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From control to causation: Validating a 'complex systems model' of running-related injury development and prevention

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ABSTRACT

Introduction: There is a need for an ecological and complex systems approach for better understanding the development and prevention of running-related injury (RRI). In a previous article, we proposed a prototype model of the Australian recreational distance running system which was based on the Systems Theoretic Accident Mapping and Processes (STAMP) method. That model included the influence of political, organisational, managerial, and sociocultural determinants alongside individual-level factors in relation to RRI development. The purpose of this study was to validate that prototype model by drawing on the expertise of both systems thinking and distance running experts.

Materials and methods: This study used a modified Delphi technique involving a series of online surveys (December 2016- March 2017). The initial survey was divided into four sections containing a total of seven questions pertaining to different features associated with the prototype model. Consensus in opinion about the validity of the prototype model was reached when the number of experts who agreed or disagreed with survey statement was ≥75% of the total number of respondents.

Results: A total of two Delphi rounds was needed to validate the prototype model. Out of a total of 51 experts who were initially contacted, 50.9% (n = 26) completed the first round of the Delphi, and 92.3% (n = 24) of those in the first round participated in the second. Most of the 24 full participants considered themselves to be a running expert (66.7%), and approximately a third indicated their expertise as a systems thinker (33.3%). After the second round, 91.7% of the experts agreed that the prototype model was a valid description of the Australian distance running system.

Conclusion: This is the first study to formally examine the development and prevention of RRI from an ecological and complex systems perspective. The validated model of the Australian distance running system facilitates theoretical advancement in terms of identifying practical system-wide opportunities for the implementation of sustainable RRI prevention interventions. This 'big picture' perspective represents the first step required when thinking about the range of contributory causal factors that affect other system elements, as well as runners' behaviours in relation to RRI risk.

1. Introduction

On both a local and global scale, the sporting activity of distance running has been increasing in popularity over the last four decades. This is likely attributable to a growing societal concern around a documented rise in several lifestyle-related chronic diseases (Harold et al., 2016; Lee et al., 2017). As a form of exercise, recreational running provides significant beneficial effects on a range of biomedical health indices (Lee et al., 2014; Hespanhol et al., 2015), and is the preferred physical activity of choice for many people given its high accessibility and relatively low financial cost (Cregan-Reid, 2016). Furthermore, the growth associated with running-related festivals, ranging from charity-based events in regional communities to major annual marathons in some of the

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world's most iconic cities, is attracting both participants and large crowds of spectators (Strout, 2016). Notwithstanding the many health-related benefits that running offers to its regular adherents, the risk of sustaining a running-related injury (RRI) can be high. Depending on the ability level of the runner, the RRI incidence rate has been found to range from 2.5 to 33.0 injuries per 1000 h of running (Videbæk et al., 2015). Over a $\geq$12-month follow-up period, the time-loss injury incidence proportion in novice, cross-country, and long-distance runners has reportedly reached 84.9%, 77.4%, and 43.2%, respectively (Kluitenberg et al., 2015).

Over the last forty-five years, the science behind RRI causation and prevention has attracted considerable interest amongst sports injury researchers and scientists. During that time, there has been a concerted scholarly effort to understand the aetiology of RRI from an epidemiological and clinical research-based standpoint (Hulme and Finch, 2016). In fact, traditional scientific approaches have attempted to identify the effect of discrete training-related, behavioural, and/or biomechanical exposures on the risk of developing either general or specific RRI (Buist et al., 2010; Grau et al., 2011; Bredeweg et al., 2013; Malisoux et al., 2013; Nielsen et al., 2013). Typical training-related and behavioural exposures are related to running practice (e.g. weekly distance, duration, and frequency), diet, psychology, footwear, and terrain and surface (Hulme et al., 2016). On the other hand, biomechanical investigations cover a range of exposures relating to ground reaction force, range of motion, static limb measurement, and muscular strength and endurance (Zadpoor and Nikooyan, 2011; Newman et al., 2013; van der Worp et al., 2016). Despite this considerable body of work, several descriptive (Hoeberigs, 1992; van Mechelen, 1992; Hreljac, 2004; Ryan et al., 2006, Fredericson and Misra, 2007; Wen, 2007; Fields et al., 2010; Gingrich and Harrast, 2015) and systematic reviews (van Gent et al., 2007; Nielsen et al., 2012; Saragiotto et al., 2014; van der Worp et al., 2015; Hulme et al., 2016) have not been able to offer any compelling reasons for why runners sustain RRI.

There are many different reasons for why it has been difficult to identify aetiological mechanisms underpinning RRI. Given the time and space required to discuss those reasons, the reader is invited to review them elsewhere (Verhagen, 2012; Nielsen et al., 2014; Malisoux et al., 2015; Hulme et al., 2016; Nielsen et al., 2016). In this article, we argue for a complementary research approach that, alongside the continuing application of epidemiological and clinical research-based applications, will help to better understand the range of contributory causal factors that precipitate the development of RRI. More specifically, there is a current need to elucidate the many political, organisational, managerial and sociocultural processes that comprise the mediating pathways that influence runners' training-related and behavioural practices in relation to the development of RRI. To address this knowledge gap, and to complement traditional forms of scientific inquiry, this paper proposes the use of systems ergonomics research approach.

