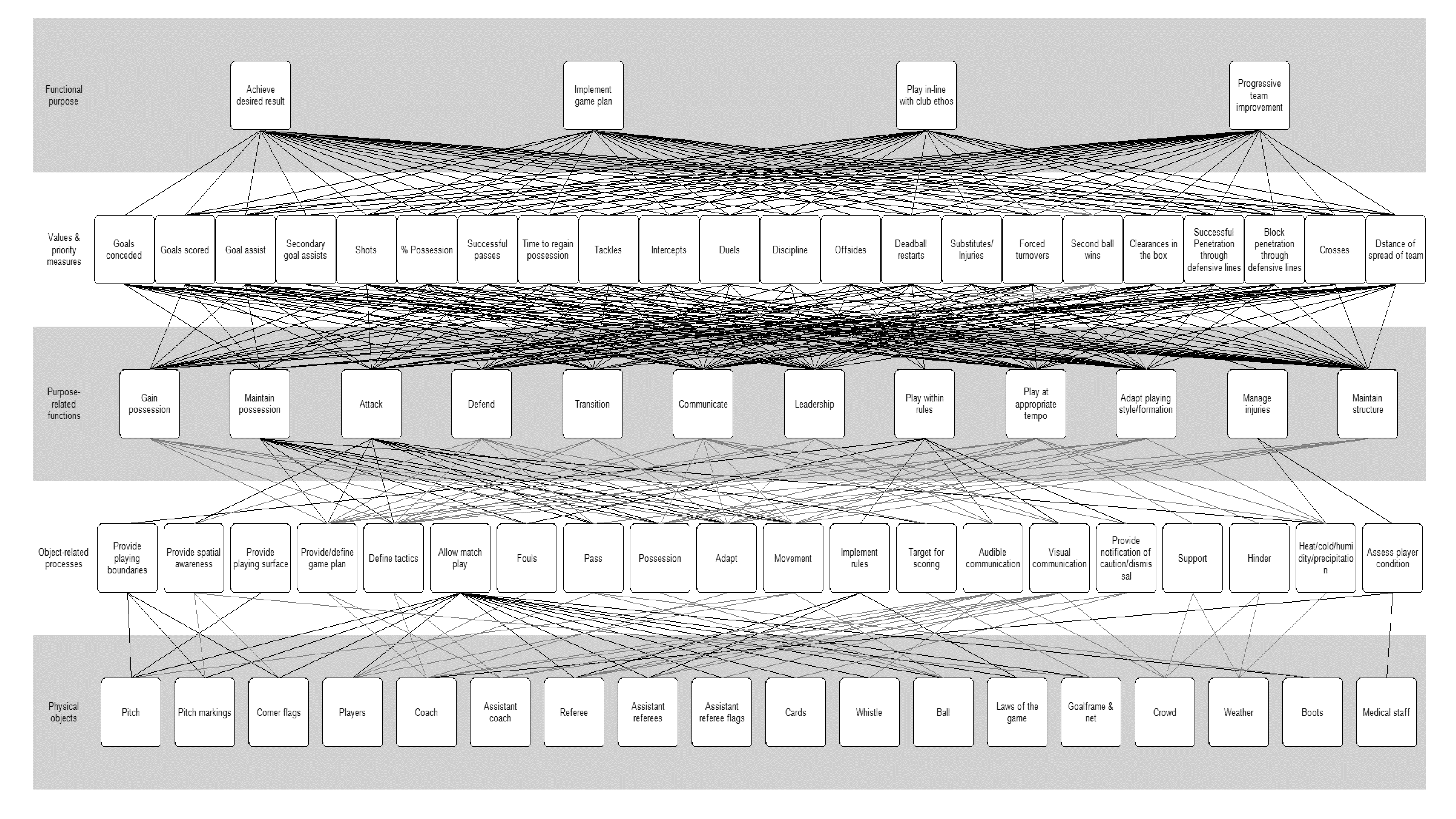
In an application of the EAST method, the development of task, social, and situation awareness networks provided an in-depth understanding of elite cycling team performance (Salmon et al., 2017b). Firstly, a task network was used to describe the tasks being performed within and between the cycling team and its vehicular support convoy. Based on video footage during the race, as well as post-race cognitive task analysis interviews, a network of 23 interrelated tasks were identified, of which five were found to be integral to performance: (i) implementation of race planning and tactics; (ii) individual peloton positioning; (iii) continuous monitoring of other riders; (iv) communication with team members; and, (v) monitoring of speed, cadence, power and distance. Secondly, a social network diagram highlighted different types of incoming and outgoing verbal and non-verbal communications both within the cycling team, and across the peloton and convoy. The team’s ‘protected’ (or general classification rider), and the immediate supporting rider(s), were found to be highly connected, and frequently engaged with a range of other persons (e.g. team directors and riders from other teams) and components (e.g. mounted bike computers and annotated handlebars) in the peloton. Thirdly, through content analysis of participant interview transcripts, a situation awareness network demonstrated how key information and knowledge was integrated to support team decision-making. According to this latter analysis, individual position monitoring in relation to other riders, topographic features of the environment, physical fatigue, and hazards, were critical pieces of information.

