Sports Medicine (2021) 51:1137–1150
https://doi.org/10.1007/s40279-020-01413-6

REVIEW ARTICLE

Training Load and Injury: Causal Pathways and Future Directions

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Accepted: 10 December 2020

Abstract

Causal pathways between training loads and the mechanisms of tissue damage and athletic injury are poorly understood. Here, the relation between specific training load measures and metrics, and causal pathways of gradual onset and traumatic injury are examined. Currently, a wide variety of internal and external training load measures and metrics exist, with many of these being commonly utilized to evaluate injury risk. These measures and metrics can conceptually be related to athletic injury through the mechanical load-response pathway, the psycho-physiological load-response pathway, or both. However, the contributions of these pathways to injury vary. Importantly, tissue fatigue damage and trauma through the mechanical load-response pathway is poorly understood. Furthermore, considerable challenges in quantifying this pathway exist within applied settings, evidenced by a notable absence of validation between current training load measures and tissue-level mechanical loads. Within this context, the accurate quantification of mechanical loads holds considerable importance for the estimation of tissue damage and the development of more thorough understandings of injury risk. Despite internal load measures of psycho-physiological load speculatively being conceptually linked to athletic injury through training intensity and the effects of psycho-physiological fatigue, these measures are likely too far removed from injury causation to provide meaningful, reliable relationships with injury. Finally, we used a common training load metric as a case study to show how the absence of a sound conceptual rationale and spurious links to causal mechanisms can disclose the weaknesses of candidate measures as tools for altering the likelihood of injuries, aiding the future development of more refined injury risk assessment methods.

1 Introduction

Training loads have been described as the input variable that is manipulated to elicit a desired training response in athletes [1] and can be described as being internal or external depending on whether the measurable aspect in question is occurring internally or externally to the athlete [1]. It follows that a range of internal and external training load measures and metrics exist, with many of these being commonly utilised across the sports science literature. Notably, the monitoring and management of training loads has been an area of substantial interest for practitioners and athletes in sport, with recent interests pertaining to its relationship with injury. However, despite an abundance of literature, causal pathways between training load, tissue damage and injury remain poorly understood. Understandings of the mechanisms underpinning tissue damage and injury

Key Points

A clear aetiology between athletic injuries and training load is yet to be established.

Training loads may be related to certain types of injuries through the mechanical load-response pathway, the psycho-physiological load-response pathway, or both. However, the capacity of currently available training load measures and metrics to reflect either of these pathways is notably limited.

Current training load measures and metrics provide unreliable assessments of injury risk. It appears that a more detailed approach centered on the specific causal mechanisms of injury should be sought to provide more rigorous assessments of injury risk.

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are important for evaluating the conceptual viability and limitations of current training load measures and metrics for injury risk assessment. This may, in turn, assist sporting practitioners and researchers to avoid the collection and utilization of redundant or unreliable data, correctly interpret scientific research findings, align expectations regarding specific metrics more appropriately, and assist with the facilitation of future research and the development of training load metrics that assess athletic injury risks more effectively.

While their manifestation or clinical presentation may differ, injury occurs when either singular or repetitive forces are applied to a tissue that result in stresses and strains that exceed tissue strength and repairability [2–7]. It is clear from such mechanisms that mechanical loading (the forces experienced by specific biological tissues) is a fundamental contributor to athletic injury. Accordingly, within this context, current training load measures and metrics should be considered based on their representation of the mechanical load-response pathway i.e., the mechanical loading experienced and the internal stress, strain, and subsequent mechanically induced tissue damage that ensues. Although athletic injuries share the common characteristic of mechanical loading, certain critical features along the causal pathway to injury may vary depending on the wider causal factors that can influence injury mechanisms and particular injury events [6]. For this reason, it seems prudent to also consider specific training load measures and metrics relative to the psycho-physiological load-response pathway, which may also influence injury risk.

A variety of internal and external training load measures and relative metrics are commonly reported across the research and sporting landscape. These metrics differ in value and applicability regarding injury risk quantification and their capacity to reflect causal pathways to injury. Recently, metrics that claim to allow for the utilisation of a variety of training load measures, such as the acute:chronic workload ratio (ACWR) have also been proposed [8]. Accordingly, this paper seeks to clarify conceptual understandings relating training load to injury and investigates how currently available training load measures and metrics may relate to the causal pathways of tissue damage and injury incidence. This will be undertaken by evaluating the mechanical and psycho-physiological load-response pathways, whilst also considering the loading patterns experienced and the non-linear relationship between load magnitude and damage [5, 9, 10]. A further purpose of this article is to provide a conceptual foundation for the selection and evaluation of training load measures and metrics when forming etiological models and assumptions, contributing a stronger conceptual basis for future injury research studies. For detailed definitions of relevant nomenclature in this article, please see Table 1.

2 Training Load and the Mechanisms of Tissue Damage and Injury

To understand the causal pathways to injury, it is important to address the core mechanical principles surrounding mechanical fatigue damage and failure in biological tissues (e.g., bones, muscles, tendons etc.). Mechanical failure occurs when the ultimate strength of a material is surpassed by excessive stress and strain induced by the application of a singular high-magnitude force, or when repeated applications of sub-ultimate loads exceeds the material's fatigue strength [7]. Within this context, "stress" is defined as the force per unit of area and is descriptive of the internal forces neighbouring particles of a given material exert on one another, while "strain" is defined as the amount of deformation expressed as a normalized change in shape or size [11, 12]. Whilst it is important to acknowledge that human tissue resides within a dynamic environment whereby physiological processes contribute to function, remodelling and recovery, tissues are also materials that exhibit many of the same fundamental principles as non-biological materials in response to applied forces [5, 13]. Accordingly, whilst tissue pathology may be an important factor that contributes to various injuries, without the application of force and the stresses and strain that ensue [2, 3, 5–7, 14], athletic injury does not occur. It follows that the vast majority of, if not all, contact and non-contact athletic injuries occur as a result of exposure to either singular, or repetitive, applied forces [5, 15–17].

