Developing a Fundamental Theoretical Definition for Athletic Injury: Metaphysics, Logic, and Mathematics

Judd T. Kalkhoven[1]

[1] School of Health Sciences, Western Sydney University, NSW, Australia

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Corresponding author:
Judd Kalkhoven
School of Health Sciences
Western Sydney University
Campbelltown campus
Narellan Rd & Gilchrist Dr, Campbelltown NSW 2560

Email: J.Kalkhoven@westernsydney.edu.au
Orcid: https://orcid.org/0000-0002-1720-6879

All authors have read and approved this version of the manuscript for preprint.

Twitter handles: @KalkhovenJudd

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Abstract

Athletic injury remains inadequately conceptualised and poorly defined. Existing definitions are overly vague and lack conceptual and logical coherence, failing to provide sufficient frameworks for their formalisation and the development of more precise understandings, operationalisations (including mathematisation) and identifications of athletic injury and associated concepts. This 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 athlete availability, 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 metaphysical inquiry grounded in Aristotelian logic. This approach employs well-established tools such as thought experiments, boundary tests, and logical reasoning 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 (*Symbebekós*, 'accidental properties') are examined for logical independence and disentangled, and the development of a more refined conceptualisation and definition of athletic injury is achieved, capturing its fundamental essence (*To ti ēn einai*, 'what it is to be') as "Tissue damage and loss of physical function during sports participation, resulting from singular, sustained, or repetitive transfer of mechanical energy, where the damage experienced 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 mathematical framework with precisely defined relationships. This increase in precision 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 injuries and associated concepts.

Key Points:

- Existing definitions of athletic injury are vague and lack conceptual and logical coherence, failing to provide sufficient frameworks for their formalisation and 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 systematic process of metaphysical inquiry grounded in Aristotelian logic. This approach leverages well-established philosophical tools such as thought experiments, boundary tests, and logical reasoning, to disentangle conflated concepts and establish 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 (D_c), expressed mathematically as $D > D_c$.
- 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 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 – Common paraphrase of 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 sufficiently coherent and robust [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 [8-12]. Certainly, theory-driven research, a fundamental component of the scientific method [7-9, 13-15], relies upon precise, logically consistent, and empirically testable concepts to explain or predict phenomena [8]. Without a sufficiently coherent definition, the formalisation (Table 1) and development of more accurate operationalisations, including the appropriate mathematisation, of athletic injury is hindered [8, 10, 12, 16], 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, athlete availability for sports participation and time-loss i.e., time-loss injury [4, 6, 17-20]. 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' [21].

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' [22].

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 for sports participation, may appear too reductionist and confusing to some [23, 24], especially when these concepts are often implicated in various operational definitions of athletic injury [4, 6, 17-20]. 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 [12, 25]. Accordingly, including these components would constitute an error in logic that would undermine the classification and scientific process [12, 25-30].

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 [31]. 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 [31-34], 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 “semantics,” since the focus is on practical interpretation (pragmatism) [31] rather than strict technical precision and formal analysis of meaning (semantics) [11, 12, 25, 35-37].

In scientific contexts, precise language and the formal analysis of meaning takes on significantly 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, 12, 25, 26, 34, 37, 38]. 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, 12, 35], 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 conceptually sound theoretical definition of athletic injury is a major concern, obscuring how athletic injury and associated concepts should be appropriately formalised, operationalised and mathematised [16], and undermining the scientific principles of falsifiability, predictability, and reproducibility (Table 1), which are core tenets of the scientific method [8]. Establishing a well-founded theoretical definition 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, the aim of this article is ambitious: to develop a robust, conceptually and logically coherent theoretical definition of athletic injury that effectively captures its fundamental essence (Aristotle's *to ti ēn einai, "*what it is to be" [12]). Once achieved, this definition is formalised and mathematised for integration into mathematical models (e.g., predictive models), laying the foundation for a structured linguistic system and semantic network (Table 1) to systematise related concepts within a unified mathematical framework. The process adopted to achieve this (illustrated in Figure 1) involves a structured approach of metaphysical inquiry, grounded in Aristotelian logic and logical reasoning towards first principles [12, 29, 30], and informed by ontology, epistemology, and the philosophies of language and science (Table 1). Specifically, this process employs a series of thought experiments, boundary tests and logical arguments (Table 1) to identify the core attributes that are essential to defining an athletic injury. These thought experiments, boundary tests and logical arguments are designed to test the logical boundaries distinguishing athletic injury from non-injury and other related phenomena. They disentangle conflated concepts (i.e., Aristotle's *symbebekós*, 'accidental properties' [12]), resolve existing logical inconsistencies, and establish a set of necessary and sufficient conditions (i.e., essential properties) (Table 1) needed for an athletic injury to exist [11, 12, 25-27, 30, 36, 39-41].