In terms of study quality, the CASP checklist ratings suggest that the cycling EAST study did not provide an adequate description of the data analysis procedure underpinning the development of the three task networks. Minimal information was provided about how the research team went about collecting and recording data with the chosen tools and techniques (e.g. real-time video footage and post-race recordings). Likewise, the possible influences of individual researcher biases and contradictory data were not discussed in relation to both participant interviewing, and the identification of key study information as derived through content analysis.

3.6.2 Performance analysis in football

In this study, the first phase of CWA, the WDA-AH, was used to develop a model of the elite football match system (McLean et al., 2017) (Figure 3). In addition to a comprehensive description of football match performance, the Subject Matter Expert (SME) analysis identified three important implications. Firstly, the WDA-AH confirmed that a given football match can (and should) be conceptualised as a complex sociotechnical system. This raised questions about the validity of traditional performance analysis methods which have typically aimed to improve the physical, technical, and/or tactical elements of the game in isolation (e.g. passing and tackling ability). Secondly, the WDA-AH identified aspects of performance that are not currently considered or measured in existing performance analysis methods, yet were deemed important by the football SMEs. For example, the main pitch locations where critical actions occur during play, penetration of passes through defensive lines, and regaining possession from forced turnovers and second ball wins, were identified as important measures not currently assessed by existing methods. For other performance-related functions not currently assessed, team adaptability, effective intra-team communication, and playing at the appropriate tempo, were identified in the analysis. Thirdly, the results pointed to a potential disconnect between theory and practice. That is, research findings produced via traditional performance analysis methods might not be meaningful to the real-world needs of end-users, including individual players, teams, and coaching staff. Regarding the evaluation of study quality, the football performance application satisfied the 10 criteria on CASP.

**Figure 3: The Work Domain Analysis Abstraction Hierarchy of the football match system (McLean et al., 2017)** (reproduced with permission under the Creative Commons Attribution (CC BY) license)



3.7 Sports injury management applications

3.7.1 Australian Football League (AFL)

In a study exploring the factors influencing player, coach, and medical teams’ decisions to remove suspected concussed players from the field of play in amateur AFL, the critical decision method (CDM) interview technique was used (Dawson et al., 2017). The interview data were subsequently mapped onto Rasmussen’s (1997) RMF to show where in the AFL system the influencing factors reside, and with whom they are associated with. Amongst the players, the most commonly cited factors influencing the decision to remain in play were: (i) underestimating the physical dangers associated with concussion; (ii) whether the game was deemed of ‘high significance’ (e.g. grand finals, or rival competition); (iii) game culture (e.g. maintaining a personal reputation); and, (iv) diagnostic consequences (i.e. not being allowed to play in subsequent matches). In terms of coaches’ decision-making, and despite the possibility of concussive injury, athletes were encouraged to keep playing due to: (i) the need to win; (ii) game significance; (iii) pressure from the players directly; and, (iv) athlete personality. When compared to the players and coaches, however, medical staff emphasised different factors that were more aligned with policy and established concussion guidelines. For example, the score provided by a well-known concussion assessment tool ultimately determined whether players should be sidelined from a match situation.