Supporting mechanical loading as a fundamental contributor to athletic injury occurrence, a recent review highlighted that biological tissues demonstrate exponential relationships between the force applied to a specific tissue and the number of load cycles to failure [10]. Although the majority of these studies were conducted in vitro [18–27], in vivo animal studies that utilized a variety of loading conditions have also been conducted. These studies investigated the influence of tissue loading on tendons and cartilage in rats [28] and mice [29], respectively, demonstrating several interactions between the critical musculoskeletal risk factors of force and repetition in relation to tissue damage and inflammation across a variety of tissues. Furthermore, epidemiological studies that have examined a force–repetition interaction have shown a pattern of risk consistent with a mechanical fatigue failure process [9, 30]. Importantly, these findings also support suggestions that various markers of mechanically induced tissue damage, such as muscle damage [31, 32], kinked fibers in tendons [33], and microcracks in bone [34], may act as precursors to more severe injury [14, 35–38]. Of notable recent significance, the accumulation of collagen molecular unfolding has been identified as

Table 1 Relevant nomenclature

Operational definitions	
Training load	*Training load* is the term used by sports scientists, trainers, and athletes as the input variable that is manipulated to elicit a desired training response in athletes. Within this context, *load* is a generic term which is qualified by the term *training* in a fashion similar to other areas of research that have adopted the term *load* within a variety of contexts (i.e., allostatic load, cognitive load, mechanical load, etc.). Accordingly, *training load* does not specifically refer to the forces experienced, as is typical in physics, or any other physical quantity. *Training load*, as a generic construct, accommodates a variety of proxy measures and metrics (spatio-temporal, mechanical, psycho-physiological, etc.) which can be described as being external or internal depending on whether the measurable aspect in question is internal or external to the athlete. See below for explanations of terms *external* and *internal*
External (training) load	In the context of training load, the term *external load* implicitly refers to the *external training load* undertaken by an athlete. *External load* has been defined as the physical work prescribed in the training plan (physical performance output). Notably, this does not refer to 'work' in the physics sense (force × distance) but more so in a generic manner. Accordingly, the term e*xternal load* accommodates quantification and prescription in variety of manners, enabling the use of a diverse range of *external load* measures and metrics. Some common measures of *external load* include GPS derived units (e.g., speed, accelerations, etc.) and level of resistance
Internal (training) load	As per external load, the term *internal load* implicitly refers to *internal training loads*. In the context of training load, *internal load* typically refers to the psycho-physiological stress experienced by an athlete. Notably, in this context *internal load* does not describe the forces or internal stresses and strains experienced by specific biological tissues. Rather, the concept of *internal load* incorporates all the psycho-physiological responses that an athlete initiates to cope with the requirements elicited by the external load, irrespective of how the external load is quantified. For examples of *internal load* please see "psycho-physiological load" below.
Psycho-physiological load	Refers to the psycho-physiological stress experienced by an athlete in response to a given external load. A range of physiological and psycho-physiological measures and metrics exist, with common physiological measures being heart rate, blood lactate etc. and a common psycho-physiological measure being rating of perceived exertion (RPE). The psycho-physiological stress experienced is considered to contribute substantially to the training outcome that presents. Notably, the value and validity of specific training load indicators depends on the context. For example, heart rate is a valid measure of internal load for endurance training but not so much for resistance training
Mechanical load	Refers to the forces experienced by specific tissues or biological structures and can be externally or internally sourced e.g., collision with an opponent or muscle pulling on bone. The mechanical load is the stimulus that results in the mechanical load-response (stress and strain)
Stress	Stress is defined as force per unit area and develops within a structure/tissue in response to externally applied mechanical loads (force). Stress is descriptive of the internal forces neighbouring particles of a given material exert on one another. 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
Strain	Refers to the amount of deformation expressed as a normalized change in shape or size. Two basic types of strain exist: normal strain, which is related to change in length, and shear strain, which is related to change in angle. Normal strain is the ratio of deformation (lengthening or shortening) to original length and as such may be tensile or compressive. Shear strain is the amount of angular deformation that occurs in a structure. For example, a rectangle drawn on one face of a solid before a shear stress is applied will appear as a parallelogram during the application of a shear stress

the "micro-damage" mechanism of cyclic fatigue damage and failure in collagenous tissues [39]. Considering the prominent role of mechanical loading in tissue damage accumulation and injury occurrence, there have recently been calls to explore musculoskeletal injury, and more specifically overuse injury [5], as a mechanical fatigue phenomenon [5, 9, 10]. This is a most prudent suggestion considering the growing body of research demonstrating that several tissues follow a number of common engineering principles regarding mechanical fatigue [9, 10, 40].

