Performance Enhancement & Health 13 (2025) 100317

Contents lists available at ScienceDirect

Performance Enhancement & Health

journal homepage: www.elsevier.com/locate/peh

Research Paper

Decoding unintentional doping: A complex systems analysis of supplement use in sport

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ARTICLE INFO

Keywords:
Doping
Supplements
Hierarchical task analysis
Complexity
Stakeholders

ABSTRACT

Unintentional doping though supplement use is an ongoing issue that has severe professional and personal impacts on athletes. Though the issue is well known, there are key knowledge gaps regarding the role of different stakeholders both in creating and managing unintentional doping. The current study aimed to identify the influential tasks and stakeholders within the Australian sport system that are associated with supplements. A Hierarchical Task Analysis (HTA) was developed during a subject matter expert workshop (n = 12) to decompose the supplement use in sport 'system' into a hierarchical structure of goals, sub-goals, operations, and plans. A task network was developed during the SME workshop and based on the first level sub-goals of the HTA. Network analysis was then applied to determine the interdependency and influence of system tasks and stakeholders. Network metrics included Density, Out-degree centrality, In-degree centrality, Betweenness centrality, Closeness centrality, and Eigenvector centrality. In total, 15 first level sub-goals were identified which were further decomposed into 71 sub-goals and operations. The overall identified goal of athletes taking supplements was to optimise health, performance, recovery, image, and achieve optimal weight. Within this overall goal, numerous tasks are required to be performed including research, manufacturing and regulation of supplements, maintaining clean sport, to the administration of supplements by athletes, to subsequent assessments of their efficacy. The most influential tasks within the system include 'maintaining clean sport' by anti-doping authorities, and 'marketing/advertising' of supplements by supplement companies. Influential stakeholders within the system included 'anti-doping agencies', 'athlete support personnel', and 'sponsors'. The analysis has demonstrated that multiple and varied stakeholders have specific roles to play in preventing unintentional doping. The findings suggest that for the prevention of unintentional doping through supplement use, interventions will need to shift away from the typical focus on athletes and athlete support personnel, to encompass a broader systemic focus.

1. Introduction

Unintentional doping through supplement use is an intractable yet preventable issue in elite sport. Doping is defined by the World Anti-Doping Agency (WADA) as the occurrence of one or more of the anti-doping rule violations (ADRV) set out in Article 2 of the World Anti-Doping Code (WADC) (World Anti-Doping Agency, 2021b). The prevalence of supplement use in sport is considerable, with between 40 % to 100 % of athletes shown to be using supplements (Garthe & Maughan, 2018; Knapik et al., 2016). Generally, supplement use in elite athletes increases with the level of training, performance, and age of the athlete, is higher in men than women, is strongly influenced by perceived cultural norms, and varies across sports (Maughan et al., 2018). For instance, higher levels of supplement consumption have been observed by athletes competing in power-based sports (e.g., weightlifting) and endurance-based sports (e.g., triathlons), compared to technical-based sports (e.g., gymnastics) (Isenmann et al., 2024; Lauritzen & Gjelstad, 2023). The prevalence of supplement use is a concern, as they can contain prohibited substances (i.e., substances and methods on the WADC prohibited list (World Anti-Doping Agency, 2024b)) (Kamber et al., 2001), can be mislabelled or inadequately labelled (Ayotte et al., 2001), and can be 'spiked' with prohibited substances (Duiven et al., 2021) to enhance the effectiveness of the product, or accidentally contaminated through the manufacturing process.