The mapping of factors across Rasmussen’s (1997) RMF demonstrated that the management of concussion in AFL is a system-wide problem encompassing player personalities, past experiences, coaching styles, management roles, social pressures, cultural influences, concerns for personal liability, the media, organisational guidelines, and the general rules of the sport. The identification of this broad set of systemic factors emphasises the responsibility of club level supervisory groups, regulatory associations, and sports governing bodies to implement appropriate and effective system-wide concussion management interventions. Despite such novel insights, CASP item nine suggested that no evidence was provided to indicate that inter-rater reliability testing was performed during the model building process.

3.7.2 Distance running-related injury

In two studies, the STAMP (Leveson, 2004) method was used to model the Australian distance running system in order to better understand how running-related injury is managed and controlled (Hulme 2017a, b). The first study involved the development of a prototype model (Hulme et al., 2017b), and the second study formally validated that model through an expert-informed, consensus-driven approach (Hulme et al., 2017a). The validated distance running STAMP model presented a hierarchical control structure containing the various actors, control mechanisms, and feedback mechanisms spanning five system levels (Figure 4). This approach confirmed: (i) that the efficacy and sustainability of individually-targeted running-related injury prevention interventions is dependent on the availability of systemic resources from across the system; and, (ii) that individual-level running-related behaviours are influenced by a myriad of political, organisational, managerial, and sociocultural determinants. The application of the STAMP method facilitated theoretical advancement in terms of potentially identifying practical, high-leverage, system-wide opportunities for managing running-related injury at the population-level. This study received positive scores across the 10 CASP criteria.

*<Note to publisher: Please insert Figure 4 and its caption in landscape page formatting: found attached as a high-resolution PNG file>*

**Figure 4: The validated Australian distance running systems model (Hulme et al., 2017a)**

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3.7.3 Rugby union

Two studies applied a systems ergonomics research approach to examine how sports-related concussion is currently identified, prevented, and treated in amateur rugby union (Clacy et al., 2016, Clacy et al., 2017). Although these two studies were comparable with regard to their purpose, only one included concussion prevention as a main focus (Clacy et al., 2016). Common to both studies, however, was the application of Rasmussen’s (1997) RMF for the purpose of conceptualising the sociotechnical hierarchical organisation of the rugby union system, including the heterogeneous actors that reside in the system across six levels. Based on participant responses from across the system about perceived concussion management responsibilities, the most frequently reported injury prevention strategies were found to be proper training (e.g. appropriate physical fitness and skill level), technique correction, and concussion education (Clacy et al., 2016). Notably, the effective implementation of those three injury prevention strategies requires action on behalf of all actors across the rugby union system, as opposed to only the actors from a single level (Clacy et al., 2015). In the second study, the mapping of actor perspectives onto the rugby union RMF indicated that there was an overreliance on field-side medics to manage suspected cases (Clacy et al., 2017). Despite medical personnel being the most qualified in terms of their diagnostic and therapeutic capability, a concerning finding was the lack of consensus amongst other actors (e.g. players, coaches, and family members) in relation their responsibilities around the need to appropriately identify the symptoms of concussion. As a result, the authors’ argued that action needs to be taken to revaluate existing policy guidelines for the purpose of delegating new role-specific system-wide concussion management responsibilities (Clacy et al., 2017).

Although both of the rugby union studies scored highly on CASP, item eight on the checklist indicated that no information was provided around whether the research team had critically examined their own role, potential biases, and influence during the analysis and selection of data for presentation. Likewise, and based off the description around CASP item nine, there was no information regarding whether inter-rater reliability testing had been applied for the purpose of mapping factors across the systems ergonomics framework.

**4.0 Discussion**

The purpose of this systematic literature review was to identify and critically evaluate studies which have applied a systems ergonomics research approach in the context of sports performance and injury management. The systematic search resulted in the inclusion of seven studies spanning five different sports. Although these numbers are relatively low, owing to the fact sports systems ergonomics research is still in its infancy, the timely nature of this review is beneficial in terms of establishing best practices and assessing the relative utility of such approaches. In consideration for the research undertaken, it is necessary to discuss: (i) the quality of the included studies; (ii) the main study findings and contributions to knowledge; and, (iii) implications for future systems ergonomics applications in sport.

