Theoretical Issues in Ergonomics Science

ISSN: 1463-922X (Print) 1464-536X (Online) Journal homepage: http://www.tandfonline.com/loi/ttie20

Closing Pandora's Box: adapting a systems ergonomics methodology for better understanding the ecological complexity underpinning the development and prevention of running-related injury

A. Hulme, P. M. Salmon, R. O. Nielsen, G. J. M. Read & C. F. Finch

To cite this article: A. Hulme, P. M. Salmon, R. O. Nielsen, G. J. M. Read & C. F. Finch (2017): Closing Pandora's Box: adapting a systems ergonomics methodology for better understanding the ecological complexity underpinning the development and prevention of running-related injury, Theoretical Issues in Ergonomics Science, DOI: 10.1080/1463922X.2016.1274455

To link to this article: http://dx.doi.org/10.1080/1463922X.2016.1274455

THEORETICAL ISSUES IN ERGONOMICS SCIENCE, 2017
http://dx.doi.org/10.1080/1463922X.2016.1274455

Taylor & Francis
Taylor & Francis Group

Closing Pandora's Box: adapting a systems ergonomics methodology for better understanding the ecological complexity underpinning the development and prevention of running-related injury

A. Hulme [a], P. M. Salmon [b], R. O. Nielsen [c], G. J. M. Read [b] and C. F. Finch [a]

[a]Department of Human Movement and Sports Science, Australian Centre for Research into Injury in Sports and its Prevention (ACRISP), Federation University Australia, Ballarat, Australia; [b]Centre for Human Factors and Sociotechnical Systems, Faculty of Arts, Business and Law, University of the Sunshine Coast, Sunshine Coast, Australia; [c]Department of Public Health, Aarhus University, Aarhus, Denmark

ABSTRACT

The popularity of running as a form of exercise continues to increase dramatically worldwide. Alongside this participation growth is the burden of running-related injury (RRI). Over the past four decades, traditional scientific research applications have primarily attempted to isolate discrete risk factors for RRI using observational study designs as commonly used in public health epidemiology. Unfortunately, only very few randomised controlled trials have evaluated the efficacy associated with a well-specified RRI prevention intervention. Even though the knowledge about risk factors as generated in observational studies is valuable for better understanding why RRI develops, it nonetheless means that there remains a major knowledge gap about how best to prevent it, especially in a way that fully addresses all causal factors. Alongside the continuing use of traditional scientific approaches, a particular systems ergonomics methodology should also be considered in light of its potential to visualise the complete distance running system. This article adapts the Systems Theoretic Accident Mapping and Processes (STAMP) model to the RRI research prevention context. The direct application of STAMP might offer new knowledge about how to prevent RRI, such as exposing questions around the feasibility of adopting novel injury prevention interventions that do not directly target runners themselves.

ARTICLE HISTORY
Received 14 September 2016
Accepted 15 December 2016

KEYWORDS
Systems ergonomics; epidemiology; running injury; STAMP; systems complexity; injury epidemiology; injury prevention

Relevance to human factors/ergonomics theory

This is the first piece of scholarly work to apply systems ergonomics theory to the context of distance running-related injury. The results generated in this work will have direct implications to both future research and the end users of the distance running sociotechnical system as presented in this manuscript.

CONTACT A. Hulme a.hulme@federation.edu.au

Supplemental data for this article can be accessed http://dx.doi.org/10.1080/1463922X.2016.1274455.

Introduction

In Greek mythology, Pandora's Box was an artefact said to contain the 'evils of the world'. According to the legend, when curiosity took hold of the bearer, the seemingly innocuous act of opening the box would have unexpected and deleterious consequences. This peculiar sense of ancestral inquisitiveness is a perpetuating trait of the human condition (Litman 2005). Indeed, despite humankind's general desire to achieve a state of solidarity in the search for broader ontological meaning, our innate curiosity in better understanding the natural world is not necessarily a good thing when devoid of critical introspection. So, what of the same degree of curiosity and interest for particular scientific topics of the modern day? The topic which concerns us here is the sporting activity of distance running, a popular physical pastime that provides enormous health benefits for the individual (Hespanhol et al. 2015), yet equally, is struggling to move past the barrier of musculoskeletal injury that afflicts many of its adherents (Kluitenberg et al. 2015; Videbæk et al. 2015).

Since the late 1970s, the scientific literature underpinning the development and prevention of running-related injury (RRI) has experienced considerable growth (Nielsen et al. 2012; Hulme et al. 2016). Few risk factors have been identified, with a history of previous injury being the most strongly supported (van Gent et al. 2007; Saragiotto et al. 2014; Hulme et al. 2016). Accordingly, further scientific investigations are now required to rule out, or not, the existence of a casual effect associated with the vast majority of other RRI exposures (Fields et al. 2010). However, does further investigation in this case comprise 'more of the same'? Should running injury prevention researchers habitually reduce understanding of a given causal mechanism by quantifying the contribution of individual-level risk factors selected a priori? From an analytical standpoint, traditional epidemiologic applications have attempted to produce effect sizes and adjusted measures of association linking time-fixed RRI exposures to injury risk using statistically driven analyses (van Middelkoop et al. 2008; Buist et al. 2010; Malisoux et al. 2013). Considerable methodological heterogeneity across studies, such as the use of different injury definitions and varied population samples, has also challenged the feasibility of being able to quantitatively synthesise data (Hulme et al. 2016).

Despite the sports medicine research community's genuine curiosity for, and sincere interest in, reducing the risk of RRI, knowledge generation about injury causation and its prevention has accumulated some inertia (Herzog 2016; Hulme and Finch 2016). The application of traditional behavioural and biomechanical studies to understand the development and prevention of injury in distance runners represents the 'metaphorical prop' exposing the inside of Pandora's Box. The proverbial box is certainly a provocative allegory, but it nonetheless signifies that a benign preoccupation to want to isolate biomedical risk factors, if continued, could start to hinder knowledge progression in relation to injury prevention efforts. Therefore, were the box to be left in its current 'open' position, the aetiology of RRI might be further promulgated as a paradigm-driven phenomenon best realised through the exclusive use of traditional scientific approaches (Hulme and Finch 2016). Closing it will necessitate the acceptance of original ideas and complementary methodologies, including a reconsideration of what it means to search for 'causes' in the health-based research disciplines, and how this informs the implementation of

RRI prevention interventions. A pragmatically oriented philosophical perspective, characterised by the mutually inclusive use of both cognisant theory and data derived via highly controlled scientific inquiry, is now required in the RRI context (Hulme and Finch 2015).

The purpose of this article is twofold: (1) to describe and discuss the counterfactual definition of causation as it applies to both public health and RRI research; and (2) to outline why a particular systems-based research approach should now be considered alongside traditional epidemiologic practice for better understanding the development and prevention of RRI. Accordingly, this narrative comprises two unique sections that will be reconciled by the time of its closure. The first section broadly orients around a purely scientific understanding of disease and injury causation and prevention as found in the health-based research disciplines, including the RRI context. The latter half subsequently shifts focus away from risk factor identification to the application of a particular ergonomics model that, quite literally, conceptualises the Australian recreational distance running system and the way in which RRI risk is controlled.

Research approaches to disease and injury causation and prevention in public health

Epidemiology and the counterfactual definition of causation

In terms of its operational description, epidemiology is the study and analysis of the distribution and determinants of health, disease and injury in defined human populations (Australian Epidemiological Association 2010). It is a multidisciplinary science that generates both descriptive and inferential statistical data, the latter of which can include highly generalisable parameter estimates around suspected cause–effect relationships (Webb, Bain, and Pirozzo 2005). There are many advantages associated with the traditional epidemiological approach, such as offering high levels of numerical precision and quantitative realism through the reduction of systematic bias (Ip et al. 2013). Epidemiology can, therefore, provide detailed information about the magnitude and severity of a specific population-level health problem, with the overall intention of quantifying the burden of disease and injury, as well as guiding the implementation of interventions and/or informing health-related policy change (British Medical Journal 2016). In the RRI context, epidemiology can provide detailed information about newly and currently injured runners (i.e. incidence and prevalence), including how many runners sustain injury over a specified period of time (i.e. usually expressed as the injury incidence rate per 1000 hours of running) (Videbæk et al. 2015).

With consideration of the highly versatile nature of epidemiologic practice, an integral aspect of the science is still very much concerned with the identification of risk factors for disease and injury. Around the 1950s, early discussions surrounding epidemiological observations to elucidate aetiological factors were highly influential, and contributed to the further development of mathematical assumptions about statistical associations for biologic inference formation (Gilliam 1953; Sartwell 1955; Lilienfeld 1957, 1959). The subsequent advent of pioneering epidemiological concepts, such as Hill's (1965) nine causal considerations and Rothman's (1976) sufficient component-cause model, were innovative in the sense that abstract causal theories were assimilated into methodological causal frameworks (Mackie 1965; Lyon 1967; Mackie 1980). Nowadays, it is self-evident that the true conceptual origins of causation in epidemiology partly emerged out of a metaphysical understanding about counterfactual reasoning (Simon and Rescher 1966; Lewis 1973a, 1973b). These philosophical roots were subsequently extended into the practical methods which most epidemiologists now use (Rubin 1974, 1978).