1.1. Applying systems ergonomics theory to RRI causation and prevention

Systems ergonomics is the study of 'sociotechnical systems' which examines the interactions between people, and a range of organisational and technological factors that influence their beliefs, decisions, and behaviours (International Ergonomics Association, 2016). By extension, the whole of society itself is one large sociotechnical system that is evolving at a rate dependant on the introduction of new procedures, knowledge, and technologies (Vicente and Christoffersen, 2006). Historically, the application of systems-based approaches was reserved for studying safety-critical domains as found in engineering and industrial work contexts, particularly in relation to improving employee well-being and optimising the performance of human-machine interactions (Walker et al., 2008; Wilson, 2014). Given the versatility and utility of these approaches for enhancing safety in other life domains (Holden, 2009; Salmon et al., 2012), scholars have recently offered compelling arguments for why otherwise 'simple' human-led physical activities are also taking place in systems that are both complex and sociotechnical in nature (Davis et al., 2014; Carden et al., 2017).

In one of our previous studies (Hulme et al., 2017), the Systems Theoretic Accident Mapping and Processes (STAMP) method (Leveson, 2004) was used to develop a prototype control structure model of the Australian recreational distance running system. The prototype model identified who might reside in the overall system (e.g. runners, athletic coaches and trainers, community allied health professionals, advocacy groups, and athletics governing bodies), as well as what 'control' and 'feedback' mechanisms might exist between them (Hulme et al., 2017). Its aim was to conceptualise that safe running practices and the management of RRI risk should be viewed as a 'control problem' that occurs when latent failures and disruptions to the normal functioning and operations across the distance running system are not adequately managed or monitored by its contained actors and organisations. The prototype model was primarily created to demonstrate the argument that systems ergonomics methods based on a systems-theoretic approach to accident analysis have much to offer to sports injury prevention research. Whilst the prototype model is useful from an ecological standpoint, there is a need to validate it to ensure that it accurately represents the system under investigation. Therefore, the purpose of this study was to draw on the expertise of both systems thinking and distance running experts to validate the prototype Australian distance running systems model.

2. Methods

This study used a modified Delphi technique whereby a panel of subject matter experts provided rounds of feedback on the content of a prototype Australian distance running systems model (hereby referred to as 'prototype model'). This study was approved by the Federation University Australia Human Research Ethics Committee (project number B16-180).

2.1. Creation of the prototype model

There are two main components associated with the STAMP method and its associated control structure: (i) system development (including both the development process itself and the resulting system design); and, (ii) system operation (which under ideal conditions, nurtures safe behaviours) (Leveson, 2004). Accordingly, the prototype model was constructed incrementally in the following stages: (i) the system operation component associated with the STAMP method was adapted to fit the target context; (ii) the actors and organisations who were considered to reside at each of the model's five different hierarchical levels were identified; and, (iii) the control and feedback mechanisms that were thought to exist between those levels were added.

Information derived across various sources facilitated the development process, including documentation related to recreational running (e.g. Athletics Australia), stakeholder websites (e.g. Australian Sports Commission), and the academic literature. In addition, the authors' own knowledge of the RRI domain (Hulme and Nielsen), and other authors' extensive experience in use of systems ergonomics methods (Salmon and Read) helped to further refine certain aspects. A more detailed description of the original STAMP method, including control theory and its adaption to the distance running context, can be found in existing resources (Leveson, 2004; Leveson et al., 2009; Hulme et al., 2017).

2.2. Delphi technique

The Delphi technique brings together the opinions and knowledge of subject matter experts, and consolidates their feedback to reach group consensus about a chosen topic of interest. An advantage of this approach over other consensus-driven methods, such as committee meetings or focus group interviewing, is the freedom from intimidating scenarios whereby certain participants might feel inhibited and/or time-pressured to express their views in the immediate presence of others (Williams and Webb, 1994). Several studies in the context of sports safety research provide support for the effective use of a Delphi technique (Donaldson and Finch, 2012; Donaldson et al., 2013, 2015; White et al., 2014; Donaldson et al., 2015). In other safety-critical domains, experts were used to validate a STAMP model of road trauma in the Australian road transport system (Salmon et al., 2016).

In this study, the Delphi technique involved a series of online surveys, and adhered to the fundamental principles of respondent anonymity and feedback between rounds. The minimally acceptable level of agreement among experts is known to differ across studies utilising a consensus-driven approach (Keeney et al., 2006). In this study, consensus in opinion about the validity of the prototype model was deemed to be reached when the number of experts who agreed or disagreed with a statement was $\geq$75% of the total number of respondents. It was not possible to know *a priori* how many Delphi rounds would be required to reach consensus.

2.3. Identification of subject matter experts

Both complex systems modelling practitioners and distance running experts were invited to participate. The former group included academics with research expertise who worked in university departments and/or research centres that were concerned with the application of systems thinking approaches towards understanding human health and/or safety in complex sociotechnical systems. The latter group comprised experts who worked with runners in coaching roles, were qualified to prescribe performance and/or injury advice, were aware of contemporary theories of endurance training, and/or who knew about, sports policy in relation to distance running. The experts were identified from the authors' personal contacts within the research community, authors of peer-reviewed publications in the scientific literature, as well as websites that included professional profiles of relevant experts. Given the limited number of distance running injury researchers operating in Australia, the sampling of participants occurred both nationally and internationally.