4.1 Study quality

According to the independent CASP checklist evaluation, the included studies satisfied the majority of the individual criteria. Methodological strengths varied from clearly stating the importance of the research aims, to offering a detailed account of how the research contributed to existing knowledge, as well as how it supposedly impacted on current sports practice or policy. Moreover, the evaluated studies justified the need for, and recruitment of, the type of participants, knowledge, and expertise required to achieve the stated aims. Notwithstanding the mostly positive results, items eight and nine on the CASP checklist received the lowest scores. This finding suggests that there is a need to improve descriptions of the analytical procedure adopted, and to provide clear statements of findings. It is here that an explicit description of the researcher’s own role and potential biases during data selection and their interpretation should also be provided. Another quality-related consideration pertains to how methods have been adapted and used more generally. For example, the cycling EAST study (Salmon et al., 2017b) did not offer a clear description around how the three task networks were developed, nor was any information provided to help the reader understand how contradictory data were handled. This is important, as future systems ergonomics methods (and models) in the sports context are required to be both objective in their application and replicable under similar circumstances.

4.1.1 A side note on the reliability and validity of ergonomics methods

The importance of assessing study quality in the ergonomics discipline cannot be overstated. Critically appraising the design and conduct of research can expose methodological shortcomings to the benefit of future ergonomics applications. A particular quality-related concern pertains to the concepts of reliability and validity. Firstly, it is implicitly assumed that ergonomics methods, especially when adapted to a new domain, have been applied ‘properly’ in the spirit for which concepts, frameworks, and/or models were originally devised (Stanton, 2014b). Secondly, commentators have raised a series of questions about the supposed methodological rigour associated with our research, including but not limited to: How ‘deep’ should analyses be? By what reasoning dictates the preferential selection of a given method? What type of expertise is required when applying the method? Are there any tools to support the use of the method? (Annett and Stanton, 2000) Thirdly, other considerations relate to whether a given ergonomics method has been used in an evaluative capacity (i.e. parameter measurement and testing), and/or analytical capacity (i.e. understanding, developing, and modelling the system) (Annett, 2002), as there are different requirements based on the intended use of the method.

Regarding the included sports studies in this review paper, there was little mention about the reliability, validity, or intended capacity of the chosen systems ergonomics methods. Although it is arguably not within the scope of individual studies to discuss the general utility of methods (i.e. the primary purpose should be a suitable and justified adaptation), the lack of a classification scheme to guide, for instance, the distance running STAMP applications (Hulme et al., 2017a, b) might expose further questions around its reliability. Likewise, the preservation of construct validity (i.e. how acceptable the underlying theory is), content validity (i.e. does a method represent all facets of a given construct), and predictive validity (i.e. criterion-referenced empirical accuracy), provides insight into whether ergonomics methods have real-world efficacy for solving domain-specific issues (Stanton, 2014b). It is worth noting that these issues are not exclusive to sports systems ergonomics applications, and there are pressing questions over the reliability and validity of systems ergonomics methods more generally (Stanton and Young, 1999, Annett and Stanton, 2000, Annett, 2002, Kanis, 2014, Stanton, 2014b, 2016). Consistent with work undertaken in other safety-critical domains e.g. (Stanton and Baber, 2005, Cornelissen et al., 2014, Goode et al., 2016, Goode et al., 2017), there will be an ongoing requirement for research to evaluate whether systems ergonomics outputs can be both consistently and accurately generated in the sports context.

4.2 Study findings and contributions to knowledge

In gaining a broader perspective and evaluating the presented body of work, there are several notable features worth discussing. Starting with the research purpose, only two systems ergonomics applications have been used for better understanding a range of factors and their relationships underpinning sports performance (Salmon et al., 2017b, McLean et al. 2017). Both of these applications did not consider the target sports system in its entirety; rather, the EAST and WDA-AH studies extended the analytical boundary to the sports club management level, and so a range of other possible factors influencing cycling and football performance may have been overlooked. Accordingly, future sports systems ergonomics applications should attempt to examine the role of governance and regulation in shaping individual-level behaviours in relation to performance optimisation.