Although the contributions of mechanical loading to tissue damage formation are well established, it is important to note that further tissue damage may emanate through physiological mechanisms (Fig. 1). This additional tissue damage is facilitated by cellular mediated processes and apoptosis that form part of the remodelling and tissue recovery process [41, 42], initiated in response to mechanical loading and the mechanically induced tissue damage that ensues [41, 42]. Accordingly, for the purposes of this paper, these processes are considered supplementary to mechanical loading and the mechanically induced tissue damage that presents, and further exploration of these processes falls outside the scope of this article. Despite this, the contributions of these processes to tissue damage, pathology, overuse/gradual onset injury and recovery remain acknowledged. It is also worth noting that certain additional mechanical factors such as strain rate may also be of importance to damage and injury outcomes; however, deeper exploration of this aspect is similarly beyond the scope of this article.

Considering the evidence supporting mechanical loading and a mechanical fatigue failure process as being etiologically relevant to tissue damage, investigation of a mechanical fatigue phenomenon in athletic populations is needed. However, the accurate quantification of mechanical loading at the tissue-specific level is essential to this process. It follows that within the context of injury, available training load measures and metrics should be evaluated based on their capacity to quantify or reflect mechanical loading and the mechanical load-response pathway, tissue damage and subsequent injury.

2.1 Mechanical Load and the Mechanical Load-Response Pathway

Considering the evident contributions of mechanical loading to tissue damage accumulation and injury, it is worthwhile exploring some key concepts that underpin the mechanical load-response pathway within a sports setting. Within this context and for the purposes of this paper the force applied to a tissue is referred to as the mechanical load, whilst the stress and strain that results in mechanically induced tissue damage is referred to as the mechanical load-response.

Although the mechanical load-response pathway is of heightened relevance to tissue damage outcomes, a series of challenges surrounding its quantification exist within athletic settings. Most notably, the tissue response (stress and strain) is not solely dependent upon the force applied to a tissue, but also to additional factors such as tissue morphology and material properties including tissue cross-sectional area, density and stiffness [2, 5, 6, 14]. This makes the accurate quantification and assessment of the mechanical load-response pathway, depicted in Fig. 2, extremely challenging. Despite these influencing factors, attempts to quantify the internal forces experienced by specific tissues have been made [43–46], with such endeavours requiring the insertion of optic fibres [43, 44] or strain gauges [45] into various tissues. However, these methods often require laboratory-based settings, and their typically invasive nature makes their application problematic in applied sporting settings. Accordingly, the non-invasive, accurate quantification of the mechanical loads experienced by specific tissues is a more feasible alternative that would provide value to injury risk assessments. Furthermore, the accurate quantification of mechanical loading may open up exciting possibilities regarding the formation and application of computational models for determining the mechanical load-responses of specific tissues [46–50].

The measurement and modelling of forces is common practice in laboratory-based settings. However, a number of challenges regarding the measurement of mechanical loads exist within applied settings [49]. For this reason, the development of appropriate, more convenient, proxy measures of force may hold considerable value. A range of external training load measures are currently used in applied sport settings, with the use of certain spatio-temporal measures, such as those derived from global positioning systems (GPS) and accelerometers, being common practice. However, the capacity of current popular external load measures and metrics, such as those derived from GPS, to accurately quantify mechanical loading in a reliable and valid capacity is unviable, especially when considering the movement patterns and variable loadings typically experienced by athletes. This concern is further emphasised when considering the lack of precision with which this equipment can quantify certain spatio-temporal variables such as changes in velocity [51, 52] or high-speed running [51, 53], as well as other potentially relevant activities such as collisions [54]. Accordingly, GPS does not provide a feasible proxy measure of the mechanical loadings experienced by specific tissues and these shortcomings inevitably contribute to many of the inconsistent results associating GPS data with injury [55–57].

To improve upon estimates of tissue damage and athletic injury risks, external training load measures and metrics should be included or dismissed based on their capacity