The epidemiologic counterfactual definition of causation remains the dominant approach in which to identify risk factors, or determine the efficacy of therapeutic or preventive interventions for disease and injury (Little and Rubin 2000; Maldonado and Greenland 2002). Counterfactual logic explains that, all things being equal, the exposure ($X_{=1}$) causes the outcome ($Y_{=1}$) if the probability of $Y_{=1}$ given $X_{=1}$ is different to the probability of $Y_{=1}$ given $X_{=0}$ (unexposed) (Parascandola and Weed 2001). Therefore, at the population level, the average causal effect is expressed as the risk difference, denoted: $\Pr(Y_{=1}|X_{=1}) - \Pr(Y_{=1}|X_{=0}) \neq 0$. In order to reach these types of subjunctive conclusions, epidemiologists deliberately manipulate exposures by allocating a well-defined intervention to one of two (or more) study groups in the form of a randomised controlled trial (RCT) (Höfler 2005a). Notably, it is not considered possible to observe multiple health-related outcomes under a single condition for the same group of individuals, and so $\Pr(Y_{=1}|X_{=0})$ represents the 'counter-to-fact' scenario. From a theoretical standpoint, the RCT is a relatively simple concept, and the processes of randomisation and statistical control, as well as the administration of a specific intervention, make it the most effective and reliable method in which to establish the cause or prevention of disease or injury (as will be later shown, this statement is dependent on the absence of systematic bias, interventional noncompliance and chance). More often than not, random group allocation or the delivery of an intervention is financially, logistically or ethically impractical, and so observational study designs are used in lieu of the RCT (Höfler 2005b).

The validity of using observational versus experimental data for causal inference formation has been a topic of much conversation in epidemiology (Vandenbroucke 2004). This is because in the absence of randomisation, a wide range of extraneous variables that operate across the life course will 'confound' the observed association between the exposure and outcome (Lawlor et al. 2004). Addressing this problem requires that observational studies are planned meticulously to account for a host of important lifestyle differences that are thought to differentiate exposed from unexposed individuals (von Elm et al. 2007). Closer to home, in the sports injury prevention research context, a number of observational RRI aetiologic investigations have attempted to control for spurious relationships with both methodological and statistical approaches. Examples have included restricting study populations to runners who do not participate in other sports (Nielsen et al. 2013), matching runners in different exposure groups according to age and injury history (Miller et al. 2007) and/or stratifying running samples so that a particular characteristic is shared, such as weekly running distance (Chang, Shih, and Chen 2012). Statistical adjustment though multivariable regression modelling is also a common approach in the health-based research disciplines more broadly, and can allow for the estimation of direct effects, which may or may not be causal, given the presence of several other covariates (Jepsen et al. 2004). For example, by including a range of exposures in a multivariable model, it was found that histories of previous injury, lower bone mass and menstrual irregularity were significant risk factors for skeletal stress fracture in female distance runners (Kelsey et al. 2007). However, caution should still be taken when interpreting results produced via variable selection based on *p* values in multivariable regression analyses, as this approach might lead to bias in small sample settings (Steyerberg, Eijkemans, and Habbema 1999). Over the years, the availability of other novel analytical constructs, such as time-to-event analyses, inverse probability weighting and structural equation modelling, has also helped to sharpen the estimation of direct causal effects from observational data (Greenland 2000; Hernán and Robins 2006b; Dekkers 2011; Naimi et al. 2014; Nielsen et al. 2016).

Despite the practical value associated with the use of analytical techniques in epidemiology, observational study designs are prone to an additional complication, namely, the absence of a well specified counterfactual intervention (Hernán 2005). In other words, modern causal inference methods are useful, not because they have the capacity to isolate risk factors per se, but because they are highly adept at identifying the effect of a well-defined intervention on a given health-related outcome (Glass et al. 2013). This delineation poses somewhat of a quandary; the epidemiologic counterfactual definition of causation is profoundly capable when used to identify discrete aetiologic factors, but in doing so, generally offers only implicit evidence in support of *how best* these factors can (or could) be manipulated in the 'real world' (Hernán and Taubman 2008). Consider, for example, a recent cross-sectional study, which after comparing differences between rearfoot alignment profiles in distance runners, found that a higher versus lower medial longitudinal arch significantly increased the risk of plantar fasciitis (Ribeiro et al. 2011). In this case, a range of possible injury prevention interventions could be suggested, including gait retraining, footwear type, training load modification, runner education, proprioceptive balancing and/or strengthening exercises.

In answering which of the above hypothesised interventions are most optimal for reducing RRI risk, the next logical step might be to conduct an RCT to determine whether, for example, the type of running shoe affects the risk of injury differently for runners who meet criteria for having high arches (Theisen et al. 2013). Even though randomisation followed by the delivery of a well-defined intervention is sound in theory, RCTs: (1) are not always feasible nor practical to conduct; or, (2) will not necessarily safeguard against an unbiased estimate of causal effects (Hernán and Robins 2006a). With regard to the latter point, reported RCTs across the RRI literature have been affected by common methodological limitations, such as loss to follow-up (e.g. Cobb et al. 2007), non-blinding (e.g. Ryan et al. 2010), interventional non-compliance (e.g. Bredeweg et al. 2012) and confounding given small sample sizes (e.g. Jakobsen et al. 1994). Out of these limitations, interventional non-compliance is particularly problematic as it might bias the effect of the injury prevention intervention, especially when it is questionable whether or not distance runners have been exposed to a comparable level of running exposure (Buist et al. 2008). In turn, these issues necessitate the same degree of due diligence towards causal inference formation that is associated with the interpretation of observational studies (Hernán 2004). Therefore, given the feasibility and/or difficulties associated with the conduct of RCTs, observational study designs have often been the only means available in which to investigate questions about the aetiology of RRI. This has resulted in the generation of a long list of potential risk factors for RRI, with many still requiring further investigation.

From individual risk factor identification to ecological frameworks

The process of identifying risk factors for disease and injury is pejoratively labelled 'black box epidemiology' (Susser 2004; Neutra 2005). Black box epidemiology essentially characterises any health-based research approach that, irrespective of the analytical techniques used to adjust for confounding factors, seeks to isolate exposure-disease or exposure-injury observations (Weed 1998). As such, black box epidemiology is limited to identifying input–output associations, and cannot expose the specific mechanism(s) of aetiology or prevention (Hafeman and Schwartz 2009). Other authors have, however, disputed the pejorative black box connotation, and argued that the inner workings of a given causal mechanism do not necessarily require that they are completely understood in order to intervene and improve population health (Savitz 1994). In fact, many public health achievements have been made possible by triangulating the evidence from different scientific disciplines and study designs, all the while accepting that any observed association has to 'make sense' in terms of it having biological plausibility (Greenland, Gago-Dominguez, and Esteban 2004). It is for this reason that a given observed causal effect in the health-based research disciplines is more likely to be real when the following conditions for causation are confirmed (Lorenz and Paneth 2003):

1. the temporal relationship between the exposure and outcome is unequivocal (this is the only necessary condition for causation, and is determined in study designs that 'follow' participants' forwards over time);
2. a dose-response association can be demonstrated (i.e. more of the exposure causes more of the outcome as reflected by the strength of the effect measure);
3. the relationship has been consistently identified in a diverse number of populations across geographic boundaries;
4. a biologically plausible causal theory is proposed.

The above causal conditions can also be demonstrated in the RRI context directly. For instance, a range of observational study designs have consistently found a significantly increased risk of both general and specific RRI given a positive history of previous injury (e.g. Macera et al. 1989; Wen, Puffer, and Schmalzried 1998; Parker et al. 2011; Hirschmüller et al. 2012; Hespanhol, Costa, and Lopes 2013; Malisoux et al. 2013; Rasmussen et al. 2013). Across all of these studies, the magnitude of the effect linking previous injury to the development of subsequent injury was not only universally strong (signified by a relative risk estimate $\geq$ 1.51), but a comparable effect direction was also identified across a diverse range of running population samples in different geographical locations (Hulme et al. 2016). Biologically plausible explanations have since been proposed in support of why and how previous injury increases the risk of subsequent injury in both the RRI and general sports injury prevention contexts (Ryan, Maclean, and Taunton 2006; Finch and Cook 2013; Saragiotto et al. 2014; Hulme et al. 2016). In light of the causal conditions of temporality, strength, replication and biologic plausibility, the results associated with many different observational study designs have converged to support the conclusion that previous injury is a risk factor for subsequent RRI injury development.