On the whole, there were mainly positive results associated with the sports performance studies. The application of the EAST method helped to identify the key task, communication, and wider situation awareness requirements underpinning the optimisation of cycling team performance (Salmon et al., 2017b). Based on the development of three task networks, one finding in particular was the need to implement agile race plans long before competition, allowing cycling teams to respond rapidly in the face of variable tactics from the opposition. Likewise, the WDA-AH of the football match system highlighted a range of novel performance analysis measures that are seldom, if ever, considered in traditional scientific practice (Mclean et al., 2017). This underscored the need to think about new ways of approaching, understanding, and quantifying these measures in future research applications.

The remaining five studies focussed on sports injury management. Three of the five were comparable regarding the use of an established RMF (Rasmussen, 1997) for better understanding the identification, prevention, and treatment of sports-related concussion (Clacy et al., 2016, Clacy et al., 2017, Dawson et al., 2017). Those studies gathered participant responses, and identified factors and/or actor perspectives that could then be mapped onto a structural hierarchy. Although useful for highlighting a myriad of system-wide factors relating to decision making around individual athlete management (Dawson et al., 2017), as well as the perceived roles and responsibilities about concussion management practices (Clacy et al., 2016, Clacy et al., 2017), such studies are best considered as preliminary investigations that now warrant further extension and testing. To be precise, it would be beneficial to recruit larger sample sizes to obtain a greater variation in actor perspectives, as well as to distribute participant numbers more evenly across the system. Likewise, a significant limitation of these studies was that no relationships or interactions between factors or actor perspectives were considered, and so it is now necessary to explore that dimension with appropriate systems ergonomics methods which have been shown to work in other, similar domains (e.g. the led outdoor activity context (Carden et al., 2017, Trotter et al., 2017)).

Finally, the distance running STAMP studies (Hulme 2017a, b) were conducted in response to the overwhelming number of traditional epidemiological investigations which have attempted to ‘reduce down’ aetiological complexity, and identify running-related injury risk factors in isolation (Hulme et al., 2017c). As such, the value of the distance running STAMP model was in its ability to conceptualise the development of running-related injury as a wider systems-based problem resulting from a lack of systemic control (Hulme et al., 2017a). Integral to this work was the incorporation of a traditional running-related injury causal framework within the organisational hierarchy itself (Figure 4, system level 5). This integration of a casual framework into the STAMP model was beneficial for the broader field of running-related injury research. In brief, the more a method is standardised with the aim of improving its reliability and validity, the less applicable its scope will be to range of foreign contexts. On the other hand, scientific pragmatism and methodological flexibility in systems ergonomics research can help to identify new insights and solve real-world problems that otherwise might have been overlooked (Davis et al., 2014, Waterson et al., 2015, Walker et al., 2017).

4.3 Scope and utility of systems ergonomics methods

The included studies indicate that systems ergonomics methods are highly flexible, and can be applied across both amateur (Clacy et al., 2016, Clacy et al., 2017, Dawson et al., 2017, Hulme et al., 2017a, b) and elite (McLean et al., 2017, Salmon et al., 2017b) levels of sport. The studies were rated as valuable, providing descriptions of injury controls and causation, the factors influencing injury management, the allocation of responsibilities for injury management and prevention, as well as the factors and their interactions underpinning sports performance. The recommendations derived from the studies covered strategies for injury prevention and management, and performance enhancement, but more importantly they covered multiple levels of the sports systems studied (i.e. not solely athletes and coaches). Despite the positive findings, it should be noted that none of the articles presented evidence that any of the recommendations or proposed interventions have been implemented in practice. This is an issue that is largely consistent across systems ergonomics applications and indeed ergonomics studies generally. An important area of future research for systems ergonomics in sport will involve testing whether the suggested recommendations and interventions are feasible and effective in a real-world setting.