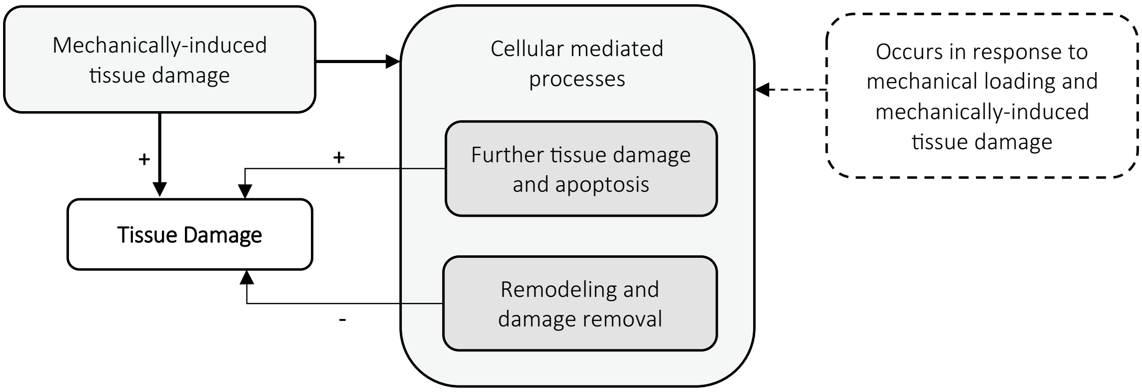

Fig. 1 Conceptual figure highlighting contributions to tissue damage in athletes

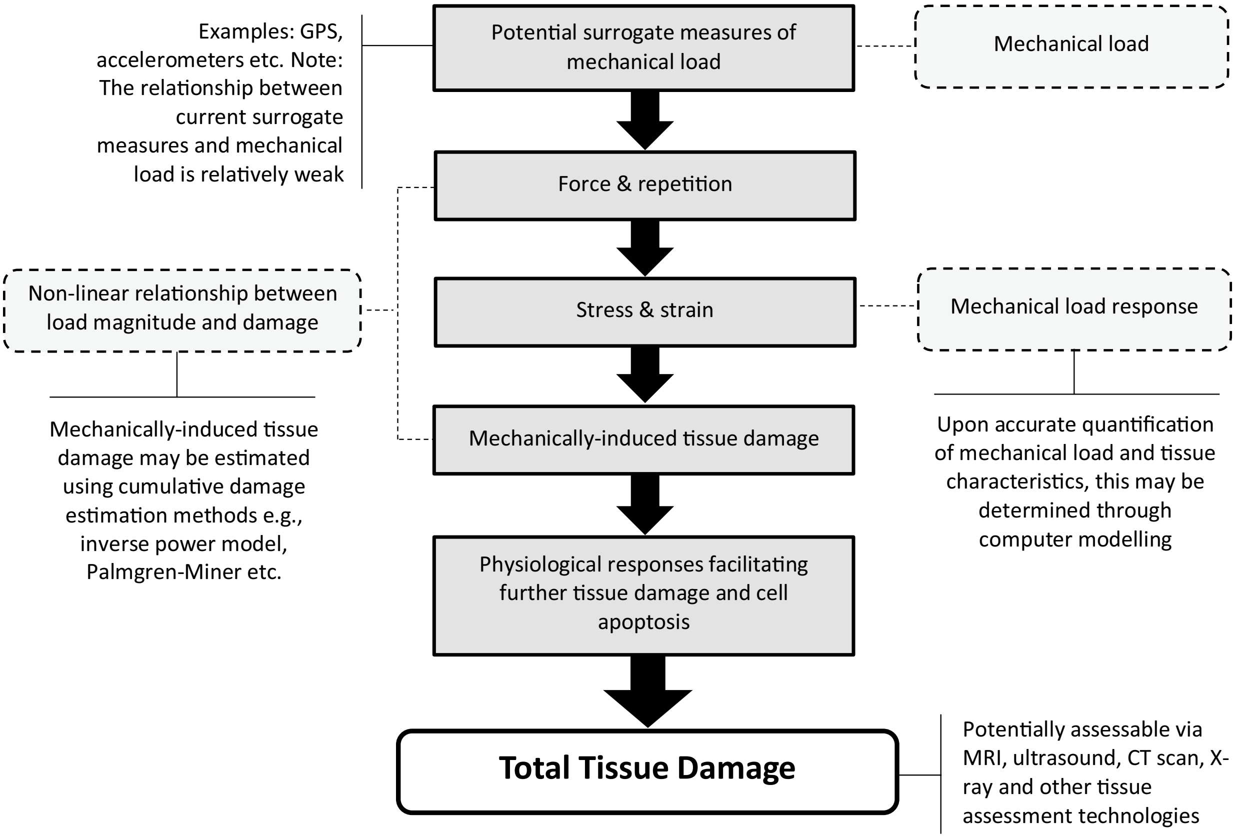

Fig. 2 A proposed sequence of steps required to enable a more precise assessment of the mechanical load-response pathway

to represent force and repetition. Importantly, considering the consistent statistical interactions between force and repetition that have been reported in relation to musculoskeletal disorders [9], the effects of force and repetition must be specifically explored in combination [5, 10], as the isolated effects of these components would provide unreliable estimates of risk in the presence of an interaction [58]. Notably, when determining proxies of force and repetition, appropriate measures would be expected to differ between specific sporting contexts. For example, in baseball, acceptable proxies for pitchers may be centred on the number of pitches thrown and the forces focused around the upper body, pitching arm and its various components. However, in running, the number of steps taken may act as an appropriate proxy for the number of load cycles, while ground reaction forces (GRF), lower limb accelerations or running speed may provide the best available measures, or proxy measures, of force acting on the lower body and its various components.

It has been suggested that acceleration-based metrics utilising accelerometers or other wearable technologies may assist with the accurate quantification of tissue-specific [55, 56, 59] and whole-body [60] mechanical loading. Although these technologies are widespread and have demonstrated potential for the accurate estimation of GRFs [61, 62], and GRFs have been associated with various types of injury such as patellofemoral pain, plantar fasciitis and Achilles tendinopathy [63], considerable limitations to this approach should be noted. Specifically, the accelerations of body segments and the correlates of GRF impact peaks [64, 65] or loading rates [63] that are commonly derived from current running wearable technologies are not equivalent to the forces experienced by specific tissues inside the body (e.g., bones, muscles, tendons) [66]. It follows that even a seemingly ecologically valid metric such as GRF may poorly reflect the loads experienced at a tissue-specific level [47, 66, 67]. This concern is emphasized when considering that the distribution of forces across specific tissues is typically unknown, while peaks in GRF often do not coincide temporally with the peak forces experienced by specific tissues [66, 68]. This can, in part, be attributed to the majority of mechanical loading being internally sourced for certain tissues, e.g., bone loading is primarily due to muscle contractions [14]. Importantly, the shortcomings of current wearable technologies are notably problematic as modest errors in the measurement of the exact forces experienced by specific tissues result in notably large errors when attempting to estimate tissue damage [69]. Accordingly, the validity and reliability of these potential proxies remain questionable and their limitations emphasized. Currently, these tools may provide the best available field-based estimates of mechanical loading; however, their relationship to the internal forces experienced by biological tissues should be viewed with extreme caution. Recent research has shown promising approaches using novel measurement modalities [70] or multiple wearable sensors in combination with biomechanics and machine learning [69] to provide targeted estimates of the loading experienced by specific biological tissues. Detailed, tissue-specific approaches such as these are encouraged as the accurate estimation or quantification of the actual forces experienced by biological tissue is of utmost importance. This will allow for the non-linear relationship between loading magnitude and damage to be accounted for and permit the valid application of damage estimation methods, enabling more reliable assessments of injury risk.