Notwithstanding the importance of study replicability and the reproducibility of epidemiological evidence, the predilection for isolating risk factors for disease and injury at a single level of determination has attracted criticism (Terris 1993; Skrabanek 1994; Taubes 1995; Rockhill 2005; McKeown 2009). In the mid-1990s, a series of articles criticised the black box paradigm, and proclaimed that the 'hunt' for individual-level risk factors would one day be supplanted by sophisticated eco-epidemiological approaches (Susser and Susser 1996a, 1996b). The postulated eco-epidemiologic approach emphasised that determinations of human health were hierarchically organised, and interpersonal determinants such as political, environmental, cultural and social factors were inextricably interconnected with those at the proximate biologic and behavioural level (March and Susser 2006). By the end of twentieth century, the salient and forceful push for a new era in epidemiology stressed the need for ecological causal thinking (Susser 1998, 609):

> …if [epidemiology] is to rise to meet expectations, we shall have to command both the genies of molecules at the microlevel, and of social forces at the macrolevel…all systems, molecular or social, are dynamic. Over time, they select, adapt, and evolve. To capture the causal cycles, one must attend to time sequences at each level and across levels… in my view, risk factor epidemiology must change or fail.

Equally discontent with the preoccupation for singling out biomedical causes, other authors shared the view that epidemiology had to either re-establish its purpose, or face the prospect of losing its central role as a public health science (McMichael 1999; Schwartz, Susser, and Susser 1999). The natural evolution of time and progress has not silenced these strongly held concerns (Pearce and Merletti 2006; Krieger 2012; Kuller 2013).

From ecological frameworks to complex systems

Into the twenty-first century, it is increasingly evident that many public health issues are calling for novel approaches and/or methodological innovation in which to augment the still prevailing paradigm of risk factor identification (Cates 2013; Galea 2013; Keyes and Galea 2015). Indeed, despite widespread understanding that an ecological framework of causal processes in the health-based research disciplines might offer new insights for disease and injury prevention (Krieger 1994; Susser and Susser 1996a, 1996b; Susser 1998; Schwartz, Susser, and Susser 1999; Susser 2004; March and Susser 2006; Krieger 2012), certain public health issues which are proving highly difficult to solve, including RRI, have not yet benefitted from its application. In the sports injury prevention research context, for example, scholars have long advocated the use of an ecological approach that recognises injury results from the complex interplay between an athlete, their physical and social environments and sports delivery factors (Eime, Owen, and Finch 2004; Hanson et al. 2005; Allegrante et al. 2010; Hanson et al. 2012). That is, the occurrence of injury and its prevention is a 'wicked problem' (Hanson et al. 2012), requiring a sophisticated understanding of the complexity underpinning the implementation of preventive interventions, including what 'works', for whom, when and *why* – all the while accounting for *how* (Bekker and Cark 2016).

More recently, sports injury prevention researchers have started to argue specifically for the application of complexity science and/or systems-based research approaches that effectively build on the ecological paradigm with greater methodological rigour (Hulme and Finch 2015; Bittencourt et al. 2016). In particular, established frameworks, such as Translating Research into Injury Prevention Practice (TRIPP) (Finch 2006), have indicated where consideration of such systems-based approaches, including systemic-related causal factors for sports injury, are most needed to progress knowledge. The TRIPP (2006) framework essentially characterises a six-staged evidence-based research process toward sports injury control:

1. injury surveillance (i.e. establishing the extent of the problem);
2. mechanisms of injury aetiology (e.g. risk factor identification);
3. the development of injury preventive measures (i.e. appropriate intervention selection);
4. the evaluation of injury prevention interventions (i.e. assessing efficacy);
5. a description of the intervention context (e.g. translating efficacy into effectiveness);
6. the evaluation of injury prevention interventions in a specific implementation context.

Unfortunately, most sports medicine research is still placed at the early stages of TRIPP, concentrated on epidemiological data collection and injury surveillance (TRIPP stage one), as well as on black box studies that attempt to identify risk factors for injury (TRIPP stage two). For instance, in a systematic review compiling the evidence about risk and protective factors for RRI (Hulme et al. 2016), the number of observational studies that had identified statistically significant exposures ($n = 29$; 45%) far outweighed the number of RCTs (n = 8; 11%). Even though knowledge about risk factors as generated in observational studies is valuable, there is nonetheless a major knowledge gap about how best to develop injury preventive measures, especially in a way that fully addresses all causal factors for RRI development. As already contended in this article, this is partly a result of the limitations associated with the routine application of epidemiological approaches for this specific purpose. As such, the third TRIPP stage is not an epidemiological phase, but rather, it encompasses the theory and knowledge as produced via other baseline disciplines in public health research. This includes understanding human systems, including interpersonal and contextual delivery factors in their entirety, so as to identify potential solutions within a broad ecological framework (Finch and Donaldson 2010).

Recognition for the powerful influence of interpersonal determinants alongside individual-level causes in epidemiology is nothing new, at least in terms of enhancing understanding about disease and injury pathogenesis (McKeown 1979; Wing 1988; Loomis and Wing 1990; Dahlgren and Whitehead 1991; Fee and Krieger 1993; Krieger 1994; Wing 1994). However, only more recently have certain past lessons been reiterated as both necessary and useful in contemporary scientific discourse. In better elucidating the nature and structure of causal mechanisms in public health research, there has been an upsurge in the number of articles that discuss the need for, and use of, complex systems modelling approaches (Leischow and Milstein 2006; Midgley 2006; Sterman 2006; Trochim et al. 2006; Ness, Koopman, and Robert 2007; Auchincloss and Diez Roux 2008; Resnicow and Page 2008; Mabry et al. 2010; Diez Roux 2011; Marshall and Galea 2014; McClure et al. 2015; Bittencourt et al. 2016). Using the obesity epidemic as a case in point to illustrate the application of a systems-based methodology, Galea, Riddle, and Kaplan (2010) explained (99):

> If [the cause of obesity] truly reflects the combined effects of the interaction of multiple factors at the genetic, metabolic, behavioural, psychological, social network, built environment, institutional, food supply and food policy levels, then it would be surprising if it could be simply understood by reference to a single level of determination.

The same line of reasoning can be extended to the development and prevention of RRI.

Epidemiologic applications have only brought us so far in understanding why RRI develops, and how best to prevent it. Alongside the continuing use of traditional scientific approaches, a number of methods native to the discipline of systems ergonomics should also be considered in light of their potential to visualise the complete Australian recreational distance running system. Systems ergonomics methods that build on the idea of ecological causation and effectively target TRIPP stage 3 (Finch 2006) might offer new knowledge about how to prevent RRI, such as exposing questions around the feasibility of adopting selected injury prevention interventions that have not yet been considered.

Research approaches to injury causation and prevention in ergonomics science

A primer to systems ergonomics

In terms of its operational description, ergonomics is (International Ergonomics Association 2016):

> The scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance.

Residing within the broader discipline are three unique sub-disciplines of specialisation: (1) physical; (2) cognitive; (3) systems ergonomics (Human Factors and Ergonomics Society of Australia 2016). Systems ergonomics has traditionally been concerned with topics such as accident causation, organisational resilience, situation awareness, inter-agency coordination and how between-human and human–machine interactions are managed within complex sociotechnical systems. Ultimately the goal is to optimise system performance by using the system as the unit of analysis rather than its individual components.

There are many examples whereby systems ergonomics practitioners have attempted to understand how to mitigate and/or prevent hazardous work-related processes in the engineering and industrial environments (Wilson 2014). In fact, the shift towards optimising safety-related processes in safety-critical domains occurred in the 1970s and 1980s in response to large-scale incidents such as the Chernobyl, Tenerife and Three Mile Island disasters (Dekker 2011). Since then, examples of systems ergonomics applications have included, but are not limited to, the transport (e.g. road, rail, aviation and shipping), industrial (photochemical processing and nuclear) and public health care systems (Reason et al. 1990; Baysari, McIntosh, and Wilson 2008; Li, Harris, and Yu 2008; Celik and Cebi 2009; Griffin, Young, and Stanton 2010; Salmon et al. 2013). More recently, systems ergonomics has demonstrated its flexibility with applications outside of the safety-critical domains, including sport and outdoor recreation (Clacy et al. 2015; Salmon et al. 2015), and cyber security (Lacey and Salmon 2015).

In learning from past engineering and industrial disasters and events, it is now widely accepted that a safe organisational environment can be achieved by designing and/or engineering systems from the 'top-down' (Leveson et al. 2009). Reforming and/or developing new government policy, as well as completely reshaping environments, is oftentimes more effective than trying to change individual-level determinants of performance and safety (Holden 2009).

Systems ergonomics incident and injury analysis methods

Systems ergonomics has a number of incident and injury analysis methods at its disposal. Associated with each method is a distinct theoretical model that conceptualises the many heterogeneous elements across a sociotechnical system (Carayon 2006). When compared to common epidemiologic study designs and statistical methods, systems ergonomics models do not intend to generate precise measures of cause–effect associations. Rather, the resulting models aim to achieve a high degree of face validity in terms of their generality and realism (Ip et al. 2013). For this reason, a given systems ergonomics application draws attention to an ecological scale of health determination, including the many subsystems that reside within it.

