A Systemic Risk Assessment of Unintentional Doping Through Supplement Use

World Anti-Doping Agency

Social Science Research Grant

Project Report 20/12/2024

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Executive summary

Unintentional doping is a complex and intractable problem in elite sport, often attributed to the high prevalence of supplements use in athletic populations. Although previous research has established and described occurrences, prevalence, and perceptions of unintentional doping, this has typically been focused on the athletes. However, recent research in doping in sport indicates that there is likely to be a complex set of contributory factors from across the entire sports system that influences unintentional doping. Further, there has been no proactive systemic risk assessment that considers the broader complexity of the sport system and how different factors from within the sport system interact to create instances of unintentional doping.

The World Anti-Doping Agency (WADA) engaged the University of the Sunshine Coast's Centre for Human Factors and Sociotechnical Systems via their Social Science Research Grant scheme to undertake an exploratory research programme applying systems thinking-based methods to model the supplement use system in elite Australian sport, and to conduct a subsequent proactive risk assessment.

The project aimed to conduct an in-depth assessment of the system of tasks and actors surrounding supplement use in Australia followed by a proactive systemic risk assessment. The aims were achieved by engaging subject matter experts in workshop settings to model the supplement use system, identify the tasks and actors involved in supplement use, identify relevant task and emergent risks of unintentional doping, and developing subsequent strategies for the safe use of supplements.

The primary research question was what are the individual, organisational, and systemic factors that interact to create unintentional athlete doping events through supplement use? This primary aim comprised the following specific research objectives:

- What are the tasks that athletes and other sport system stakeholders undertake to create, acquire, and administer supplements?
- What interactions and coupling exist between tasks and stakeholders?
- What are the systemic factors that interact to create unintentional doping events through supplement use?
- What are the potential risk management strategies for supplement use? Which stakeholders are responsible for implementing them?

Summary of key findings

- The overall goal identified that athletes use supplements to optimise health, performance, recovery, image, and achieve optimal weight.
- To achieve this goal, 15 high level sub-tasks were involved in supplement use, including conducting health and sport science research, manufacturing supplements, marketing/advertising, distributing supplements, and using supplements, among others. The high level sub-tasks were broken down into 71 more specific sub-tasks.
- The most influential tasks within the system were 'maintaining clean sport' by anti-doping authorities and 'marketing/advertising' of supplements by supplement companies.
- The most influential stakeholders within the system included 'anti-doping agencies', 'athlete support personnel', and 'sponsors'.
- The risk analysis of the supplement use system in Australia identified over 1800 risks associated with supplement use.
- The origin for the majority of risks included the tasks 'manufacture supplements', 'identify need to use supplements', 'research supplements', 'conduct health and sport science research', and 'regulate sport supplement sector' that are responsible for vast amounts of emergent risks.
- The prevention of unintentional doping through supplement use may require interventions that shift away from the typical focus on athletes and athlete support personnel, to encompass a broader systemic focus to include manufacturing of supplements, and regulation of the supplement sector, among others.
- Intervention strategies should encompass a broad range of approaches for reducing unintentional doping through supplement use, including educational interventions, advancements in technology, and strategically targeted increases in resources.

Dissemination activities

Peer reviewed journal articles

- McLean, S., Morrison, M., Naughton, M., & Salmon, P. M. (2024). Decoding unintentional doping: A complex systems analysis of supplement use in sport. *Performance Enhancement & Health*, 100317.
- Morrison, M., Salmon, P. M., Naughton, M, & McLean, S. (in preparation). A Proactive Risk Assessment of Supplement Use in Athletes: An Application of The Networked Hazard Analysis and Risk Management Systems (Net-HARMS).

Presentations of findings

- University of the Sunshine Coast (UniSC) Research Conference 2024
- Sport Integrity Australia stakeholder presentation

A report describing the overall findings and the risk assessment will be made freely available on the University of the Sunshine Coast's Centre for Human Factors and Sociotechnical Systems website.

Part one: introduction

Unintentional doping through supplement use is an intractable yet preventable issue in elite sport. Research has demonstrated that athletes regularly use supplements, and in some sports, it is estimated that up to 100% of athletes use supplements (Erdman et al., 2007; Nieper, 2005; Tscholl et al., 2010). Additionally, a considerable percentage of supplements used by athletes may contain prohibited substances, be mislabelled or inadequately labelled, or even specifically 'spiked' with prohibited substances (Baylis et al., 2001; De Cock et al., 2001; de Hon & Coumans, 2007; Delbeke et al., 2002; Duiven et al., 2021; Geyer et al., 2011; Maughan, 2005; Van der Merwe & Grobbelaar, 2005). For example, 216 sports nutrition supplements claiming to modulate hormonal regulation, stimulate muscle mass gain, increase fat loss, and/or boost energy were analysed, with 38% containing undeclared banned substances (Duiven et al., 2021). Consequently, athletes can be unwittingly and unintentionally exposed to doping when consuming supplements, as they are oblivious of the specific ingredient content (Chan et al., 2016; Chan et al., 2019).

The high rate of supplement usage among athletes, coupled with the potential for contaminated and mislabelled supplements, has resulted in an ongoing problem of athletes returning adverse analytical findings through supplement use (Outram & Stewart, 2015). Alarmingly, it is estimated that up to 9% of all positive doping tests are caused by elite athletes using poorly labelled sports nutrition and dietary supplements (Outram & Stewart, 2015). Further, a WADA study into athlete doping vulnerabilities has indicated that nutritional and dietary supplements are the most important risk factor for unintentional doping (World Anti-Doping Agency, 2022). While the risks associated with acquiring contaminated supplements may be reduced at elite levels through enhanced controls over supplement sourcing (Outram & Stewart, 2015), up to 50% of elite athletes purchase supplements through standard retail sources such as stores and the internet (Baltazar-Martins et al., 2019).

Though there is a strong knowledge base regarding the issue of unintentional doping involving supplements, there are key gaps. The research conducted to date has typically focused on isolated components including the behaviour and psychological factors of athletes (Chan et al., 2016; Hurst et al., 2019; Hurst et al., 2024), perceptions of coaches and support staff (World Anti-Doping Agency, 2022), education and recommendations on supplement use (Close et al., 2022; Filleul et al., 2024), independent testing of supplements for banned substances (Duiven et al., 2021), and identification of individual risk factors for unintentional doping (Chan et al., 2019; Ntoumanis et al., 2024), among others. While this research has advanced our knowledge of unintentional doping, it has failed to capture the complexity of the interactions between factors that enable emergent behaviours across the system. As a result, many influential factors are likely left unaddressed by strategies that aim to prevent unintentional doping. A major challenge is the difficulty in conceptualising the

interactions between system components to identify the best places to intervene for effective prevention. While recent research has suggested that anti-doping efforts should consider broader organisational, systemic, and societal contributory factors to reduce doping in general, this has not been forthcoming as existing research programmes have rarely adopted complex systems analysis methods. In particular, there has been no prospective systems thinking-based risk assessment undertaken within anti-doping. The proposed research is a direct response to this.

The need for a systems thinking-based risk assessment:

The concept of complexity is currently receiving increasing attention in sport research (McLean, Naughton, et al., 2024; McLean, Robertson, et al., 2024; Salmon & McLean, 2020). Recently, the adoption of complex systems approaches in doping prevention has emerged. For example, McLean, Naughton, et al. (2023) demonstrated the inherent complexity of anti-doping within Australian football codes by modelling the anti-doping control structure using Systems Theoretic Accident Model and Processes (STAMP). Further, Naughton et al. (2024) identified contributory factors related to doping in sport and used Rasmussen's Risk Management Framework (Rasmussen, 1997) to map the contributory across several levels within the anti-doping system, demonstrating doping is an emergent property of sport systems and represent a complex systemic problem that will require whole-of-system interventions.

It could be argued that without the adoption of complexity science and systems thinking approaches, it is not possible to fully understand the myriad of factors influencing behaviour, and thus it is not possible to introduce appropriate and effective interventions designed to improve outcomes. Further, the risks associated with unintentional doping have not been assessed in a proactive and systemic manner. Rather, reactive and isolated approaches have been used to investigate previous incidents. Given the complexity of the issue of doping in sport (Backhouse et al., 2018; Houlihan & Vidar Hanstad, 2019; Naughton et al., 2024), a complex systems risk assessment is required to understand the risks associated with unintentional doping through supplement use.

Systems thinking-based risk assessment methods are currently recognised as state-of-the-art in the safety critical domains. These methods offer two key strengths across traditional approaches. First, they enable the identification of risks across the broader system and not just those related to front line workers (in this case athletes and athlete support personnel). Second, they support the analysis of interactions between conditions across the system, enabling the identification of so-called emergent risks that are typically difficult to foresee. While systemic risk assessment has not yet been applied in anti-doping, or sport in general, its use in safety critical domains, such as healthcare, road safety, aviation, and outdoor recreation, among others, has demonstrated its importance to proactively identify risk, and develop subsequent risk management strategies.

Accidents are now widely acknowledged to be a systems phenomenon (Dekker, 2011), which could be argued for unintentional doping. Within the field of safety science it is now largely accepted that accidents are a result of multiple interacting contributory factors situated across entire work systems (Dekker, 2011). Risk assessment describes the process of determining the likelihood of a risk occurring within a work system, and the likely consequences of that risk (Ostrom & Wilhelmsen, 2019). Dallat et al. (2019) reported that the most common methods currently described in the safety science literature are underpinned by quantitative (or probabilistic) approaches and further, that they focus largely on risks at the so-called 'sharp-end of performance', predominantly viewing accidents as emerging from linear, or a chain-of-events process. Such approaches fail to consider the interactions between these factors, which is a key principle behind systems thinking in relation to accident causation (Leveson, 2016; Rasmussen, 1997). Furthermore, risks elsewhere in the system (e.g., procedural, policy, training, and managerial risks) are not considered. Existing risk assessment methods are unable to identify the non-routine, emergent risks; those additional risks that arise as a result of the interaction between risks across the system.

