Developing a Fundamental Theoretical Definition for Athletic Injury: Logical Reasoning, Boundary Testing, and the Importance of Necessary and Sufficient Conditions

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Abstract

The absence of a conceptually robust theoretical definition of athletic injury is problematic in sports science and medicine, as such a definition provides the essential conceptual framework for scientifically studying this concept. Existing definitions are overly vague and lack conceptual and logical coherence, failing to provide sufficient frameworks for the development of more precise understandings, operationalisations (including mathematisation) and identifications of athletic injury and associated concepts, which undermines the critical scientific principles of predictability, falsifiability, and reproducibility. Furthermore, related concepts that are often integrated into various operational definitions of athletic injury, such as pain and participation in sports, are commonly conflated as fundamental criteria. To address these concerns, this article proposes a new theoretical definition of athletic injury, developed through a systematic process of logical reasoning. This approach employs well-established tools such as thought experiments, boundary tests, and logical arguments to test for conceptual and logical coherence in existing definitions, and to establish a set of necessary and sufficient conditions for an athletic injury to exist. Through this process, commonly conflated concepts are disentangled, and the development of a more refined conceptualisation and definition of athletic injury is achieved, capturing its fundamental essence as "Tissue damage and loss of physical function during sports participation, resulting from rapid or repetitive transfer of kinetic energy, that is not a normal part of the physical training and positive adaptation process, but exceeds the threshold of mechanical and physiological tolerance. This is dependent upon the nature and degree of tissue damage sustained." By introducing a demarcating threshold of tissue damage and loss of physical function to distinguish athletic injury from non-injury, this definition aligns athletic injury more closely to the definitions of (general) injury proposed by the World Health Organization and International Classification of Diseases. Furthermore, by grounding athletic injury in objectively measurable physical parameters that can be appropriately mathematised for inclusion in mathematical (e.g., predictive) models, and that also function within a unified physics-based framework, athletic injury can be mathematically defined as occurring when the damage (D) experienced by a tissue exceeds a critical damage threshold (D_c), i.e., $D > D_c$. Here, $D = 0$ corresponds to an undamaged state and $D = 1$ corresponds to complete tissue failure. This definition lays the foundation for a formalised linguistic system and semantic network for mathematical modelling (e.g. predictive modelling), defining athletic injury and related concepts within a logically coherent mathematical framework with precisely defined relationships. This significantly enhances the predictability, falsifiability, and reproducibility of athletic injury research, paving the way for advancements in assessment technologies and data analysis methods that improve the identification, measurement, and prediction of athletic injury and its associated concepts.

Key Points:

- Existing definitions of athletic injury are vague and lack conceptual and logical coherence, failing to provide sufficient frameworks for the development of more precise understandings, operationalisations (including mathematisation), and identifications of athletic injury. This undermines the critical scientific principles of predictability, falsifiability, and reproducibility in athletic injury research.
- To address this, a new theoretical definition of athletic injury is proposed, developed through a process of logical reasoning and the utilisation of well-established tools such as thought experiments, boundary tests, and logical arguments, to disentangle conflated concepts and determine necessary and sufficient conditions for an athletic injury to exist.
- The newly proposed definition introduces a demarcating threshold of tolerance to distinguish athletic injury from non-injury, and grounds the concept in objectively measurable physical parameters. This definition is then operationalised into a mathematised framework, where athletic injury is defined as occurring when the damage sustained by a tissue (D) exceeds a critical damage threshold (Dc), expressed mathematically as $D > Dc$.
- This definition establishes the foundation for a formalised and mathematised linguistic system and semantic network, where athletic injury and related concepts, such as injury severity and recovery, are systematically defined and interconnected through precise mathematical relationships. These relationships facilitate consistent integration into mathematical models, enhancing the clarity, predictability, and applicability of athletic injury research moving forward.

"Hitting on the direct definition of a concept, though often an essential contribution to progress, remains a preliminary to the discovery of mathematical truths" – Michael Dummett [1]

Every kind of science, if it has only reached a certain degree of maturity, automatically becomes a part of mathematics – paraphrased from David Hilbert [2]

1.0 Introduction:

In sports science and medicine, a variety of theoretical definitions (Table 1) of athletic injury have been proposed [3-6], but none are conceptually robust and sufficiently coherent [7]. This is problematic for athletic injury research, just as an axiom provides the foundational truths for a logical or mathematical system, a theoretical definition establishes the essential conceptual framework within which a concept can be understood scientifically [8-11]. Certainly, theory-driven research, a fundamental component of the scientific method [7-9, 12-14], relies upon precise, logically consistent, and empirically testable concepts to explain or predict phenomena [8]. Without a logically coherent definition, the development of accurate operationalisations, including the appropriate mathematisation, of athletic injury is hindered [8, 10], limiting advancements in its identification, measurement and prediction.

Currently, the International Olympic Committee (IOC) offers one of the more refined definitions of sports (athletic) injury, describing it as:

'Tissue damage or other derangement of normal physical function due to participation in sports, resulting from rapid or repetitive transfer of kinetic energy" [6].

Definition 1

This definition is widely adopted for the recording and reporting of epidemiological data on injury in sport [6], providing the theoretical framework from which various operational definitions of athletic injury are developed, with these typically focused on physical complaints, availability for sports participation and time-loss i.e., time-loss injury [4, 6, 15-18]. Moreover, this definition partially aligns with broader definitions of injury (not to be confused with *athletic injury*) articulated by various authoritative sources (Table 2). For instance, the World Health Organization (WHO) and International Classification of Diseases (ICD-11) define injury as:

'A bodily lesion at the organic level, resulting from acute exposure to energy (mechanical, thermal, electrical, chemical, or radiant), in amounts that exceed the threshold of physiological tolerance' [19].

Definition 2

And

'Physical or physiological bodily harm resulting from the interaction of the body with energy (mechanical, thermal, electrical, chemical, or radiant, or due to extreme pressure) in an amount, or at a rate of transfer, that exceeds physical or physiological tolerance. Injury can also result from a lack of vital elements, such as oxygen. Poisoning by, and toxic effects of, substances are included, as is damage to or due to implanted devices' [20].

Definition 3

However, despite sharing some similarities with the definitions of injury proposed by the WHO and ICD-11, the definition of sports (athletic) injury put forward by the IOC (Definition 1) lacks conceptual coherence in some areas [6], particularly with respect to thresholds of tolerance, which are central to the definitions of the WHO and ICD-11.

In applied sports settings concerned with the day-to-day practical management of athletes, the absence of a conceptually and logically sound theoretical definition of athletic injury may, depending on the circumstance, be of little practical significance. Here, the concept of athletic injury is often treated as some vague amalgamation or latent construct (Table 1) consisting of numerous loosely defined elements—such as tissue damage, pain, functional impairment, and psychological state—typically culminating in time away from sport. Accordingly, the exclusion of some of these components from the theoretical definition put forward by the IOC, such as pain and availability to participate in sports, may appear too reductionist and confusing to some [21], especially when these concepts are often implicated in various operational definitions of athletic injury [4, 6, 15-18]. However, the IOC is correct to exclude these components from their proposed theoretical definition of athletic injury, as including them would not only be inconsistent with the historical and current definitions of the term injury (Table 2) but would also conflate multiple distinct concepts that are fundamentally different from injury i.e., they are neither necessary nor sufficient for an injury to exist. Accordingly, including these components would constitute an error in logic that would undermine the classification and scientific process [22-26].