Once conflated concepts have been tested for logical independence, disentangled, and athletic injury has been theoretically defined in a conceptually and logically coherent manner, a critical foundation for developing robust mathematical systems, this definition can then be mathematised for application in mathematical modelling (e.g., predictive modelling). This establishes the foundation for a formalised linguistic system and semantic network surrounding athletic injury, offering a structured framework that seamlessly integrates related concepts such as injury severity, recovery, rate of recovery etc. [10, 16, 42]. This facilitates the clarification and refinement of these previously vague concepts, often used in contradictory ways, into objectively measurable and predictable entities with precise, consistent and mathematically defined relationships to one another [16, 42].

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 conceptually coherent mathematical objects with well-defined semantics and well-founded logic, enhancing the predictability, falsifiability and reproducibility of athletic injury research moving forward [8, 16].

Figure 1: The Tree of Precision

Inspired by and adapted from Descartes' *Tree of Philosophy*, which encompasses metaphysics, physics, and the other sciences (medicine, mechanics, and morals) [43], the *Tree of Precision* illustrates the hierarchical process of refining and formalising scientific concepts adopted in this article. The roots symbolise metaphysical inquiry, providing the foundational clarity necessary for disentangling and defining concepts [8, 12, 29, 30, 41]. The trunk represents logical reasoning, ensuring structural coherence and logical consistency—a prerequisite for the development of mathematical systems [8, 10, 26]. The branches and leaves embody mathematics, the universal language of precision, where these clarified concepts are operationalised into precise, quantifiable, and predictive frameworks [16, 42, 44].

For an insightful discussion on the desirability of formalisation in science, see Suppes [16]. It is important to note that not all concepts lend themselves to formalisation (e.g., love, beauty, etc.), highlighting the inherent limitations of mathematical systems and the importance of alternative approaches, such as qualitative frameworks, for exploring and understanding complex and subjective phenomena such as these.

Table 1: Relevant Nomenclature

Operational definitions	
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, 12, 37, 45-47]
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, 37, 45-47]. In this respect, the task of setting clear and measurable boundaries falls to the process of operationalisation
Formalisation	Formalisation is the process of expressing ideas, concepts, or systems in a precise, structured, and standardised form, often using symbols, rules, or formal logic to ensure clarity, consistency, and lack of ambiguity.
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. It is important to note that 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
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.
Metaphysics	Metaphysics is the branch of philosophy that examines the fundamental nature of reality, exploring concepts such as existence, causality, time, and space. It also involves disentangling and clarifying concepts to provide a coherent framework for understanding the principles and structures underlying reality.
Aristotelian logic (in relation to definition)	Aristotelian logic, as it relates to definition, is a system of reasoning that seeks to identify the essence (*to ti ēn einai*, "what it is to be") of a concept by distinguishing its essential properties (those necessary and sufficient for its definition) from its accidental properties (*symbebekós*, "non-essential attributes"). Definitions are constructed through universals (*katholou*, general categories) that encompass the particulars (*kath' hekaston*, specific instances) of the concept, ensuring clarity and precision. This approach emphasises categorising entities into their substance (*ousia*, "substance") and attributes, providing a rigorous framework for establishing logically coherent and precise definitions, as outlined in detail in Aristotle's *Posterior Analytics* [12].
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
Deduction	A form of reasoning where specific conclusions are logically derived from general premises. If the premises are true, the conclusion must also be true. Such reasoning often takes the form of a syllogism.
Induction	A form of reasoning where general conclusions are drawn from specific observations. The conclusions are probable but not guaranteed to be true.
Syllogism	A syllogism, developed by Aristotle in his *Prior Analytics [29]*, is a form of deductive reasoning consisting of a major premise, a minor premise, and a conclusion that follows logically from the premises. It establishes valid relationships between concepts, ensuring that if the premises are true, the conclusion must also be true.
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
Tissue Damage	Tissue damage refers to a disruption or alteration in the structural integrity and functional capacity of biological tissues resulting from the transfer of energy, such as mechanical, radiant, thermal, chemical, or electrical energy. In the context of athletic injury, where the transfer of energy has been restricted to mechanical energy, tissue damage is best conceptualised as mechanically induced disruption of the intermolecular bonds maintaining tissue integrity. This results in measurable reductions in the mechanical properties of tissues, with physical manifestations varying across tissue types at larger scales. For example, microcracks, diffuse, and cracking in bone [48]; collagen molecular unfolding, kinked fibers and tearing in