The Networked Hazard Analysis and Risk Management System (Net-HARMS) method:

The Networked Hazard Analysis and Risk Management System (Net-HARMS) (Dallat et al., 2017) is a systems theory-based risk assessment method that supports the proactive identification of risks within complex sociotechnical systems by providing a description of the system under analysis on which a taxonomy is applied to identify task and emergent risks. Net-HARMS provides two key advances over existing risk assessment methods: first, it enables analysts to identify risks across the overall system, as opposed to 'sharp-end' risks only, and second, it enables analysts to identify 'emergent risks' that arise when different risks interact with one another. As a complex system risk assessment method, Net-HARMS is a novel and suitable approach to identify emergent risks from across the system to understand and prevent unintentional doping in sport. The research team have substantial experience in applying Net-HARMS across safety critical domains.

Project aims and scope

This project provides a description of the tasks and actors involved with supplement use within the Australian sporting system. Further, the application of the Net-HARMS systems theory-based risk assessment method was used to support the proactive identification of risks pertaining to unintentional doping through supplement use within the complex sporting system in Australia.

Project phases

This report describes the findings from the following activities conducted over four phases:

Phase 1. Development of a Hierarchical Task Analysis (HTA) and task and social networks for supplement use.
Phase 2. Identification of task risks
Phase 3. Identification of emergent risks
Phase 4. Development of risk management strategies

Structure of the report

The report is structured to provide an overview of the approach taken throughout this project and the key findings from each research phase.

Part two represents Phase 1 of the project and presents the findings from the HTA and network analysis of the tasks and actors involved in supplement use in Australian sport.

Part three represents Phases 2-4 of the project and presents the task and emergent risks identified from the application of the Net-HARMS proactive risk assessment, along with the accompanying proposed risk management strategies.

Institutional ethical approval was obtained from the University of the Sunshine Coast's human research ethics committee for the project (A231924).

Part two: hierarchical task analysis and network analysis of supplement use

Materials and methods

Design

This phase was designed to develop a HTA (Annett et al., 1971) of compliant supplement use in an Australian athlete context. A generic HTA structure is presented in Figure 1. Further, network analysis (Wasserman & Faust, 1994) was applied to identify the interdependency of the first level sub-goals within the HTA, as well as the stakeholders involved in performing the tasks. Network analysis provides a set of theoretical concepts, analytical tools, and computational techniques to explore the complex interdependencies within system components (Wasserman & Faust, 1994). For example, nodal metrics are used to investigate the influence and prominence of individual nodes (tasks or stakeholders) within a network, whereas overall network metrics can be used to investigate the structure of the entire network (McLean, King, et al., 2023).

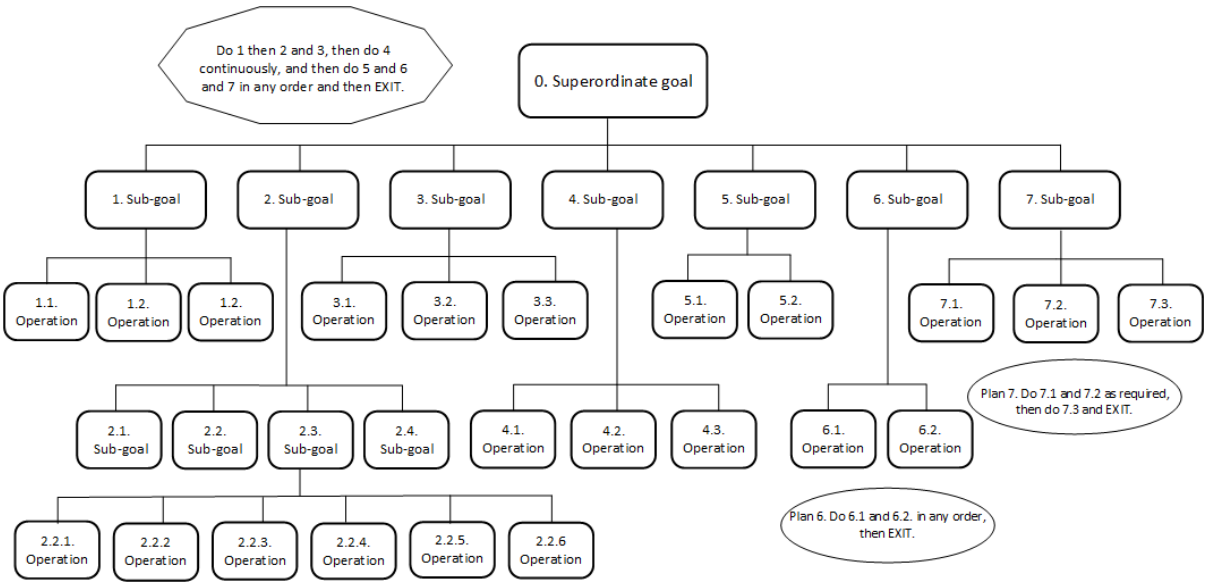

Figure 1. Example HTA structure demonstrating the superordinate goal, sub-goals, operations, and plans (circled text).

Participants

Twelve adults (eight female, four male; age: mean ± standard deviation (SD): 41.8 ± 11 years) with expertise in anti-doping across multiple sports in Australia and internationally, participated as subject matter experts (SME) within this project. Participants all held positions at Sport Integrity Australia (SIA) (3.7 ± 5.4 years' experience), Australia's National Anti-Doping Organisation (NADO), which included a variety of roles within anti-doping, such as Directors and Assistant Directors from multiple departments. Previously, participants had been employed in roles related to anti-doping at the

Australian Institute of Sport (AIS), Australian Sports Commission (ASC), and Australian Olympic Committee (AOC) (7.7 ± 8.4 years' experience). Further, SIA liaises with organisations such as Department of Health, Therapeutic Goods Association, Food Standards Australia New Zealand, and Department of Department of Agriculture, Fisheries, and Forestry, to understand and manage the broader system regarding food standards, supplement importation, and regulation. As such, the SMEs in the current project were considered to have a detailed understanding of the broader 'supplement use in sport system'.

Procedure

HTA development

The boundary for the HTA was set to capture the behaviour of the entire sociotechnical system, which included knowledge generation and dissemination, manufacturing, regulation, promotion and sale, acquisition, administration, and evaluation of the effects of supplements. The HTA was developed across three stages. First, an in-person SME workshop (see Participants section) was conducted (3 hrs duration) to develop the first two levels of the HTA (the superordinate goal and the first sub-goal level). The workshop was structured to determine the overall superordinate goal of the system, then to decompose the superordinate goal into its sub-goals and plans. Second, the research team decomposed the sub-goals further into second level sub-goals and component operations, and detailed plans (see Figure 1). This was achieved through publicly available sources, including anti-doping stakeholder websites, anti-doping policy documents, anti-doping strategies, media, and peer reviewed literature. The final phase in the HTA development involved sending the complete draft HTA to the SMEs from the SME workshop to review and refine the HTA. The SMEs were given three weeks to provide comments, and the research team revised the HTA based on their feedback.

Task network

A task network of the first level sub-goals of the HTA was developed to determine the connectivity between sub-goals, to understand the interactions and coupling that exists between tasks across the system (Salmon et al., 2022; Stanton et al., 2017). The task network was developed during the SME workshop following identification of the superordinate goals and the first level sub-goals. Participants were instructed that tasks were connected based on four criteria: if they are undertaken sequentially; undertaken together; if the outcomes of one task influence the conduct of another; or if the conduct of one task would be dependent on completion of another (Salmon et al., 2022). The development of the task network was performed through an adjacency matrix in Microsoft Excel, which included directionality (e.g., from Task A to Task B). Participants were asked to determine the connectivity between each of the tasks using 1 for connected tasks, and 0 where tasks were not connected (Table 1). All first level HTA sub-goals are described in Appendix 1.

Table 1. Truncated task network adjacency matrix of the first level sub-tasks from the HTA.

	Conduct health & sports science research	Demand for use	Regulate sports supplement sector	Maintain clean sport	Manufacture supplements
Conduct health & sports science research		1	1	1	1
Demand for use	1		1	1	1
Regulate sports supplement sector	1	0		1	1
Maintain clean sport	1	1	1		1
Manufacture supplements	1	0	1	1	

Social network

A social network of the stakeholders within the project boundary was developed to determine the connectivity and interdependency between them, to enable an understanding of roles and responsibilities and relative influence of stakeholders within the system. The initial step in developing the social network was to identify the stakeholders that undertake each of the first level sub-goals in the HTA. For example, anti-doping authorities are tasked to promote clean sport. This was undertaken by the research team using publicly available sources, including anti-doping stakeholder websites, anti-doping policy documents, anti-doping strategies, media, and peer reviewed literature. A draft list of stakeholders associated with each of the first level sub-goals of the HTA was sent to the SME group for review and refinement. The SMEs were given three weeks to provide comments, after which, the list of stakeholders associated with tasks was refined by the research team based on the SMEs feedback. A summary of all stakeholders, and a brief description of their associated tasks in the supplement use in sport system are presented in Appendix 2.