Despite this, in practical settings, precision of word choice and adherence to rigid definitional standards is often of secondary importance to the primary goal of conveying meaning. For example, a coach or staff member might describe an absent athlete as “injured,” “in pain,” “unavailable to participate,” “busted,” or (insert swearword of choice), and if the intended meaning is successfully conveyed (social etiquette aside), the adopted word choice is considered effective. This highlights that words are symbols used to convey meaning [27-29], and when the focus is on shared and timely understanding rather than strict definitional accuracy, their relatively loose application is of little consequence. It follows that, in applied sporting contexts, if meaning is effectively communicated, individuals can adopt whichever word choices they please, and debates over specific terminology can typically be dismissed as “mere semantics,” since the focus is on practical interpretation (pragmatism) [30] rather than strict technical precision and formal analysis of meaning (semantics) [31-33].

In scientific contexts, precise language and the formal analysis of meaning takes on increased importance, as words and their definitions play a critical role in distinguishing between concepts and phenomena so that they can be accurately identified, measured, and analysed without conflation [8, 24, 25, 29, 33, 34]. This precision is crucial for formulating hypotheses, making accurate predictions, communicating findings, and building theories that can be consistently tested and applied across contexts [8]. Indeed, the relationship between ontology, epistemology, and semantics (Table 1) is a central component to scientific inquiry [8], with ontology concerning itself with the nature of the entities, concepts or phenomena to which terms refer, while semantics is responsible for defining and clarifying the meaning of those terms. In sports science and medicine, the absence of a coherent and logically sound theoretical definition of athletic injury is a major concern, obscuring how athletic injuries should be appropriately operationalised (and mathematised), and undermining the scientific principles of falsifiability, predictability, and reproducibility (Table 1), which are core tenets of the scientific method [8]. Establishing a robust theoretical definition that is logically coherent and that appropriately captures the fundamental essence of athletic injury is therefore crucial, as it provides the foundational framework upon which all operational definitions (Table 1) are developed, facilitating advancements in the identification, measurement, mathematisation and prediction of athletic injuries, and a clearer understanding of any limitations inherent in any chosen operational criteria.

Given these considerations, this article aims to develop a robust, logically coherent theoretical definition of athletic injury that appropriately captures its fundamental essence, and that can be effectively mathematised for inclusion in mathematical models, e.g., predictive models. This is achieved through a systematic approach grounded in logical reasoning towards first principles (Table 1), ontology, epistemology, and the philosophies of language and science. Specifically, this process employs a series of thought experiments, boundary tests and arguments (Table 1) to identify the core attributes that are fundamental to defining an athletic injury. These thought experiments, boundary tests and arguments are designed to test the logical boundaries distinguishing athletic injury from non-injury and other related phenomena, disentangling conflated concepts and resolving existing logical inconsistencies, and to establish a set of necessary and sufficient conditions (Table 1) needed for an athletic injury to exist [22, 24-26, 32, 35-37].

Once conflated concepts have been disentangled and athletic injury has been theoretically defined in a conceptually and logically coherent manner (a necessary prerequisite to forming a mathematical system), this definition can then be mathematised for application in mathematical modelling (e.g., predictive modelling). This establishes the foundation for a formalised and mathematised linguistic system and semantic network (Table 1) surrounding athletic injury, offering a logically coherent framework that seamlessly integrates related concepts, such as injury severity, recovery, rate of recovery etc. [10, 38]. This transforms these previously vague concepts, often used in contradictory manners, into objectively measurable and predictable entities with precise, consistent and mathematically defined relationships to one another [38].

Ultimately, the procedures undertaken in this article will facilitate the development of more appropriate and precise, ideally tissue-specific, operationalisations of athletic injury, allowing athletic injury (and associated concepts) to be objectively determined from measurable physical parameters that can be appropriately mathematised for application in mathematical (e.g., predictive) models. Altogether, this transforms athletic injury and associated concepts from vague notions, subject to inconsistent interpretations and applications, i.e., bias, into mathematical objects with well-defined semantics and well-founded logic, enhancing the predictability, falsifiability and reproducibility of athletic injury research moving forward [8].

Table 1: Relevant Nomenclature

<u>Operational definitions</u>	
Theoretical Definition	A theoretical definition is an explanation of a concept that establishes its fundamental properties and relationships, providing a conceptual framework for understanding, analysing, and distinguishing it from related concepts. The primary role of a theoretical definition is to ensure theoretical accuracy and logical consistency, capturing the fundamental essence of a concept as accurately as possible. This allows the concept to be consistently and appropriately operationalised [8, 33, 39-41]
Operational Definition	An operational definition outlines how a concept will be measured or observed in practice, specifying the procedures, criteria, or variables used to quantify and identify it within a given context [8, 33, 39-41]. In this respect, the task of setting clear and measurable boundaries falls to the process of operationalisation
Latent construct	A latent construct is an abstract concept that cannot be directly observed or measured but is inferred through indirect indicators or variables
Ontology	Ontology is the branch of philosophy that studies the nature of being, existence, and reality, focusing on the categorisation and relationships of entities and concepts
Epistemology	Epistemology is the branch of philosophy that studies the nature, sources, and limits of knowledge, focusing on how we know what we know
Semantics	Semantics is the study of the meaning of words, phrases, and symbols, and how they are used to convey information and concepts
Falsifiability	Falsifiability is a fundamental criterion in the scientific method, referring to the degree to which a hypothesis or theory can be shown to be false through observation or experimentation. A falsifiable theory must make precise, testable predictions that may be contradicted by empirical evidence. As philosopher Karl Popper [8] argued, if a theory cannot be tested or potentially refuted in this way, it does not qualify as scientifically valid and instead begins to fall into the realm of pseudoscience. This is because a theory that cannot be invalidated is immune to critical evaluation. However, this principle is not without controversy. Falsifiability is often seen as an ideal rather than an absolute requirement, as real-world scientific testing rarely yields definitive refutation. Instead, theories are generally subjected to repeated testing, and scientists aim for theories with a high degree of falsifiability, continually refining them as new evidence emerges
Predictability	Here, predictability refers to a theory's ability to generate specific, testable predictions about future observations or experiments. It implies that the theory should outline what outcomes are expected under certain conditions and what results would contradict the theory. Predictability is crucial for falsifiability, as it establishes clear criteria for testing and determining whether the theory can be refuted, thereby making it scientifically meaningful. Without predictability, a theory cannot be tested and, thus, cannot be falsified [8]
Reproducibility	Reproducibility is the extent to which consistent results can be obtained using the same methods, data, and conditions when an experiment or study is repeated by different researchers or at different times
Logical reasoning	Logical reasoning is the process of using structured, coherent thinking to analyse information, draw conclusions, and solve problems based on principles of validity and soundness. It involves identifying relationships