2.2 Estimating Mechanically Induced Damage: The Non-linear Relationship Between Load Magnitude and Damage

To assist with the determination of material damage accumulation, validated methods for predicting and estimating damage accumulation have been formed [71, 72]. Such methods specifically assist with capturing the combined effects of stress magnitude and the number of load cycles on material fatigue damage, which when excessive, eventually results in failure. Considering the evidence demonstrating that biological tissue follows many of the same principles as non-biological material when exposed to repetitive mechanical loads, particularly regarding mechanical fatigue and microdamage formation [13, 33, 34, 73, 74], proposals suggesting the application of these methods for determining cumulative tissue damage and assessing injury risk within a sporting context [5] are most appropriate. One of the earliest examples of such a method is the Palmgren–Miner rule [71, 72]. As recently emphasized by Edwards and others [5, 9, 10, 71], an important feature of commonly used damage accumulation estimation methods, such as the Palmgren–Miner rule, is that they recognise the non-linear relationship between load magnitude and damage [5, 71, 72], depicted in Fig. 3. Such is the influence of this relationship, a 10% reduction in stress generally is associated with a corresponding 100% increase, or more, in the number of cycles to failure [13]. It follows that cumulative damage can vary substantially depending on the loading pattern experienced (exact combination of loading magnitude and number of loading cycles), even when cumulative loads are similar [5, 71, 72]. This concept holds particular relevance to athletic injury risk determination considering the variable loading regimens (combinations of loading magnitudes and loading cycles) typically experienced by athletes.

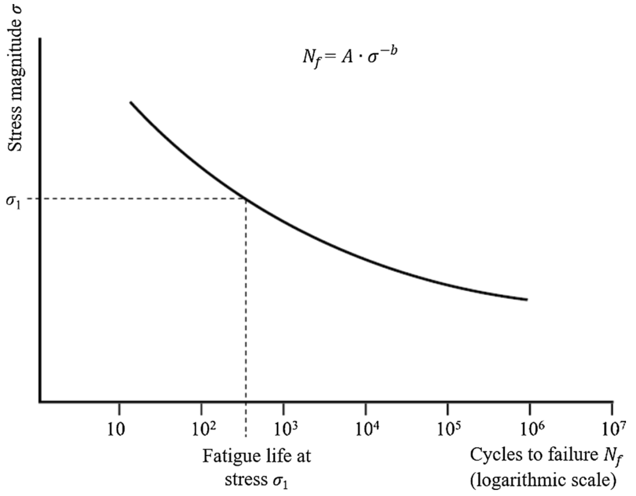

Fig. 3 Theoretical stressed-life plot (S–N curve) for a material subjected to cyclic loading demonstrating the non-linear relationship between load magnitude and damage. Fatigue life is defined as the number of cycles to failure N_f at a particular stress magnitude σ. Reproduced from Edwards with permission [5]

Notably, the non-linear relationship between peak stress magnitude (induced by an applied load) and the number of cycles to failure is well described by an inverse power law, which describes the stress-life relationship of a material using a power function (Eq. 1). Within this function, N_f is the number of cycles to failure, A is a proportionality constant, σ is the stress magnitude, and b is the slope of the S–N curve

$$N_f = A \cdot \sigma^{-b}. \tag{1}$$

While the inverse power law model and damage accumulation estimation methods are useful for the approximation of fatigue damage, there are limitations, such as the inability to account for localised stress concentrations or changes in molecular orientation [75, 76]. Considering many of these challenges, engineers typically do not seek to determine an exact point of failure but commonly attempt to determine a failure range and the probability of failure which may be most appropriate for athletic injury risk determination. For a more detailed examination of damage accumulation estimation methods within biological tissues and athletic specific contexts, the reader is directed to an article by Edwards [5] on modelling overuse/gradual onset injuries as a mechanical fatigue phenomenon.

2.3 Measures of Internal Load and the Psycho-Physiological Load-Response Pathway

Although mechanical loading and the mechanical load-response pathway hold considerable conceptual relevance to tissue damage accumulation and injury, an additional pathway that requires attention is the psycho-physiological load-response pathway. This pathway is concerned with the psycho-physiological responses of an athlete to a given training stimulus, which may be related to injury. Measures of physiological (e.g., heart rate, lactate concentrations, etc.) and psycho-physiological [e.g., rating of perceived exertion (RPE)] internal loads are commonly used across the sporting landscape to assess the internal psycho-physiological responses of an athlete to an applied training stimulus [1, 77]. Although stress and strain are internal to an athlete and can therefore be categorized as a measure of internal load, in both training and research settings, internal load measures typically refer to those that are psycho-physiological in nature. Accordingly, within this section, internal load primarily refers to the psycho-physiological stress experienced by an athlete. However, considering that there are interrelations between psycho-physiological functioning, tissue properties, and mechanical loading [6], both the mechanical load-response and psycho-physiological load-response pathways are, indeed, somewhat interrelated. Despite this, it is worth noting that psycho-physiological responses to any given external stimulus are highly variable and individualised. Accordingly, despite the interrelation between the relevant pathways, external training load metrics and mechanical loading do not necessarily reflect internal psycho-physiological loads and should not be used to assess the psycho-physiological load-response pathway. Despite this limitation, psycho-physiological responses to external training loads may conceptually be related to injury outcomes based on activity intensity and a range of factors potentially related to the relative psycho-physiological stress experienced, such as psycho-physiological fatigue and alterations to psycho-physiological functioning. These relationships are based on an increased risk of a sudden traumatic injury event occurring or an increase in various tissue loadings due to a range of potential psycho-physiological fatigue-related factors, such as those related to neuromuscular functioning, i.e., impairments in technique [78, 79], motor coordination [78], muscle activation timing [78, 80], muscle functioning [78, 79], as well as other factors such as changes in psychological state [81]. Despite these conceptual links, the evidence supporting current measures of internal load as acceptable proxies of these factors is scarce and the contributions of many of these factors to injury incidence remain uncertain and likely highly variable.