2.4. Survey development and methods

For each round of the Delphi process (December 2016–March 2017), participants were sent an e-mail which included an electronic version of the prototype model, as well as instructions for completing the online survey which included an explanation and definitions form (Electronic Supplementary Material A). Participants were given four weeks to return the initial survey, and two weeks thereafter for follow-up surveys. Non-responders received a reminder email during the week following each deadline. The initial survey solicited information about participants' age, gender, primary occupation, qualifications, and perceived level of expertise in relation to complex systems thinking and modelling, as well as distance running and injury prevention more generally. Following that, the survey was divided into four sections containing a total of seven questions (Table 1). Each survey question followed an answer format of 'yes', 'no', or 'don't know'.

2.5. Model changes and methods

If participants did not agree with any of the question(s) presented in Table 1, they were asked to specify further, with comments, why they considered that the prototype model did not meet that criterion. It was here that the experts could elaborate and describe explicitly what changes and/or additions were needed. Participants were advised that their suggestions might feature in a revised systems model that would be resent with another survey containing the same four sections and seven questions. It was here that participants were also notified about the specific changes that had been made following the first round. However, initially deciding whether to incorporate the experts' feedback was a matter of careful deliberation between authors (Hulme, Nielsen, Salmon and Read). To achieve this, meetings were held to identify common or conflicting views, and each suggestion was debated until a joint decision about the feasibility of including the change(s) was made.

2.6. Participant demographics and personal characteristics

Out of a total of 51 experts who were initially contacted through email, 50.9% (n = 26) completed the first round of the Delphi. A total of 92.3% (n = 24) of the round one participants also completed the second (and final) survey, and answered all questions. Of the two participants who did not respond to the follow-up survey, one was an academic researcher aged 45–54 years, with a high self-reported level of expertise in systems thinking/theory. The other was a qualified health professional and running coach and athletic trainer aged 25–34 years, with a high self-reported level of expertise in distance running. There were 14 Australian and 10 international experts.

Most of the participants (n = 24) were between the ages of 25–44 years, and three-quarters of responders identified as being male (Table 2). In terms of area(s) of expertise, over half of the participants reported practicing running, closely followed by working as a qualified health professional. There were two running coaches or athletic trainers, with eight experts identifying as being a systems thinker and/or modeller. Regarding the alignment of disciplinary expertise, more participants considered themselves to be a running expert rather than systems thinker. The highest self-reported level of expertise was associated with the science of distance running, followed by a moderate level of expertise for injury prevention research (Table 3). Half of the sample indicated a moderate or high level of expertise in the systems ergonomics and modelling disciplines.

3. Results

3.1. Modifications to the prototype model

Based on the feedback provided by the 24 experts who participated in both rounds of the Delphi process, numerous modifications to the prototype model were made. Many of those modifications were minor, and included changes to existing features associated with the prototype model, as well as new additions that were initially absent (Table 4). Conversely, other modifications were major in nature given that they considerably changed the model's overall appearance.

3.2. Major changes

In the prototype model, level five contained a relatively simple representation of the runner and their immediate environment, including a range of distinct factors such running surface, terrain, and the built environment (Hulme et al., 2017). As such, many of the experts did not agree that the prototype model appropriately accounted for the theoretical causal relationships between those individual and environmental factors and RRI development. This prompted a revision to level five to better conceptualise the imbalance between the application of running load, and the capacity of the musculoskeletal system to tolerate it. Therefore, the interaction between, and the effect of, anthropometric and biomechanical exposures (e.g. body mass index, ground reaction force), other personal characteristics (e.g. genetics, psychosocial factors), and lifestyle-related variables (e.g. diet, sleep, activities of daily living), was incorporated.

3.3. Overall validation results and final model

The results associated with each round of the Delphi are presented in Table 5. Only question seven associated with round one reached a ≥75% level of agreement, prompting the need to further incorporate relevant expert feedback, revise the prototype model accordingly, and disseminate it for a second time. Regarding the first round of Delphi, questions three (25.0%), five (37.5%), and six (29.2%) attracted the lowest agreed consensus values. Group consensus was reached in the second round, and 91.7% of the experts agreed that the STAMP model was a valid description of the Australian distance running system. For this reason, the Delphi process was stopped after round two. The validated model is presented in Fig. 1.

3.4. The Australian distance running systems model

Fig. 1 contains two mutually inclusive components: (i) a sociotechnical systems context that contains multiple actors and organisations including the numerous control and feedback mechanisms between them (i.e. level one to level four, inclusive); and, (ii) a theoretical causal schematic that visualises the relationship between individual-level factors and RRI development (i.e. level five).

The downward flowing control mechanisms that connect levels one to four with level five, indicate the system-wide constraints that are imposed on other actors and organisations, as well as the runner and their behaviours. Likewise, the feedback mechanisms that connect level five with levels four to one, indicate varied types of information and communication that are passed from the runner to other actors and organisations across the system. The permeated boundary around level five demonstrates that the causal schematic is mutually inclusive with the sociotechnical systems context.

The legend/key associated with Fig. 1 needed to reflect the major changes that occurred between round one and round two of the Delphi process. Notably, there are two legends; one that applies to the sociotechnical systems context, and the other to the theoretical causal schematic. Included in the latter is a definition of the only necessary causal factor for RRI development (i.e. running participation expressed as stride number), alongside other important concepts that are unmeasurable in field-based studies (i.e. structure-specific load capacity and structure-specific cumulative load).

Table 2
Demographic characteristics, and the area(s) and alignment of expertise for the 24 experts who participated in both rounds of the Delphi.