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https://doi.org/10.1016/j.peh.2024.100317
Received 14 July 2024; Received in revised form 25 November 2024; Accepted 28 November 2024
Available online 5 December 2024
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The prevalence of unintentional doping has been challenging to quantify (Backhouse, 2023; Duiven et al., 2021) but remains a clear risk to athletes (Baylis et al., 2001). Estimates suggest 6–9 % of reported doping cases identified between 2006 and 2013 in Australia, the United Kingdom, and the United States, are due to athletes consuming supplements which contain prohibited substances (Outram & Stewart, 2015). In Norway, between 2003–2020, athletes claimed 49 (26 %) of 192 analytical ADRV cases were attributed to prohibited substances being consumed via supplements (Lauritzen, 2022). Research into unintentional doping has typically focused on isolated components such as the supplements themselves (Kozhuharov et al., 2022; Martínez-Sanz et al., 2017), athlete risk factors, including behavioural and psychological factors (Chan et al., 2016; Hurst et al., 2019), and the independent testing of supplements for prohibited substances (Duiven et al., 2021). Further, athlete education programmes appear to be the key strategy adopted by National Anti-Doping Organisations (NADO's) to combat doping in sport (World Anti-Doping Agency, 2021a, 2021c). However, previous research has not been focussed on the complexity of the interactions between factors that enable emergent behaviours across the supplement use system. Consequently, many contributory factors to unintentional doping are likely left unaddressed by educational strategies that target lower-level system actors such as athletes and their support personnel. The complexity of the anti-doping systems and the numerous stakeholders involved in the system directly and indirectly require consideration when attempting to understand ADRVs (McLean, Naughton, et al., 2023). A major challenge is the difficulty in conceptualising the interactions between system components to identify the best leverage points to intervene for safe supplement use and effective doping prevention. Research has suggested that anti-doping efforts should consider broader organisational, systemic, and societal factors to reduce doping (Boardley et al., 2021; McLean, Naughton, et al., 2023). As such, research is now beginning to characterise doping as a complex system (McLean, Naughton, et al., 2023; Naughton et al., 2024).

The negative consequences of unintentional doping on athletes and the stakeholders involved are substantial. Numerous high-profile cases of unintentional doping have occurred across multiple sports, including swimming (Court of Arbitration for Sport, 2020), Rugby League (Sport Integrity Australia, 2020), and athletics (Sport Integrity Initiative, 2018). The impacts can be severe, with sanctioned athletes often forced to withdraw from competition, prohibited from training alongside teammates, and risk losing income and sponsorship opportunities (Greenwood, 2023; Sport Integrity Australia, 2021). Furthermore, athletes receiving ADRV sanctions have reported declines across various biopsychosocial domains, including their professional and financial situations, mental and psychological wellbeing, social environment, physical condition, and attitudes towards the practice of sport (van der Kallen et al., 2023).

Complex systems thinking methods are commonly applied in the disciplines of human factors and ergonomics (HFE) and safety science (Abedi et al., 2024; Read et al., 2021) and have begun to be applied in anti-doping research (McLean, Naughton, et al., 2023; Naughton et al., 2024). However, to our knowledge there has been no systems thinking-based analyses of supplement use and its association to unintentional doping. To safely consume supplements, stakeholders across the entire system are likely required to work in synergy across multiple domains such as manufacturing, marketing, and sales, to administration by the athlete. To date, no published studies have conducted an analysis of the components that underpin the safe and effective use of supplements from a systems level perspective. Without a comprehensive understanding of the tasks required to facilitate safe supplement use, assessing the efficacy of the system and being able to implement effective strategies to mitigate unintentional doping from supplement use is challenging.

Task analysis methods provide a structured approach to identifying, decomposing, and understanding tasks that are integral to achieving system goals. Hierarchical Task Analysis (HTA) is a versatile task analysis tool that facilitates an in-depth understanding of a system by decomposing tasks into a hierarchical structure of goals, sub-goals, operations, and plans (Salmon et al., 2010; Stanton, 2006). A HTA provides a breakdown of complex activities within a system and allows for the identification of related tasks and workflows which can offer valuable insight into a system's operational dynamics. By identifying potential inefficiencies and areas for improvement, HTA serves as a foundation for enhancing system design and functionality (Stanton et al., 2017). Accordingly, HTA has been applied to support design and analysis in many domains such as aviation, healthcare, and Defence (Kirwan & Ainsworth, 1992; Stanton, 2006).