The aforementioned concerns are augmented when considering the growing body of research contesting the relationship between certain injury types, such as anterior cruciate ligament injuries, and psycho-physiological fatigue [80–85]. Despite this, the relevance of the relationship between psycho-physiological fatigue and injury likely varies between specific injury types and may, therefore, be more applicable and causally related to certain types of injury [78] compared to others [82, 85]. Of further importance, although measures of internal load may act as acceptable proxies of psycho-physiological load, they are not actual measures of psycho-physiological fatigue [86] nor do they accurately reflect the mechanical load experienced since the same psycho-physiological loads can be associated with different mechanical stimuli. It follows that, for the above-mentioned reasonings, current measures of psycho-physiological load cannot account for mechanically induced tissue fatigue damage, negating its relevance to tissue deterioration and particularly overuse/gradual onset injuries. Considering the aforementioned concerns, metrics that utilise these measures would expectedly show inconsistent and unreliable findings with injury, which certainly appears to be the case [85–91].

2.4 Association is Not Causation: Cumulative Load and Exposure Time

An important consideration when examining relationships between certain risk factors and injury is that the association of variables does not necessarily imply causation [92, 93]. This is a commonly reiterated mantra within the scientific community [92, 93] which holds considerable relevance to the training load–injury relationship, especially when considering the underlying relationship between exposure time and cumulative load. Within this context, exposure time refers to the length of time that an athlete is exposed to a particular activity that puts them at risk of injury i.e., matches, training, sprinting, etc. and which is also used as the denominator when calculating the risk of injury. This should not be confused with previous exposure time to an activity and the accumulation of chronic loads, which may influence the injury risk for subsequent exposures [94, 95]. It is well established that injury risk increases with exposure time [96]. This is a logical, positive relationship as the longer the exposure time, the longer an athlete's exposure to the very activity and environment that puts the athlete at risk of injury [97]. Accordingly, injury risk is commonly expressed relative to exposure time which sets a time paradigm within which risk can be assessed [97]. It follows that altering the associated time period would inevitably modify the risk.

Similar to the injury risk–exposure time relationship is the inherent positive relationship between cumulative load and exposure time. Considering that training loads are accumulated over time, the longer the exposure time to a given activity the more time is afforded for load accumulation. The acknowledgement of this relationship is of high importance as the associations between training load and injury would expectedly be influenced and strengthened by exposure time acting as a confounder. Accordingly, it follows that the associations established between injury and training load are not necessarily causal for many injury types, and significant associations and alterations to injury risk may arise as a mere reflection of the exposure time–injury relationship, depending on the analysis conducted. This holds particular relevance considering the growing body of recent literature challenging fatigue as an important risk factor for certain injury types [80–85] that have commonly been associated with training loads.

Establishing causal relationships between cumulative load, fatigue (mechanical and psycho-physiological) and injury is critical to the formation of appropriate injury risk mitigation strategies, as per the popularised 'sequence of prevention' for sports injuries [98]. Importantly, if training load is not causally related to certain injuries, injury risk mitigation strategies that are based on managing training loads may be simply influencing injury risk by manipulating exposure times. Although managing injury risk based on exposure time management may still be appropriate within specific contexts and circumstances, such strategies may also be harmful to the performance, training, and developmental goals of the athlete and must therefore be implemented with caution. To determine whether training load is indeed causative to injuries, the contributions of fatigue, both mechanical and psycho-physiological, to specific types of injuries needs to be explored in detail and their contributions to injury aetiology established and not just assumed. Such causal understandings will assist in the determination of the appropriateness of specific injury risk mitigation strategies and training load metrics, such as the ACWR which will be discussed in the following section, to inform injury risk mitigation strategy.

3 The Acute:Chronic Workload Ratio: A Case Study

Of recent interest in sport science is the application of a training load metric called the "acute:chronic workload ratio" (ACWR) which has been proposed as a 'valid' measure for quantifying and reducing the risk of athletic injury [8]. Notably, the ACWR has gained substantial traction within the sport science literature with over 100 studies existing on the topic [99]. Although recent studies and articles have highlighted a number of computational concerns [98–102], and the relationships exhibited between this metric and injury have recently been revealed to be caused by statistical artefact [99], the widespread popularity and application of this metric [8, 101–105] as well as the spurious etiological foundations that underpin it, justify the ACWR as an ideal, topical case study from which more advanced, conceptually sound measures of injury risk assessment may be developed.