	between concepts, evaluating evidence, and applying rules of logic to reach conclusions that are consistent with given premises
First principles	First principles are the most basic, foundational concepts or assumptions that cannot be deduced from any other idea. In problem-solving or reasoning, starting from first principles means breaking down complex issues into their simplest, most fundamental elements, and building understanding or solutions from these core truths. In essence, it involves asking "why" repeatedly until you reach the most basic truth or axiom that cannot be reduced further
Thought experiments	A thought experiment is a mental exercise used to explore various scenarios (e.g., factual scenarios, counterfactuals, hypotheticals etc.), analyse concepts, test logical boundaries, or evaluate the implications of ideas without the need for physical experimentation. By constructing and manipulating these scenarios, and applying deductive and inductive reasoning methods, thought experiments help reveal logical inconsistencies and consequences and provide insights into complex problems or theories
Boundary testing	Boundary testing is a process of evaluating the limits of a system, concept, or theory by examining how it behaves or holds true at the extreme edges of its defined parameters
Argument	An argument is a set of statements or reasons given to support or refute a conclusion. It typically consists of premises (the supporting statements) and a conclusion (the statement being argued for). The goal of an argument is to demonstrate that the conclusion logically follows from the premises. In essence, an argument is a rational attempt to persuade someone of the truth or validity of a specific point
Necessary condition	A necessary condition refers to a condition or requirement that must be true or satisfied for a particular statement, outcome, or event to occur
Sufficient condition	A sufficient condition refers to a condition that, if met, guarantees a particular outcome or event
Linguistic system	A linguistic system is a structured set of rules and components, such as vocabulary, grammar, and syntax, that govern how language is used to convey meaning, enabling consistent communication within a language or framework.
Semantic network	A semantic network is a conceptual framework that represents relationships between concepts or entities in a structured graph-like model, where nodes represent concepts and edges represent the relationships between them, facilitating understanding and inference of meaning.
Modus tollens	(Latin) The rule of logic which states that if a conditional statement (‘if *p* then *q*’) is accepted, and the consequent does not hold (*not-q*) then the negation of the antecedent (*not-p*) can be inferred
Reductio ad absurdum	(Latin: “reduction to absurdity”), in logic, a form of refutation showing contradictory or absurd consequences following upon premises as a matter of logical necessity
Logical Positivists	Logical positivists, a group of 20th-century philosophers associated with the Vienna Circle, argued that meaningful statements must be empirically verifiable or analytically true. They rejected metaphysical, ethical, and theological claims as meaningless if they could not be tested through observation or logic. Emphasizing science and formal reasoning, they sought to distinguish scientific knowledge from unverifiable assertions.

Mechanical loading	Mechanical loading refers to the external force or combination of forces applied to a tissue, causing stresses and strains. Depending on the nature and direction of the applied forces, loading can come in a variety of modes e.g., tension, compression, shear, bending, or torsion
Mechanical Stress	Stress is defined as the intensity of force per unit area that develops within a tissue in response to an applied force. Stress may be characterised as normal (force perpendicular to a plane) or shear (force parallel to a plane) Normal stress may be tensile or compressive depending on the mode of loading
Mechanical Strain	Strain is a normalized measure of tissue deformation expressed as the ratio of deformation to the initial dimensions. Two types of strain exist: normal strain, which is related to changes in size, and shear strain, which is related to changes in shape. Normal strain may be tensile or compressive depending on the type of loading

Table 2: (General) Injury Definitions

World Health Organization (WHO) [19]:	A bodily lesion at the organic level, resulting from acute exposure to energy (mechanical, thermal, electrical, chemical, or radiant), in amounts that exceed the threshold of physiological tolerance
Centers for Disease Control and Prevention (CDC) and The International Classification of External Causes of Injuries (ICECI) [42]:	A (suspected) bodily lesion resulting from acute overexposure to energy (mechanical, thermal, electrical, chemical, or radiant) interacting with the body in amounts or at rates that exceed the threshold of physiological tolerance
International Classification of Diseases (ICD-11) [20]:	Physical or physiological bodily harm resulting from interaction of the body with energy (mechanical, thermal, electrical, chemical or radiant, or due to extreme pressure) in an amount, or at a rate of transfer, that exceeds physical or physiological tolerance. Injury can also result from lack of vital elements, such as oxygen. Poisoning by and toxic effects of substances are included, as is damage of or due to implanted devices
Oxford English Dictionary (OED; 2024) [43]:	A physical hurt or damage
Cambridge Dictionary (2024) [44]:	Harm or damage done to a living thing
The concise Oxford dictionary of current English (1921) [45]	Harm, damage
Modern dictionary of the English language (1911) [46]	Hurt or damage

2.0 A Brief Introduction into Logical Reasoning, Necessity and Sufficiency, Thought Experiments and Boundary Testing

Logical reasoning is a cornerstone of scientific inquiry, enabling researchers to construct valid arguments, evaluate concepts and definitions, and systematically interpret evidence [8, 10, 23, 25, 34, 37, 42-48]. Through logical reasoning, arguments can be assessed for soundness and consistency, flaws in reasoning can be identified, and coherent frameworks for understanding complex phenomena developed [7, 8, 25, 34, 42, 47]. This structured approach typically involves applying deductive and inductive methods (Table 1) to distinguish valid arguments from invalid ones [8, 42, 43, 49, 50], ensuring that conclusions are derived from objective, logically consistent criteria rather than subjective biases [8, 22, 23, 25, 34, 37, 42-44, 47-51].

To better introduce this, an explanation with some examples of deductive and inductive reasoning may prove useful. Deductive reasoning starts with general principles or premises and applies them to specific cases, establishing conclusions that are logically certain if the premises are true [42]. For example, consider the following premises and conclusion:

All 100m Olympic gold medallists are human.

Usain Bolt is a 100m Olympic gold medallist.

Therefore, Usain Bolt is human.

This type of inference is deductive because given that the premises are true and the reasoning is valid, then the conclusion must be true. It is absolute in its logic. Deductive reasoning is particularly useful for defining necessary conditions, highlighting what conditions are needed for a concept or definition to hold.

Inductive reasoning, on the other hand, involves drawing general conclusions from specific observations. For instance, consider the following premise and conclusion:

Jamaicans have performed well in the past in the 100m event at the Olympics.

Therefore, Jamaicans will perform well in future 100m events at the Olympics.

Of course, the presented inference is probabilistic and not a certainty, and it is for this reason that, due to its absolute nature (and depending on the context), deduction is commonly preferable to induction in the philosophy of science, allowing for logically certain conclusions (assuming the premises are valid) [23, 42, 46]. However, while inductive reasoning does not guarantee certainty, it does help identify patterns and relationships, making it a valuable tool for formulating new hypotheses.

By integrating deductive and inductive approaches, researchers can develop more comprehensive theoretical models and precise definitions. These methods enable the use of thought experiments, boundary tests and arguments to eliminate logical inconsistencies, disentangle and refine concepts of interest, and identify necessary and sufficient conditions for a concept to be upheld [42, 52]. Through these methods, logical reasoning contributes to a deeper understanding of the underlying principles that define a theory or concept [8, 23, 25, 34, 42, 44, 47, 48].

2.1 Necessity and Sufficiency

In the philosophy of science and language, necessity and sufficiency are foundational criteria for constructing precise theories and definitions [8, 22-26, 33, 37, 43, 45, 47, 48, 51-55]. These criteria determine which conditions must be met (necessary) and which are enough (sufficient) to define the boundaries of a concept. Consequently, they play a crucial role in forming definitions by clarifying core attributes and eliminating logical inconsistencies or conflated ideas, ultimately leading to a more systematic and coherent understanding of various phenomena and concepts.

To elaborate, a necessary condition is one that must be met for a concept to apply. This allows for deductive inferences as if the condition is not satisfied, the concept or phenomenon cannot hold. For example, consider the following scenario:

Being human is a *necessary condition* for competing in the 100m at the Olympics (as per current and historical rules).

Usain Bolt competes in the 100m at the Olympics.

Therefore, Usain Bolt is human.