Construction of the social network involved determining the relationships between stakeholders in the social network. Stakeholders were deemed to be connected if they directly communicate information regarding knowledge, manufacturing, regulation, promotion and sale, acquisition, administration, and evaluation of the effects of supplements. This was done via the construction of a social network adjacency matrix in Microsoft Excel. The networks were directed (e.g., information is communicated from actor A to actor B), using 1 for a connection between stakeholders, and 0 if no connection between stakeholders was determined (Table 2). Two members of the research team and one member of the SME group with relevant expertise developed the social network adjacency matrix across two online workshops (1 hr duration each).

Table 2. Truncated social network adjacency matrix of the stakeholders within the supplement use in sport system.

	Academics	Anti-doping agencies	Applied sport scientists	Athlete	Athlete support personnel
Academics		1	1	1	1
Anti-doping agencies	1		1	1	1
Applied sport scientists	1	0		1	1
Athlete	1	1	1		1
Athlete support personnel	1	1	1	1	

Network analysis

In the current project, five nodal metrics and one network metric were applied to the task and social networks (Table 3). Nodes of interest (tasks or stakeholders) in the networks were identified as those that were one standard deviation away (above and below) from the mean of each network metric (Houghton et al., 2006; Stanton & Harvey, 2017). Highly connected nodes in the network were identified as being one standard deviation above the mean, and loosely connected nodes were those that were one standard deviation below the mean. The network analysis was performed in the Social Network Visualiser (SocNetV) program, which has been previously used to analyse task and social networks (McLean, King, et al., 2023). For the centrality metrics, the standardised index was calculated, which adjusts the raw centrality scores to account for the size of the network, making it possible to compare centrality scores across different networks or subnetworks by normalising them (Freeman, 1977).

Table 3. Network and nodal metrics applied to the task and social networks.

Network metric	**Definition**
Network Density	Network density calculates the proportion of actual connections (edges) in a network compared to the total possible connection. For example, a network density score of 1 means that all nodes are connected, whereas a network density score of 0 means no nodes are connected. Thus, a network density score between 0 and 1 reflects the proportion of actual connections compared to all possible connections in the network. A higher density score indicates a more interconnected network, where many nodes are directly linked, while a lower score suggests a sparser network with fewer connections between nodes.
Out-Degree Centrality	Out-degree centrality is the calculation of outgoing connections that a node initiates towards other nodes in a network. It measures the proactivity, influence, or connectivity tendencies of a specific node within the networks. For example, a node with high relative Out-degree centrality value would indicate that it directly influences many other nodes in the network, suggesting it plays a key role in disseminating information/resources within the network by having numerous outgoing links.
In-Degree Centrality	In-degree centrality is the calculation of incoming connections that a node receives from other nodes in a network. It helps measure the popularity, influence, or dependency on a specific node within the networks. For example, a node with high relative In-degree centrality value would indicate that it receives a large number of direct connections from other nodes in the network, suggesting it holds prominence or influence within the network based on the number of incoming interactions or references.
Betweenness Centrality	Betweenness centrality quantifies the extent to which a node lies on the shortest paths between other nodes. It helps identify key stakeholders who play a crucial role in connecting other nodes (e.g., a node that acts as a bridge between nodes). For example, a node with high relative betweenness centrality would indicate that it serves as a crucial bridge or intermediary in the network, frequently lying on the shortest paths between other nodes. This suggests it plays a key role in controlling the flow of information/resources by connecting different nodes in the network
Closeness Centrality	Closeness centrality is a measure of efficiency or how quickly a node can access other nodes in the network. It helps identify stakeholders who are in close proximity to other stakeholders and can connect efficiently. For example, a node with high relative closeness centrality would indicate that it is centrally located within the network, with short average distances to all other nodes. This suggests it can quickly access or influence other nodes, making it efficient for spreading information/resources throughout the network
Eigenvector Centrality	Eigenvector Centrality is calculated based on the principle that connections to high-scoring nodes contribute more to the score of a node than equal connections to low-scoring nodes. This means that a node is considered important if it is connected to other important nodes. The key idea behind eigenvector centrality is that not all connections are equal; connections to nodes that are themselves central are more valuable. For example, a node with high relative Eigenvector centrality value would indicate that it is connected to other nodes that are themselves highly central, suggesting it holds significant influence within the overall network due to its connection to important or well-connected nodes.

Results

Hierarchical Task Analysis

The HTA revealed that the overall goal of athlete supplement use was to optimise health, performance, recovery, image, and achieve optimal weight (Figure 2). This superordinate goal was further decomposed into 15 sub-goals that are required for the overall goal to be achieved. Within Figure 2, the 15 sub-goals were further decomposed into a total of 71 subsequent sub-goals underpinning the overall goal. The plans indicate the sequence in which the tasks are completed.

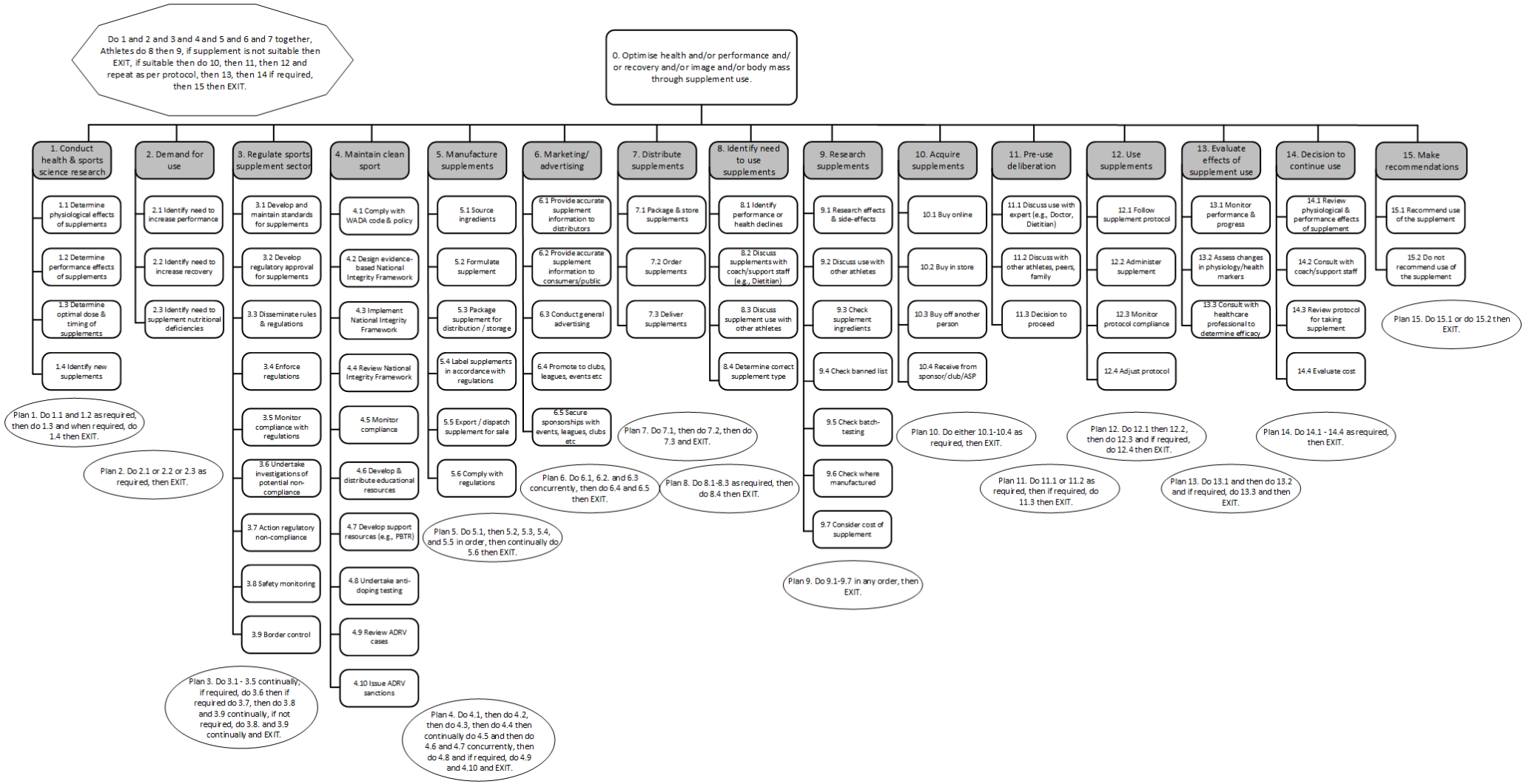

Figure 2. HTA for athletes taking supplements to optimise health, performance, recovery, image, and achieve optimal weight. The first sub-goal level is shaded to represent the level used for the task network. *Task network*

The task network of the 'optimising health, performance, recovery, image, and achieve optimal weight through supplement use' HTA is displayed in Figure 3. The key tasks (one standard deviation above the mean), according to the network analysis metrics were 'conduct health and sports science research', 'demand for use', 'maintain clean sport', 'marketing/advertising', and 'make recommendations' (Table 4). Loosely connected nodes (one standard deviation below the mean) included 'pre-use deliberation', and 'evaluate effects of supplement use'. The task network had a network density of .54 which indicates a moderate to high level of interconnectedness (Stanton & Harvey, 2017) between tasks in the network. Definitions of tasks are available in Appendix 1.