The ACWR metric was created with the intention of quantifying injury risk based on the effect of acute changes in athletic workloads and was based on Banister's Fitness-Fatigue concept [106]. However, although there is some evidence to support certain facets of the ACWR, even when considering more recent variations such as the use of exponentially weighted moving averages, a number of major conceptual flaws exist. Some of these include the interchangeable use of a variety of training load measures and metrics as input variables into the ratio [107, 108], the limitations of these current inputs, the inability to account for mechanical loading, the lack of tissue-specific measures of strength or loading, the absence of the non-linear relationship between load magnitude and damage, as well as more generally, the questionable relationship between training load, fatigue and the causal mechanisms of many types of injury.

3.1 Conceptual Basis of the Acute:Chronic Workload Ratio

Evaluating the conceptual strengths, limitations, and overall viability of the ACWR is beneficial to the development of understandings regarding training load and injury, and serves as an example of the need for a detailed reasoning when proposing a metric or any measure as a proxy of causal mechanisms of injuries. Fundamentally, this ratio was not proposed as an indication of long-term undertraining or overtraining, but rather as an indication of excessive acute (e.g., 1-week) changes in load relative to an athlete's chronic (3–6 weeks) load exposure [8]. Within this interpretation, the ACWR was proposed as a tool to assess the injury risk associated with acute changes in workload. Specifically, when the acute load rises relative to the chronic load, a higher value presents, bestowing an increased risk of injury. For a given acute load, an athlete with a high chronic load yields a lower score, which has been suggested to be indicative of a lower injury risk [103, 104, 109]. Although it has been suggested that a "sweet spot" exists, whereby one can maximise net performance potential by having an appropriate training load, while limiting the negative consequences of training [8], typically, heightened chronic loads are considered to have a protective effect on an athlete. If the chronic load is low, the athlete is less resilient and presents with a heightened score for a given acute load. An excessive rise in acute load has been termed a 'spike' in workload, which has been associated with an increased injury risk [55, 103, 109]. While this rationale appealed to practitioners, when examined from a conceptual perspective, taking into account many of the concepts presented earlier within this article, considerable weaknesses emerge.

3.2 Deconstructing the Acute:Chronic Workload Ratio

3.2.1 Chronic Load: A Proxy for Athlete Resilience?

Within the ACWR, chronic workload represents the rolling average of the most recent 3–6 weeks of training. In this respect, it is maintained that chronic training loads are analogous to a state of 'fitness' which may protect against injury [8], and is the sole protective input into the ratio. Accordingly, for chronic loads to be the sole protective input for the ratio, one must assume that 3–6 weeks of chronic load data acts as a viable proxy measure of the multitude of factors contributing to athlete resilience. Although some authors have suggested that chronic loads are protective for an athlete [95, 110], and there is evidence to support that adequate physical preparation reduces injury risk [94, 95, 110, 111], there are a number of limitations related to this concept that warrant attention. At the forefront, chronic loads are not a measure of the myriad of physical competencies that may have protective effects on athletes, nor are chronic loads a measure of tissue resilience. Of particular concern regarding this is the "one size fits all" approach highlighted by the variety of external and internal training load measures that have commonly been used as input measures and metrics into the ACWR, such as various GPS-derived measures [103, 105, 112] and RPE [87, 90, 109]. As explored previously, the various training load measures and metrics have differing purposes and are not interchangeable. Furthermore, their contributions to athlete and tissue resilience range from nil to variable. These concerns are further reinforced when considering that recovery, strength training, mechanical loadings and inter-athlete differences are not properly accounted for or excluded entirely from the ACWR and the various input variables.

Although its simplicity is enticing and within certain sporting contexts chronic load data may act as a tentative quasi-indicator of athlete resilience, it must be acknowledged that athlete resilience is a complex phenomenon that is often developed over large periods of time [113, 114] and incorporates a number of tissues and risk factors [14, 115, 116] that may have weak or non-existent relationships with the variety of training load measures and metrics available. While a simple surrogate measure of athlete resilience is attractive, careful metric input selection is stressed and caution surrounding the limitations of chronic loads acting as a valid proxy measure of athlete resilience are emphasized.

3.2.2 Acute Load

Within the calculation of the ACWR, acute training loads can be as short as one session or as long as one week. In this respect, it has been suggested that acute training loads are analogous to a state of 'fatigue' that, when excessive relative to chronic load, leads to injury. Accordingly, for acute load to be the sole negative function of the ACWR calculation is to imply that acute training loads act as the primary stimulus for injury occurrence. This is a most concerning assumption as although acute loads may act upon the psycho-physiological and mechanical load-response pathways, a rigorous causal explanation of justification for this assumption does not exist. Of immediate concern, the metric is not tissue or injury specific, and tissue loading is not accounted for in any valid capacity within any of the input variables currently available. Furthermore, the relationship between the psycho-physiological load-response pathway and injury remains ambiguous. When also considering that tissue damage accumulation is not estimated in any capacity, acute loads are not a measure of psycho-physiological fatigue, and many injuries appear to occur in a manner that is largely independent of prior training load and psycho-physiological fatigue [80–84], it is evident that any potential causal explanation is not only speculative but also unsupported by a sound rationale. Of additional concern, the "appropriateness" of the time windows used to capture the acute load is often justified by the training schedule [117, 118], with it having been suggested that in team sports, 1 week of training appears to provide a logical and convenient unit [8]. Such justifications are, therefore, based on convenience as opposed to physiological, mechanical or mechanistic reasoning. Accordingly, considerable doubts regarding the relevance of acute training loads to injury causality are evident in the current application of the ACWR. There is currently no evidence or even conceptual framework supporting acute training loads as being causal to injury and minimal evidence exists supporting the inclusion of acute training loads as the main negative causal factor determining injury risk.

