

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 an essential framework for scientifically studying this concept. Existing definitions are overly vague and lack logical coherence, failing to provide sufficient frameworks for the development of more precise understandings, operationalisations (including mathematisation) and identifications of athletic injury, 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 logical coherence in existing definitions, and to establish a set of necessary and sufficient conditions for an athletic injury to occur. 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 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 mathematically unified physics-based framework, the predictability, falsifiability, and reproducibility of athletic injury research can be enhanced. Altogether, this transforms athletic injury from a vague concept, subject to inconsistent interpretations and applications i.e., bias, into a mathematical object with well-defined semantics and well-founded logic, guiding the formation of more precise, ideally tissue-specific, operational definitions of athletic injury. Over time, this will aid in the development of objective measurement tools that can more accurately assess and distinguish athletic injuries from non-injuries, supporting scientific advancements in the identification, measurement and prediction of athletic injuries.

Key Points:

- Existing definitions of athletic injury are vague and lack 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 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 athletic injury in objectively measurable physical parameters that can be appropriately mathematised for inclusion in mathematical (e.g., predictive) models. This enhances the predictability, falsifiability, and reproducibility of athletic injury research.
- Altogether, this transforms athletic injury from a vague concept, subject to inconsistent interpretations and applications, i.e., bias, into a mathematical object with well-defined semantics and well-founded logic, guiding the formation of more precise, ideally tissue-specific, operational definitions of athletic injury.

“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) – 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 practical management of athletic injuries, the absence of a 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 common uses of the term injury (Table 2) but would also conflate multiple distinct concepts that are fundamentally different from athletic injury i.e., they are neither

necessary nor sufficient for an athletic 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 minimal practical 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) rather than strict technical precision and formal analysis of meaning (semantics).

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, 29-31]. 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 critical components 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 and logically coherent theoretical definition of athletic injury that better captures its fundamental essence. 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]. Ultimately, this will facilitate the development of more appropriate and precise, ideally tissue-specific, operationalisations of athletic injury, allowing athletic injury 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 from a vague concept, subject to inconsistent interpretations and applications, i.e., bias, into a mathematical object 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, 31, 36-38]
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, 31, 36-38]. 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	<p>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.</p> <p>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</p>
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	<p>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.</p> <p>In essence, it involves asking "why" repeatedly until you reach the most basic truth or axiom that cannot be reduced further</p>
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	<p>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.</p> <p>In essence, an argument is a rational attempt to persuade someone of the truth or validity of a specific point</p>
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
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
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) [39]:	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) [40]:	A physical hurt or damage
Cambridge Dictionary (2024) [41]:	Harm or damage done to a living thing
The concise Oxford dictionary of current English (1921) [42]	Harm, damage
Modern dictionary of the English language (1911) [43]	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, 30, 35, 44-50]. 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, 30, 44, 49]. This structured approach typically involves applying deductive and inductive methods (Table 1) to distinguish valid arguments from invalid ones [8, 44, 45, 51, 52], ensuring that conclusions are derived from objective, logically consistent criteria rather than subjective biases [8, 22, 23, 25, 30, 35, 44-46, 49-53].

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 [44]. 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 must be 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, 44, 48]. 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 [44, 54]. Through these methods, logical reasoning contributes to a deeper understanding of the underlying principles that define a theory or concept [8, 23, 25, 30, 44, 46, 49, 50].

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, 31, 35, 45, 47, 49, 50, 53-57]. 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 rules).

Usain Bolt is a 100m Olympic gold medallist.

Therefore, Usain Bolt must be human.