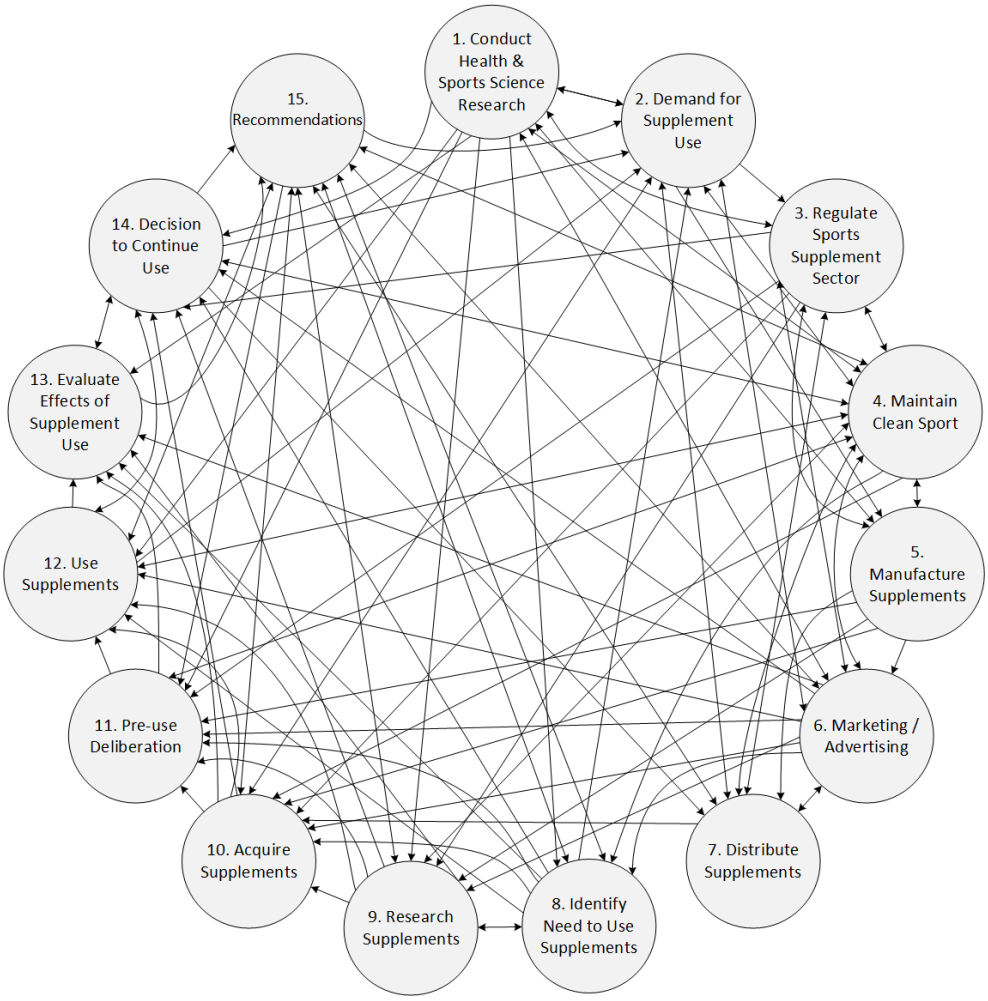

Figure 3. Task network for the goal of 'optimising health, performance, recovery, image, and achieve optimal weight through supplement use' in elite Australian sport.

Table 4. Network metrics for the task network (shading denotes values one standard deviation above (grey) or below (blue) the mean).

Task	Out-Degree Centrality	In-Degree Centrality	Closeness Centrality	Betweenness Centrality	Eigenvector Centrality
Conduct health & sports science research	**0.786**	***0.357***	**0.824**	0.020	**0.829**
Demand for use	0.500	0.643	0.667	**0.086**	0.682
Regulate sports supplement sector	0.643	0.429	0.737	0.014	0.739
Maintain clean sport	**0.929**	**0.786**	**0.933**	**0.157**	**1.000**
Manufacture supplements	0.517	***0.286***	0.700	0.004	0.684
Marketing and advertising	**0.929**	0.500	**0.933**	0.042	**0.937**
Distribute supplements	0.429	0.500	0.636	0.013	0.584
Identify need to use supplements	0.571	***0.357***	0.700	0.005	0.456
Research supplements	0.571	0.500	0.700	0.014	0.494
Acquire supplements	0.429	0.643	0.636	0.025	0.345
Pre-use deliberation	***0.214***	0.643	***0.560***	0.007	***0.207***
Use supplements	0.357	0.643	0.609	0.013	0.397
Evaluate effects of supplement use	***0.143***	0.571	***0.483***	0.004	***0.153***
Decision to continue use	0.429	0.643	0.636	0.034	0.466
Make recommendations	0.643	0.643	0.737	**0.105**	0.680
Mean ± standard deviation	**0.539 ± 0.219**	**0.543 ± 0.135**	**0.699 ± 0.120**	**0.036 ± 0.043**	**0.577 ± 0.241**
Mean + 1 standard deviation	**0.759**	**0.678**	**0.819**	**0.080**	**0.818**
Mean - 1 standard deviation	***0.320***	***0.408***	***0.580***	***-0.007***	***0.336***

Stakeholder identification and social network

The identified system stakeholders (n=33) and their related tasks are presented in Table 5. The tasks of 'regulate sports supplement sector', 'maintain clean sport' and 'acquire supplements' were associated with the highest number of associated stakeholders. The social network comprising 33 stakeholders involved across the tasks in the HTA is presented (Table 6). The key stakeholders (one standard deviation above the mean), according to the network metrics included anti-doping agencies, the athlete, athlete support personnel (ASP), institutes/academies of sport, professional/local clubs, sponsors, and supplement companies (Table 6). Loosely connected stakeholders (one standard deviation below the mean) included 'athlete's friends/family', 'athlete's manager', 'batch-testing companies', and 'general population' (Table 6). The social network had a network density of .31 which indicates a relatively low level of interconnectedness (Stanton & Harvey, 2017) between stakeholders in the network. Definitions of stakeholders' roles are available in Appendix 2.

Table 5. The system stakeholders associated with the tasks they perform in the task network.

Task	Stakeholders
1. Conduct health and sport science research	Academics (University) Applied sport-scientists (e.g., National Institute Network, Australian Institute of Sport (AIS)) Industry R&D teams
2. Demand for use	Athletes Coaches General population
3. Regulate sports supplement sector	Anti-doping agencies (e.g., SIA & WADA) Event organisers National Sporting Organisations (e.g., Swimming Australia) Australian Sports Commission Parliament and legislators Therapeutic Goods Association (compliance and enforcement) Department of Agriculture, Fisheries, and Forestry Department of Health & Aged Care Food Standards Australia New Zealand (FSANZ) Commonwealth Sport Supplements Working Group
4. Maintain clean sport	National Anti-doping agencies (NADOs) (e.g., SIA, & WADA; doping control officers) Event organisers Australian Sports Commission National Sporting Organisations (e.g., AIS) National Sporting Organisation for People with Disability Institutes/academies of sport Athletes Independent anti-doping testing providers (e.g., LGC Assure; doping control officers) Professional and local clubs Coaches Doping control officers (e.g., collection officers and chaperones) Batch-testing companies (e.g., HASTA) Athlete support personnel (e.g., sports scientists, doctors, psychologists, strength and conditioning coaches) Professional associations (e.g., ESSA, AMA)
5. Manufacture supplements	Supplement companies
6. Marketing/advertising	Supplement companies Supplement retailers Sales representatives
7. Distribute supplements	Supplement companies Transporters (e.g., delivery drivers) Supplement retailers Wholesalers/distributors Manufacturers

	Sales representatives Sponsors
8. Identify need to use supplements	Athlete Coaches Athlete support personnel (e.g., sports scientists, doctors, psychologists, strength and conditioning coaches) Sponsors
9. Research supplements	Athletes Coaches Athlete support personnel (e.g., sports scientists, doctors, psychologists, strength and conditioning coaches)
10. Acquire supplements	Athlete Athlete's friends/family Athlete's manager Supplement retailers Sponsors Coaches Athlete support personnel (e.g., sports scientists, doctors, psychologists, strength and conditioning coaches)
11. Pre-use deliberation	Athlete Athlete's friends/family Athlete support personnel (e.g., sports scientists, doctors, psychologists, strength and conditioning coaches)
12. Use supplements	Athlete
13. Evaluate effects of supplement use	Athlete Coaches Athlete support personnel (e.g., sports scientists, doctors, psychologists, strength and conditioning coaches)
14. Decision to continue use	Athlete Athlete's friends/family Athlete support personnel (e.g., sports scientists, doctors, psychologists, strength and conditioning coaches)
15. Make recommendations	Athlete

Table 6. Network metrics for social network stakeholders.