Here, if the necessary condition is accepted as valid (Usain Bolt's retirement aside), it facilitates deductive reasoning, as either the condition is met and the concept is upheld, or it is not. However, while being human is a necessary condition for winning the Olympic gold medal in the 100m, it is not a sufficient condition, as not all humans are Olympic champions. Indeed, a sufficient condition is one that, when met, guarantees that the concept or definition applies. For example, consider the following scenario:

Winning the 100m final at the Olympics guarantees a gold medal.

Therefore, winning the 100m final is a *sufficient condition* for being an Olympic gold medallist.

Here, winning the 100m final at the Olympics is considered a sufficient condition for being an Olympic gold medallist because it satisfies all criteria needed for this classification. Of course, there may be more than one sufficient condition, as is the case with winning an Olympic gold medal. Being an Olympic gold medallist can result from winning events other than the 100m final, such as the Javelin or High Jump.

When developing theoretical definitions, such as a fundamental theoretical definition for athletic injury, it is important to identify both necessary and sufficient conditions that define a concept to achieve conceptual clarity. This process refines definitions by distinguishing essential features from those that are merely associated, removing logical inconsistencies and reducing vagueness, resulting in a more precise and reliable understanding of a concept.

2.2 Thought Experiments and Boundary Testing

The process of refining theoretical definitions through logical reasoning often incorporates the application of "boundary tests". Boundary testing involves pushing a definition to its conceptual limits through a series of thought experiments [9, 24, 52, 56, 57]. While many of these thought experiments may appear extreme in nature, pressing at the edges of a concept, to dismiss them as such is to misunderstand their purpose, as this is their fundamental strength. By 'testing boundaries', these experiments explicitly highlight potential logical inconsistencies or cases where any proposed necessary or sufficient conditions breakdown, and the concept or definition does not hold. Accordingly, thought experiments have an important role in refining definitions by disentangling conflated concepts and more clearly defining the boundaries of various concepts of interest. In science, defining the boundaries of a concept is critical so that the concept can be appropriately conceptualised, operationalised and investigated using the scientific method, facilitating its uniform application across studies. This allows for valid comparisons and more reliable conclusions.

3.0. Developing a Fundamental Theoretical Definition of Athletic Injury

Considering the IOC is a leading authority in global sports and its definitions significantly influence international standards and practices [6], to provide a starting point for developing a fundamental theoretical definition of athletic injury, there is arguably no better place to start than to revisit the current definition proposed by this organisation (Definition 1) [6]. Here, there are a series of key features that highlight identified necessary conditions for an athletic injury to exist, as proposed by the IOC; 1) tissue damage or other derangement of normal physical function, 2) due to participation in sports, and 3) resulting from rapid or repetitive transfer of kinetic energy. Some of these conditions may be surprising to some. Why does tissue damage or other derangement of normal physical function warrant inclusion, but pain does not? Is this not an important component of athletic injury worthy of inclusion? What about other symptoms such as swelling and tissue inflammation? Or availability for sports participation? Certainly, various operational definitions of athletic injury have incorporated or imply many of these elements [4, 6, 15-18]. For example, Fuller et al. [17] operationally defined athletic injury as:

"Any physical complaint requiring medical attention resulting in a missed A-League match" [17].

Definition 4

Similarly, Ekstrand et al. [15, 18] have operationally defined athletic injury as:

"Any physical complaint sustained by a player that resulted from a football match or football training and led to the player being unable to take full part in future football training or match play" [15, 18].

Definition 5

So why then, would symptoms such as pain and swelling, which are implied in "any physical complaint" [17], or availability for sports participation, be excluded from a theoretical definition of athletic injury? Are these not necessary or sufficient conditions for an athletic injury to exist? The following sections will provide a logical examination of the conditions proposed within the theoretical definition put forward by the IOC, as well as the absence of those conditions whose exclusion may appear confusing to some.

3.1. Disentangling Conflated Concepts:

3.1.1 The Exclusion of Pain and Other Symptoms

Considering pain and other symptoms such as swelling and inflammation are important considerations in the practical management and diagnosis of athletic injury in applied sports settings, as well large-scale epidemiological studies, their absence from the proposed theoretical definition from the IOC may appear counterintuitive. Indeed, these concepts are commonly conflated as fundamental criteria [21]. However, their exclusion is logically accurate. To illustrate this, consider the following thought experiment: an athlete breaks their leg during a soccer match after a poorly timed slide tackle from the opposition. Reasonably, the athlete has sustained an athletic injury; their leg is broken, they are in excruciating pain and must be stretchered from the field. To assist with this pain, the doctors administer an anaesthetic, and shortly after, the athlete no longer experiences pain. Is the athlete still considered to have an athletic injury despite the absence of pain? To answer no would be unreasonable as per the common definitions and uses of the term (Table 2) [19, 20, 58-60]. The athlete's leg is broken, and they are surely unable to play for an extended period, facing extensive surgery and months of recovery to mend their broken leg.

While this thought experiment may appear 'extreme' to some, injuries in sports that require painkillers, anaesthetics and surgical intervention e.g., anterior cruciate ligament ruptures, Achilles tendon ruptures, bone fractures etc. are not uncommon, while other instances exist where physical injuries are clearly present in humans, but pain does not present or subsides for various reasons [61-63]. More importantly however, any perceived extremity of this thought experiment is ultimately irrelevant, with the proposed scenario serving a clear and concise logical purpose. From the proposed scenario, an important conclusion can be deduced from the following premises:

The athlete has an athletic injury.

The athlete is not experiencing pain.

Therefore, pain is not a necessary condition for an athletic injury to exist.

By presenting even a single scenario where an athletic injury exists but pain does not and adhering to the logical principle of *modus tollens* (Table 1), any claims that pain is a necessary condition for an athletic injury can be falsified. Indeed, to falsify the claim that all swans are white, only a single black swan is needed, regardless of how many white swans have been observed previously [8]. As a result, assertions that pain is a necessary condition for athletic injury are logically negated and rendered untenable. Any perceived extremity of the proposed hypothetical, or the inclusion of an exogenous substance (such as an anaesthetic) to remove the pain, is of no relevance. This reflects the fundamental strength of the thought experiment: a single counterexample is sufficient to falsify a universal claim (refutation by counterexample [8, 10, 23, 51, 55]). This provides a clear demonstration of absolute logic where the conclusion that pain is not a necessary condition for athletic injury deductively follows from the premises. However, this thought experiment does not end here, as it is still possible that pain is a sufficient condition for an athletic injury to exist. To address this, let us consider other scenarios where tissue damage does not exist, but pain does. Is it reasonable to consider these scenarios as athletic injuries? No, it is not. Pain may arise during sports participation for reasons unrelated to athletic injury, for example, medical conditions that are distinct from athletic injuries, such as cancer, angina, blood clots, autoimmune diseases, and neurological disorders. Labeling such conditions as athletic injuries would result in an unreasonably broad application of the term, effectively categorising almost all medical conditions involving pain during sports participation as injuries. Accordingly, the following premises can be set:

The athlete is experiencing pain due to a medical condition such as a cardiac infarction or neurological disorder.

The athlete has not sustained an athletic injury.

Therefore, pain is not a sufficient condition for an athletic injury to exist.