Complexity and systems thinking protagonists argue that, without the adoption of a 'complex systems approach', it is impossible to fully understand the myriad of factors that influence behaviour in any system (Monat & Gannon, 2015; Salmon et al., 2022). As such, it is important to understand the complex interaction between the tasks and the stakeholders within a system or to introduce appropriate and effective interventions designed to improve outcomes (i.e., reduce unintentional doping through supplement use) (Mclean et al., 2024). It is essential to understand the tasks that are undertaken within the 'supplement use in sport system' and to identify the key stakeholders and interactions involved, to further understand unintentional doping through supplement use in elite sport. Therefore, the aims of this study were to: 1) develop a HTA of the 'supplement use in sport system' in an Australian context, 2) identify the connectivity and interactions between tasks, and the stakeholders associated with supplement use in sport in Australia.

2. Methods

2.1. Design

This study was designed to develop a HTA (Annett et al., 1971) of compliant supplement use in an Australian context. A generic HTA structure is presented in Fig. 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). Institutional ethical approval was obtained from the University of the Sunshine Coast's human research ethics committee (A231924).

2.2. 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 study. Participants all held positions at Sport Integrity Australia (SIA) (3.7 ± 5.4 years' experience), Australia's 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 study were considered to have a detailed understanding of the broader 'supplement use in sport system' in Australia.

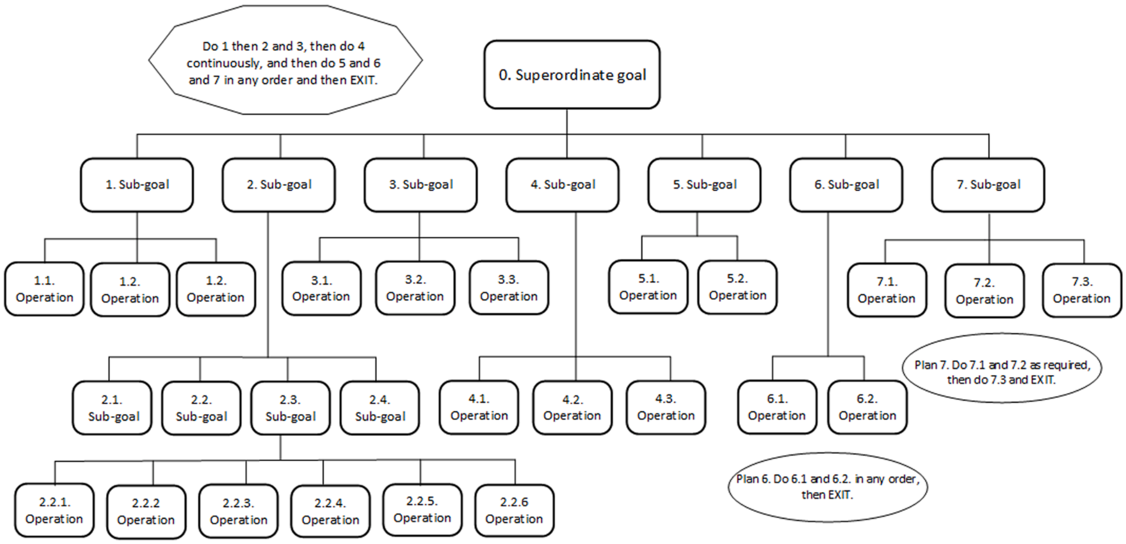

Fig. 1. Example HTA structure demonstrating the superordinate goal, sub-goals, operations, and plans (circled text).

2.2.1. Procedure

2.2.1.1. 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 Fig. 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.

2.2.1.2. 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 Supplementary Table 1.

2.2.1.3. Social network. A social network of the stakeholders within the study 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 Supplementary Table 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

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	

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).

2.2.1.4. Network analysis. In the current study, 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 sub-networks by normalising them (Freeman, 1977).

3. Results

3.1. 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 (Fig. 2). This superordinate goal was further decomposed into 15 sub-goals that are required for the overall goal to be achieved. Within Fig. 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.

The task network of the 'optimising health, performance, recovery, image, and achieve optimal weight through supplement use' HTA is displayed in Fig. 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 0.54 which indicates a moderate to high level of interconnectedness (Stanton & Harvey, 2017) between tasks in the network. Definitions of tasks are available in Supplementary Table 1.