	Frequency (n)	Sample proportion (%)
Age range (years)		
25–34	8	33.3
35–44	10	41.7
45–54	3	12.5
55–64	3	12.5
Gender		
Male	18	75.0
Female	6	25.0
Expertise area(s) [a]		
Runner	14	58.3
Qualified health professional	13	54.2
Academic researcher	10	41.7
Systems thinking/modeller	8	33.3
Running coach or athletic trainer	2	8.3
Expertise alignment		
Distance running	16	66.7
Systems thinking/theory	8	33.3

[a] Participants were permitted to state ≥1 area of expertise.

4. Discussion

The purpose of this study was to draw on the expertise of both systems thinking and distance running experts to validate a prototype Australian distance running systems model (Hulme et al., 2017). To achieve this, a total of 24 experts answered a series of questions in relation to several different features associated with the model. Group consensus about its overall validity, defined *a priori* as a ≥75% level of agreement for a given question, was reached after two Delphi rounds. The validated model of the Australian distance running system will now be able to facilitate theoretical advancement in terms of identifying key areas of further research, alongside practical system-wide opportunities for the implementation of sustainable RRI prevention interventions. This 'big picture' perspective also represents the first step required when thinking about the range of contributory causal factors that function externally to the runners themselves. From a systems ergonomics perspective, RRI occurs when the control or feedback mechanisms described in the model are inadequate or deficient, and for that reason, it is worth highlighting what control and

Table 1
Delphi sections and questions.

Delphi category and associated question(s)
Review of levels, and actors and organisations
1. Are each of the level descriptors labelled appropriately?
2. Are the actors and/or organisations labelled appropriately on each level?
3. Have all relevant actors and/or organisations been included?
4. Are there any actors and/or organisations better placed at another level?
Review of control mechanisms
5. Have all relevant control mechanisms been included?
Review of feedback mechanisms
6. Have all relevant feedback mechanisms been included?
Overall
7. Is the prototype model a valid description of the distance running system?

Table 3
Perceived level of disciplinary/practice expertise based on different criteria for the 24 experts who participated in both rounds of the Delphi.

	Expertise rating % (n)			
Criteria	None	Low	Medium	High
The science of distance running (i.e. endurance training theory/injury prevention)	8.3 (2)	20.8 (5)	16.7 (4)	54.2 (13)
Participation in distance running itself (i.e. coach/runner)	16.6 (4)	29.2 (7)	29.2 (7)	25.0 (6)
Systems thinking/theory (i.e. ergonomics methods/simulation modelling)	4.2 (1)	45.8 (11)	37.5 (9)	12.5 (3)
Injury prevention research in general (e.g. road/workplace safety)	4.2 (1)	16.7 (4)	45.8 (11)	33.3 (8)

Table 4
A list of minor changes which includes several modifications to existing features, as well as new additions that were factored into the prototype model based on the feedback from the 26 and 24 experts who participated in round one and round two of the Delphi, respectively.

Changes to existing features	New additions
Level 5 renamed to 'Runner & The Running Process'	'Running-Related Injury' was included in the model
Level 4 renamed to 'Running Management, Supervision & Injury Prevention'	'Internet Forums' added to level 4
Level 3 renamed to 'General Service & Healthcare Providers'	'Instruction & Supervision' added as a control from level 3 to level 5
The 'Australian Sports Commission' moved from level 1 to level 2	'Education & Advice' added as a control from level 2 to level 5
'Government Health Departments' omitted	'World Health Organisation' added to the International Context
'Event Organisers' renamed to 'Event & Charity Organisers' (level 3)	'Funding & Resource Allocation' added as a control from level 2 to level 4
'Employers' renamed to 'Employer & Worksite' (level 3)	Targets & Performance Measures' added as a control from level 2 to level 4
'Running Clubs' renamed to 'Running & Sports Clubs' (level 3)	'Public Opinion & Advocacy' added as feedback between level 5 and level 3
Athletics Facilities renamed to 'Athletics and Sports Facilities' (level 3)	'Funding & Resource Allocation' added as a control from level 3 to level 5
'Peer Groups' and 'Family Members' merged into a single entity (level 4)	'Orthotists' added and merged with 'Podiatrists' to form a single entity

feedback mechanisms are in place, who is responsible for them, and which ones are likely to be most integral in relation to RRI risk. The following discussion touches on those features, focussing initially on who shares responsibility for the development and prevention of RRI, as well as the practical implications associated with the sociotechnical systems context (i.e. system levels one to four) and the causal schematic component which was introduced into the model based on the feedback received during the Delphi process (i.e. system level five).

4.1. Who and what is in control of RRI?

Traditional accident and injury analysis methods, which are typically used to identify and understand the role of discrete causes, are highly suitable if the goal is to intimately understand how individual-level 'parts' function in relation to the 'whole'. Indeed, in the sports injury prevention context, well-designed and rigorous epidemiological and clinical research-based applications are profoundly capable at determining the strength of the effect between singular proximate causes and RRI development (Hulme et al., 2016). Such information is useful, primarily because it means that researchers and scientists can attempt to manipulate significant training-related, behavioural, and biomechanical exposures with a targeted and well-defined RRI prevention intervention (Hulme et al., 2017). On the other hand, reductionist scientific approaches are limited in the sense that they cannot understand how dynamic interrelationships between various system-wide elements might contribute to the RRI problem across both time and space (Hulme and Finch, 2015). Therefore, when attempting to better understand the aetiology and prevention of RRI, the overarching research approach that is used, including its specific focus, purpose and questions being asked, will dictate where one intends to initially penetrate the system and commence the process of scientific inquiry. A continuum of biological organisation that incorporates systems ergonomics theory is visualised (Fig. 2).