Through the presented thought experiments, it can be conclusively deduced that pain is neither a necessary nor sufficient condition for an athletic injury to exist (i.e., it does not define it [51]), and athletic injury and pain are distinct phenomena. Indeed, by adhering to the principles of necessity and sufficiency, any claims that pain is a defining feature of injury can be negated through a *reductio ad absurdum* (Table 1), a logical process which demonstrates the falsity of an assumption by showing that it leads to absurd or contradictory outcomes.

Assumption: Pain is a defining feature of athletic injury.

Premise 1: An injury can exist without pain (pain is not necessary for injury).

Premise 2: Pain can exist without injury (pain is not sufficient for injury)

Conclusion: If pain is neither necessary nor sufficient for athletic injury, it cannot logically be a defining feature of injury. This directly contradicts the initial assumption, reducing it to absurdity and invalidating the claim that pain is essential to the definition of athletic injury.

It is clear, pain has no place in a fundamental theoretical definition of athletic injury, and the IOC's decision to exclude pain from their proposed definition of athletic injury is vindicated and logically sound. Including pain would, by definition, be illogical [64], as doing so would have meant committing a notable logical error, conflating two associated but separate phenomena, whereby the second phenomenon is neither necessary nor sufficient for the first phenomenon to exist.

Thought experiments and arguments, such as those presented here, are not simply philosophical exercises with little practical importance. Rather, they have significant consequences for the scientific method. Erroneously including pain as a defining feature of athletic injury, when pain is neither necessary nor sufficient for an athletic injury to exist, would have major implications for studying this concept scientifically. To elaborate, consider a scenario where athletic injury is defined using both tissue damage and pain, but neither are necessary or sufficient for an athletic injury to exist. This would transform athletic injury into a vague and contradictory construct with no clear or consistent criteria for operationalisation (or mathematisation), as such a definition of athletic injury would accommodate all possible tissue damage and pain states. This significantly diminishes the reliable application of the concept [10, 25, 37], as there would be no formalised criteria to determine whether an athlete has, or has not, sustained an injury using these parameters. Rather, any interpretation of injury becomes inherently subjective, introducing bias. Indeed, some (e.g. logical positivists; Table 1) might go as far as to say that this would render the statement "this athlete has (or alternatively has not) sustained an injury" meaningless, as there would be no way to verify (or falsify) whether an injury does or does not exist [65, 66]. While this is an outdated and controversial thesis, as meaning is context-dependent [30], it does an effective job at emphasising a critical issue; such an understanding of athletic injury lacks a boundary of demarcation to distinguish injury from non-injury [10, 25, 51]. In a scientific context, this is highly problematic as it undermines the critical scientific principles of predictability, falsifiability and reproducibility [8]. If there are no clear criteria to distinguish an injury from a non-injury, how can an injury be reliably identified or predicted? Without such criteria, what does it even mean to 'predict an injury'? The famous philosopher of science, Karl Popper, would likely label such a vague and inconsistent interpretation of athletic injury as a concerning shift towards pseudoscience [8, 67], as all possible tissue damage and pain states can be classified as an injury or non-injury, with no means of falsification, explaining everything and predicting nothing. Ultimately, these same logical concerns would hold for all other symptoms of injury such as swelling or bruising, which may or may not accompany an athletic injury. It is largely for this reason that these conditions are commonly termed *symptoms* of injury, as by definition, *symptoms* indicate a condition but do not define it [68]. To include them in the fundamental theoretical definition of athletic injury would be to mistakenly conflate observable correlates (indicators) with the condition itself.

Importantly, the distinction between pain and injury does not diminish the significance of pain, swelling or any other symptoms of injury in the practical management of athletes. Symptom assessments provide timely and cost-effective indicators (correlates) of injury that offer value for their practical assessment, management and rehabilitation. Furthermore, symptoms (such as pain) may, depending on the context, be of more clinical concern than the actual underlying physical injury. The purpose of disentangling pain and other symptoms from the concept of athletic injury was to highlight that: 1) each of these (athletic injury, pain, swelling etc.) represent distinct but associated concepts, with each of these being worthy of their own consideration and scientific inquiry; 2) while symptoms may offer practical value, they are ultimately limited and unreliable as definitive measures of injury [61, 69-72], underscoring the need for more objective markers; 3) applied practitioners are faced with the difficult task of managing a variety of phenomena beyond simply athletic injury; and 4) for the purposes of precision and prediction within the sciences, it is important that distinct phenomena (such as pain and injury) are conceptually disentangled so that advancements in operationalisation, identification and measurement of these concepts may be developed.

3.1.2 Availability for Sports Participation

To provide a practical demarcation boundary to assist with distinguishing athletic injury from non-injury in applied athletic injury research, and in particular large-scale epidemiological studies, operationalisations of athletic injury (typically of the theoretical definition proposed by the IOC; Definition 1) have commonly centred around availability for participation and time-loss, i.e., whether an athlete is available to participate in training or match play e.g., Definition 4 & 5 [15, 17, 18]. Accordingly, the absence of availability for sports participation from the definition of injury proposed by the IOC may be confusing to some. Is availability for sports not a necessary or sufficient condition for an athletic injury to exist?

Operational definitions are essential for translating theoretical concepts and definitions into assessable variables, turning these into identifiable, measurable and predictable entities [8, 33, 39-41]. However, these definitions often sacrifice theoretical rigor to accommodate the limitations of available assessment tools, prioritising practicality (e.g., cost effectiveness, limitations in measurement technologies etc.) over conceptual precision.

Depending on the context, this may be problematic [73]. The greater the misalignment between a theoretical definition and its operationalisation, the poorer the measurement, as the operationalisations deviate from the concept they are intended to measure.

While availability for sports participation serves as a practical criterion for demarcating injury from non-injury in applied settings and large-scale epidemiological studies, arguably aligning more closely with what sporting entities often prioritise, which is availability to train or compete, it is important to recognise that defining athletic injuries by their impact on participation constitutes a theoretical compromise. This is why such an approach is more accurately termed a 'time-loss injury,' which is a different concept to an 'athletic injury'. Regardless, the concept of time-loss is fundamentally grounded in an absence of participation, and accordingly, it is important to examine whether availability for participation in sports is a necessary or sufficient condition for an athletic injury to exist.

Consider the following scenario: In 2008, Tiger Woods won the U.S. Open in golf despite competing with a torn anterior cruciate ligament and a double stress fracture in his leg. Based on any reasonable interpretation of the term injury (Table 2), it would be illogical to suggest that Tiger Woods did not have an athletic injury—his anterior cruciate ligament was ruptured, and he required knee reconstruction surgery after the tournament. Therefore, the following premises can be established, leading to a deductive conclusion:

Tiger Woods has an athletic injury.

Tiger Woods is participating in sport despite having an athletic injury.

Therefore, an inability to participate in sports is not a necessary condition for an athletic injury to exist.

While participation in sports is not a necessary condition for an athletic injury to exist, perhaps it is a sufficient condition? No, it is not. There are many reasons an athlete may make themselves unavailable for participation. Perhaps they are angry at their team for not passing them the ball and no longer want to play, or perhaps they are faking an injury because they are hungover. Perhaps they simply want to go on holiday for a few weeks. Clearly, it would be unreasonable to consider such circumstances as athletic injuries, and accordingly, availability to participate in sports is neither a necessary nor sufficient condition for an athletic injury to exist, and the IOC is correct to exclude this from their theoretical definition of athletic injury.