3.1.1. 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

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	

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 indicates a 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 0ut-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.

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 0.31 which indicates a relatively low level of interconnectedness (Stanton & Harvey,

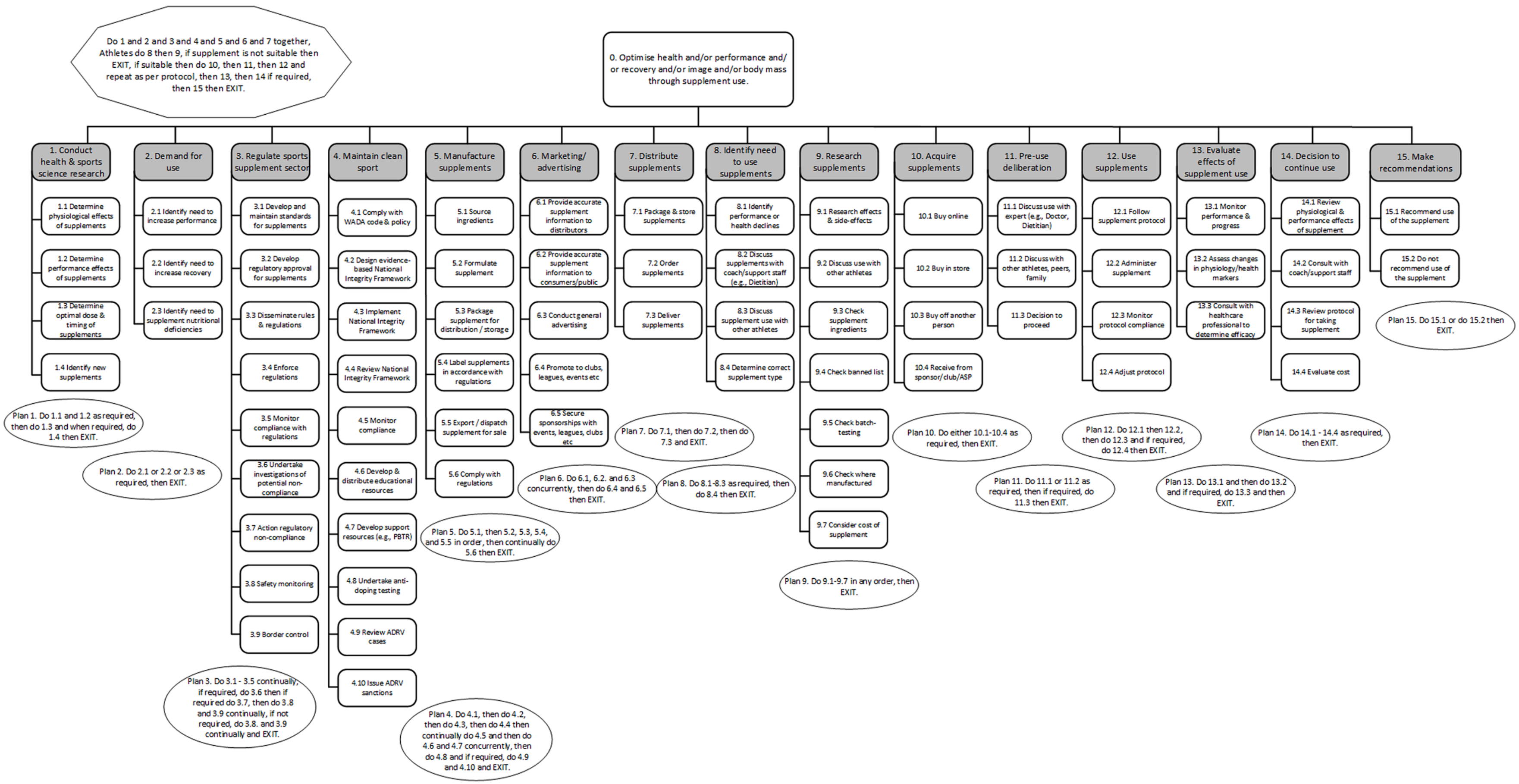

Fig. 2. HTA for athletes taking supplements to optimise health, performance, recovery, image, and achieve optimal weight. The first sub-goal level is shaded to represent the level used for the task network. *Task network*.