A key contribution of the approach taken in this study is that a diverse set of actors and organisations were confirmed by experts to share responsibility for the development and prevention of RRI. Whilst some of the actors and organisations are expected (e.g. other runners, sports coaches, and physiotherapists), others are perhaps less often considered in relation to role they play in RRI management (e.g. event organisers, the media, state and territory sport and recreation departments, and tertiary research institutions). The validated model demonstrates that the depicted actors and organisations place numerous constraints on other elements across the system, including runners' behaviours through a series of control mechanisms. Likewise, runners and other actors and organisations provide information regarding the state of the system back to the

Table 5
Comparison of consensus results between round one and round two of the Delphi.

	Round one sample proportion (%)			Round two sample proportion (%)		
Delphi category and associated question(s)	Yes	No	Unsure	Yes	No	Unsure
Review of levels, and actors and organisations						
1. Are each of the level descriptors labelled appropriately?	70.8	16.7	12.50	87.5	12.5	0.0
2. Are the actors and/or organisations labelled appropriately on each level?	66.7	16.7	16.7	87.5	12.5	0.0
3. Have all relevant actors and/or organisations been included?	37.5	25.0	37.5	75.0	20.8	4.2
4. Are there any actors and/or organisations better placed at another level?	25.0	50.0	25.0	20.8	79.2	0.00
Review of control mechanisms						
5. Have all relevant control mechanisms been included?	50.0	37.5	12.5	79.2	12.5	8.3
Review of feedback mechanisms						
6. Have all relevant feedback mechanisms been included?	45.8	29.2	25.0	83.3	8.3	8.3
Overall						
7. Is the prototype model a valid description of the distance running system?	83.3	8.3	8.3	91.7	4.2	4.2

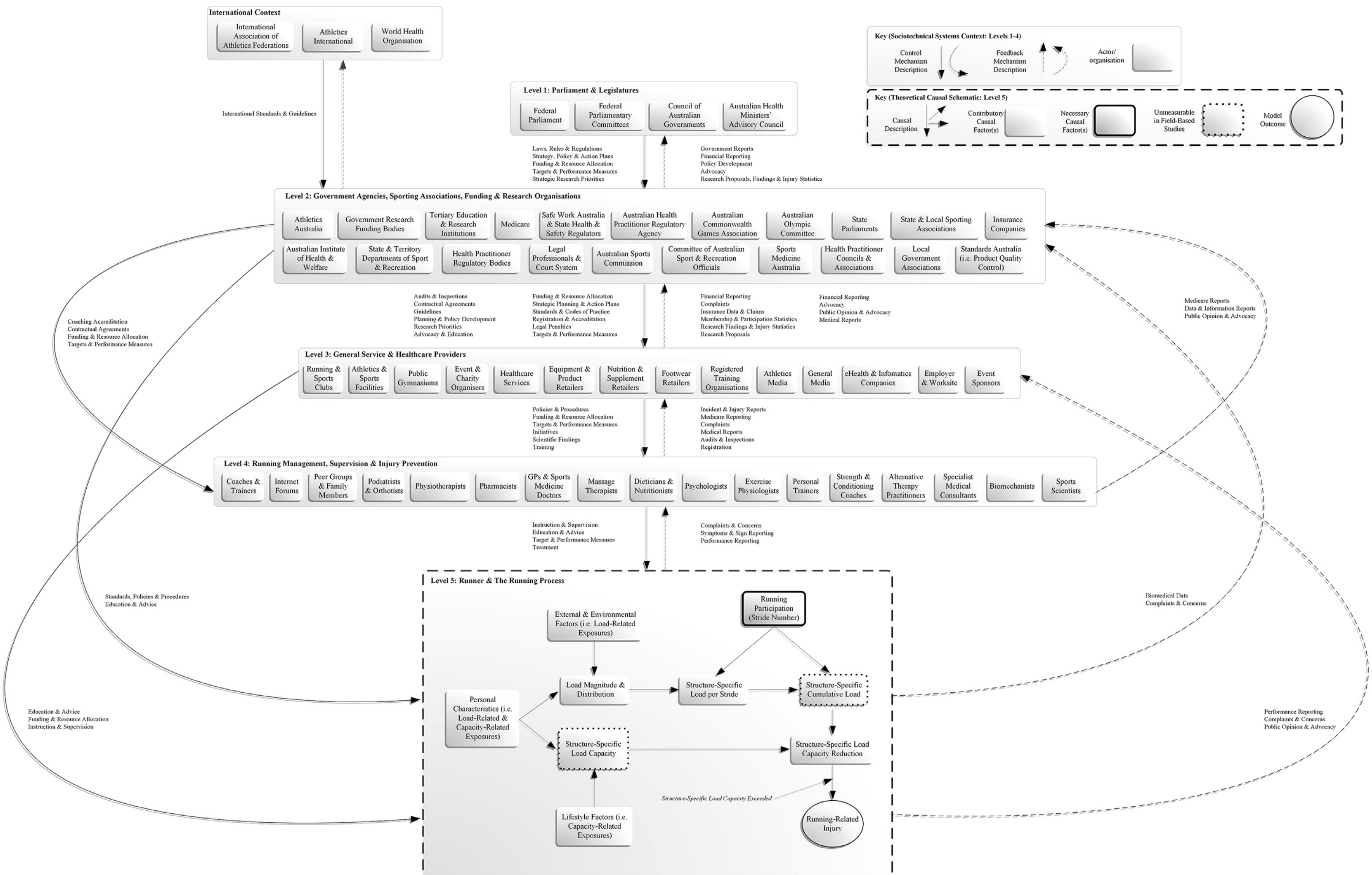

Fig. 1. The validated 'complex systems model' of the Australian distance running system.