There are four prominent incident and injury analysis methods that dominate the systems ergonomics literature: (1) Systems Theoretic Accident Mapping and Processes (STAMP) model (Leveson 2004); (2) Rasmussen's (1997) Risk Management Framework (RMF) accompanied by the 'Accimap' technique; (3) the Human Factors Analysis and Classification System (HFACS) (Wiegmann and Shappell 2003); (4) Functional Resonance Accident Model (FRAM) (Hollnagel 2012). Each method has its own strengths; however, for the RRI context, some are more important than others. For example, even though Rasmussen's (1997) RMF has been successfully operationalised in a range of highly specific sociotechnical system contexts (e.g. Cassano-Piche, Vincente, and Jamieson 2009; Jenkins et al. 2010; Goode et al. 2014; Scott-Parker, Goode, and Salmon 2014; Salmon et al. 2014), it does not focus explicitly on control and feedback relationships as STAMP does (Salmon, Cornelissem, and Trotter 2012). Likewise, the strong theoretical base associated with STAMP, RMF and HFACS is not shared by FRAM, particularly given that the latter has traditionally investigated the causes associated with aviation incidents, and so its domain-generic potential remains questionable (Stanton et al. 2013). Whilst all of the methods described have their utility, a key requirement for understanding interactions and complexity lies in the ability to describe who resides within the system of interest, and the nature of the relationships that exist between them. Leveson's (2004) STAMP model provides this capability through its hierarchical control structure template. It is contended here that the development of a control structure model represents the first required step in implementing a systems ergonomics approach to RRI.

Overview of the STAMP approach applied to RRI

Control theory forms the theoretical basis for the STAMP model, and promotes the view that incidents and injury result from inadequate control structures and deficiencies surrounding the enforcement of health- and safety-related constraints. In other words, human health and safety are emergent and irreducible properties that are directly controlled or influenced by policies, procedures, shared values, organisational culture, services, people and products (Leveson 2004). For example, biomechanical researchers investigating the aetiology of RRI in a controlled laboratory setting have determined that foot pronation during the first 10% of stance is a significant predictor for anterior knee pain (Duffey et al. 2000). Whilst this finding provides useful information for RRI prevention, the development of anterior knee pain can also be understood in terms of a series of inadequate or absent control-related constraints that increase the susceptibility of RRI in the already predisposed runner. These control-related constraints (or lack thereof) potentially span the entire sociotechnical system, and ultimately manifest as adaptive or maladaptive behaviours at the individual component-cause level. For example, runners might receive training-related advice and instruction from a range of sources, including but not limited to, other runners, athletic coaches and/or via social and general sports media releases. In turn, these persons and providers of advice are controlled or influenced by macro policy-level factors, such as state and local training organisations and sporting associations that deliver coaching accreditation courses.

The motivations and goals underpinning and driving safety behaviours are, therefore, also important considerations for preventing RRI. Accordingly, performance-shaping mechanisms and the context(s) in which runners' actions and decisions are carried out depending on the relationships between persons and organisations across the entire distance running system. Under this view, RRI might not necessarily occur when the predisposed runner makes a conscious decision to engage in risky behaviour per se, but rather because the design and operation associated with the *system itself* has allowed for certain maladaptive training-related behaviours to take place. Recreational distance running is, in and of itself, an autonomously driven activity with arguably few imposed rules and safety-related constraints for protection against RRI. This self-agency on behalf of the runner necessitates that the operative processes associated with a given distance running system STAMP model need to be designed in such a way as to directly or indirectly enforce appropriate behaviours that help to reduce RRI risk. To achieve this, the control structure model incorporates a series of hierarchical system levels that include both control (i.e. reference channels) and feedback loops (i.e. measuring channels) (Figure 1).

Figure 2 shows the adapted STAMP control structure applied to the Australian recreational distance running system. For the purpose of this article, only system operation has been visualised, and this provides a starting point for mapping out who resides at the different hierarchical levels, inclusive of control relationships. Development of the model involved: (1) adapting the systems operation component of the STAMP control structure levels as shown in Figure 1 to fit the recreational distance running context; (2) identifying actors and groups who reside at each of the control structure levels; (3) identifying the control and feedback loops that might exist between the different control structure levels. These activities were based on information derived from various sources, including documentation related to recreational running (e.g. Athletics Australia), stakeholder websites (e.g. Australian Sports Commission, Australian Institute of Sport), the academic literature; the authors' own knowledge of the RRI domain (A. Hulme and R.O. Nielsen), and other authors' extensive experience in use of systems ergonomics methods (P.M. Salmon and G.J.M. Read). Three analysts (A. Hulme, P.M. Salmon and G.J.M. Read) worked through

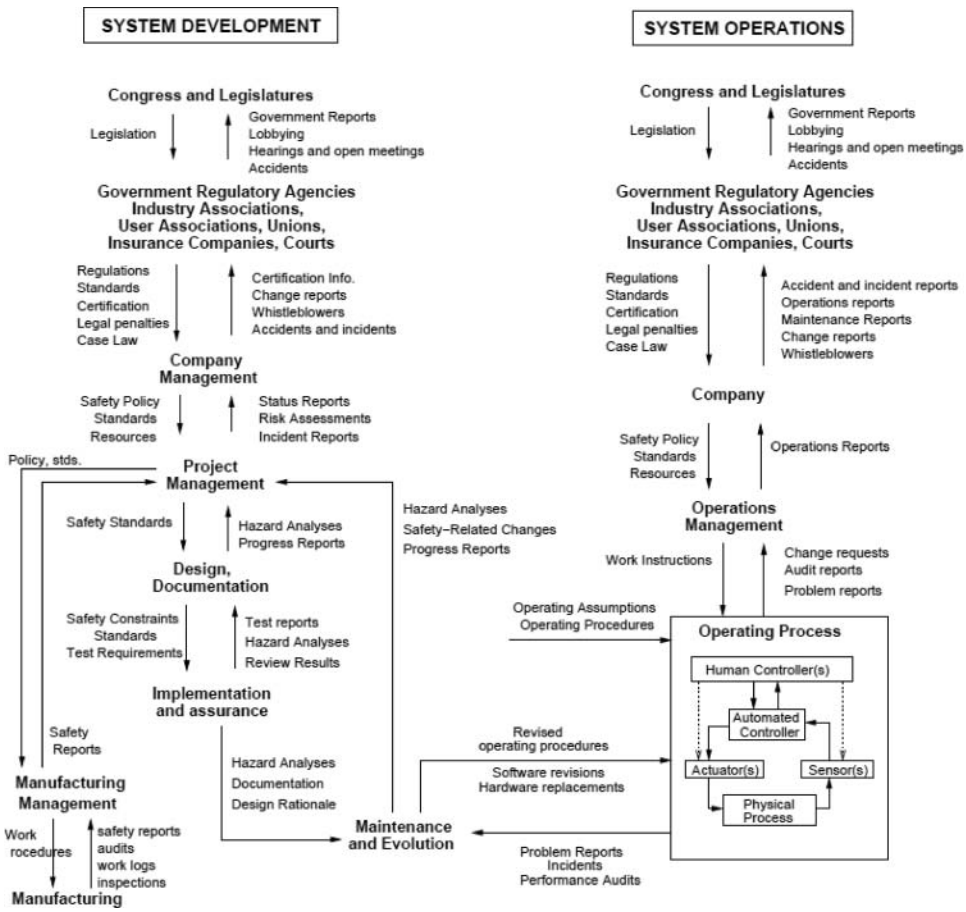

Figure 1. Leveson's (2004) original Systems Theoretic Accident Mapping and Processes Model (STAMP). Note: Permission to reuse granted on 11 August 2016 by RightsLink Copyright Clearance Centre. License number: 3926241265118.

the model until consensus was reached regarding its structure, components and the relationships to be depicted.

By identifying relevant actors and organisations, along with the control and feedback relationships between them, the adapted STAMP model has the potential to provide a comprehensive account of who and what shares responsibility for the development and prevention of RRI. In addition, it is possible to examine existing system-wide controls and identify areas in which they may require strengthening, or alternatively, where new controls could be added. For example, novel solutions could be introduced into the system, such as strategies that encourage runners to formally register their personal details with a local athletics club, which would then regularly share training-related advice with its members in relation to performance goals and injury prevention. Similar to the generation of a recent adaptation of STAMP to the Queensland road transport system (Salmon, Read, and Stevens 2016), a final RRI STAMP model requires expert ratification to ensure face and content validity. This could be gathered from distance running and systems ergonomics subject matter experts through a consensus generating approach in which the model is

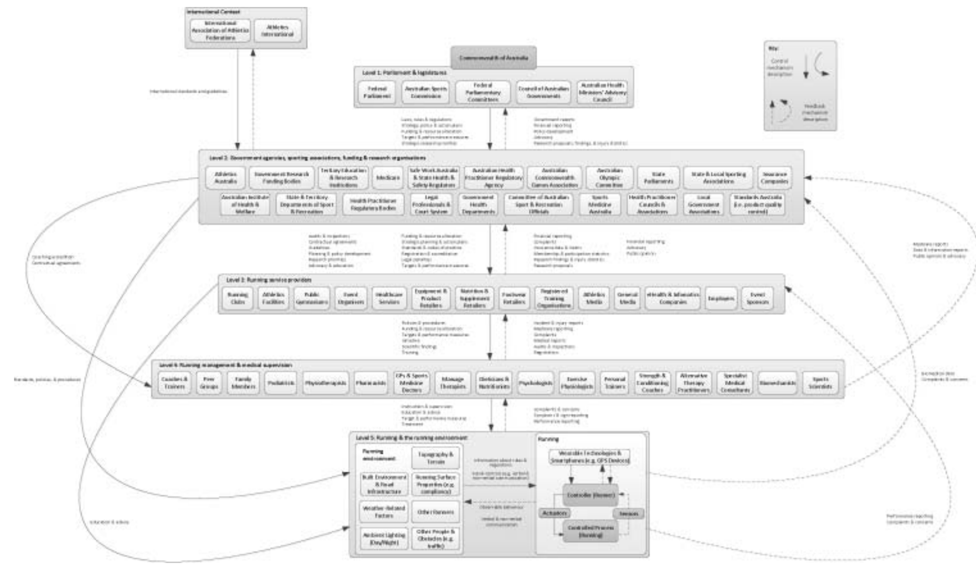

Figure 2. A prototype Australian recreational distance running system modelled using the STAMP approach.
Note: This figure can be viewed in high resolution in the supporting supplemental material.