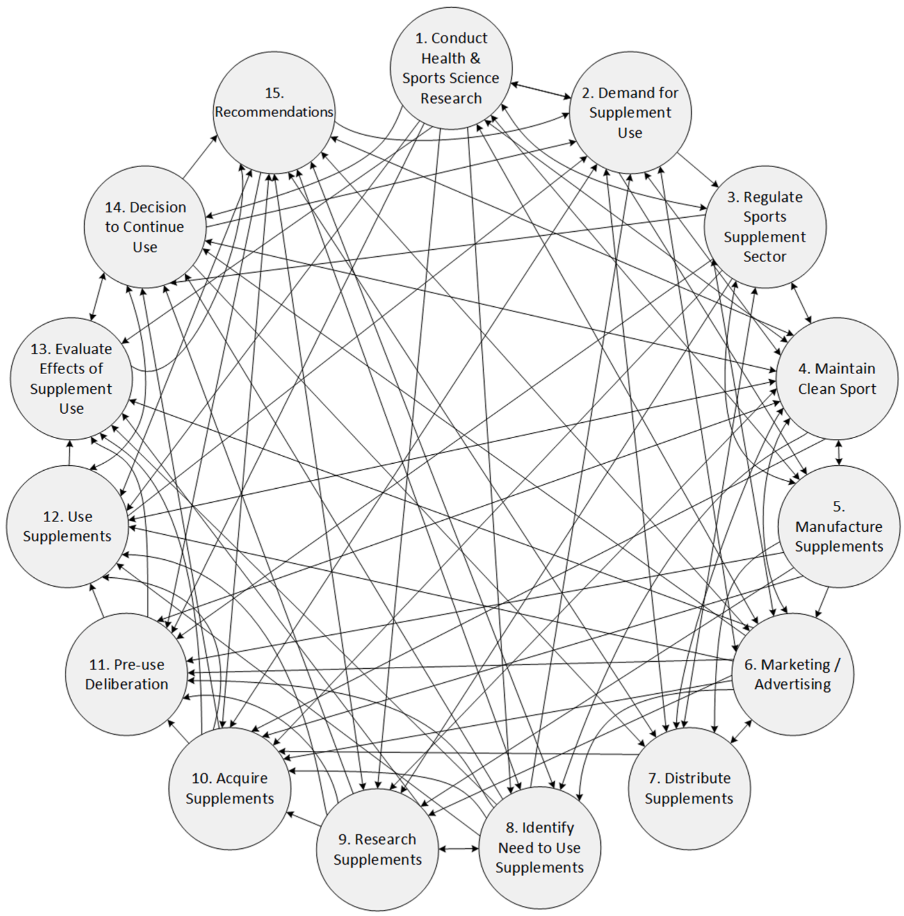

Fig. 3. Task network for the goal of 'optimising health, performance, recovery, image, and achieve optimal weight through supplement use' in elite Australian sport.

2017) between stakeholders in the network. Definitions of stakeholders' roles are available in Supplementary Table 2.

4. Discussion

The aim of the current study was to develop a HTA of the 'supplement use in sport system' in Australia, and identify the connectivity and interactions between tasks, and the stakeholders associated with supplement use in sport in Australia. This study is the first-of-its kind to decompose the supplement use in sport 'system' using HTA and network analysis.

The developed HTA provides a comprehensive analysis of the lifecycle of supplement use, from supplement research, development, regulation, the administration of supplements by athletes, to subsequent assessments of their efficacy. As such, the HTA is fundamental for understanding how broader lifecycle tasks may contribute to unintentional doping through supplement use. 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. Further, the market for supplement companies is not elite athletes (Alonso & Fernández-García, 2020), who represent only a small percentage of the population and that are bound by the WADC (World Anti-Doping Agency, 2021c). Arguably, recreational and amateur athletes provide a larger target market for supplement companies (Alonso & Fernández-García, 2020) to generate revenue. Therefore, there may be little motivation for supplement companies to comply with the strict policies of the WADC and the WADC Prohibited List, as this will require additional resources and likely impact short-term revenue, with little potential upside. That said, it may be in the best interest for companies to comply, as they may suffer reputationally and financially from an athlete committing an ADRV from using one of their products. As such, there is a vested interest in supplement companies and anti-doping authorities working together so both can achieve positive outcomes (World Anti-Doping Agency, 2024a).