Actor	Out-Degree Centrality	In-Degree Centrality	Closeness Centrality	Betweenness Centrality	Eigenvector Centrality
Academics	0.406	0.281	0.604	0.023	**0.799**
Anti-doping agencies	**0.625**	**0.594**	**0.696**	**0.188**	**1.000**
Applied sport-scientists	0.219	0.375	***0.500***	0.018	0.486
Athlete	0.375	**0.656**	0.604	**0.067**	0.792
Athlete support personnel	**0.438**	**0.531**	**0.627**	0.051	**0.928**
Athlete's friends/family	***0.125***	0.219	***0.444***	0.004	***0.256***
Athlete's manager	***0.188***	***0.156***	***0.457***	0.001	0.388
Australian Sports Commission	0.375	0.313	0.582	0.033	0.770
Batch-testing companies	***0.188***	***0.094***	0.533	0.006	***0.279***
Coaches	0.313	0.438	0.582	0.027	0.642
CSSWG	0.281	0.250	0.508	0.010	0.443
DAFF	0.250	0.188	0.542	0.003	0.381
DHAC	0.250	0.188	0.542	0.003	0.381
Doping control officers	0.219	0.188	0.525	0.005	0.454
Event organisers	0.313	0.250	0.582	0.024	0.611
FSANZ	0.281	0.281	0.561	0.018	0.430
General population	***0.125***	0.281	***0.438***	0.005	***0.256***
Independent anti-doping testing providers	0.219	0.250	0.525	0.007	0.454
Industry R&D teams	0.250	***0.125***	0.552	0.011	0.436
Institutes/academies of sport	**0.469**	0.438	**0.627**	0.036	**0.953**
Manufacturers	0.281	0.250	0.582	0.037	0.450
NSOD	0.281	0.375	0.542	0.013	0.591
NSO	0.281	0.375	0.542	0.013	0.591
Parliament and legislators	0.250	0.281	0.542	0.013	0.393
Professional/local clubs	**0.438**	**0.500**	**0.627**	0.037	**0.901**
Professional associations	0.313	0.281	0.571	0.010	0.704
Sales representatives	0.344	0.375	0.571	0.038	0.693
Sponsors	**0.500**	0.344	**0.627**	0.042	**0.935**
Supplement companies	0.375	0.344	0.593	**0.069**	0.585
Supplement retailers	0.344	0.344	0.533	0.027	0.674
TGA	0.219	0.313	0.516	0.015	***0.303***
Transporters	0.313	***0.156***	0.542	0.005	0.588
Wholesalers/distributors	0.344	***0.156***	0.552	0.006	0.666
Mean ± standard deviation	**0.309 ± 0.107**	**0.309 ± 0.133**	**0.557 ± 0.55**	**0.026 ± 0.034**	**0.582 ± 0.216**
Mean +1 standard deviation	**0.416**	**0.441**	**0.612**	**0.060**	**0.798**
Mean -1 standard deviation	***0.201***	***0.176***	***0.502***	***-0.008***	***0.366***

Notes: FSANZ = Food Standards Australia New Zealand; CSSWG = Commonwealth Sport Supplements Working Group; DAFF = Department of Agriculture, Fisheries, and Forestry; DHAC = Department of Health & Aged Care; NSOD = National Sporting Organisation for People with Disability; NSO = National Sporting Organisations; TGA = Therapeutic Goods Administration.

Part three: Application of Net-HARMS risk assessment to supplement use

Materials and methods

Design

This phase was designed to conduct a proactive risk assessment of the supplement use system in Australia, using the Net-HARMS. The task network developed from the HTA in phase 1 was used to conduct the Net-HARMS analysis. The Net-HARMS risk assessment method was applied by the research team to each task within the task network to identify tasks risks and emergent risks. The identified risks allowed for the subsequent risk mitigation strategies to be developed by SMEs.

To develop the risk mitigation strategies, thirteen participants (nine female, four male) acted as SMEs for the development of risk management strategies for the risks identified through the application of Net-HARMS. Participants (age: 37.3 ± 7 years) held positions such as Director, Assistant Director, Science Officer, Head of Department, Academics & PhD students, and Sports Dietitian, Pharmacists, at organisations involved in the sporting system, including SIA, National Sporting Organisations, Universities, and supplement retailers. SMEs had previous experience with roles including intelligence officers, intelligence analysts, educators, and directors at anti-doping organisations such as anti-doping laboratories and the Therapeutic Goods Association, as well as previous experience in high-performance sport, with roles such as head of science and innovation, physiotherapists, head of strength and conditioning, former athlete, and sports dietetics (3.9 ± 4 years' experience).

Procedure

Task network development

The task network developed in phase 1 of the project was used for the Net-HARMS analysis.

Net-HARMS application

To identify the risks and emergent risks from the supplement use landscape, the Net-HARMS risk mode taxonomy (Table 1) was applied to each task in the task network. The taxonomy consists of 10 potential ways that a task could be completed sub-optimally (Salmon et al., 2022). A task risk was defined as a risk that may occur if the task is not completed optimally (Salmon et al., 2022). The analyst systematically applied the taxonomy to every task and for each resulting risk that was identified, a description of the risk along with the potential consequences associated with that risk were provided. Further, a criticality rating of either low (unlikely to result in an ADRV), medium (may result in an ADRV), or high (likely to result in an ADRV) and a probability rating of either low (unlikely to occur), medium (may occur from time to time), or high (likely to occur) were allocated to each identified risk (Salmon et al., 2022). A risk classification taxonomy (Table 2) was then applied to

each risk to determine the potential domains (i.e., reputational, financial, safety, performance, and legal) that may be affected if the risk were to occur. For further information regarding the Net-HARMS procedure, see Dallat et al. (2017).

The next phase of the analysis involved identifying emergent risks that may manifest from risks identified in phase one interacting with a connected task in the network. Emergent risks were classified for tasks risks that were identified as having high probability and high criticality ratings. To identify emergent risks, the task network and Net-HARMS risk mode taxonomy were used. The direction of the relationship between tasks were identified and recorded, along with a description of the initial risk modes and tasks identified in the first phase. The Net-HARMS risk mode taxonomy was then applied to these connections to identify potential emergent risks. A description of the consequence of each emergent risk along with a rating of criticality and probability were then recorded.

Finally, risk management strategies to either prevent the risk from occurring or mitigate the consequences of the risk were identified in conjunction with SMEs for the five task risks responsible for the most frequent emergent risks.

Table 1. Net-HARMS risk mode taxonomy

Behaviour	**Risk Modes**
Task	T1 – Task mistimed T2 – Task omitted T3 – Task completed inadequately T4 – Inadequate task object T5 – Inappropriate task
Communication	C1 – Information not communicated C2 – Wrong information communicated C3 – Inadequate information communicated C4 – Communication mistimed
Environmental	E1 – Adverse environmental conditions

Table 2. Net-HARMS risk types

Risk Category	Description
Reputational	Risks that may adversely impact the reputation of stakeholders associated with the task or system under analysis
Financial	Risks that may adversely impact the financial status of stakeholders associated with the task or system under analysis
Safety	Risks that may adversely impact the safety of stakeholders associated with the task or system under analysis
Performance	Risks that may adversely impact the performance the task or system under analysis
Legal	Risks with legal implications for stakeholders associated with the task or system under analysis

Identifying risk control

Once task and emergent risks were identified, the research team developed four case studies to represent the tasks which were responsible for the most high-criticality and high-probability risks (Supplementary Table 2). Risk controls were developed during a 3-hour workshop with SMEs and then later refined by the research team. Each control was provided with an estimated timeline that would be required for the control to be implemented, including short (i.e., completed within 12 months), medium (i.e., completed within 5 years), and long-term (i.e., >5 years to complete).

Results

Net-HARMS

Task risks

Across the 15 tasks from the task network involved in supplement use, 331 task risks were identified, with 61 high probability and high criticality risks. The prevalence of tasks is presented in Table 3. An exert of high probability and high criticality risks with their respective risk descriptions, risk consequences, risk mode, and risk types are presented in Table 4. The tasks with the highest number of risks were ‘maintain clean sport’ (n = 43) and ‘research supplements’ (n = 43) contrasting ‘acquire supplements’ (n = 10) and ‘make recommendations’ (n = 7), with the least risks.

Risk mode behaviours

The most prevalent risk mode behaviour for the task risks were 'task risks' (n = 218; 65.86%), followed by 'communication risks' (n = 111; 33.54%), and 'environmental risks' (n = 2; 0.6%) (Table 5). The most frequent 'task risk' mode behaviours were 'T2 – task omitted' with 70 risks and 'T3 – task completed inadequately' with 57 risks. The task risk mode behaviours with the least risks, were 'E1 – adverse environmental conditions' with 2 risks, and 'C3 – Inadequate information communicated' with 14 risks.

Risk type

Of the five risk types, 295 task risks were classified as 'safety' risks, 229 task risks were identified as 'reputational' risks, 178 task risks were categorised as 'performance' risks, 93 task risks were 'legal' risks, and 58 task risks were financial.

Emergent risks

A total of 1506 emergent risks were identified, with 354 (23.51%) high-probability and high-criticality emergent risks. A count of the task risks, emergent risks and high probability and high criticality emergent risks is provided in Table 6. Of the emergent risks, there were 289 low probability risks, 857 medium probability risks, and 360 high probability risks whilst 29 low criticality risks, 225 medium criticality risks, and 1252 high criticality risks. The most emergent risks were identified for 'maintain clean sport' (n = 244) and 'research supplements' (n = 193), with the least emergent risks originating from 'distribute supplements' (n = 25) and 'conduct health & sport science research' (n = 35). Of the high probability and high criticality risks, the most emergent risks were identified for 'maintain clean sport' (n = 106) and 'research supplements' (n = 48) whereas the least were identified for 'make recommendations' (n = 0) and 'decision to continue use' (n = 2).

Emergent risk mode behaviours

The most prevalent emergent risk mode behaviours were 'task risks' (n = 1106; 73.44%), 'communication risks' (n = 399; 26.49%), and 'environmental risks' (n = 1; 0.07%). The most prevalent emergent risk mode behaviours were 'T3 – task completed inadequately' with 649 emergent risks, 'T4 – Inadequate task object' with 239 emergent risks, whereas the risk mode behaviours with the least risks were 'E1 – adverse environmental conditions' with one risk and 'T5 – inappropriate task' with 17.

Emergent risk types

Of the five risk types identified during emergent risks, 1488 were 'safety' risks, 1377 were 'financial' risks, 1369 were 'reputational', 1354 were 'legal' risks, and 334 were 'performance' risks.