Based on the limited number of studies identified, there is arguably a need for further systems ergonomics applications in the sports context. Although there are likely to be many reasons for the paucity of work, it is reasonable to speculate that this new and emerging area of research has simply not yet found its way into mainstream sports science. Indeed, all of the included studies were published within a year of writing this review, and this could be considered promising from the perspective of encouraging further applications. Similarly, there is a possibility that sports science researchers do not (yet) recognise the wider scope of ergonomics science. That is, as much as the physical design of sports artefacts and products is an integral sub-domain of the ergonomics discipline, so too is the way in which those products interact with a wide range of cognitive, psychosocial, environmental, and systemic demands of a given sports situation. Accordingly, under the assumption that systems ergonomics methods will be further promulgated into the broader sports science research thematic, there may be a requirement for practitioners to defend and/or justify both the value and relevance of their profession. Specifically, from a sports performance and injury prevention standpoint, it is necessary to ask: what can systems ergonomics methods offer over and above traditional epidemiological and clinical scientific applications? Likewise, what types of problems in sports science research are ergonomics methods best used for? Although this review and its results can help to partly answer those, and other similar questions, there is a definitive need for scholarly debate about the scope and utility of systems ergonomics methods in sport moving forwards. Accordingly, the few existing studies which have been applied represent a useful starting point, and comprise the foundations to now argue for, and justify why, systems ergonomics methods should continue to attract the attention from the sports science community.

A final feature of the studies reviewed was that their outputs were static – that is, they provide a ‘snap shot’ of what are supposedly complex and dynamic systems. This is a key limitation of the studies assessed (and also systems ergonomics studies generally), particularly in reference to the central tenets of complexity and systems theory, including but not limited to, adaptation, emergence, causal feedback, sensitivity on initial conditions, phase transitions, historical dependency, self-organisation, and tight coupling (Trochim et al., 2006, Diez Roux, 2011, Rutter et al., 2017). As ergonomists, we must be mindful that although useful, the current suite of systems-based methods cannot, in the case of wanting to understand dynamic causal processes, account for some of the main characteristics of complexity. This is a far broader issue, of which penetrates the core of the systems ergonomics discipline, and naturally has implications for how sports ergonomists will conceptualise their own set of problems. Further methodological development and/or the integration with other computational system science approaches is required, enabling systems ergonomics applications to simulate dynamic complexity over time. These methods are readily available (e.g. systems dynamics and agent-based modelling) (Macal and North, 2010, Luke and Stamatakis, 2012), however their uptake and application to date has been limited.

4.4 Limitations and future research implications

This review has limitations which should be noted. First and most importantly, the studies in this review were all found to be associated with a single research institute, of which five of the authors are affiliated (AH, GR, SM, AC and PS). Accordingly, two external assessors (JT and KP) were invited to evaluate study quality using the CASP checklist. The use of this generic checklist was necessary as there is no established quality appraisal checklist that has been specifically developed for the systems ergonomics field. The CASP checklist has its own set of limitations, one being that the scoring of a given study is largely a subjective process that is facilitated by a series of methodological quality considerations. It uses only dichotomous scoring for each item, and its specificity could potentially be enhanced by providing sub-scaling. This lack of specificity was reflected by the relatively low inter-relater reliability metric, and might have equally contributed to the relatively high-quality scores across studies. In addition, it is important to note that the CASP was not developed specifically to examine ergonomics studies, and therefore may not be comprehensive in this respect. Future work should attempt to develop a quality appraisal checklist for the wider systems ergonomics discipline, covering all aspects of research, including the underpinning theoretical framework, through to data analyses and conclusion formation.