refined according to a number of specific questions. The adaptation of STAMP to the RRI sociotechnical systems context: (1) extends the conceptualisation of what constitutes a 'system'; (2) fosters theoretical advancement in terms of increasing practical opportunities for problem resolution and (3) invigorates existing or initiates new conceptual ideas that bolster the importance of taking a pragmatic approach to solution generation (Davis et al. 2014). This latter point includes the development of potentially effective RRI prevention interventions that are not amenable to evaluation in traditional scientific study designs.

Conclusion

The popularity of running as a form of recreational exercise continues to increase dramatically. National and international running festivals, comprising fun runs and park runs, charity events and major annual marathons, are attracting a growing number of participants. Alongside this participation growth is the burden of RRI. There is therefore a requirement for new research to help better understand its causes to inform the development of efficacious and effective injury prevention interventions. In the late 1990s, Weed (1998, 14) proclaimed:

> Epidemiologists should get beyond the pejorative connotation of black box thinking by embracing a systems theory approach while remaining aware of its weaknesses. In doing so, they will secure access to the broad scope of scientific knowledge with the behaviour of populations near one extreme and the behaviour of molecules at the other.

We conclude that the intention of this article is not to propose the reconciliation of epidemiology and systems ergonomics for RRI per se, but rather, to argue they be used in parallel. The challenge of directly integrating the two has, and will continue to, push frontiers of current knowledge and available technologies beyond their present capabilities.

The following points summarise a number of key themes as they apply to the current status of RRI prevention research: the epidemiologic counterfactual definition of causation has been invaluable for reliably establishing statistically significant associations in black box studies that isolate risk factors for RRI. The counterfactual approach is, however, best used to identify the effect of a well-defined RRI prevention intervention. Specific causal effects are most amenable to evaluation in RCTs. Despite this, RCTs are not always possible to conduct due to financial, logistic and/or ethical reasons, and the few RCTs that do exist in the RRI literature have common methodological limitations (Jakobsen et al. 1994; Cobb et al. 2007; Buist et al. 2008; Ryan et al. 2010; Bredeweg et al. 2012; Hulme et al. 2016). Despite the use and availability of both conventional methods and advanced statistical constructs in which to control and adjust for confounding, successfully preventing a given RRI depends on how best to manipulate exposure(s) through specific intervention, particularly when different hypothesised injury prevention interventions will produce different magnitudes of effect on RRI risk. The overwhelming focus on biological, behavioural and biomechanical risk factors to date suggests that the individual runner is, and has been, the most appropriate target for RRI prevention interventions. Implicit in this assumption is that interpersonal-level determinants ultimately manifest in proximal RRI factors that are most amenable to change. Because complex systems modelling approaches have gained traction in the wider field of public health, similar complementary options should now be explored in the RRI prevention context (Hulme and Finch 2015, 2016). One complementary complex system modelling option is a methodology native to the discipline of systems ergonomics. Adapting STAMP (Leveson 2004) to the Australian recreational distance running context as presented in this paper offers the potential for new knowledge about how to prevent RRI, such as exposing questions around the feasibility of implementing novel injury prevention interventions.

This article shows that a systems ergonomics methodology based on control theory provides a useful adjunct to traditional epidemiologic applications. Epidemiology starts bottom-up, and reduces complexity to seek the detailed, objective and quantifiable reality behind observed associations and direct causal effects at the downstream levels. In contrast, systems ergonomics starts top-down, and promotes an ecological framework that includes control and feedback mechanisms between multiple hierarchical levels of determination. The prototype STAMP model presented in this paper is intended to counteract the metaphorical prop that has been holding open Pandora's Box for the better part of four decades. The next step for systems ergonomists working in the RRI prevention context is to further validate the prototype distance running STAMP model using consensus-based qualitative research approaches.

Acknowledgments

We would like to thank Dr Lauren Fortington for her valuable input that helped to improve certain sections of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

Federation University Australia supported this research via the Australian Research Training Scheme (RTS) program.

Notes on contributors

Adam Hulme undertook this work as part of his PhD studies under the supervision of Caroline F. Finch and Paul M. Salmon.

Paul M. Salmon is supported through an Australian Research Council Future Fellowship (FT140100681).

Rasmus O. Nielsen is the research coordinator of the RUNSAFE group.

Gemma J. M. Read is a research fellow specialising in the application of systems thinking approaches to a range of different sociotechnical systems contexts. The Australian Collaboration for Research into Injury in Sport and its Prevention (ACRISP) is one of nine research centres worldwide to be selected by the International Olympic Committee (IOC) as a member of the IOC Medical Research Network.

Caroline F. Finch is supported by a National Health and Medical Research Council (of Australia) Principal Research Fellowship (ID: 1058737).

ORCID

A. Hulme http://orcid.org/0000-0002-3305-8538
C. F. Finch http://orcid.org/0000-0003-1711-1930

References

Allegrante, J.P., D.W. Hanson, D.A. Sleet, and R. Marks. 2010. “Ecological Approaches to the Prevention of Unintentional Injuries.” *Italian Journal of Public Health* 7: 24–31.

Auchincloss, A.H., and A.V. Diez Roux. 2008. “A New Tool for Epidemiology: The Usefulness of Dynamic-Agent Models in Understanding Place Effects on Health.” *American Journal of Epidemiology* 168: 1–8.

Australian Epidemiological Association. 2010. “What is Epidemiology?” Accessed April 20 2016. https://aea.asn.au/about-us/what-is-epidemiology.

Baysari, M.T., A.S. McIntosh, and J.R. Wilson. 2008. “Understanding the Human Factors Contribution to Railway Accidents and Incidents in Australia.” *Accident Analysis and Prevention* 40: 1750–1757.

Bekker, S., and A.M. Clark. 2016. “Bringing Complexity to Sports Injury Prevention Research: From Simplification to Explanation.” *British Journal of Sports Medicine* 50: 1489–1490.

Bittencourt, N.F.N., W.H. Meeuwisse, L.D. Mendonça, A. Nettel-Aguirre, J.M. Ocarino, and S.T. Fonsesca. 2016. “Complex Systems Approach for Sports Injuries: Moving from Risk Factor Identification to Injury Pattern Recognition-Narrative Review and New Concept.” *British Journal of Sports Medicine* 50: 1309–1314.

Bredeweg, S.W., S. Zijlstra, B. Bessem, and I. Buist. 2012. “The Effectiveness of a Preconditioning Programme on Preventing Running-Related Injuries in Novice Runners: A Randomised Controlled Trial.” *British Journal of Sports Medicine* 46: 865–870.

British Medical Journal. 2016. “What is Epidemiology?” Accessed April 20 2016. http://www.bmj.com/about-bmj/resources-readers/publications/epidemiology-uninitiated/1-what-epidemiology.

Buist, I., S.W. Bredeweg, K.A.P.M. Lemmink, W. van Mechelen, and R.L. Diercks. 2010. "Predictors of Running-Related Injuries in Novice Runners Enrolled in a Systematic Training Program: A Prospective Cohort Study." *American Journal of Sports Medicine* 38: 273–280.

Buist, I., S.W. Bredeweg, W. van Mechelen, K.A.P.M. Lemmink, G. Pepping, and R.L. Diercks. 2008. "No Effect of a Graded Training Program on the Number of Running-Related Injuries in Novice Runners." *American Journal of Sports Medicine* 36: 33–39.

Carayon, P. 2006. "Human Factors of Complex Sociotechnical Systems." *Applied Ergonomics* 37: 525–535.

Cassano-Piche, A.L., K.J. Vicente, and G.A. Jamieson. 2009. "A Test of Rasmussen's Risk Management Framework in the Food Safety Domain: BSE in the UK." *Theoretical Issues in Ergonomics Science* 10: 283–304.

Cates, W. 2013. "Invited Commentary: Consequential(ist) Epidemiology: Let's Seize the day." *American Journal of Epidemiology* 178: 1192–1194.

Celik, M., and S. Cebi. 2009. "Analytical HFACS for Investigating Human Errors in Shipping Accidents." *Accident Analysis and Prevention* 41: 66–75.

Chang, W., Y. Shih, and W. Chen. 2012. "Running Injuries and Associated Factors in Participants of the ING Taipei Marathon." *Physical Therapy in Sport* 13: 170–174.