Table 3. Distribution of task risks by criticality and probability

Task	Tasks risks total	High criticality and high probability	Criticality			Probability		
			High criticality	Medium criticality	Low criticality	High probability	Medium probability	Low probability
Conduct health & sport science research	16	7	16	-	-	7	9	-
Demand for use	12	-	5	2	5	-	-	12
Regulate sports supplement sector	31	9	31	-	-	9	17	5
Maintain clean sport	43	-	38	3	2	-	9	34
Manufacture supplements	38	13	28	7	3	13	7	18
Marketing/advertising	27	2	7	14	6	2	2	23
Distribute supplements	21	-	1	5	15	-	1	20
Identify need to use supplements	27	9	21	4	2	9	11	7
Research supplements	43	12	39	3	1	12	24	7
Acquire supplements	10	1	8	2	-	1	8	1
Pre-use deliberation	13	5	10	-	3	5	4	4
Use supplements	14	3	5	9	-	3	7	4
Evaluate effects of supplement use	14	-	1	8	5	-	1	13
Decision to continue use	15	-	-	13	2	-	10	5
Make recommendations	7	-	4	3	-	1	5	1
Total	331	61	214	73	44	62	115	154

Table 4. Example high-probability and high-criticality risks with the respective risk mode, risk description, risk consequence, and risk type

Task	Risk mode	Task risk description	Risk consequence	Risk type
Conduct health & sports science research	T2: Task omitted	Research determining the safety of supplements for consumption is not undertaken	Supplements may be unsafe for consumption, have detrimental side-effects, or contain dangerous substances resulting in ADRVs or illness	Safety Reputational Legal
Regulate sports supplement sector	T3: Task completed inadequately	Regulations for supplement companies are developed but not implemented	Supplement companies may briefly comply with regulations but then act outside (willingly or unwillingly) as they are not being monitored for compliance, causing dangerous supplements to be manufactured and available for purchase	Safety Reputational Legal
Manufacture supplements	T5: Inappropriate task	Incorrect equipment is used to manufacture supplement	Supplements may become contaminated by inappropriately manufacturing equipment	Safety Reputational Legal Financial
Marketing / advertising	C2: Wrong information communicated	Advertising makes false or incorrect claims regarding the supplement	Athletes consuming the supplement may be misled and unable to make an informed decision regarding the supplement	Safety Performance Legal Reputational
Identify need to use supplement	T1: Task mistimed	Appropriate supplement for use is not correctly identified prior to commencing supplement regime	Incorrect supplements are being consumed, potentially containing inappropriate or prohibited substances	Safety Performance Reputational
Research supplements	C1: Information not communicated	Supplement ingredients are not listed on product container	Athletes may consume the supplement without knowing what is in there	Safety Performance Legal Reputational
Pre-use deliberation	C4: Communication mistimed	Experts provide recommendation not to consume a supplement after athlete has already decided to consume it	Athlete ignores advice and consumes a supplement that may be unsafe or contains a prohibited substance	Safety Performance Reputational
Use supplements	T4: Inadequate task object	Athlete uses an inappropriate location/instrument to prepare and consume supplement	Athlete may consume a supplement that has been contaminated by an inappropriate instrument	Safety Performance Reputational

Table 5. Number of risks per category of the Net-HARMS risk mode taxonomy

		Number of risks	
Behaviour	Risk Modes	Task risks	Emergent risks
Task	T1 – Task mistimed	43	57
	T2 – Task omitted	70	144
	T3 – Task completed inadequately	57	649
	T4 – Inadequate task object	20	239
	T5 – Inappropriate task	28	17
Communication	C1 – Information not communicated	37	96
	C2 – Wrong information communicated	36	156
	C3 – Inadequate information communicated	14	147
	C4 – Communication mistimed	24	-
Environmental	E1 – Adverse environmental conditions	2	1

Table 6. Number of origin task risks, emergent task risks, and high-probability and high-criticality emergent risks

	Origin task risk	Emergent task risk	High-probability and high-criticality emergent risks
Conduct health & sports science research	281	35	9
Demand for use	-	38	8
Regulate sports supplement sector	274	120	38
Maintain clean sport	-	244	106
Manufacture supplements	323	88	17
Marketing/advertising	54	121	38
Distribute supplements	-	25	12
Identify need to use supplements	170	56	12
Research supplements	286	193	48
Acquire supplements	13	116	24
Pre-use deliberation	56	130	27
Use supplements	49	83	7
Evaluate effects of supplement use	-	97	5
Decision to continue use	-	114	2
Make recommendations	-	46	0

Risk management strategies

Risk management strategies, their definition, and likely timeline required to be implemented pertinent to the five origin task risks responsible for the most emergent risks are presented in Table 7. Interventions identified for mitigating risks related to the manufacturing of supplements were related to government owned and manufactured supplements, and technological advancements. Interventions for identifying the need to use supplements were related to broader and targeted education, increased resources, and better support for in-need athletes. Three strategies were identified for mitigating risks

associated with researching supplements, related to broadening education, resources for athlete support, and improved scientific literacy. Mitigation strategies related to the task of conduct health and sport science research were the development of a gold-standard research framework for supplements, technological advancements, and developing an independent scientific supplement review board. Four strategies were developed to mitigate potential risks associated with the regulate sport supplement sector task, including adopting plain packaging for supplements, overhaul supplement standards and regulations, increased resources for greater capacity, and supplement safety data systems.

Table 7. Potential risk management strategies identified for mitigating unintentional doping through supplement use			
Manufacture supplements	1. All supplements are safe for consumption and free of prohibited substances 2. Government owned and manufactured supplements 3. Technological advancements	1. All supplements produced are safe for consumption, compliant to clean sport requirements, and do not contain any prohibited substances. 2. Government owned and manufactured supplements would allow for a safe and reliable source of supplements for athletes, with guaranteed safety standards and quality control. 3. Using blockchain technology to ensure full transparency throughout the supplement production process. Each stage, from sourcing raw materials to distribution, is recorded on the blockchain, providing traceability and accountability for every batch. By scanning QR codes on each supplement, athletes and stakeholders can instantly access detailed information about the product's origin and testing history.	1. Long 2. Long 3. Long
Identify need to use supplements	1. Broader and targeted education	1. Tailored education provided to all stakeholders involved in the decision for an athlete to use supplements. Providing targeted education to coaches and athlete support personnel on how their influence can impact an athlete's decision to use supplements (e.g., language used) and educated organisations on the inclusion of appropriate cultural representatives who model desired behaviours. Provide clarity regarding the definition of what constitutes a supplement (e.g., clear criteria separating food vs drink vs supplement). Supplement manufacturers and retailers who produce and sell supplements that are safe for sport are advocated for by relevant stakeholders to	1. Short

	2. Resources 3. Better support for in-need athletes 4. Competition scheduling	promote a pathway for athletes to safely access supplements. 2. Sporting organisations and teams are resourced adequately, to provide appropriate access and support from sports dietitians and sports medicine doctors, as well as providing athletes with appropriate supplements to mitigate the need for athletes to source their own. 3. Increased support for athletes across the entire sporting system, with a particular focus on in-need and emerging athletes. For example, providing additional support for athletic demographics that are often under-resourced, including female athletes, semi-elite or emerging athletes (who may often have competing demands such as work), and ageing athletes. 4. Competition schedules are reformatted to reduce fatigue associated with congested match schedules and allow for more recovery time for athletes, reducing the need for supplement use.	2. Medium 3. Medium 4. Medium to long
Research supplements	1. Broadening education	1. An active, online presence advocating for safe supplement use is provided by NADOs to raise online awareness of safe supplement use for athletes. For example, moderating popular forums related to supplement use and providing accurate and up-to-date information regarding safe supplement use. Athletes are provided with additional resources to help guide them through the process of selecting and consuming supplements such as apps and decision-making frameworks. Education programmes are targeted at a broader range of stakeholders involved in the supplement se lifecycle (e.g., parents, family, friends) and education is provided to emerging and young athletes, outside of professional sport.	1. Medium

	2. Resources for athlete support	2. Sporting organisations are provided with sufficient resources to allow for athletes to have in-depth discussions with appropriate support staff and have access to supplements that are screened and provided by the sporting organisation.	2. Long
	3. Scientific literacy	3. Stakeholders within the sport system are upskilled in the ability to understand and interpret good scientific practice.	3. Short
Conduct health and sport science research	1. Development of a gold-standard research framework for supplements	1. The scientific community of practices develops a gold-standard framework for conducting sport science research relating to supplements. For example, producing registered reports and pre-prints, registering scientific projects with organisations such as Open Science Framework, to promote transparent practice. The development of dedicated centres of excellence for supplement research which could develop and manage a safe supplement manufacturing framework.	1. Long
	2. Technological advancements	2. Developing technology that can conduct rapid, low-cost, on-site supplement testing.	2. Long
	3. Independent scientific supplement review board	3. The development and implementation of an independent scientific supplement review board would allow the verification of scientific claims made by supplement manufacturers.	3. Medium
Regulate sport supplement sector	1. Plain packaging for supplements	1. Supplements that are not independently tested and verified as safe for consumption, are required to be packaged in basic nondescript packaging. Where supplements that are independently tested and verified are not required to be sold in plain packaging.	1. Long
	2. Overhaul supplement standards and regulations.	2. Conduct a systemic overhaul of the regulation on advertising claims, distribution, and retail of supplements. Including supplement retailers are	2. Long

		required to display safe for sport supplements in a dedicated section of the store with clear signage that supplements are safe for athletes and only supplements that have been appropriately tested and verified as safe for sport are able to be presented in this section. Additionally, supplement retailers should complete training related to safe supplement use for athletes to become accredited safe supplement retailers. Supplement claims are independently verified. A framework for standardised reporting on product labels and consistent universal definitions for supplement-related terminology are developed.	
	3. Resources for greater capacity	3. Increased capacity for Border force to screen supplements being imported into Australia, as well as gathering intelligence on manufacturers providing supplements which are being imported that do not meet clean sport requirements.	3. Long
	4. Supplement safety data systems	4. The development of data systems to identify importation trends, profiles of unsafe supplements, and provide a dynamic warning system for supplements that have been identified as having a poor safety profile. This system could be used to identify hidden factors associated with emerging unsafe supplements through machine/deep learning analyses.	4. Medium
Manufacture supplements	1. All supplements that are manufactured are safe for consumption and free of prohibited substances	1. All supplements produced are safe for consumption, compliant to clean sport requirements, and do not contain any prohibited substances.	1. Long
	2. Government owned and manufactured supplements	2. Government owned and manufactured supplements would allow for a safe and reliable source of supplements for athletes, with guaranteed safety standards and quality control.	2. Long
		3. Using blockchain technology to ensure full	