	tendons [49, 50]; and sarcomere disruption and fiber tears in muscles [51, 52].
Finite Element Modelling	Finite element modelling is a numerical method used to approximate solutions to complex physical problems by dividing a structure or system into smaller, simpler parts called finite elements. These elements are connected at discrete points (nodes), and mathematical equations are applied to simulate how the system responds to forces, stresses, or other physical phenomena.
Continuum Damage Mechanics	Continuum Damage Mechanics is a theoretical framework used to model and predict the initiation and progression of material damage at a macroscopic scale. It describes the gradual degradation of material properties, such as stiffness and strength, through the use of damage variables that represent the accumulation of microscopic defects, like cracks or voids, within the material.

Table 2: (General) Injury Definitions

World Health Organization (WHO) [21]:	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) [53]:	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) [22]:	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) [54]:	A physical hurt or damage
Cambridge Dictionary (2024) [55]:	Harm or damage done to a living thing
The concise Oxford dictionary of current English (1921) [56]	Harm, damage
Modern dictionary of the English language (1911) [57]	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 both metaphysical and scientific inquiry, enabling researchers to construct valid arguments, evaluate concepts and definitions, and systematically interpret evidence [8, 10, 12, 26, 29, 38, 41, 58-63]. 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, 12, 26, 29, 38, 58, 63-65]. This structured approach typically involves applying deductive and inductive methods (Table 1) to distinguish valid arguments from invalid ones [8, 12, 29, 41, 58, 59, 66, 67], ensuring that conclusions are derived from objective, logically consistent criteria rather than subjective biases [8, 12, 26, 29, 30, 38, 41, 58-60, 63, 66, 67].

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 [29, 58]. For example, consider the following syllogism (Table 1):

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 [12, 25].

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. It is for this reason that, depending on the context, deduction may be preferable to induction in the philosophy of science, allowing for logically certain conclusions (assuming the premises are valid) [29, 58, 62]. 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 logical arguments to eliminate logical inconsistencies, disentangle and refine concepts of interest, and identify necessary and sufficient conditions for a concept to be upheld [12, 25, 29, 58, 68]. Through these methods, logical reasoning contributes to a deeper understanding of the underlying principles that define a theory or concept [8, 12, 25, 26, 29, 38, 58, 60, 63].

2.1 Necessity and Sufficiency

Necessity and sufficiency are foundational criteria in metaphysics, the philosophy of science, and the philosophy of language for constructing precise theories and definitions [8, 11, 12, 25-27, 29, 30, 37, 41, 43, 59, 61, 63, 68-71]. 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 [11, 12, 25].

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 (setting aside, for the sake of this example, the fact that Usain Bolt is now retired), 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 [12, 25, 59, 65, 72]. 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 (*to ti ēn einai*) from those that are merely associated (*symbebekós*), removing logical inconsistencies and reducing vagueness, resulting in a more precise and reliable understanding of a concept [8, 12, 25, 29, 30].

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, 25, 68, 73, 74]. 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 testing for logical independence, 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 [8, 12]. This allows for valid comparisons and more reliable conclusions [8, 12].

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, 17-20]. For example, Fuller et al. [19] operationally defined athletic injury as:

"Any physical complaint requiring medical attention resulting in a missed A-League match" [19].

Definition 4

Similarly, Ekstrand et al. [17, 20] 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" [17, 20].