entities that reside above them in the form of feedback mechanisms, which in turn informs decision making.

Consistent with STAMP and control theory, safety is an emergent property that results from the functioning and interactions that occur across an overall system (Leveson, 2011). In that regard, the control and feedback mechanisms that feature in the distance running systems model specify the expected relationships that constitute a non-hazardous or safe-system state. For example, ‘coaching accreditation courses’ associated with organisations such as Athletics Australia, are regulatory-based controls for sports coaches and trainers to enact out procedural-based controls on runners (level two → level four → level five). Similarly, ‘targets and performance measures’ can be imposed on practicing dieticians and physiotherapists by Health Practitioner Councils and Associations (level two → level four), whereas ‘standards and codes of practice' are enforced on employers and worksites from Safe Work Australia and state health and safety regulators (level two → level three). ‘Adequate funding and resource allocation’ from Federal Parliament is a necessary political-based control for tertiary education and research institutions to fulfil their varied roles, such as entering ‘contractual agreements’ with other registered training organisations (level one → level two → level three). Importantly, controls do not have to be political, regulatory, or procedural in nature (Leveson et al., 2009). ‘Instruction and supervision’ is an example of a value-based control that can influence running behaviours (level two → level five, and level three → level five). Likewise, ‘education and advice’ from podiatrists to the runner will not necessarily enforce constraints on behaviours (level four → level five), but under certain conditions, such instruction might result in biomechanical alterations that affect how the magnitude and/or distribution of running load is applied across specific musculoskeletal structures.

For the Australian distance running system to function as it should (i.e. to operate safely to minimise RRI risk), the control and feedback mechanisms across its levels are required to exhibit a state of dynamic equilibrium (Hale et al., 2006; Dekker and Pruchnicki, 2014). This means that any organisational and/or technological changes that occur within or across levels can, in certain instances, lead to unanticipated effects. For example, under the assumption that control or feedback mechanisms are inadequate or deficient, the introduction of specialised running footwear, the promotion of a new running event, or modifications to a national athletics coaching curriculum, might create the emergent conditions necessary for RRI to develop. As the complexity of the Australian distance running system increases in parallel with the proliferation of other innovative technologies, such as wearable fitness devices and electronic health tracking platforms (Rettner, 2013; Andreasson and Johansson, 2014; Piwek et al., 2016), it becomes ever more challenging to ensure that control mechanisms are balanced against varied forms of feedback (Carayon, 2006). Accordingly, the process leading up to a RRI event can be described as a maladaptive feedback function that fails to maintain safety as performance-oriented athletics goals and other organisational targets change over time. Fostering safe running practices is a continual control task, and runners’ motivations and behaviours should not be separated from the broader systems context and studied in isolation. Therefore, the systematic migration of organisational behaviour across the distance running system needs to be understood from the perspective of how it changes, adapts, and evolves.

Although the validated model was based on the system operation and not the system development component of the STAMP method (Leveson, 2004), it should be noted that human behaviours are also be influenced and partly ‘controlled’ by engineering the system in a different way. This presents an interesting line of further inquiry because, unlike other safety-critical system domains which can be engineered to achieve safety and reliability from the ground up (e.g. transportation networks, photochemical and nuclear power plants), the distance running system is somewhat of a subsystem nestled inside of a broader social system. The autonomy and free-agency of runners (i.e. their operative processes), are not constrained in any way by the maintenance of well-defined and engineered sociotechnical systems domain. For example, the validated model does not include the engineering processes underpinning the design and manufacturing of running footwear or the composition of road surfaces – it only includes actors and organisations such as footwear retailers and standards Australia. Despite the model's focus on the operative component of the STAMP method, system levels one to four provide an accurate description of the actors, organisations, and control and feedback mechanisms as found today.

4.2. The causal schematic of RRI development

In the broader field of RRI prevention research, scientists have, for the most part, been motivated by what are seemingly important questions. Does more cushioning in running footwear reduce the risk of RRI? (Theisen et al., 2013) Is muscular weakness associated with an increased risk of sustaining pathologies to the knee? (Thijs et al., 2011) Does bone mineral density have a relationship with the development of stress fracture? (Kelsey et al., 2007) Even though such questions are important for predictive purposes, the overwhelming majority of traditional scientific investigations have not attempted to examine how the external training load interacts with an underlying biological predisposition for RRI. Fortunately, to address this problem, a recent conceptual paper has presented a theoretical causal schematic to facilitate the design and conduct of future scientific studies in the RRI aetiological space (Bertelsen et al., 2017). That paper essentially argued that future investigations should focus on addressing how certain participatory-related exposures (e.g. running distance, time spent running, session frequency, or stride number) and non-participatory-related exposures (e.g. diet, body mass index, and footwear compliancy) change over time in relation to RRI risk (Bertelsen et al., 2017).