Importantly, the absence of necessity or sufficiency does not mandate that athletic injuries must not be operationally defined in terms of physical complaints, availability for participation, or time-loss for large-scale epidemiological studies, as these remain practical solutions in many contexts. Rather, it highlights that such approaches represent theoretical compromises that diverge from the fundamental concept of injury. By prioritising practical ease of data collection and standardisation, these methods introduce greater subjectivity, inconsistency, and measurement inaccuracies, often at the expense of precision.

Certainly, the decision to participate in sports is ultimately subjective, influenced by factors such as injury severity, individual pain tolerance, competition level, and internal motivation. For instance, an athlete in poor physical condition, with a severe injury and significant pain, may still choose to play due to high motivation or external pressures (e.g., a cup final is approaching). Conversely, another athlete with relatively minor tissue damage (insufficient to be considered an injury) might opt to abstain from participation for personal reasons (e.g., they are hungover, have some minor niggles, and want a holiday). In such cases, the first scenario may fail to register an injury because the athlete pushes through the pain barrier, while the second scenario may inaccurately register an injury simply because the athlete makes themselves unavailable, regardless of their actual physical condition.

This inconsistent and contradictory approach conflates the objective reality of injury with subjective decisions about availability to play. Consequently, when athletic injury is operationalised as availability for participation, it becomes synonymous with this broader concept, diverting attention from the injury itself. Compromises such as these can skew research findings [73], conflating athletic injury with subjective decisions around availability rather than objectively measuring the injury. Furthermore, studies attempting to predict athletic injuries based on this operationalisation are, in reality, attempting to predict the inherently less predictable (and arguably more cared about in professional sporting contexts) concept of availability to play, which is influenced by subjective and context-dependent factors often unrelated to the injury itself.

To address these issues, some studies incorporate additional measures, such as MRI or other imaging techniques, to confirm the presence of physical damage [74-76]. While these approaches certainly offer a superior level of precision, it is also crucial to recognise that the absence of identifiable damage does not necessitate an absence of injury; it may simply reflect limitations in injury identification and measurement technologies or processes (e.g., imaging resolution, radiographer expertise etc.). Accordingly, advancements in injury assessment technologies (e.g., higher-resolution imaging), methodologies (e.g., artificial intelligence analysis, data integration, and mathematical modelling), and accessibility to these tools may, in time, drive further progress in this field, enabling more precise and consistent reporting of athletic injuries while disentangling them from subjective factors such as availability and pain tolerance.

3.2 Bodily Harm and Transfer of Energy: The Necessary Essence of Injury

Considering pain, swelling, participation in sport and other associated concepts are neither necessary nor sufficient for an athletic injury to exist, it may appear confusing to some that tissue damage and the transfer of kinetic injury warrants inclusion. Is tissue damage and the transfer of kinetic energy not subject to the same arguments? Simply, the answer is no. One explanation lies within the manner through which athletic injuries are formed, and an important necessary causal condition that underpins this. Let us revisit the definition presented by the IOC (Definition 1), whereby the following necessary conditions are presented; 1) due to participation in sports, and 2) resulting from rapid or repetitive transfer of kinetic energy. The first condition presented here is hardly controversial, as it is only reasonable that for a sports or athletic injury to exist, it must have occurred during participation in sports. This distinguishes athletic injuries from injuries that occur in other contexts outside of sport, such as workplace or household accidents. However, the second condition is of notable significance, providing a bold causal condition that an athletic injury results from rapid or repetitive transfer of kinetic energy i.e., a transfer of kinetic energy is a necessary cause of athletic injury. Together, these two conditions play a key role in distinguishing athletic injury from general injury (Table 2) [19, 58, 77-81].

Considering the transfer of kinetic energy has been identified as a necessary cause for an athletic injury to exist, it is important to evaluate whether this is a logically sound condition. Consider a range of some of the most common and problematic injuries in sport, such as anterior cruciate ligament ruptures, leg fractures, hamstring tears, Achilles tendon ruptures, and shoulder dislocations. Each of these injuries involve the application of physical forces (kinetic energy) to stress and ultimately disrupt the molecular structures maintaining the integrity of these tissues. Indeed, extensive evidence demonstrates that mechanically induced tissue damage mirrors the damage profiles observed in sports-related injuries [82-91]. Even in complex active tissues like muscle, mechanical loads (Table 1) are essential for causing fiber or musculo-tendinous ruptures [90, 92]. Accordingly, the IOC's condition that a transfer of kinetic energy is a necessary condition for athletic injury occurrence appears logically sound. However, while this may seem like a compelling argument, it relies on inductive reasoning, generalising observed cases of common sports injuries to claim that kinetic energy transfer is necessary for all athletic injuries. This reasoning is not absolute; a single counterexample of an athletic injury occurring without mechanical loading would refute the claim, rendering it insufficient as a definitive foundation for understanding athletic injuries. Indeed, as per the definitions of the WHO and ICD-11, a sunburn should be classified as an injury, and this is caused by radiant energy.

To address this point, one must probe at the fundamental essence of what an injury is by considering the historical and contemporary definitions of injury as provided by various authoritative sources (Table 2), as well as the decision of the IOC to deviate from these sources to exclude bodily harm caused by other forms of energy besides kinetic. Historically and currently, prominent dictionaries such as the *Oxford English Dictionary* and the *Cambridge Dictionary* have defined injury as:

- "A physical hurt or damage" - Oxford English Dictionary (2024) [60]
- "Harm or damage done to a living thing" - Cambridge Dictionary (2024) [59]
- "Harm, damage" - The concise Oxford dictionary of current English (1921) [93]
- "Hurt or damage" - Modern dictionary of the English language (1911) [94]

The WHO and ICD-11, widely regarded as global authorities in health-related definitions and classifications, offer expanded definitions considered the gold standard for consistency and accuracy in health science. As detailed earlier (Table 2), the WHO defines injury as "a bodily lesion at the organic level" (Definition 2), and the ICD-11 describes it as "physical or physiological bodily harm" (Definition 3). A consistent theme across these definitions is that injury entails harm or damage to the body, encompassing physical hurt, lesions, and structural or physiological disruption. Such harm necessitates a disruption to the body's physical structures or functions, which cannot occur spontaneously or in isolation—it requires a transfer of energy [95-98].

Energy, whether kinetic, thermal, chemical, electrical, or other forms relevant to physical systems drives all physical change and is fundamental to the concept of injury. Without energy transfer, molecular bonds cannot be damaged, and no structural or functional changes can occur within the body—ligaments cannot tear, bones cannot fracture, and cells cannot be damaged [95-99]. It follows that bodily harm, resulting from the transfer of energy, constitutes the fundamental essence of what an injury is, reflecting the essential properties that are necessarily tied to its identity [24]. In the complete absence of a transfer of energy and any resulting bodily harm, an injury, by definition (as per the WHO and ICD-11), cannot exist.

When considering this foundational understanding of injury, the IOC's decision to limit the definition of athletic injury to those caused by kinetic energy is intriguing, as it diverges from the broader definitions proposed by the WHO and ICD-11. Indeed, injuries caused by the transfer of other energy forms besides kinetic, such as sunburn (radiant energy) or drowning (absence of energy), can certainly occur during sports participation. According to the WHO and ICD-11 definitions, these should be classified as injuries.