Here, if the necessary condition is accepted as valid, 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 critical 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, 54, 58, 59]. While many of these thought experiments may appear extreme in nature, pushing 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]. Within this definition there are a series of key features that highlight identified necessary and sufficient 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 [19, 20, 39-41]. 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 [60-62]. 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. As a result, assertions that pain is a necessary condition for athletic injury are logically 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; In fact, this reflects the fundamental strength of the thought experiment, providing a clear example 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. To label such conditions as athletic injuries would constitute an unreasonable application of the term that would be inconsistent with existing definitions and uses. 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 [53]), 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. Therefore, 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 [63], 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 would have major implications for studying this concept scientifically, transforming athletic injury into a vague and contradictory construct with no clear or consistent criteria for operationalisation (or mathematisation). This significantly diminishes the reliable application of the concept [10, 25, 35], making it impossible to consistently and accurately determine when an athletic injury has or has not occurred [10, 25, 53]. As a result, any interpretation of injury becomes inherently subjective, introducing bias. This is highly problematic as such vagueness and inconsistency undermines the critical scientific principles of predictability, falsifiability and reproducibility [8]. Indeed, 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]. 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 [64]. To include them in the fundamental theoretical definition of athletic injury would be to mistakenly conflate observable correlates (indicators) with the condition itself.

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. In addition, 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. Additionally, while symptoms may offer practical value, they are ultimately limited and unreliable as definitive measures of injury [60, 65-68], underscoring the need for more objective markers, 2) Applied practitioners are faced with the difficult task of managing a variety of phenomena beyond simply athletic injury, 3) 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

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 for 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 measurable variables, turning these into identifiable, measurable and predictable entities [8, 31, 36-38]. 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 [69]. 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 useful practical criterion for identifying and managing injuries 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 and time-loss for large-scale epidemiological studies, as these remain practical solutions. Rather, it does highlight that such approaches represent theoretical compromises that diverge from the fundamental concept of athletic injury. By introducing greater subjectivity, inconsistency and measurement inaccuracies, practical ease of data collection and standardisation is prioritised at the expense of precision. Certainly, the decision to participate in sports is

ultimately a subjective decision dependent upon a myriad of factors such as injury severity, individualised pain tolerance, competition level, internal motivation etc. and this compromise has the potential to skew research findings [69]. It follows that, advancements in injury assessment technologies and methodologies may, in time, help address these limitations and improve accuracy in athletic injury reporting.

3.2 Tissue Damage and Transfer of Kinetic Energy

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 warrants inclusion. Is tissue damage not subject to the same arguments? Simply, the answer is no, and the 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 an 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, 39, 70-74].

Considering the transfer of kinetic energy has been identified as a necessary cause for an athletic injury to exist, it is important to examine whether this constitutes a logically sound necessary condition. To assess this, consider a range of common injury types such as an anterior cruciate ligament rupture, a leg fracture, a hamstring tear when sprinting, an Achilles tendon rupture, and a shoulder dislocation. There are currently no credible theories suggesting that any of these injuries can occur in sports in the complete absence of a mechanical load (transfer of kinetic energy) (Table 1) being applied to the respective tissues of interest. Indeed, without mechanical loading, how can an athlete sustain these injuries? More specifically, how can the molecular structures maintaining tissue integrity become stressed, leading to athletic injuries like bone fractures or ligament ruptures? There is no other identified or even hypothesised mechanism for these injuries to arise spontaneously, and such

injuries certainly do not occur when no movement or interactions with the physical environment are taking place.

The evidence supporting the critical role of mechanical loading and tissue damage in athletic injury mechanisms is extensive, with tissue loading arising through physical interactions with the environment, such as gravity, ground contacts, collisions, or other (externally or internally derived) mechanical forces. Indeed, there is a large quantity of research demonstrating that mechanically induced tissue damage mirrors the damage profiles observed in sports-related injuries [75-84]. Even for complex active tissues such as muscle, mechanical forces have been shown to be essential in causing muscle fiber or musculo-tendinous ruptures [83, 85]. No evidence suggests that such sporting injuries result from spontaneous neurochemical events alone. Thus, the transfer of kinetic energy serves as a well-supported necessary condition for the occurrence of athletic injuries.