Definition 5

So why then, would symptoms such as pain and swelling, which are implied in "any physical complaint" [19], or athlete 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: ***to ti ēn einai*** (essence) vs ***symbebekós*** (accidental properties)

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 with injury [23, 24]. 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) [21, 22, 53-55]. 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 [75-77]. 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 this 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 <u>not</u> 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 to exist are falsified. This approach mirrors the classical example of falsification in science: to falsify the claim that all swans are white, observing just one black swan is sufficient, 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. In fact, this reflects the fundamental strength of the thought experiment: a single counterexample (refutation by counterexample [8, 10, 12, 25, 29, 71]) is sufficient to falsify a universal claim (*Katholou* [12]), providing a clear demonstration of absolute logic where the conclusion that pain is not a necessary condition for athletic injury deductively follows from the premises [12, 25].

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 many reasons unrelated to athletic injury, for example, medical conditions that are distinct from athletic injuries, such as angina, cancer, blood clots, autoimmune diseases, and neurological disorders can all lead to pain when participating in sports. Labelling such conditions as athletic injuries would result in an unreasonably broad application of the term, effectively categorising all medical conditions involving pain as injuries. Accordingly, the following premises can be set:

The athlete is experiencing pain due to a medical condition, such as an autoimmune or neurological disorder.

The athlete has not sustained an athletic injury.

Therefore, pain is <u>not</u> 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 [12, 25]), and athletic injury and pain are distinct concepts. 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 insufficient for injury)

Conclusion: If pain is neither necessary nor sufficient for an athletic injury to exist, 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 be illogical [12, 78], 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 i.e., it is a contingent or 'accidental' property (*symbebekós*) [12, 25].

Thought experiments and logical 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 illustrate, consider a scenario where athletic injury is defined in terms of both tissue damage and pain, yet neither, individually or collectively, is 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) when utilising these 'defining' parameters. Indeed, such a definition of athletic injury would accommodate all possible tissue damage and pain states, resulting in no formalised criteria to determine whether an athlete has, or has not, sustained an injury. This lack of criteria erodes the reliable application of the concept as any interpretation of injury becomes inherently subjective, introducing bias [8, 10, 12, 25, 26, 41]. 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 [79, 80]. While this is a controversial thesis, as theories are never empirically verifiable in the absolute sense [8] and meaning is context-dependent, not necessarily requiring a truth value [31], it does an effective job at emphasising a critical consideration for the scientific method. Namely, such an understanding of athletic injury lacks a boundary of demarcation distinguishing injury from non-injury [10, 12, 26].

In a scientific context, the absence of a clearly defined demarcation boundary is highly problematic, undermining the critical scientific principles of predictability, falsifiability and reproducibility [8]. If there are no clear criteria to distinguish injury from non-injury, how can an injury be reliably identified or predicted? Without such criteria, what does it mean to 'predict' or 'have' 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, 81], as all possible tissue damage and pain states can be classified as an injury or non-injury, with no means of falsification, explaining all possible conditions 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. Unsurprisingly, these conditions are commonly termed *symptoms* of injury, as by definition, *symptoms* indicate a condition but do not define it [82]; they are *symbebekós*. To include them in the fundamental theoretical definition of athletic injury would be to mistakenly conflate contingent properties and observable correlates with the condition itself (*to ti ēn einai*) [12, 25].

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 [75, 83-86], 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 [8, 16].

3.1.2 Athlete Availability for Sports Participation: An Appropriate Boundary of Demarcation?

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 athlete availability for sports participation and time-loss, i.e., whether an athlete is available to participate in training or match play e.g., Definition 4 & 5 [17, 19, 20]. Accordingly, the exclusion of athlete availability from the definition of injury proposed by the IOC may be confusing to some. Is a discontinuation of sports participation neither a necessary nor 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, 37, 45-47]. However, these definitions often sacrifice theoretical rigour 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 [87, 88]. 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 whether an athlete is available to train or compete, it is important to recognise that defining athletic injuries in this manner constitutes a theoretical compromise. This is why such an approach is commonly 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, and by extent 'time-loss', 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 absence of sports participation is <u>not</u> a *necessary condition* for an athletic injury to exist.