3.2.3 ACWR Summary

When proposing and selecting a metric as a proxy of factors involved in a causal pathway, the examination of its plausibility from a mechanistic perspective is crucial. From this perspective, it is evident there are substantial conceptual shortcomings of the ACWR and similar metrics, which are simplistic attempts to capture injury risk for a number of injury types with varying mechanisms, across a variety of tissues, and within different sporting contexts. When considering that there is no attempt to estimate cumulative tissue damage, and neither tissue strength, mechanical loads, recovery, or the plethora of other factors contributing to a given injury event appear to be quantified in any meaningful capacity in the ratio, the ACWR (or similarly developed metrics) appears to be a poor proxy of the mechanisms of injury. Furthermore, the relationship between the psycho-physiological load-response pathway and injury remains uncertain, and many injuries may occur largely independent of prior training loads, proliferating the considerable limitations of this particular metric. Along with the noted statistical artefact [99], these aspects contribute to the diverse findings evident with the ACWR, whereby associations with injury have been shown in a multitude of contradictory directions, or not at all [8, 87, 87–91, 103, 109, 118, 119, 122, 123]. Any measure or metric used as a potential causal factor for injury should be conceptually scrutinised prior to its application within applied research. This is also the case in exploratory studies when the derived associations are used to develop hypotheses. A thorough understanding of the roles of the factors related to injury risk is fundamental to develop causal structures and aetiological theories to be tested. The use of the ACWR as a case study was presented here to emphasise the need for metrics with a rigorous underlying rationale and to focus research on metrics with strong conceptual foundations.

4 Conclusion

Considering the fundamental contributions of mechanical loads to injury occurrence, attempts to relate injury and training load should seek to determine and apply appropriate measures of force and the number of load cycles, or appropriate surrogate measures of these. This approach will more closely reflect the mechanical contributions to tissue fatigue and failure and may allow for the application of models that account for the mechanical load-response of specific tissues. Internal load measures of psycho-physiological load, although somewhat conceptually related to injury, provide limited insight into tissue resilience, the loading of various tissues, specific injury mechanisms, or the array of factors that influence an injury event. It follows that these measures are likely too far removed from injury causation to provide meaningful, reliable relationships with injury.

When the example of the ACWR, a highly popularised method of estimating injury risk is scrutinised, it is evident that the ACWR possesses a number of limitations and conceptual flaws. While a ‘one size fits all’ injury risk quantification is attractive, the multifaceted and complex occurrence of athletic injury appears to require a more detailed approach. Understanding whether the manipulation of a given variable can alter the likelihood of a future event necessitates the implementation of well conducted experimental studies or estimations from observational studies whereby causal structures are defined a priori. Forcing explanations attempting to justify “significant” study results can generate involuntary HARK-ing (hypothesizing after the results are known) [120].

To advance injury research and understandings, it is recommended that a superior approach to quantifying tissue injury risk is undertaken. Such an approach would rely upon focussing efforts towards a tissue-specific, injury mechanism-specific, and sport-specific approach, basing such enquiry on the development and utilisation of detailed conceptual frameworks. This approach will encourage researchers to better understand the mechanisms and causal pathways that contribute to athlete and tissue resilience, tissue loading, and specific types of injury within particular sporting contexts, and facilitate the investigation of various causal links and assumptions. To move training load research forward in this area, it is recommended that researchers focus efforts towards developing innovative methods to quantify the mechanical loads experienced by specific tissues, with recent approaches potentially serving as inspiration for such endeavours [69, 70]. Approaches such as these may encourage the development and application of computational models that accurately describe tissue behaviour and open up new possibilities regarding the accurate estimation of cumulative tissue damage. Of additional importance, it is essential that the contributions of psycho-physiological fatigue to specific types of injury are established, while researchers must also continue to develop methods to monitor and assess tissue health and strength in applied settings.

Considering the shortcomings of currently available training load metrics and data when reflecting causal pathways to injury, it is recommended that the utilisation of currently available training load metrics and data for injury risk assessment and manipulation should be avoided as such assessments have proven unreliable. Accordingly, it is recommended that training load data should be primarily utilized for monitoring whether an athlete is undertaking what is prescribed, along with contributing to the assessment of how an athlete is coping with the prescribed loads [121]. In this respect, training load data can continue to inform applied practice and periodization. The evident limitations associated with attempting to quantify injury risk from current training load data imply that extreme caution must be exercised when considering any evident relationships with injury and when utilising such information for decision making processes.

Acknowledgements The authors would like to thank Blake McLean, Michael Rennie, Emily Matijevich, and Brook Kalkhoven for their contributions to the manuscript.

Declarations

Conflict of Interest Judd Kalkhoven, Mark Watsford, Aaron Coutts, W. Brent Edwards and Franco Impellizzeri declare that they have no conflicts of interest.

Author contributions JTK conceived the idea for the article, wrote the first draft of the manuscript and all versions thereafter. MLW contributed substantially to the editing and conceptual direction of the manuscript. AJC contextualised the information provided in the manuscript within the current climate of training load research. WBE contributed to the tissue engineering and mechanical load components of the manuscript. FMI contributed to the conceptual formation and editing of the manuscript as a whole with a special emphasis to Sect. 3. All authors read and approved the final manuscript.

Funding No sources of funding were used to assist in the preparation of this article.

Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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