Ultimately, the issue outlined above is a matter of preference and poses minimal concern, as it can be easily addressed if necessary. Mechanical injuries remain the most prevalent and consequential in sports, making the IOC's definition of injury closely aligned with the primary objectives of sports medicine and injury research. This serves a practical purpose by isolating these injuries from rarer forms of injury caused by other energy sources (e.g., sunburn, chemical burns, electrical injuries) or the absence of energy (e.g., drowning, asphyxia). However, if desired, expanding the definition of athletic injury to include other forms of energy poses little linguistic or semantic difficulty. A straightforward solution would be to expand the definition of athletic injury to encompasses all injuries that occur during sport irrespective of the energy source, aligning with the broader scope of the WHO and ICD-11. Under this framework, subcategories such as mechanical, radiant, and thermal injuries could be established, allowing for specific classifications while maintaining conceptual clarity. Furthermore, there are increasing efforts to expand the concept of injury to include other concepts such as psychological injury [100, 101]. This can be addressed by redefining injury to a broader concept and qualifying injuries as either physical or psychological, ensuring clarity while accommodating broader definitions of injury.

3.3 Tissue Damage: Necessary but Insufficient

While tissue damage due to a transfer of kinetic energy is a necessary condition for an athletic injury to occur (as per the IOC), is it sufficient? Reasonably, the mere presence of tissue damage should not constitute an athletic injury. This highlights a critical theoretical shortcoming in the definition proposed by the IOC (Definition 1): it fails to establish sufficient conditions for the existence of an athletic injury. To elaborate, tissue damage is an inevitable consequence of regular sporting participation [102-104], with even minor loading exposures resulting in some degree of tissue damage [85, 86, 105]. Under the IOC's definition, the quest for athletic injury prediction is over, as every athlete would incur an injury shortly after commencing their training, an outcome that is clearly unreasonable. Moreover, tissue damage often serves as a critical stimulus for tissue remodelling and adaptation [106-108], forming a normal part of the physical training and positive adaptation process. Consequently, equating the mere presence of tissue damage to an athletic injury sets an exceptionally low threshold for an athletic injury to occur, resulting in all athletes sustaining athletic injuries soon after engaging in sport.

An additional concern arises with the criterion of "other derangement of normal physical function" (Definition 1). Besides being overly vague, such derangements can occur without the presence of an injury. For instance, neuromuscular fatigue could be classified as a form of "other derangement of normal physical function." Considering an athlete to have sustained an athletic injury as soon as they experience some degree of neuromuscular fatigue would similarly be unreasonable, while neuromuscular fatigue is also neither a necessary nor sufficient condition for an injury to exist, further demonstrating the logical shortcomings of this definition.

4.0 Proposing a New Fundamental Theoretical Definition for Athletic Injury

Considering tissue damage is a necessary but insufficient condition for an athletic injury to exist, reasonably, there must be some demarcating threshold of tissue damage that distinguishes an athletic injury from non-injury, which more closely reflects the definitions of (general) injury presented by the WHO (Definition 2) [19] and other notable organisations [20, 58] (Table 2). Accordingly, to address this, the following condition is proposed; the tissue damage sustained should not form part of the normal physical training and positive adaptation process but must exceed the threshold of mechanical and physiological tolerance. This is dependent upon the *nature* and *degree* of tissue damage sustained.

With the inclusion of this new proposed condition for an athletic injury to exist, a new fundamental theoretical definition for athletic injury is presented:

“Tissue damage and loss of physical function during sports participation, resulting from rapid or repetitive transfer of kinetic energy, that is not a normal part of the physical training and positive adaptation process, but exceeds the threshold of mechanical and physiological tolerance. This is dependent upon the nature and degree of tissue damage sustained.”

Definition 6

4.1 Nature and Degree of Tissue Damage Sustained

Within the proposed definition (Definition 6) "*nature and degree of tissue damage sustained"* refers to the specific characteristics, properties, or type of tissue damage that distinguishes an athletic injury from normal responses to physical training. It encompasses both the qualitative aspect (e.g., the type of structures affected) and the quantitative aspect (e.g., the extent or *severity* of the damage sustained).

An illustrative example highlighting the importance of considering the *nature* of tissue damage sustained is the distinction between muscle damage and muscle injury, which are distinct clinical entities [109]. Muscle damage is characterised by sarcomere dissolution i.e., desmin disruption and catabolism, Z-disk streaming etc [91] and is a largely unavoidable and normal part of the physical training process [103, 104] that commonly precedes positive adaptations such as the repeated bout effect [110], and increased muscle hypertrophy and strength (although the causal nature of this relationship has been questioned [108, 111]). Given its frequent occurrence during and after training [103, 104], and the beneficial adaptations that commonly ensue, reasonably, muscle damage should not be classified as an athletic injury. Rather, muscle injury more accurately occurs when there are structural tears in muscle fibers [109], which provides no adaptive benefit and typically requires long and incomplete recovery processes [109].

The significance of considering the *degree* of tissue damage is exemplified by the distinction between the mechanical fatigue of bone and the development of bone cracks and fractures. Mechanical fatigue damage, characterised by a temporary reduction in bone stiffness and strength, is a stimulus for positive bone adaptation in accordance with Wolff's Law [107, 112, 113]. In this context, the bone damage and microstructural changes that occur reflect a normal mechanical and physiological process that strengthens bone over time [107, 112, 113]. Conversely, the formation of bone cracks or fractures due to excess damage represents a pathological outcome, resulting in prolonged losses in bone density and strength, ultimately compromising bone health [114].

Within Definition 6, is another distinct alteration from the definition proposed by the IOC (Definition 1): 'other derangement of normal physical function' has been omitted. This has been excluded because it is overly vague, but more importantly, and as highlighted within the neuromuscular fatigue example presented in Section 3.4, it is also neither necessary nor sufficient for an athletic injury to exist.

4.2 Loss of Physical Function

In the proposed definition (Definition 6), "loss of physical function" refers to the objectively measurable deterioration in a tissue's mechanical properties, such as load-bearing capacity (mechanical strength), stiffness, and elasticity. As these properties are fundamentally governed by atomic bonding within the tissue, tissue damage i.e., damage to molecular bonds, necessarily compromises these mechanical characteristics. Accordingly, this concept is not viewed in isolation but is designed to exist with tissue damage within a unified physics-based framework. In this respect, loss of physical function provides an alternative conceptualisation of the same physical phenomenon as tissue damage, with their relationship to one another being mathematically defined and modelled, allowing for a precise understanding of how tissue damage impairs functional capacity. While at the structural level these relationships may become disassociated, this is a function of scale due to emergent behaviours such as stress redistribution and deformation (discussed further in section 4.3).

4.3. Operationalisation: Physical Manifestation and Mathematisation of Athletic Injury

While the operationalisation and deeper implications of the new proposed theoretical definition of athletic injury (Definition 6) will be explored in more detail in future works, several important considerations are highlighted here. Central to the proposed definition of athletic injury is its emphasis on tissue damage (a physical parameter), which is crucial for developing operational definitions aligned with objective criteria. This approach ensures consistent and unbiased understandings of athletic injury, minimising the influence of human perception and decision-making. For example, if bone injury is operationalised as the onset of cracking (or a certain degree of cracking), this is not reliant upon subjective bias but can be objectively identified and assessed. Such objectivity enhances the predictability, falsifiability, and reproducibility of athletic injury research, while also facilitating the development of more sensitive measurement tools [8].