Clacy, A., R. Sharman, N. Goode, P.M. Salmon, and G.P. Lovell. 2015. "Responsibilities in the Prevention of Concussion in Community Rugby Union". *Procedia Manufacturing* 3: 1173–1180. doi:10.1016/j.promfg.2015.07.195

Cobb, K.L., L.K. Bachrach, M. Sowers, J. Nieves, G.A. Greendale, K.K. Kent, B.W. Brown, K. Pettit, D.M. Harper, and J.L. Kelsey. 2007. "The Effects of Oral Contraceptives on Bone Mass and Stress Fractures in Female Runners." *Medicine & Science in Sports & Exercise* 39: 1464–1473.

Dahlgren, G., and M. Whitehead. 1991. *Policies and Strategies to Promote Equity in Health*. Stockholme: Institute for Future Studies.

Davis, M.C., R. Challender, D.N.W. Jayewardene, and C.W. Clegg. 2014. "Advancing Socio-Technical Systems Thinking: A Call for Bravery." *Applied Ergonomics* 45: 171–180.

Dekker, S. 2011. *Drift into Failure*. Surrey: Ashgate.

Dekkers, O.M. 2011. "On Causation in Therapeutic Research: Observational Studies, Randomised Experiments and Instrumental Variable Analysis." *Preventive Medicine* 53: 239–241.

Diez Roux, A.V. 2011. "Complex Systems Thinking and Current Impasses in Health Disparities Research." *American Journal of Public Health* 101: 1627–1634.

Duffey, M.J., D.F. Martin, W. Cannon, T. Craven, and S. Messier. 2000. "Etiologic Factors Associated with Anterior Knee Pain in Distance Runners." *Medicine & Science in Sports & Exercise* 32: 1825–1832.

Eime, R., N. Owen, and C.F. Finch. 2004. "Protective Eyewear Promotion: Applying Principles of Behaviour Change in the Design of a Squash Injury Prevention Programme." *Sports Medicine* 34: 629–638.

Fee, E., and N. Krieger. 1993. "Understanding AIDS: Historical Interpretations and the Limits of Biomedical Individualism." *American Journal of Public Health* 83: 1477–1486.

Fields, K.B., J.C. Sykes, K.M. Walker, and J.C. Jackson. 2010. "Prevention of Running Injuries." *Current Sports Medicine Reports* 9: 176–182.

Finch, C.F. 2006. "A New Framework for Research Leading to Sports Injury Prevention." *Journal of Science and Medicine in Sport* 9: 3–9.

Finch, C.F., and J. Cook. 2013. "Categorising Sports Injuries in Epidemiological Studies: The Subsequent Injury Categorisation (SIC) Model to Address Multiple, Recurrent and Exacerbation of Injuries." *British Journal of Sports Medicine* 48: 1276–1280.

Finch, C.F., and A. Donaldson. 2010. "A Sports Setting Matrix for Understanding the Implementation Context for Community Sport." *British Journal of Sports Medicine* 44: 973–978.

Galea, S. 2013. "An Argument for Consequentialist Epidemiology." *American Journal of Epidemiology* 178: 1185–1191.

Galea, S., M. Riddle, and G.A. Kaplan. 2010. "Causal Thinking and Complex System Approaches in Epidemiology." *International Journal of Epidemiology* 39: 97–106.

Gilliam, A.G. 1953. "Opportunities for Application of Epidemiologic Method to the Study of Cancer." *American Journal of Public Health and the Nation's Health* 43: 1247–1257.
Glass, T.A., S.N. Goodman, M.A. Hernán, and J.M. Samet. 2013. "Causal Inference in Public Health." *Annual Reviews in Public Health* 34: 61–75.
Goode, N., P.M. Salmon, M.G. Lenné, and P. Hillard. 2014. "Systems Thinking Applied to Safety During Manual Handling Tasks in the Transport and Storage Industry." *Accident Analysis and Prevention* 68: 181–191.
Greenland, S. 2000. "An Introduction to Instrumental Variables for Epidemiologists." *International Journal of Epidemiology* 29: 722–729.
Greenland, S., M. Gago-Dominguez, and J. Esteban. 2004. "The Value of Risk-Factor ("Black-Box") Epidemiology." *Epidemiology* 15: 529–535.
Griffin, T.G.C., M.S. Young, and N.A. Stanton. 2010. "Investigating Accident Causation Through Information Network Modelling." *Ergonomics* 53: 198–210.
Hafeman, D.M., and S. Schwartz. 2009. "Opening the Black Box: A Motivation for the Assessment of Mediation." *International Journal of Epidemiology* 38: 838–845.
Hanson, D.W., C.F. Finch, J.P. Allegrante, and D. Sleet. 2012. "Closing the Gap Between Injury Prevention Research and Community Safety Promotion Practice: Revisiting the Public Health Model." *Public Health Reports* 127: 147–155.
Hanson, D., J. Hanson, P. Vardon, K. McFarlane, J. Lloyd, R. Muller, and D. Durrheim. 2005. "The Injury Iceberg: An Ecological Approach to Planning Sustainable Community Safety Interventions." *Health Promotion Journal of Australia* 16: 5–10.
Hernán, M.A. 2004. "A Definition of Causal Effect for Epidemiological Research." *Journal of Epidemiology and Community Health* 58: 265–271.
Hernán, M.A. 2005. "Invited Commentary: Hypothetical Interventions to Define Causal Effects – Afterthought or Prerequisite?" *American Journal of Epidemiology* 162: 618–620.
Hernán, M.A., and J.M. Robins. 2006a. "Estimating Causal Effects From Epidemiological Data." *Journal of Epidemiology and Community Health* 60: 578–586.
Hernán, M.A., and J.M. Robins. 2006b. "Instruments for Causal Inference: An epidemiologist's Dream?" *Epidemiology* 17: 360–372.
Hernán, M.A., and S.L. Taubman. 2008. "Does Obesity Shorten Life? The Importance of Well-Defined Interventions to Answer Causal Questions." *International Journal of Obesity* 32: S8–S14.
Herzog, W. 2016. "The Problem with Running Injuries." *Journal of Sport and Health Science* 5: 171.
Hespanhol, L.C., L.O.P. Costa, and A.D. Lopes. 2013. "Previous Injuries and Some Training Characteristics Predict Running-Related Injuries in Recreational Runners: A Prospective Cohort Study." *Journal of Physiotherapy* 59: 263–269.
Hespanhol, J.L.C., J.D. Pillay, W. van Mechelen, and E. Verhagen. 2015. "Meta-Analyses of the Effects of Habitual Running on Indices of Health in Physically Inactive Adults." *Sports Medicine* 45: 1455–1468.
Hill, A.B. 1965. "The Environment and Disease: Association or Causation?" *Proceedings of the Royal Society of Medicine* 58: 295–300.
Hirschmüller, A., V. Frey, L. Konstantinidis, H. Baur, H.H. Dickhuth, N.P. Südkamp, and P. Helwig. 2012. "Prognostic Value of Achilles Tendon Doppler Sonography in Asymptomatic Runners." *Medicine and Science in Sports and Exercise* 44: 199–205.
Höfler, M. 2005a. "The Bradford Hill Considerations on Causality: A Counterfactual Perspective?" *Emerging Themes in Epidemiology* 2: 11.
Höfler, M. 2005b. "Causal Inference Based on Counterfactuals." *BMC Medical Research Methodology* 5: 28.
Holden, R.J. 2009. "People or Systems? To Blame is Human. To Fix is to Engineer." *Professional Safety* 54: 34–41.
Hollnagel, E. 2012. *FRAM: The Functional Resonance Analysis Method: Modelling Complex Socio-Technical Systems*. Surrey: Ashgate.