Tiger Woods is far from the only example of perseverance through injury to achieve a sporting goal. Just as Diomedes continued to fight after being struck by an arrow during the Battle of Troy, the sporting world is similarly filled with heroic examples of athletes enduring injuries in their quest for sporting glory. Accordingly, it is clear that an absence of sports participation is not a necessary condition for an athletic injury to exist. However, perhaps it is sufficient? 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 got kicked in the shin and are now 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 injury.

Injury is injury, and athlete availability is athlete availability; they are distinct but associated concepts, with athlete availability serving as a *symbebekós* of injury. The decision to participate in sports is ultimately a subjective decision, influenced by a myriad of factors such as injury severity, individual pain tolerance, competition level, and internal motivation. 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 world 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., their next match does not matter much, they have some minor niggles and want a holiday). If athletic injury is operationalised as an absence from sports participation, in such cases, the first scenario may fail to register an injury because the athlete pushes through and continues participating, while the second scenario may inaccurately register an injury simply because the athlete makes themselves unavailable, regardless of their actual physical condition.

When athletic injury is operationalised as an absence from sports participation, it becomes synonymous with this concept, diverting attention from the injury itself. Compromises such as these can skew research findings [87, 88], conflating athletic injury with subjective decisions around availability rather than objectively assessing the injury. However, 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 often come at the expense of precision, introducing greater subjectivity, inconsistency, and measurement inaccuracies.

To address these issues, some studies incorporate additional measures, such as MRI or other imaging techniques, to confirm the presence of physical damage [89-91]. While these approaches certainly offer a superior level of precision, it is also crucial to recognise that the absence of identifiable physical damage does not necessitate an absence of damage or injury; it may simply reflect limitations in identification and measurement technologies or processes (e.g., imaging resolution, radiographer expertise etc.). Accordingly, advancements in damage and 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 decisions surrounding athlete availability and pain tolerance.

3.2 Bodily Harm and Transfer of Energy: The Necessary Essence (*to ti ēn einai*) of Injury

Considering pain, swelling, athlete availability 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 energy warrants inclusion. Is tissue damage and the transfer of kinetic energy not subject to the same arguments? Simply, the answer is no (although the transfer of kinetic energy alone provides an incomplete explanation, a point that will be elaborated on shortly). 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. Together, these two conditions play an important role in defining the boundaries of this concept and distinguishing sports or athletic injury from general injury (Table 2) [21, 53, 88, 92-95].

The first condition presented here is hardly controversial, as it is only reasonable that for a sport or athletic injury to exist, it must have occurred during participation in sports. This distinguishes these 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. This condition is partially reflected in other descriptions of athletic injury presented in the literature, which describe an athletic injury as occurring when the stresses and strains (Table 1) experienced by a tissue result in damage severe enough to be considered an injury [96, 97]. Note that the area under a stress-strain curve represents the energy absorbed during tissue deformation, which is sometimes (but not exclusively) due to a transfer of kinetic energy.

Given that the transfer of kinetic energy has been identified as a necessary cause for an athletic injury to occur, it is important to evaluate whether this condition is logically sound. Consider a range of some of the most common and significant injuries in sport, such as anterior cruciate ligament (ACL) ruptures, leg fractures, hamstring tears, Achilles tendon ruptures, and shoulder dislocations. These injuries typically arise from rapid movements that transfer kinetic energy to the affected tissues, generating stresses that ultimately compromises the molecular integrity of these structures. Accordingly, at face value, the IOC's condition that a transfer of kinetic energy is a necessary condition for athletic injury occurrence may appear logically sound.

However, while this might seem like a compelling argument, it relies on inductive reasoning, generalising observed cases of common sports injuries to make a universal 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 a transfer of kinetic energy would refute the claim, rendering it insufficient as a definitive foundation for understanding athletic injuries [8]. For example, a sustained load of high magnitude, such as those commonly encountered during weightlifting or arm wrestling, can result in tissue failures like bone fractures or tendon ruptures [98]. These scenarios arise from mechanical energy applied slowly or statically to a tissue, resulting in prolonged mechanical stress and creep deformation, and do not rely on either a rapid or repetitive transfer of kinetic energy. Furthermore, according to the definitions provided by the WHO and ICD-11, a sunburn obtained during sports participation should also be classified as an injury, and this is caused by radiant energy.