Given that many of the experts in this study agreed that the prototype model did not sufficiently take into consideration the causal relationships between individual-level exposures and RRI development, we adapted Bertelsen et al.'s (2017) causal schematic and incorporated it into the revised model (Fig. 3). Regarding Fig. 3, the only necessary causal factor for RRI development is running participation itself (denoted by a shaded box and solid line at level five), and this is expressed as ‘stride number’, since running distance or time spent running will not equally load a given runner's musculoskeletal system in the same way. The incorporation of Fig. 3 within the larger sociotechnical systems context provides an important integration of systems thinking with more traditional RRI scientific approaches.

4.3. Practical implications of the method and model moving forwards

In terms of the method employed in this study, future applied ergonomics research applications – whether related to the physical, cognitive or organisational domains of specialisation – could also consider using a Delphi technique with subject matter experts when attempting to either build or validate models and/or theoretical concepts. Indeed, in relation to validating the Australian distance running system, the systems thinking and distance running experts provided several important suggestions that led to essential changes associated with different aspects of the model.

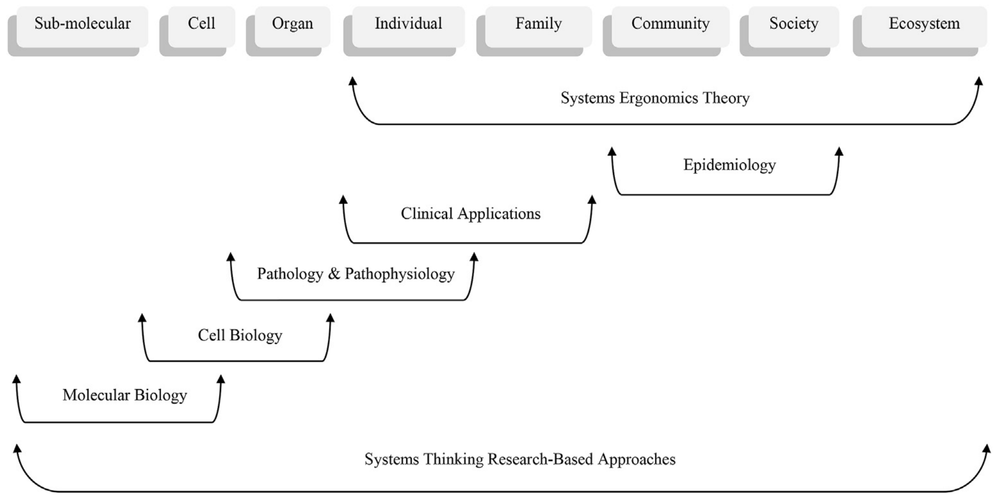

Fig. 2. A continuum of biological organisation. Adapted from Stallone with permission (1980).
The different levels of biological organisation, which range from the sub-molecular to the ecosystem levels, each have a firm role to play when it comes to understanding the functioning and behaviour of the natural world. However, from a scientific and research-based standpoint, where one intends to initially penetrate the system depends on the lowest and highest relevant points that are associated with a given topic and/or research question. Therefore, regarding the causal processes that underpin the aetiology of RRI, it makes little sense to investigate the sub-molecular, cell, or organ sub-system levels if primary prevention is the driving force behind the research. The traditional scientific approach in the RRI literature encompasses epidemiological and clinical research-based applications, but no study has yet considered the importance of social and ecosystem levels of determination.

The process itself was relatively problem-free and largely effective, and should be replicable provided others take a similar approach.

This paper presents a validated Australian distance running systems model that can now be used to inform two mutually exclusive purposes. Firstly, the validated model represents a standalone tool for making sense of system-wide complexity when planning and designing injury prevention interventions, and/or when thinking about their sustainability long term. For instance, closely examining the elements associated with levels one to four of the distance running system might expose possible leverage points when considering how to introduce the most effective organisational and policy-level options for RRI prevention. As such, the depicted control and feedback mechanisms indicate which other factors, actors and/or organisations are likely to be affected were a given change implemented at those systemic levels. Likewise, decision makers can refer to the validated model to identify where possible inadequacies in control and feedback mechanisms might reside. Secondly, practitioners can draw on the heuristic power of the validated model as a point of reference when planning to utilise more advanced systems-based computational modelling techniques (Mabry et al., 2010; Luke and Stamatakis, 2012). The validated model is a useful conceptual precursor to a range of sophisticated system science methods because it shows who and what is contained in the distance running system, as well as where existing control and feedback mechanisms are found.