	3. Technological advancements	transparency throughout the supplement production process. Each stage, from sourcing raw materials to distribution, is recorded on the blockchain, providing traceability and accountability for every batch. By scanning QR codes on each supplement, athletes and stakeholders can instantly access detailed information about the product's origin and testing history.	3. Long

Part four: discussion of findings

Discussion

This project was the first-of-its kind to decompose the supplement use in sport 'system' using HTA, develop task and social networks involved in supplement use, and conduct a proactive risk assessment on unintentional doping via supplement use in Australian sport.

The developed HTA provides a comprehensive analysis of the lifecycle of supplement use, from supplement research, development, and regulation to the administration of supplements by athletes, to subsequent assessments of their efficacy. As such, the HTA is fundamental for understanding how broader lifecycle tasks involved in supplement use may contribute to unintentional doping. The HTA demonstrates that regulatory oversight, manufacturing, sale, and distribution processes are critical areas where substandard performance of a task can potentially create conditions for unintentional doping downstream for athletes. For example, gaps in regulatory practices, such as inconsistent enforcement of rules or inadequate safety testing, can lead to contamination during manufacturing or inadequate labelling, which can mislead consumers about a product's contents (Duiven et al., 2021; Outram & Stewart, 2015). Furthermore, the global nature of supply chains (Tse & Tan, 2011) complicates the enforcement of consistent standards, introducing variability in product quality and compliance (Shah, 2004). Therefore, it is essential that all components of the supply chain are rigorously monitored and held to global best practices, which no doubt will be difficult to achieve.

The task network metrics analysed indicate that two influential tasks were identified to be in direct conflict with each other, 'maintain clean sport' from NADO's and 'marketing/advertising/ of products by supplement companies. These two nodes act as key influencers within the system and will impact the decisions and actions of athletes and other stakeholders, yet they send mixed messages. For instance, athletes are subjected to advertising and marketing of supplements (Maughan et al., 2018), whilst NADOs are advising, where possible, to avoid supplements and take a 'food-first' approach (Australian Institute of Sport, 2022). Additionally, a low In-degree centrality value for 'manufacturing' was identified, which indicates it receives few incoming connections from other tasks in the network. Thus, 'manufacturing' is not as dependent on other tasks in the network compared to other nodes, and that manufacturing of supplements is conducted relatively independently. An area to strengthen the supplement use task network would be to include additional tasks that influence 'manufacturing', such as laws, policies, and collaborations with other system stakeholders. The restructuring of the task network by increasing incoming ties to manufacturing, will increase its dependence on other tasks in the network.

The social network analysis identified the numerous roles and influences of different stakeholders in the sports supplement use system. Anti-doping agencies emerged as the most influential and central actor, scoring highly across all centrality measures. This highlights their direct connections within the network and their strategic positioning, allowing them to influence the supplement use system. Institute/academies of sport (i.e., The National Institute Network), and professional clubs (i.e., professional sports) were also identified as influential system stakeholders through the centrality metrics, which represents a shift beyond the athlete level. A potential concern identified from the social network was the high level of influence by sponsors within the social network, which could potentially promote the use of supplements to athletes, or pressure athletes to perform which may lead to supplement use (Naughton et al., 2024). An opportunity to strengthen the social network could be to enhance the engagement of stakeholders who were identified as having low centrality values, or little influence by fostering direct interactions with central entities.

The application of the Net-HARMS proactive risk assessment to the Australian supplement use system revealed numerous task and emergent risks associated with supplement use. The analysis demonstrated a considerable proportion of the risks identified were deemed to be of high probability and high criticality. Furthermore, the findings highlight that most risks are likely to be introduced several steps prior to the athlete acquiring or consuming the supplements, which emphasises the importance of implementing risk management strategies for safe supplement use throughout the entire supplement use system. Often, interventions such as education (Manges et al., 2022; Patterson et al., 2016; World Anti-Doping Agency, 2021) are targeted towards athletes and athlete support personnel at the ‘sharp-end’ of the system, yet intervening higher in the system may be a more appropriate leverage point (Meadows, 2015) to enact meaningful change and reductions in unintentional doping violations as a results of supplement use.

The volume of risks identified from across the system highlight the complexity involved in the safe use of supplements by Australian athletes. Consequently, mitigation strategies need to be implemented across multiple stages of the supplement use lifecycle and target actors from all levels of the system to improve the safety of supplement use by athletes. By implementing strategies that target the tasks identified as causing the most frequent high probability and high criticality risks, there would be potential for meaningful reductions in risk associated with supplement use.

Targeting risks related to manufacturing supplements would likely enable positive downstream effects on the supplement use system, as a consequence of safer products being produced. One potential strategy recommended by the SMEs that could be implemented would be technological advancements related to documenting the lifecycle of each specific supplement. By implementing blockchain technology (Pinto et al., 2022), a transparent record of all details pertinent to the manufacturing of each supplement, including data related to the source of ingredients, manufacturing

details, transportation and distribution history, batch-testing results, among others would be available for the consumer to access prior to consuming the supplement (potentially via a scannable QR code on the packaging). By recording all details related to the manufacturing and consumption of supplements, greater transparency and accountability may be required by the various stakeholders across the supplement use system. Furthermore, a documented trail of the supplement's lifecycle may allow for retrospective analysis of events and contributory factors in the case of a supplement-related ADRV.

Risk management strategies targeted towards the 'identify need to use supplements' task would facilitate an environment that may reduce the need for athletes to use supplements whilst empowering stakeholders to make more informed decisions regarding supplement use. For example, sporting organisations and teams prioritising the accessibility of relevant experts for athletes, such as sports dietitians and sports medicine doctors (Maughan et al., 2018) to discuss the needs of the individual athlete. Increasing the capacity of organisations and clubs may allow for the athletes to be provided with individualised supplement regimes, removing the need for athletes to source and purchase their own supplements. Thus, shifting the onus of appropriately screening supplements from the athlete to stakeholders higher in the sporting system, who are educated and trained appropriately to do so. Additionally, increasing funding, resources, and accessibility across the sporting system to better support in-need and emerging athletes with education, access to appropriate athlete support personnel, and financial support could cause a reduction in the need for supplement use. Emerging athletes are often required to navigate the competing demands of elite sport whilst also undertaking external commitments such as work or study. Numerous high-profile cases exist in Australia where elite athletes have turned to supplements to help meet the demands of their busy lifestyles, but have received unintentional ADRVs by using tainted supplements (Sport Integrity Australia, 2021; Sport Integrity Initiative, 2018). Consequently, by increasing the resources available to emerging or in-need athletes, there may be less need for supplement consumption and athletes become more appropriately supported.

Providing athletes with support while they research potential supplements to take would be a viable strategy to reduce the risk of unintentional doping through supplement use. Broadening the educational tools available to athletes, particularly pertaining to online resources could help to improve decision-making when identifying and selecting a supplement regime. Developing an online presence for anti-doping organisations that can advocate for safe supplement use, whilst also 'fact-checking' and moderating popular social media platforms that provide information related to supplements could help improve the level of information available to athletes. Further, the development of a decision-making matrix that an athlete could use to guide the procurement of supplements could be a practical tool for aiding athletes to acquire appropriate supplements. Further, improving the scientific literacy of stakeholders involved in the use of supplements would allow for

users to undertake a critical evaluation of any scientific claims being made by a supplements advertising, reducing the likelihood of consumption being influenced by spurious advertising claims.

The SME's identified that targeting how health and sport science research is conducted is also an opportunity to mitigate risks associated with unintentional doping via supplement use. Raising the standard of research pertaining to sport supplements may be beneficial, and one approach to do so would be for the scientific community to develop a gold-standard research framework to ensure studies undertaken are safe, valid, reliable, and fit for purpose. Establishing an independent scientific supplement review board to oversee the verification of scientific claims would help minimise false or spurious claims being made by supplement companies. Additionally, technological advancements may enable more accessible supplement batch testing, allowing for rapid on-site supplement testing or at-home supplement testing. The ability to undertake on-demand supplement testing would increase the probability of detecting contaminated or spiked supplements prior to consumption.