Furthermore, this condition also does an effective job of distinguishing athletic injuries from different types of injury that result from exposures to various other forms of energy besides kinetic energy such as sunburn, chemical burns, electrical etc. or an absence of energy such as drowning, asphyxia etc. It is for these reasons that, elsewhere in the literature, an athletic injury has also been described as occurring when the stresses and strains (Table 1) experienced by a tissue result in damage severe enough to be considered an injury [86, 87]. Note that this description adopts the same causal condition as the IOC, with the area under a stress–strain curve representing the energy absorbed during deformation, typically resulting from a transfer of kinetic energy.

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, is it sufficient? Reasonably, the mere presence of tissue damage should not constitute an athletic injury, highlighting a theoretical shortcoming within the theoretical definition proposed by the IOC (Definition 1). To elaborate, tissue damage is an inevitable consequence of regular sporting participation [88-90], with even minor loading exposures resulting in some degree of tissue damage [78, 79, 91]. Under the IOC's definition, this would imply that every athlete incurs an injury soon after commencing their training, which is unreasonable. Moreover, tissue damage often serves as a critical stimulus for tissue remodelling and adaptation [92-94], 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 simply by engaging in sport.

An additional concern arises with the criterion of "other derangement of normal physical function." 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 athletic 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, 39] (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 proposed:

“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 [95]. Muscle damage is characterised by sarcomere dissolution i.e., desmin disruption and catabolism, Z-disk streaming etc [84] and is a largely unavoidable and normal part of the physical training process [89, 90] that commonly precedes positive adaptations such as the repeated bout effect [96], and increased muscle hypertrophy and strength (although the causal nature of this relationship has been questioned [94, 97]). Given its frequent occurrence during and after training [89, 90], 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 [95], which provides no adaptive benefit and typically requires long and incomplete recovery processes [95].

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, characterised by a temporary reduction in bone stiffness and strength, is a stimulus for positive bone adaptation in accordance with Wolff's Law [93, 98, 99]. In this context, the bone damage and microstructural changes that occur reflect a normal mechanical and physiological process that strengthens bone over time [93, 98, 99]. 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 [100].

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' has been added, with this addition specifically referring to the measurable deterioration in the mechanical functioning of a tissue. This includes key mechanical attributes such as load-bearing capacity, stiffness, and elasticity, which are directly influenced by

both the original state of the tissue and the extent of any damage sustained. Importantly, this concept is not viewed in isolation but is designed to exist with tissue damage within a mathematically 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. By integrating both the physical properties of tissues and the dynamics of damage accumulation, this approach offers a structured and objective approach to assessing and predicting functional losses, which is important for more accurate injury diagnosis and recovery prognosis.

4.3. Operationalisation: Physical Manifestation and Mathematisation of Athletic Injury

While the operationalisation, mathematisation 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 measurable 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 [91, 101, 102].

Adopting a similar approach, athletic injury can be mathematically defined as:

$$D \geq D_c$$

Definition 7

In Definition 7, first proposed by Edwards [91], an athletic injury occurs when the damage (D - quantified between 0 and 1) sustained by a tissue is greater than or equal to a critical damage threshold (D_c - also quantified between 0 and 1), i.e., $D \geq D_c$. 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 [80], kinked fibers and tearing in tendon [81], sarcomere disruption and fiber tears in muscle [95] etc. and accordingly, tissue-specific operationalisations of athletic injury are ultimately needed.

Importantly, while mechanical models commonly determine damage accumulation based on the mechanical loading pattern experienced by a structure [91], 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 [91, 103]. This is particularly relevant to athletic injuries exhibiting a gradual onset mechanism, whereby significant damage removal can occur during periods of rest and recovery [104, 105].

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 predictive models. This objective framework transforms athletic injury from a vague concept, subject to inconsistent interpretation and bias, into a mathematical object 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 accuracy of athletic injury identification, measurement and prediction.

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