4.4. Limitations

Despite the novelty of this study and its theoretical contribution to the literature, several limitations should be noted. First, the initial proportion of responders was 51%, which might indicate selection bias as only those individuals who have a serious interest in reducing the risk of, or preventing RRI, could have agreed to participate. Second, a larger sample size might have produced a greater variation in terms of the feedback received given that both distance running and systems thinking experts were required. However, the inclusion of 24 participants in this study is in line with previous Delphi studies (White et al., 2014; Donaldson et al., 2015). Third, although much of the feedback from the experts was incorporated, not every suggestion was addressed given that the overall purpose was to achieve group consensus. Fourth, many of the identified experts were sampled from an international context even though they were being asked to comment on a model for the Australian setting. Nonetheless, their depth and range of knowledge was found to be highly relevant and useful. Fifth, most of the experts self-identified as being a distance running expert, and only half of the final sample indicated a moderate or high level of expertise in the systems ergonomics and/or modelling disciplines. Including feedback from experts with background in sports policy is likely to have benefitted the validation of the systemic levels associated with the sociotechnical systems context. Sixth, other questions regarding the model could have been asked of the experts, such as which actors and organisations, or control and feedback mechanisms are considered most influential in relation to the RRI problem. However, such questions were not included because they relate more to a model building phase rather than a validation process. Seventh, the model is highly abstract and does not illustrate one-to-one control or feedback mechanisms such that it is possible to know that a given actor or organisation imposes constraints on another.

5. Conclusion

There has been a recognised need in the RRI prevention research context for a systems thinking theoretical perspective to complement traditional forms of scientific inquiry. The use of a systems ergonomics method in a previous study informed the creation of a prototype model of the Australian recreational distance running system. In this study, 24 systems thinking and distance running experts validated that prototype model. The theoretical benefits of the validated model are: (i) it recognises that multiple persons and organisations are, in some way, involved in RRI and its control; (ii) that runners' beliefs are formed, and behaviours and actions are executed, when systemic determinants exert their influence on more proximal factors; (iii) that the efficacy of targeted educational programmes and behavioural change interventions at reducing the

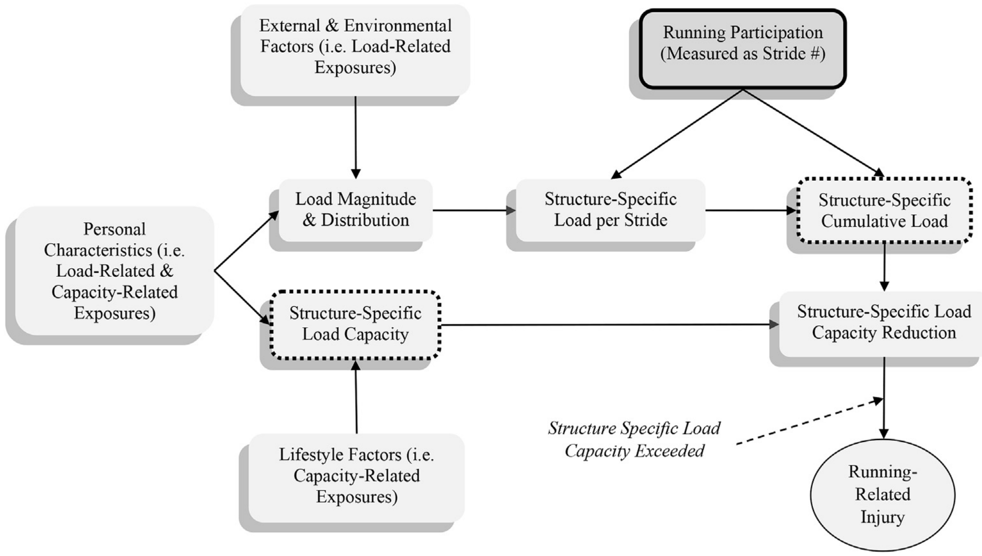

Fig. 3. The relationship between Structure-Specific Load Capacity, Structure-Specific Cumulative Load, and RRI. Adapted from Bertelsen et al. (2017) with permission. In describing Fig. 3, both the structure-specific load capacity and structure-specific cumulative load can be affected, both directly and indirectly, by personal characteristics, such as demographics (e.g. age and sex), anthropometrics (e.g. height, weight, and body mass index), biomechanics (e.g. ground reaction forces), psychology (e.g. personality disposition), and genetics. External and environmental factors (e.g. footwear, surface, and terrain) do not affect structure-specific load capacity, given that the latter has been defined as the capacity of a specific bodily structure to withstand load prior to entering a single running session. Conversely, lifestyle factors (e.g. diet, sleep, activities of daily living, employment obligations, and rest periods between running sessions) can influence the level of structure-specific load capacity that a runner enters a training or competitive session with. The structure-specific load capacity exceeded (or 'inciting event') occurs when the reduction of a specific-structure's capacity to tolerate the applied structure-specific cumulative load surpasses a physiologic threshold resulting in RRI. Notably, external and environmental factors, personal characteristics, and lifestyle factors, do not have a direct relationship with RRI. Moreover, structure-specific load capacity and structure-specific cumulative load cannot be quantified in large scale epidemiological and field-based studies (denoted by dashed lines), and so proxy measures are used.

risk of RRI can be affected based on the availability of system-wide resources that ultimately ensure their sustainability; (iv) that a dynamic interface exists between the individual runner and their political, organisational, managerial, and sociocultural environments, and it is a series of latest system-wide control-based deficiencies or failures that manifest as a localised and identifiable event immediately preceding RRI development. The practical benefits associated with the validated model are: (i) it can be used as a standalone tool when making sense of system-wide complexity. Here, the validated model might expose possible leverage points when thinking about how to introduce the most effective organisational and policy-level options for RRI prevention; (ii) its heuristic power can be used as a point of reference when planning to utilise more advanced systems-based computational modelling techniques; and, (iii) the validated model can serve as a point of reference when thinking about how it can be adapted to the distance running and/or chosen sports system as found in other jurisdiction and countries.

Author information

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.apergo.2017.07.005.

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