To address this, one must probe at the fundamental essence (*to ti ēn einai*) of what an injury is [12, 30]. While deduction and induction are invaluable tools for disentangling and refining concepts, testing their coherence and logical independence to achieve greater precision and understanding, these methods are ultimately insufficient for grasping the original essence of a concept [12, 30]. Instead, the essence of a concept must be apprehended through intellectual insight (*nous*) into its nature. Once grasped, it can then be named, defined, and assessed for coherence through logical demonstration (*Apodeixis*) [12, 29, 30, 99]. Indeed, just as the concept of 'triangle' cannot be used to prove that it means 'triangle,' the concept of 'injury' cannot be used to prove that it means 'injury' — Its definition is rooted in its essence (*to ti ēn einai*, 'what it is to be'), which must be taken as the starting point for any further analysis [12, 30]. In fact, all reasoning conducted in this article (e.g., disentangling pain and athlete availability from injury) was only possible by assuming that an injury means what an injury means ('what it is to be') [12]. So, what does an injury mean? To answer this, let's consider 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) [54]
- "Harm or damage done to a living thing" - Cambridge Dictionary (2024) [55]
- "Harm, damage" - The concise Oxford dictionary of current English (1921) [56]
- "Hurt or damage" - Modern dictionary of the English language (1911) [57]

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 all 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 *necessarily* requires a transfer of energy [100-102].

Energy, whether mechanical, 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 [100-103]. It follows that bodily harm resulting from the transfer of energy is the *to ti ēn einai* of injury, constituting its fundamental essence and reflecting the essential properties necessarily tied to its identity [12, 25]. Indeed, how can an ACL or tendon injury exist, if the ACL or tendon has not been harmed? In the complete absence of a transfer of energy and any resulting bodily harm, an injury, by definition [21, 22], 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. 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, these should be classified as injuries.

Ultimately, this issue is of little concern, as it can be easily addressed if needed. Mechanical injuries remain the most prevalent and consequential in sports, making the IOC's definition of sports injury closely aligned with the primary objectives of sports medicine and injury research. This serves a practical purpose by distinguishing these injuries from other forms of injury that are not what is typically meant by an *athletic* or *sports* injury, such as those caused by alternative 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 minimal 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 general concept of injury to include other sub concepts such as psychological injury [88, 104, 105]. If desired, 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

As the IOC restricts sports injury to the transfer of kinetic energy, bodily harm has been appropriately conceptualised as tissue damage (Table 1). However, while tissue damage forms part of the *to ti ēn einai* of athletic injury, serving as a necessary condition for its existence, is the mere presence of tissue damage *sufficient* for an athletic injury to exist? Reasonably, no. This highlights a critical theoretical shortcoming in the definition proposed by the IOC (Definition 1); it fails to establish any reasonable sufficient conditions for an athletic injury to exist. To elaborate, tissue damage is an inevitable consequence of sporting participation [106-108], with even minor loading exposures resulting in some degree of tissue damage [109-111]. By adhering to the IOC's definition, the quest for athletic injury prediction is over, as every athlete would inevitably 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 [112-114], 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) [21] and other notable organisations [22, 53] (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 newly 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 singular, sustained, or repetitive transfer of mechanical energy, where the damage experienced 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 [51]. Muscle damage is characterised by sarcomere dissolution i.e., desmin disruption and catabolism, Z-disk streaming etc [51, 52, 115] and, in some contexts, is a largely unavoidable and normal part of the physical training process [107, 108] that commonly precedes positive adaptations such as the repeated bout effect [116], and increased muscle hypertrophy and strength (although the causal nature of this relationship has been questioned [114, 117]). Given its frequent occurrence during and after training [107, 108], 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 [51], which provides no adaptive benefit and typically requires long and incomplete recovery processes [51].

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 [113, 118, 119]. In this context, the bone damage and microstructural changes that occur reflect a normal mechanical and physiological process that strengthens bone over time [113, 118, 119]. 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 [120].