A key finding from the HTA was that the administration of supplements by athletes does not occur until the twelfth sub-goal 'use supplements'. Previous research on supplement use and ADRVs has typically focused on the athlete and the ASP, and their roles in supplement use (Denham, 2017; Garthe & Maughan, 2018). While this previous research is important for understanding athlete and ASP influences and perceptions around supplement use, it is concerning that multiple tasks prior to athletes taking supplements are often not considered in research on supplement use, despite their critical influence on supplement use. When thinking about the risks of unintentional doping, the multiple tasks preceding athletes use of supplements introduces numerous opportunities for risk (e.g., manufacturing, regulation). The HTA highlights that within the current system there are various opportunities for intervention beyond the athletes, for example, research, manufacturing, regulation and advertising, that will aid unintentional doping prevention. For the athletes, themselves, the discussion with

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***

coaches and ASP represents a potential intervention point to assist with athlete decision making and actions. However, it appears that athletes are solely responsible for driving these steps and are not required to complete them prior to using supplements. Further, this self-directed assistance-seeking sentiment is prevalent in educational materials and policy regarding supplement use, with recommendations for athletes to seek assistance from sports doctors and accredited sports dietitians to make an informed decision regarding supplements (Maughan et al, 2018; Close, Kasper, Walsh, & Maughan, 2022*)*, yet there is no mechanism in place to ensure this happens.

Athletes rely heavily on accurate information to make informed decisions about supplements (Van Thuyne et al., 2006). The HTA reveals a dependency on multiple sources for this information, including from NADO's, coaches, ASP, marketing materials, pharmaceutical companies, and other athletes. Misinformation or inadequate understanding of supplement ingredients and their effects can lead athletes to unintentionally consuming supplements containing prohibited substances (Maughan, 2005). Given the focus on education as the primary tool for doping prevention by NADO's (McLean, Naughton, et al., 2023), the HTA itself could be used as an educational resource for stakeholders, as it decomposes the required tasks and plans to avoid unintentional doping. Further, the current HTA could be supported by including the appropriate anti-doping contacts and educational resources at the various identified sub-goals, as an interactive educational tool.

When analysing complex systems it is essential to understand the interdependencies between system components, as this is the very essence of complexity (Meadows, 2008). The task and social networks in the current study have demonstrated this interdependency among the tasks and system stakeholders. The task network displayed relatively high connectivity of the tasks in the HTA, via network density, indicating a tightly coupled task network. This tight coupling has potential negative implications. In a tightly coupled task network, if one task is not performed or is performed inadequately it can negatively and rapidly impact the entire task network (McLean et al, 2023). For example, if 'regulation' or 'manufacturing' is performed inadequately, this will have knock on effects throughout the system, which could lead to unintentional doping and ADRVs.

A pertinent finding from the individual nodal metrics indicates 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. On the one hand, athletes are subjected to advertising and marketing of supplements (Maughan et al., 2018), and on the other hand, NADOs are advising, where possible, to avoid supplements (Australian Institute of Sport, 2022; Sport Integrity Australia, 2024). A further key finding was the low In-degree centrality value for 'manufacturing', which indicates it receives few incoming connections from other tasks in the network. This means that 'manufacturing' is not as dependant on other tasks in the network compared to other nodes, and that it is conducted relatively independently. In contrast, 'maintain clean sport' has numerous incoming connections, which indicates that the function and performance of this task is influenced by multiple other tasks. One area to strengthen the supplement use task network may be to include additional tasks that influence 'manufacturing' such as, laws, policies, and collaborations with other system stakeholders, among others. This will restructure the task network by increasing the incoming ties to

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

manufacturing, which will increase its dependence on other tasks in the network. As the task network moves towards the more individual aspects of the network, such as individual decisions to use supplements, deliberation, and evaluation, the centrality decreases. This shift indicates a transition from industry-wide influences to more individual, athlete-centric considerations, which are shaped by the broader system but are less influential on the system as a whole. This finding may provide further evidence for a shift away from the individual level focus to a more systemic focus for doping prevention (McLean, Naughton, et al., 2023; Naughton et al., 2024).