Hulme, A., and C.F. Finch. 2015. "From Monocausality to Systems Thinking: A Complementary and Alternative Conceptual Approach for Better Understanding the Development and Prevention of Sports Injury." *Injury Epidemiology* 2: 31.
Hulme, A., and C.F. Finch. 2016. "The Epistemic Basis of Distance Running Injury Research: A Historical Perspective." *Journal of Sport and Health Science* 5: 172–175.
Hulme, A., R.O. Nielsen, E.A. Verhagen, T. Timpka, and C.F. Finch. 2016. "Risk and Protective Factors for Middle- and Long-Distance Running-Related Injury: A Systematic Review." *Sports Medicine*. doi:10.1007/s40279-016-0636-4.
Human Factors and Ergonomics Society of Australia. 2016. "Definitions." Accessed April 20 2016. http://www.ergonomics.org.au/resource_library/definitions.
International Ergonomics Association. 2016. "Definition and Domains of Ergonomics." Accessed June 30 2016. http://www.iea.cc/whats/
Ip, E.H., H. Rahmandad, D.A. Shoham, R. Hammond, T.K. Huang, Y. Wang, and P.L. Mabry. 2013. "Reconciling Statistical and Systems Science Approaches to Public Health." *Health Education & Behavior* 40: 123–131.
Jakobsen, B.W., K. Krøner, A. Schmidt, and A. Kjeldsen. 1994. "Prevention of Injuries in Long-Distance Runners." *Knee Surgery, Sports Traumatology, Arthroscopy* 2: 245–249.
Jenkins, D.P., P.M. Salmon, N.A. Stanton, and G.H. Walker. 2010. "A Systemic Approach to Accident Analysis: A Case Study of the Stockwell Shooting." *Ergonomics* 53: 1–17.
Jepsen, P., P.S. Johnsen, M.W. Gillman, and H.T. Sørensen. 2004. "Interpretation of Observational Studies." *Heart* 90: 956–960.
Kelsey, J.L., L.K. Bachrach, E. Procter-Gray, J. Nieves, G.A. Greendale, M. Sowers, B.W. Brown, K.A. Matherson, S.L. Crawford, and K.L. Cobb. 2007. "Risk Factors for Stress Fractures Among Young Female Cross-Country Runners." *Medicine & Science in Sports & Exercise* 39: 1457–1463.
Keyes, K., and S. Galea. 2015. "What Matters Most: Quantifying an Epidemiology of Consequence." *Annals of Epidemiology* 25: 305–311.
Kluitenberg, B., M. van Middelkoop, R. Diercks, and H. van der Worp. 2015. "What are the Differences in Injury Proportions Between Different Populations of Runners? A Systematic Review and Meta-Analysis." *Sports Medicine* 45: 1143–1161.
Krieger, N. 1994. "Epidemiology and the Web of Causation: Has Anyone Seen the Spider?" *Social Science and Medicine* 39: 887–903.
Krieger, N. 2012. "Methods for the Scientific Study of Discrimination and Health: An Ecosocial Approach." *American Journal of Public Health* 102: 936–944.
Kuller, L.H. 2013. "Point: Is there a Future for Innovative Epidemiology?" *American Journal of Epidemiology* 177: 279–280.
Lacey, D., and P.M. Salmon. 2015. "It's Dark in there: Using Systems Analysis to Investigate Trust and Engagement in Dark Web Forums." In *Engineering Psychology and Cognitive Ergonomics: Proceedings of the 17th International Conference on Human-Computer Interaction*, edited by D. Harris, 117–128. Springer International Publishing.
Lawlor, D.A., G.D. Smith, K.R. Bruckdorfer, D. Kundu, and S. Ebrahim. 2004. "Those Confounded Vitamins: What Can We Learn from the Differences Between Observational Versus Randomised Trial Evidence?" *The Lancet* 363: 1724–1727.
Leischow, S.J., and B. Milstein. 2006. "Systems Thinking and Modeling for Public Health Practice." *American Journal of Public Health* 96: 403–405.
Leveson, N.G. 2004. "A New Accident Model for Engineering Safer Systems." *Safety Science* 42: 237–270.
Leveson, N.G., N. Dulac, K. Marais, and J. Carroll. 2009. "Moving Beyond Normal Accidents and High Reliability Organizations: A Systems Approach to Safety in Complex Systems." *Organization Studies* 30: 227–249.
Lewis, D. 1973a. *Counterfactuals*. Oxford, MA: Blackwell Publishers.
Lewis, D. 1973b. "Counterfactuals and Comparative Possibility." *Journal of Philosophical Logic* 2: 418–446.

Li, W.C., D. Harris, and C.S. Yu. 2008. “Routes to Failure: Analysis of 41 Civil Aviation Accidents from the Republic of China Using the Human Factors Analysis and Classification System.” *Accident Analysis and Prevention* 40: 426–434.
Lilienfeld, A.M. 1957. “Epidemiological Methods and Inferences in Studies of Noninfectious Diseases.” *Public Health Reports* 72: 51–60.
Lilienfeld, A.M. 1959. ““On the Methodology of Investigations of Etiologic Factors in Chronic Diseases” – Some Comments.” *Journal of Chronic Diseases* 10: 41–46.
Litman, J.A. 2005. “Curiosity and the Pleasures of Learning: Wanting and Liking new Information.” *Cognition and Emotion* 19: 793–814.
Little, R.J.A., and D.B. Rubin. 2000. “Causal Effects in Clinical Epidemiologic Studies via Potential Outcomes: Concepts and Analytical Assumptions.” *Annual Review of Public Health* 21: 121–145.
Loomis, D., and S. Wing. 1990. “Is Molecular Epidemiology a Germ Theory for the end of the Twentieth Century?” *International Journal of Epidemiology* 19: 1–3.
Lorenz, J.M., and N. Paneth. 2003. “When are Observational Studies Adequate to Assess the Efficacy of Therapeutic Interventions?” *Clinics in Perinatology* 30: 269–283.
Lyon, A. 1967. “Causality.” *British Journal for the Philosophy of Science* 18: 1–20.
Mabry, P.L., S.E. Marcus, P.I. Clark, S.J. Leischow, and D. Mendez. 2010. “Systems Science: A Revolution in Public Health Policy Research.” *American Journal of Public Health* 100: 1161–1162.
Macera, C.A., R.R. Pate, K.E. Powell, K.L. Jackson, J.S. Kendrick, and T.E. Craven. 1989. “Predicting Lower-Extremity Injuries Among Habitual Runners.” *Archives of Internal Medicine* 149: 2565–2568.
Mackie, J.L. 1965. “Causes and Conditions.” *American Philosophical Quarterly* 2: 245–264.
Mackie, J.L. 1980. *The Cement of the Universe: A Study of Causation*. New York: Oxford University Press.
Maldonado, G., and S. Greenland. 2002. “Estimating Causal Effects.” *International Journal of Epidemiology* 31: 422–429.
Malisoux, L., J. Ramesh, R. Mann, R. Seil, A. Urhausen, and D. Theisen. 2013. “Can Parallel Use of Different Running Shoes Decrease Running-Related Injury Risk?” *Scandinavian Journal of Medicine & Science in Sports* 25: 110–115.
March, D., and E. Susser. 2006. “The Eco- in Eco-Epidemiology.” *International Journal of Epidemiology* 35: 1379–1383.
Marshall, B.D.L., and S. Galea. 2014. “Formalizing the Role of Agent-Based Modeling in Causal Inference and Epidemiology.” *American Journal of Epidemiology* 181: 92–99.
McClure, R.J., C. Adriazola-Steil, C. Mulvihill, M. Fitzharris, P. Bonnington, P.M. Salmon, and M. Stevenson. 2015. “Simulating the Dynamic Effect of Land Use and Transport Policies on the Development and Health of Populations.” *American Journal of Public Health* 105: S223–S229.
McKeown, T. 1979. *The Role of Medicine. Dream, Mirage or Nemesis*? Oxford: Basil Blackwell.
McKeown, R.E. 2009. “The Epidemiologic Transition: Changing Patterns of Mortality and Population Dynamics.” *American Journal of Lifestyle Medicine* 3: S19–S26.
McMichael, A.J. 1999. “Prisoners of the Proximate: Loosening the Constraints on Epidemiology in an age of Change.” *American Journal of Epidemiology* 15: 887–897.
Midgley, G. 2006. “Systemic Intervention for Public Health.” *American Journal of Public Health* 96: 466–472.
Miller, R.H., J.L. Lowry, S.A. Meardon, and J.C. Gillette. 2007. “Lower Extremity Mechanics of Iliotibial Band Syndrome During an Exhaustive run.” *Gait & Posture* 26: 407–413.
Naimi, A.I., E.E. Moodie, N. Auger, and J.S. Kaufman. 2014. “Constructing Inverse Probability Weights for Continuous Exposures: A Comparison of Methods.” *Epidemiology* 25: 292–299.
Ness, R.B., J.S. Koopman, and M.S. Robert. 2007. “Causal System Modeling in Chronic Disease Epidemiology: A Proposal.” *Annals of Epidemiology* 17: 564–568.
Neutra, R.R. 2005. ““Black-box” Epidemiology.” *Epidemiology* 16: 418–419.
Nielsen, R.O., I. Buist, E.T. Parner, E.A. Nohr, H. Sørensen, M. Lind, and S. Rasmussen. 2013. “Predictors of Running-Related Injuries Among 930 Novice Runners: A 1-Year Prospective Follow-up Study.” *Orthopaedic Journal of Sports Medicine* 1: 1–7.

Nielsen, R.O., I. Buist, H. Sørensen, M. Lind, and S. Rasmussen. 2012. “Training Errors and Running Related Injuries: A Systematic Review.” *International Journal of Sports Physical Therapy* 7: 58–74.

Nielsen, R.O., L. Malisoux, M. Moller, D. Theisen, and E.T. Parner. 2016. “Shedding the Light on the Etiology of Sports Injuries: A Look Behind the Scenes of Time-to-Event Analyses.” *Journal of Orthopeadic Sports Physical Therapy* 46: 300–311.

Parascandola, M., and D.L. Weed. 2001. “Causation in Epidemiology.” *Journal of Epidemiology and Community Health* 55: 905–912.

Parker, D.T., T.W. Weitzenberg, A.L. Amey, and R.J. Nied. 2011. “Group Training Programs and Self-Reported Injury Risk in Female Marathoners.” *Clinical Journal of Sport Medicine* 21: 499–507.

Pearce, N., and F. Merletti. 2006. “Complexity, Simplicity, and Epidemiology.” *International Journal of Epidemiology* 35: 515–519.