4.2 Singular, Sustained, or Repetitive Transfer of Mechanical Energy

Within Definition 6, "rapid or repetitive transfer of kinetic energy" has been replaced with "singular, sustained, or repetitive transfer of mechanical energy." This change is proposed as a more accurate and inclusive approach, with mechanical energy encompassing kinetic energy while also accounting for injuries resulting from sustained high-magnitude loads, such as those encountered in weightlifting. It is agreed, however, to exclude other forms of energy (e.g., radiant, electrical, chemical), as these are not typically what is meant by an 'athletic' injury. Currently, extensive evidence demonstrates that mechanically induced tissue damage reflects the damage profiles observed in sports-related injuries [48-50, 52, 98, 109, 110, 121-123]. Even in complex active tissues like muscle, mechanical loads are essential for causing fiber or musculo-tendinous ruptures [123, 124]. Another distinct alteration from the definition proposed by the IOC (Definition 1) is the omission of the phrase "other derangement of normal physical function." This phrase has been excluded for two reasons: it is overly vague, and, as highlighted in the neuromuscular fatigue example presented in Section 3.4, it is neither necessary nor sufficient for an athletic injury to exist.

4.3 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 (i.e., mechanical strength), stiffness, and elasticity. As these properties are fundamentally governed by molecular bonding, tissue damage (i.e., damage to molecular bonds) necessarily compromises these mechanical characteristics. 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 4.4). 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.

4.4. Operationalisation: Physical Manifestation and Mathematisation of Athletic Injury

While the practical implications of the newly proposed theoretical definition of athletic injury (Definition 6) will be explored in 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 appropriate 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 [111, 125, 126]. Adopting a similar approach, athletic injury can be formalised and mathematically defined as:

$$\mathbf{D > D_c}$$

Definition 7

In Definition 7, first proposed by Edwards [111], 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., microcracks, diffuse and cracking in bone [48], collagen molecular unfolding, kinked fibers and tearing in tendon [49, 50], sarcomere disruption and fiber tears in muscle [51, 52] etc. and accordingly, tissue-specific operationalisations of athletic injury are ultimately needed.

Importantly, as direct measurements 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 mechanical properties. This links microscopic damage to observable functional impairments. In most engineering settings, damage is commonly quantified and modelled by assessing the degradation of load bearing capacity i.e., mechanical strength [111]. However, while load bearing capacity certainly warrants special consideration, determining whether a tissue ultimately fails, a tissue's role may extend beyond load bearing to include functional tasks such as storing and releasing energy to drive locomotion. Accordingly, other mechanical properties, such as stiffness and elasticity, should also be considered.

At the structural level, the relationship between localised damage and mechanical properties may 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 behaviours [127, 128].

Finally, while traditional mechanical models modelling fatigue damage accumulation commonly determine damage accumulation based on the mechanical loading pattern experienced by a structure or material [97, 111, 129], in the context of athletic injury, which involves tissues, damage includes both damage due to loading and any alterations in damage induced by physiological processes, such as remodelling and repair [97, 111, 130]. This is particularly relevant to athletic injuries exhibiting a gradual onset mechanism, whereby significant damage removal can occur during periods of rest and recovery [131, 132].

5.0 Developing a Formalised and Mathematised Linguistic System and Semantic Network for Modelling Injury and Associated Concepts: Foundations and Initial Expansions

By mathematically defining injury as $D > D_c$, where damage exceeds a critical damage threshold, the foundation is set 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, such as severity and recovery, transforming these previously 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 extent of injury, naturally follows as the degree to which damage surpasses the critical damage threshold, mathematically expressed as:

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

Equation 1

Sev can then be rescaled and normalised to be expressed 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., $D \leq Dc$), and 1 represents complete tissue failure i.e., $Sev = 1 \Leftrightarrow D = 1$, corresponding to maximal injury severity. To do this, Sev can be represented as:

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

Equation 2

Tissue Recovery (R) can be defined as a reduction in tissue damage, 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,
- D_{t2} represents the level of damage at a later time point,
- R quantifies the amount of damage removed between D_{t1} and D_{t2}, assuming $D_{t2} < D_{t1}$. If $D_{t2} \geq D_{t1}$, recovery has not occurred. If $D_{t2} > D_{t1}$ additional damage has been accumulated.