Mitigating risks related to regulating the sport supplement sector may reduce numerous downstream risks associated with supplement use. Developing a framework for reporting essential information on product labels (e.g., fully transparent ingredient lists and dosages) using universally agreed upon definitions of commonly used terminology (e.g., defining what a 'supplement' is or what 'batch-tested' represents etc) would allow for the standardisation of supplement labelling, globally. Strategies identified include adopting plain packaging for supplements that are not verified as safe for sport, similar to what has been implemented with tobacco products, may be an effective way to reduce the unnecessary consumption of supplements by athletes. The use of plain packaging in tobacco products has led to increased awareness of the dangers of tobacco use (Drovandi et al., 2019) and reductions in the appeal of tobacco products (Germain et al., 2010). Overhauling regulation regarding how supplements are sold, including the way they are advertised and distributed may be an opportunity to reduce supplement-related ADRVs. For example, developing mandatory training and accreditation for supplement retailers may enhance the retail experience and safety of athletes acquiring supplements. Intervening at a higher level may also prove valuable, increasing resources provided to Australia's Border Force may enable greater capacity for enhanced screening of imported supplements, as well as intelligence gathering to inform future screening of supplements and anti-doping strategies. Furthermore, the increase in safety data generated may necessitate the development of appropriate data systems to identify importation trends, develop profiles of unsafe supplements, and provide dynamic warning systems for supplements that may present with a poor safety profile.

Despite the strengths of the HTA, task and social network, and the Net-HARMS proactive risk assessment, this project is not without limitations. First, the small sample size of SMEs that participated in the model building process and subsequent analysis that relied on participant's subjective insights must be acknowledged. However, the SMEs in the project were highly experienced

and contained extensive expertise in anti-doping and dietary needs of athletes in Australia. A second limitation of the project is the specificity of the Australian context and further research may be required to develop more globally generalisable findings. Third, the models built are a static depiction of the system at a specific point in time, given the fast-paced nature of sport, sports doping, and anti-doping, the models will need to be regularly updated to remain relevant in practice. Finally, by choosing to focus risk controls on emergent risks deemed of high criticality and high probability, controls for risks with lower criticality and probability were omitted. Thus, future research expanding the prospective risk analysis to risks of low and moderate criticality and probability may yield important results.

Conclusion

The current project has demonstrated the complexity of the supplement use in sport system and highlighted the structure and mechanisms within the system that introduce risks to unintentional doping. The numerous tasks and actors involved in supplement use, coupled with the highly connected network of actors and tasks in the system manifest many risks associated with supplement use in Australia. Consequently, implementing strategies targeted towards multiple tasks, particularly from high levels within the system may be required to enact downstream reductions in cases of unintentional doping via supplement use. The findings indicate that for the prevention of unintentional doping through supplement use, combinations of prevention interventions that target multiple areas of the system will be required. For example, prevention interventions that target tasks earlier in the supplement use lifecycle (e.g., regulation and manufacturing) are required in addition to those currently in place (e.g., education). This will provide a whole of system approach to reducing the risks associated with unintentional doping through supplement use.

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Appendices

Appendix 1. Level one HTA tasks and their role in the supplement use in sport system	
Level one task	Description
Conduct health & sports science research	Undertake health and sports science research to investigate the optimal ingredients, timing, and dosages of supplements to enhance physical performance, health, recovery, image, or body mass. Additionally, undertaking research to develop new supplements and assessing their safety and efficacy.
Demand for use	Demand for supplement use may be created by consumers wishing to address an identified need to increase performance or recovery or address nutritional deficiencies using supplements.
Regulate sports supplement sector	The sport supplement sector is regulated to ensure the safe development of supplements. Regulation provides safe, standardised guidelines for manufacturers to adhere to. Regulations must be enforced and monitored for compliance with any acts of non-compliance investigated and actioned to ensure the safety of the sports supplements sector.
Maintain clean sport	Clean sport strives to ensure a level playing field for athletes. International governing organisations such as WADA, develop and implement policy and regulations to guide clean sport. Additionally, developing, implementing, and monitoring a National Integrity Framework for athletes and sporting organisations to adhere to allows for the promotion and maintenance of clean sport. Implementing education and support programs, in conjunction with a mechanism to test for adherence to clean sport and having an appropriate review and sanction process to deal with breaches of clean sport is also an important component of maintaining clean sport.
Manufacture supplements	The manufacturing, packaging, labelling, and exporting of supplements for sale in accordance with regulations.
Marketing / Advertising	Provide accurate information to supplement retailers, distributors, prospective users, and the public for marketing and informed consent purposes. Marketing and advertising may provide an opportunity for sponsorship opportunities in various levels of sporting competition.

Distribute supplements	Supplements are packaged, stored, ordered, and sold to consumers and retailers.
Identify need to use supplements	Identifying the specific use or need for the supplement, such as combating nutritional deficiency, managing body mass, or increasing physical performance, recovery, or body image. The need to use supplements may be identified intrinsically, or via discussions with ASP.
Research supplements	Investigate whether the supplement is safe for use, affordable, and conforms with the pertinent anti-doping legislation. Identifying outcomes expected from the supplement and how they align with the needs of the consumer.
Acquire supplements	Acquire or purchase supplement for consumption from various retail outlets or receive supplement from ASP or sponsor.
Pre-use deliberation	Prior to use, discussing the use and potential cost-benefit of consuming the identified supplement with various parties, such as a sports medicine professional, ASP, and/or fellow athletes.
Use supplement	The use or consumption of the supplement, in accordance with the required protocol.
Evaluation effects of supplement use	The consumer reflects and analyses the effectiveness of the supplementation regime using subjective and/or objective markers for evaluation. A discussion with a sports medicine professional or ASP may occur to quantify/evaluate the effects of the supplement.
Decision to continue use	Consumer reflects on outcomes and experiences with the supplement and decides in consultation with ASP whether to proceed with consuming the supplement, change configuration of current supplement regime, try an alternate supplement, or cease consuming the supplement.
Make recommendations	Consumer may recommend or not recommend the consumption of the supplement to others, after they have consumed the product.

Appendix 2. Stakeholders and their role in the supplement use in sport system	
Actor	**Description of role**
Academics (University)	Conduct sport science research relevant to supplements in an academic setting.
Anti-doping agencies (e.g., SIA, & WADA; doping control officers)	Develop, implement, and monitor compliance to anti-doping rules and regulations. Design and implement testing programs. Provide accreditation to testing laboratories. Produce and distribute educational resources. Sanction breaches of anti-doping rules and regulations.
Applied sport-scientists (e.g., National Institute Network)	Conduct sport science practices and research relevant to supplements in an applied setting.
Athlete	Undertake training and compete at their chosen sport. Represent their team/organisation in competition and during public events.
Athlete Support Personnel (e.g., sports scientists, doctors, psychologists, strength and conditioning coaches)	Provide expert, professional services to the athlete by providing knowledge and support across various domains related to the health and performance of the athlete.
Athlete's friends/family	Support the athlete throughout their day-to-day life.
Athlete's manager	Support the athlete throughout their professional career.
Australian Sports Commission	The Australian Government commission responsible for support and investing in sport in Australia.
Batch-testing companies (e.g., HASTA)	Undertake scientific analysis of supplements to determine ingredients within each product/batch and determine if a batch of supplements is safe for consumption. Results are made publicly available.
Coaches	Provide technical and tactical advice to athletes during training and competition. Typically, an expert in a specific discipline or sport.
Commonwealth Sport Supplements Working Group	Communicate and coordinate with government agencies and sporting organisations regarding the safe use of supplements in sport.

Department of Agriculture, Fisheries, and Forestry	Enhance agricultural industries and trade, and manage the threat of biosecurity risks to Australia.
Department of Health & Aged Care	Develop and deliver policies and programs and advise the Australian Government on health, aged care, and sport.
Doping control officers (e.g., collection officers and chaperones)	Organise and undertake anti-doping testing.
Event organisers	Planning and coordinating relevant stakeholders to facilitate sporting events.
Food Standards Australia New Zealand (FSANZ)	Develop evidence-based standards for regulators and industry, monitor the safety of the food supply, support consumers to make informed choices and coordinating food incidents and recalls in Australia.
General population	View, support, and attend sporting competitions. Purchase and consume supplements.
Independent anti-doping testing providers (e.g., LGC Assure; doping control officers)	Perform anti-doping testing and services independently from governing anti-doping agencies.
Industry R&D teams	Conduct research to develop novel or refine existing supplements.
Institutes/academies of sport	Act as a hub for elite athletes that provides academic and applied sport science support.
Manufacturers	Produce supplements for supplement companies.
National Sporting Organisation for People with Disability	Responsible for overseeing and promoting sports for individuals and teams with disabilities at the National level.
National Sporting Organisations (e.g., AIS)	Responsible for overseeing and promoting sports for individuals and teams at the National level.
Parliament and legislators	Make and amend laws, whilst representing the views and interests of the Australian people.
Professional and local sports	Facilitate training and competition for athletes at a variety of levels.
Professional associations (e.g., ESSA, AMA)	Provide industry leadership through advocacy, research, education, and regulation to various professionals in the Australian community.
Sales representatives	Sell supplements on behalf of a company or retailer.
Sponsors	Provide resources to support events, organisations, and individuals.
Supplement companies	Design, have manufactured, advertise, and sell supplements to retailers and wholesalers.

Supplement retailers	Sell supplements direct to consumers.
Therapeutic Goods Administration (compliance and enforcement)	The medicine and therapeutic regulatory agency of the Australian Government that oversees the quality, supply, and advertising of medicines, pathology devices, medical devices, blood products, and most other therapeutics.
Transporters (e.g., delivery drivers)	Pick up and deliver supplements.
Wholesalers/distributors	Provide wholesale distribution of supplements to various outlets of supplement retailers.