Rasmussen, J. 1997. “Risk Management in a Dynamic Society: A Modelling Problem.” *Safety Science* 27: 183–213.

Rasmussen, C.H., R.O. Nielsen, M.S. Juul, and S. Rasmussen. 2013. “Weekly Running Volume and Risk of Running-Related Injuries Among Marathon Runners.” *International Journal of Sports Physical Therapy* 8: 111–120.

Reason, J., A. Manstead, S. Stradling, J. Baxter, and K. Campbell. 1990. “Errors and Violations on the Roads: A Real Distinction?” *Ergonomics* 33: 1315–1332.

Resnicow, K., and S.E. Page. 2008. “Embracing Chaos and Complexity: A Quantum Change for Public Health.” *American Journal of Public Health* 98: 1382–1389.

Ribeiro, A.P., F. Trombini-Souza, V. Tessutti, F.R. Lima, I. De Camargo, N. Sacco, and S.M.A. Joao. 2011. “Rearfoot Alignment and Medial Longitudinal Arch Configurations of Runners with Symptoms and Histories of Plantar Fasciitis.” *Clinics* 66: 1027–1033.

Rockhill, B. 2005. “Theorizing About Causes at the Individual Level While Estimating Effects at the Population Level: Implications for Prevention.” *Epidemiology* 16: 124–129.

Rothman, K.J. 1976. “Causes.” *American Journal of Epidemiology* 104: 587–592.

Rubin, D.B. 1974. “Estimating Causal Effects of Treatments in Randomized and Nonrandomized Studies.” *Journal of Educational Psychology* 66: 688–701.

Rubin, D.B. 1978. “Bayesian Inference for Causal Effects: The Role of Randomization.” *The Annals of Statistics* 6: 34–58.

Ryan, M.B., C.L. Maclean, and J.E. Taunton. 2006. “A Review of Anthropometric Biomechanical, Neuromuscular, and Training Related Factors Associated With Injury in Runners.” *International SportMed Journal* 7: 120–137.

Ryan, M.B., G.A. Valiant, K. McDonald, and J.E. Taunton.2010. “The Effect of Three Different Levels of Footwear Stability on Pain Outcomes in Women Runners: A Randomised Control Trial.” *British Journal of Sports Medicine* 45: 715–721.

Salmon, P.M., M. Cornelissen, M.J. Trotter. 2012. “Systems-Based Accident Analysis Methods: A Comparison of Accimap, HFACS, and STAMP.” *Safety Science* 50: 1158–1170.

Salmon, P.M., N. Goode, M.G. Lenné, C.F. Finch, and E. Cassell. 2014. “Injury Causation in the Great Outdoors: A Systems Analysis of led Outdoor Activity Injury Incidents.” *Accident Analysis and Prevention* 63: 111–120.

Salmon, P.M., N. Goode, N. Taylor, C. Dallat, C.F. Finch, and M.G. Lenne. 2015. “Rasmussen’s Legacy in the Great Outdoors: A New Incident Reporting and Learning System for Led Outdoor Activities.” *Applied Ergonomics* 59: 637–648.

Salmon, P.M., G.M. Read, N.A. Stanton, and M.G. Lenné. 2013. “The Crash at Kerang: Investigating Systemic and Psychological Factors Leading to Unintentional Non-compliance at Rail Level Crossings.” *Accident Analysis and Prevention* 50: 1278–1288.

Salmon, P.M., G.J.M. Read, and N.J. Stevens. 2016. “Who is in Control of Road Safety? A STAMP Control Structure Analysis of the Road Transport System in Queensland, Australia.” *Accident Analysis and Prevention* 96: 140–151.

Saragiotto, B.T., T.P. Yamato, L.C. Hespanhol, M.J. Rainbow, I.S. Davis, and A.D. Lopes. 2014. “What are the Main Risk Factors for Running Related Injuries?” *Sports Medicine* 44: 1153–1163.

Sartwell, P.E. 1955. “Some Approaches to the Epidemiologic Study of Chronic Disease.” *American Journal of Public Health and the Nation’s Health* 45: 609–614.

Savitz, D.A. 1994. “In Defense of Black box Epidemiology.” *Epidemiology* 5: 550–552.

Schwartz, S., E. Susser, and M. Susser. 1999. “A Future for Epidemiology?” *Annual Review of Public Health* 20: 15–33.

Scott-Parker, B., N. Goode, and P. Salmon. 2014. “The Driver, the Road, the Rules … and the Rest? A Systems-Based Approach to Young Driver Road Safety.” *Accident Analysis and Prevention*. 74: 297–305.

Simon, H.A., and N. Rescher. 1966. “Cause and Counterfactuals.” *Philosophy of Science* 33: 323–340.

Skrabanek, P. 1994. “The Emptiness of the Black box.” *Epidemiology*. 5: 553–555.

Stanton, N.A., P.A. Salmon, L.A. Rafferty, G.H. Walker, C. Baber, and D.P. Jenkins. 2013. *Human Factors Methods*. Surrey: Ashgate.

Sterman, J.D. 2006. “Learning From Evidence in a Complex World.” *American Journal of Public Health* 96: 505–514.

Steyerberg, E.W., M.J. Eijkemans, and J.D. Habbema. 1999. “Stepwise Selection in Small Data Sets: A Simulation Study of Bias in Logistic Regression Analysis.” *Journal of Clinical Epidemiology* 52: 935–942.

Susser, M. 1998. “Does Risk Factor Epidemiology Put Epidemiology at Risk? Peering into the Future.” *Journal of Epidemiology and Community Health* 52: 608–611.

Susser, E. 2004. “Eco-Epidemiology: Thinking Outside the Black Box.” *Epidemiology* 15: 519–520.

Susser, M., and E. Susser. 1996a. “Choosing a Future for Epidemiology: I. Eras and Paradigms.” *American Journal of Public Health* 86: 668–673.

Susser, M., and E. Susser. 1996b. “Choosing a Future for Epidemiology: II. From Black Box to Chinese Boxes and Eco-Epidemiology.” *American Journal of Public Health* 86: 674–677.

Taubes, G. 1995. “Epidemiology Faces its Limits.” *Science* 269: 164–169.

Terris, M. 1993. “The Society for Epidemiologic Research and the Future of Epidemiology.” *Journal of Public Health Policy* 14: 137–148.

Theisen, D., L. Malisoux, J. Genin, N. Delattre, R. Seil, and A. Urhausen. 2013. “Influence of Midsole Hardness of Standard Cushioned Shoes on Running-Related Injury Risk.” *British Journal of Sports Medicine* 48: 371–376.

Trochim, W.M., D.A. Cabera, B. Milstein, R.S. Gallagher, and S.L. Leischow. 2006. “Practical Challenges of Systems Thinking and Modeling in Public Health.” *American Journal of Public Health* 96: 538–546.

Vandenbroucke, J.P. 2004. “When are Observational Studies as Credible as Randomised Trials?” *The Lancet* 363: 1728–1731.

van Gent, R.N., D. Siem, M. van Middelkoop, A.G. van Os, S.M.A. Bierma-Zeinstra, and B.W. Koes. 2007. “Incidence and Determinants of Lower Extremity Running Injuries in Long Distance Runners: A Systematic Review.” *British Journal of Sports Medicine* 41: 469–480.

van Middelkoop, M., J. Kolkman, J. van Ochten, S.M.A. Bierma-Zeinstra, and B.W. Koes. 2008. “Risk Factors for Lower Extremity Injuries Among Male Marathon Runners.” *Scandinavian Journal of Medicine & Science in Sports* 18: 691–697.

Videbæk, S., A.M. Bueno, R.O. Nielsen, and S. Rasmussen. 2015. “Incidence of Running-Related Injuries per 1000 h of Running in Different Types of Runners: A Systematic Review and Meta-Analysis.” *Sports Medicine* 45: 1017–1026.

von Elm, E., D.G. Altman, M. Egger, S.J. Pocock, P.C. Gøtzschee, and J.P. Vandenbroucke. 2007. “The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) Statement: Guidelines for Reporting Observational Studies” *Preventive Medicine* 45: 247–251.

Webb, P., C. Bain, and S. Pirozzo. 2005. *Essential Epidemiology*. New York: Cambridge University Press.

Weed, D.L. 1998. “Beyond Black Box Epidemiology.” *American Journal of Public Health* 88: 12–14.

Wen, D.Y., J.C. Puffer, and T.P. Schmalzried. 1998. “Injuries in Runners: A Prospective Study of Alignment.” *Clinical Journal of Sports Medicine* 8: 187–194.

Wiegmann, D.A., and S.A. Shappell. 2003. *A Human Error Approach to Aviation Accident Analysis*. Surrey: Ashgate.
Wilson, J.R. 2014. "Fundamentals of Systems Ergonomics/Human Factors." *Applied Ergonomics* 45: 5–13.
Wing, S. 1988. "Social Inequalities in the Decline of Coronary Mortality." *American Journal of Public Health* 78: 1415–1416.
Wing, S. 1994. "The Limits of Epidemiology." *Med Global Surv* 1: 74–86.