R can then also be rescaled and normalised to range between 0 and 1, where 0 represents no recovery (i.e., no tissue damage removal) and 1 represents complete recovery (i.e., a return to an undamaged state, $R = 1 \Leftrightarrow D = 0$). To do this, R can be represented as:

$$\textbf{If } D_{t1} \geq D_{t2}\textbf{, then } R = 1 - \frac{Dt2}{Dt1}$$

Equation 4

This scaling allows R to function as a percentage, where R = 0 corresponds to 0% recovery (no damage removal) and R = 1 corresponds to 100% recovery (complete restoration to an undamaged state). Values between 0 and 1 reflect the proportion of recovery achieved as a percentage.

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

$$\textbf{If } D_{t1} \geq D_{t2}\textbf{, then } (\dot{R}) = \frac{Dt1 - Dt2}{t2 - t1}$$

Equation 5

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),
- $\dot{R}$ quantifies the amount of damage removed between D_{t1} and D_{t2} over the defined time period (t2−t1), assuming $D_{t2} \leq D_{t1}$. If $D_{t2} \geq D_{t1}$, no recovery has occurred. If $D_{t2} > D_{t1}$, additional damage has been accumulated.

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

$$\textbf{If } D > D_c\textbf{, and } Sev_{t1} \geq Sev_{t2}\textbf{, then } R_{injury} = Sev_{t1} - Sev_{t2}$$

Equation 6

where:

- Sev_{t1} represents the level of injury severity at an initial time point,
- Sev_{t2} represents the level of injury severity at a later time point,
- R_{injury} quantifies the reduction in injury severity between Sev_{t1} and Sev_{t2}, assuming $Sev_{t1} > Sev_{t2}$. If $Sev_{t1} \leq Sev_{t2}$, no recovery from injury has occurred. If $Sev_{t2} > Sev_{t1}$ additional damage has been accumulated, and injury severity has increased.

R_{injury} can also be rescaled and normalised to be expressed 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.

$$\textbf{If } D_{t1} \geq D_{t2} \geq D_c\textbf{, then } R_{injury} = \frac{Dt1 - Dt2}{Dt1 - Dc}$$

Equation 7

where:

- D_{t1} represents the level of damage at an initial time point,
- D_{t2} represents the level of damage at a later time point,
- D_c represents the critical damage threshold distinguishing injury from non-injury.

This scaling allows R_{injury} to function as a percentage, where $R_{injury} = 0$ corresponds to 0% recovery (no damage removal) and $R_{injury} = 1$ corresponds to 100% recovery from injury (i.e., $D \leq D_c$) and a return to an uninjured state. Values between 0 and 1 reflect the proportion of recovery from injury achieved as a percentage.

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

$$\dot{R}_{injury} = \frac{Sevt1 - Sevt2}{t2 - t1}$$

Equation 8

where:

- Sev_{t1} represents the severity of injury at an initial time point (t1),
- Sev_{t2} represents the severity of injury at a later time point (t2),
- $\dot{R}_{injury}$ quantifies the reduction in injury severity over the defined time period (t2−t1), assuming $Sev_{t2} < Sev_{t1}$. If $Sev_{t2} \geq Sev_{t1}$, no recovery from injury has occurred. If $Sev_{t2} > Sev_{t1}$, additional damage has been accumulated.

While the further expansion and utilization of this linguistic system and semantic network will be addressed in more comprehensive future works, the importance and precision of this approach should already be evident. Each concept is introduced with logical consistency and defined through precise mathematical relationships, all coherently linked to the foundational definition of injury ($D > Dc$) and its derivatives. These expansions establish a structured network where concepts such as injury, severity, recovery, rate of recovery, recovery from injury, and adaptation collectively contribute to a comprehensive and mathematically precise understanding of the overarching system of injury.

6.0 Conclusion

This article has introduced a new theoretical definition of athletic injury, developed through a systematic process of logical reasoning, thought experiments, boundary testing and argument. By identifying necessary and sufficient conditions, commonly conflated concepts (*symbebekós*) have been disentangled, and the logical shortcomings of existing definitions have been resolved, capturing the true essence (*to ti ēn einai*) of athletic injury as:

"Tissue damage and loss of physical function during sports participation, resulting from singular, sustained, or repetitive transfer of mechanical energy, where the damage experienced 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."

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 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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