Additionally, tissue damage and athletic injury can be mathematised for application in predictive modelling. To elaborate, in mechanical models quantifying the accumulation of damage over time, damage is commonly represented using a damage variable (D) ranging between 0 and 1, where ($D = 0$) corresponds to an undamaged state and ($D = 1$) corresponds to complete mechanical failure, i.e., an inability to carry load [105, 115, 116]. Adopting a similar approach, athletic injury can be mathematically defined as:

$$D > D_c$$

Definition 7

In Definition 7, first proposed by Edwards [105], an athletic injury occurs when the damage (D - quantified between 0 and 1) sustained by a tissue is greater than a critical damage threshold (D_c – also quantified between 0 and 1), i.e., $D > D_c$. To provide an example of this, the formation of cracks (or a certain degree of cracking) in bone would be represented by a specific damage threshold, allowing for its prediction within mathematical models. Ultimately however, the physical manifestation of damage and injury varies between tissues e.g., cracking in bone [87], collagen molecular unfolding [82], kinked fibers and tearing in tendon [88], sarcomere disruption and fiber tears in muscle [109] etc. and accordingly, tissue-specific operationalisations of athletic injury are ultimately needed.

Importantly, as direct measurement of damage to individual molecular bonds within a tissue is not currently feasible, and in the absence of overt physical damage such as cracking or tearing, tissue damage must be inferred from measurable changes in its mechanical properties, linking microscopic damage to observable functional impairments. This is typically quantified by assessing the degradation of mechanical strength, which reflects the capacity of a tissue to withstand applied loads. However, as a tissue's role extends beyond merely bearing loads to performing functional tasks such as storing and releasing energy for movement, other mechanical properties, including stiffness and elasticity, must also be considered.

At the structural level, the relationship between localised damage and mechanical properties can become disassociated. However, this is a function of scale, due to scale-dependent emergent behaviours such as stress redistribution and deformation. To address this complexity and increase precision, practical engineering approaches like finite element modelling and continuum damage mechanics (Table 1) are commonly utilised to model the effects of localised damage on mechanical properties [117, 118].

Finally, while traditional mechanical models modelling fatigue damage accumulation commonly determine damage accumulation based on the mechanical loading pattern experienced by a structure [105], in the context of athletic injury, damage includes both damage due to loading and any alterations in damage induced by physiological processes, such as remodelling and repair [105, 119]. This is particularly relevant to athletic injuries exhibiting a gradual onset mechanism, whereby significant damage removal can occur during periods of rest and recovery [120, 121].

4.4 Mathematics as a Formalised Linguistic System for Modelling of Injury and Associated Concepts: Foundations and Initial Expansions

By mathematically defining injury as D > Dc, where damage exceeds a critical damage threshold, the foundation is established for the development of a formalised and mathematised linguistic system for application in mathematical modelling (e.g., predictive modelling). This system, provides a logically coherent framework that seamlessly integrates concepts commonly associated with injury [10, 38], transforming these vague concepts, often used in contradictory manners, into measurable (and predictable) entities with precise, logically consistent and mathematically defined relationships to one another. For example, injury severity (Sev) i.e., the degree of injury, naturally follows as the extent to which damage surpasses the critical damage threshold, mathematically expressed as:

$$\textbf{If } D > Dc, \textbf{ then } Sev = D - Dc$$

Equation 1

This can be rescaled and normalized to express Sev as a quantity between 0 and 1, where 0 represents the complete absence of injury severity, which corresponds to a state of no injury (i.e., D ≤ Dc), and 1 represents complete tissue failure i.e., Sev = 1 ⟺ D = 1, corresponding to maximal injury severity. To do this, Sev can be represented as:

$$\textbf{If } D > Dc, \textbf{ then } Sev = \frac{D-Dc}{1-Dc}$$

Equation 2

Tissue Recovery (R) can be defined as a reduction in tissue damage over time, expressed mathematically as:

$$\textbf{If } D_{t1} > D_{t2}\textbf{, then } R = D_{t1} - D_{t2}$$

Equation 3

where:

- D_{t1} represents the level of damage at an initial time point (t1),
- D_{t2} represents the level of damage at a later time point (t2),
- R quantifies the amount of damage removed between t1 and t2, assuming $D_{t2} < D_{t1}$. If $D_{t2} > D_{t1}$, recovery has not occurred, and additional damage has been accumulated.

R can also be rescaled and normalised to be expressed as a quantity between 0 and 1, where 0 represents no recovery i.e., no tissue damage removal, and 1 represents complete damage removal i.e., a return to an undamaged state.

Rate of recovery ($\dot{R}$) can be defined as the amount of damage removed over a defined time period, mathematically expressed as:

$$\textbf{If } D_{t1} > D_{t2}\textbf{, then } \dot{R} = \frac{D_{t1} - D_{t2}}{t2 - t1}$$

Equation 4

Recovery from injury (R_{injury}) can be defined as the rate of damage removal up to the injury threshold, and can be mathematically expressed as a function of Sev:

$$\textbf{If } \mathbf{D > Dc,\ R_{injury} = Sev_{t1} - Sev_{t2}}$$

Equation 5

This can also be rescaled and normalized to express R_{injury} as a quantity between 0 and 1, where 0 represents no recovery i.e., no removal of tissue damage, and 1 represents a return to an uninjured state.

The rate of recovery from injury (**$\dot{R}_{injury}$**) can then be defined as the rate at which injury severity decreases, mathematically represented as:

$$\dot{\mathbf{R}}_{\mathbf{injury}} = \frac{\mathbf{Sev(t1) - Sev(t2)}}{\boldsymbol{t2 - t1}}$$

Equation 6

Susceptibility to injury (Sus) can be quantified as the probability of damage exceeding the critical damage threshold (D > Dc) in a tissue of interest, represented as:

$$\mathbf{Sus = P\ (D > Dc)}$$

Equation 7

where:

- **P: Represents probability.**
- **D > Dc: The event of interest, where D exceeds the critical threshold Dc.**

While further expansion of this linguistic system will be addressed in more comprehensive future works on the topic, the importance, value, and precision of this approach should be evident. Each concept is introduced with logical consistency and defined through precise mathematical relationships, all coherently linked to the foundational definition of injury ($D > D_c$) and its derivatives. These expansions create a semantic network where concepts such as injury, severity, recovery, rate of recovery, recovery from injury, susceptibility and others contribute to a comprehensive and rigorously structured understanding of the overarching system of injury [38].

5.0 Conclusion

This article has introduced a new theoretical definition of athletic injury, developed through a process of logical reasoning, thought experiments, boundary testing and argument. By identifying necessary and sufficient conditions, commonly conflated concepts have been disentangled and logical shortcomings present in existing definitions resolved. This increase in conceptual clarity and precision provides an important foundation for enhancing the predictability, falsifiability and reproducibility of athletic injury as a scientific concept, facilitating the development of more accurate and objectively assessable tissue-specific operationalisations. Indeed, by providing a conceptually robust and logically coherent definition of athletic injury, one that emphasises the importance of objectively measurable physical parameters, such as tissue damage, loss of physical function and the crossing of a critical damage threshold (all of which operate within a mathematically unified, physics-based framework), athletic injury can be appropriately mathematised for application in mathematical models e.g., predictive models. This lays the foundation for a formalised and mathematised linguistic system and semantic network defining athletic injury and related concepts for application in mathematical modelling (e.g., predictive modelling). This objective framework transforms athletic injury and its associated concepts from vague notions, subject to inconsistent (e.g., contradictory) interpretation and bias, into logically consistent mathematical objects with well-defined semantics and well-founded logic. Ultimately, this increase in understanding will facilitate advancements in assessment technologies and data analysis processes, improving the identification, measurement and prediction of athletic injury and related concepts.

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