The social network analysis highlights the numerous roles and influence 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 indicates their direct connections within the network and their strategic positioning, allowing them to influence the 'supplement use system'. This influence has recently been demonstrated, with SIA, the Australian NADO, reporting to have had no unintentional doping cases in recent years (Sport Integrity Australia, 2022). However, there are likely several unique characteristics that enable this achievement, which may not be possible in other geographical locations. One being that Australia is an island nation with strict importation laws and food standards (Ghosh, 2014). Further, SIA have formed integral partnerships with upstream system stakeholders such as Therapeutic Goods Association, food standards and health departments, and batch-testing companies (Sport Integrity Australia, 2022). This represents a necessary shift away from focussing solely on the athlete and ASP level for potential interventions, to other system stakeholders where greater leverage can be achieved. These relationships and collaborations with higher-level system stakeholders would appear essential given the lack of legal power given to NADOs in most countries to influence the behaviour of other system stakeholders (e.g. manufacturers) (WADA, 2020). 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, again this represents a shift beyond the athlete level. A potential concern was the high influence of 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).

The social network analysis highlights potential areas for improvement in the supplement use in sport system. For example, 'athlete's friends/family', and 'athlete's managers' had little influence on the social network, evidenced through their low centrality values.

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.

Interventions designed to enhance the engagement of these stakeholders could be considered. For instance, increasing the influence of peripheral stakeholders could be achieved by fostering more direct interactions with central entities, potentially by providing broader educational programs to system stakeholders indirectly involved in sport (McLean, Naughton, et al., 2023). This broader education could also benefit athletes in individual sports who may not be provided supplements or have regular access to expert dietary advice, unlike those in academies or professional team sports. Improving the connectivity of these peripheral nodes may enhance their influence and also increase awareness and compliance regarding supplement regulations more effectively. Additionally, enhancing the betweenness centrality of coaches and ASP may create more optimal communication channels within the social network.

The current study contained potential limitations. First, a small sample of SMEs participated in the model building process and the analysis relied on participant's subjective insights. There is also a potential for biased views from participants as they were all employed at SIA. However, the SMEs in the current study were highly experienced and contained extensive expertise in anti-doping in Australia. In addition, SIA collaborates with broader system organisations and departments, such as the TGA, FSANZ, DAFF, and the Department of Health. Further, the members of the research team who facilitated the workshop have extensive experience in conducting systems analysis workshops. Participants were continually reminded that the HTA and task and social networks were to represent the current system, and not an idealised system. A second limitation is the specificity of the

Australian context and further research may be required to develop a more globally generalisable HTA and network stakeholders. Finally, the HTA is 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 HTA will need to be regularly updated to remain relevant in practice.

5. Conclusion

This study has demonstrated the complexity of the supplement use in sport system and highlighted the structure and mechanisms within the system where potential risks could be introduced. The findings indicate that for the prevention of unintentional doping through supplement use, interventions will need to shift away from the typical focus on athletes and ASP, to encompass a broader systemic focus. Often, stakeholders within systems are aware of the problem symptoms, however, they are often not aware of how the structure of the system contributes to the problems. As such, the developed HTA could be used a practical tool for education across the entire system, as well as a guide for improving the system structure and functioning. Further research applying a similar approach is required to broaden the scope beyond Australia, as other countries will face unique challenges. In addition, HTA serves as method to inform proactive risk assessment methods. A necessary next research step is to extend the current study to conduct a formal proactive systemic risk assessment on unintentional doping through supplement use.

CRediT authorship contribution statement

Scott McLean: Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Matthew Morrison:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Mitchell Naughton:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Paul M Salmon:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.peh.2024.100317.

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