**5.0 Conclusion**

This systematic literature review identified seven studies in which a systems ergonomics approach was used in the sports performance or injury management context. Although the studies were largely effective in terms of achieving their aims, there is a need for future work to consider the whole sports system, and focus on the interactions between factors spanning its multiple levels. In relation to establishing best practices from a study quality perspective, adequate detail needs to be provided around the collection, recording, and analysis of data. The reader should also have information that informs them of how contradictory data were handled, which highlights the extent to which researcher biases were accounted for. Ideally, inter-rater reliability testing during the process of developing models is advised, and future applications should justify how, and by what means, the methods were adapted and/or validated to address the main context-specific problem. Moreover, as sports systems ergonomics research continues to gain traction, there will be a requirement for studies to provide evidence that the suggested recommendations are feasible, and can ‘work’ in practice. The results associated with this systematic review suggest that ergonomists have critical role to play in understanding and optimising both amateur and elite sports systems. As sports systems continue to become more complex, competitive, and technology-centric, the requirement for ergonomics research and practice will increase considerably. Nevertheless, the utility of our industrial-age methods will arguably be brought under further scrutiny were it not for the proposal of new strategic directions and the encouragement of interdisciplinary integration.

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**Supplementary Material A**

**Table A1: The Critical Appraisal Skills Programme (CASP) checklist that was used to guide the assessment of the quality of the included articles**

|  |  |
| --- | --- |
| **Question** | **Descriptors to aid with a qualitative interpretation** |
| 1. Was there a clear statement of research aims? | What was the goal of the research?  Why was the research considered important?  Was its relevance established? |
| 2. Was a qualitative methodology appropriate? | If the research seeks to interpret or illuminate the actions and/or subjective experiences of research participants  Is qualitative research the right methodology for addressing the research goal? |
| 3. Was the research design appropriate to address the aims of the research? | If the researcher has justified the research design (e.g. have the authors discussed how they went about deciding which systems ergonomics method to use, and why it was the most appropriate)? |
| 4. Was the recruitment strategy appropriate to the aims of the research? | If the researcher has explained how the participants were selected  If they explained why the participants selected were the most appropriate to provide access to the type of knowledge sought by the study  If there are any discussions around recruitment (e.g. why some people chose not to take part) |
| 5. Were the data collected in a way that addressed the research issue? | If the setting for data collection was justified  If it is clear how data were collected (e.g. focus group, semi-structured interview etc.), and why such approaches were chosen over others  If the researcher has made the methods explicit (e.g. for interview method, is there an indication of how interviews were conducted, or did they use a topic guide)?  If methods were modified during the study. If so, has the researcher explained how and why? (e.g. the chosen systems ergonomics method has, by default, been adapted from a safety-critical domain and applied to sports. Accordingly, have any issues around its adaptation been described?)  If the form of data is clear (e.g. tape recordings, video material, notes etc.)  If the researcher has discussed data saturation |
| 6. Has researcher-participant relationships been adequately considered? | If the researcher critically examined their own role, potential bias and influence during: (i) formulation of the research questions; and, (ii) data collection, including sample recruitment and choice of location  How the researcher responded to events during the study, and whether they considered the implications of any changes in the research design |
| 7. Have ethical issues been taken into consideration? | If there are sufficient details of how the research was explained to participants for the reader to assess whether ethical standards were maintained  If the researcher has discussed issues raised by the study (e.g. issues around informed consent or confidentiality or how they have handled the effects of the study on the participants during and after the study)  If approval has been sought from the ethics committee |
| 8. Was the data analysis sufficiently rigorous? | If there is an in-depth description of the analysis process  If thematic analysis is used. If so, is it clear how the categories/themes were derived from the data?  Whether the researcher explains how the data presented were selected from the original sample to demonstrate the analysis process  If sufficient data are presented to support the findings  To what extent contradictory data are considered  Whether the researcher critically examined their own role, potential bias and influence during analysis and selection of data for presentation |
| 9. Was there a clear statement of research findings? | If the findings are explicit  If there is adequate discussion of the evidence both for and against the researchers’ arguments  If the researcher has discussed the credibility of their findings (e.g. triangulation, respondent validation, more than one analyst)  If the findings are discussed in relation to the original research question |
| 10. Was the research valuable? | If the researcher discusses the contribution the study makes to existing knowledge or understanding (e.g. they consider the findings in relation to current practice or policy? Or, relevant research-based literature?  If they identify new areas where research is necessary  If the researchers have discussed whether or how the findings can be transferred to other populations, or considered other ways the research may be used |