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CURRENT OPINION

Training Load Monitoring in Team Sports: A Novel Framework Separating Physiological and Biomechanical Load-Adaptation Pathways

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Abstract There have been considerable advances in monitoring training load in running-based team sports in recent years. Novel technologies nowadays offer ample opportunities to continuously monitor the activities of a player. These activities lead to internal biochemical stresses on the various physiological subsystems; however, they also cause internal mechanical stresses on the various musculoskeletal tissues. Based on the amount and periodization of these stresses, the subsystems and tissues adapt. Therefore, by monitoring external loads, one hopes to estimate internal loads to predict adaptation, through understanding the load-adaptation pathways. We propose a new theoretical framework in which physiological and biomechanical load-adaptation pathways are considered separately, shedding new light on some of the previously published evidence. We hope that it can help the various practitioners in this field (trainers, coaches, medical staff, sport scientists) to align their thoughts when considering the value of monitoring load, and that it can help researchers design experiments that can better rationalize training-load monitoring for improving performance while preventing injury.

Key Points

Easy access to a huge diversity of training load data in modern team sports has caused confusion about the load-adaptation mechanisms to which different data are expected to be associated.

We propose a new theoretical framework in which physiological and biomechanical load-adaptation pathways are considered separately, and for which the distinction between internal and external load measures is revisited.

Load-adaptation pathways have different response rates, which has consequences for the planning of training and/or rehabilitation sessions when attempting to enhance performance and prevent (re-)injury.

1 Introduction

Team sports are demanding activities and when players are challenged to an appropriate level this can lead to physiological adaptations of the aerobic, cardiovascular and muscular systems. These adaptations benefit sporting performance through increased endurance, speed, strength or power. However, excessive amounts of training can lead to overload of the system's capacity and increased risk of injury and illness. Otherwise, insufficient training may annihilate the performance benefits. It is thus generally accepted that players should be challenged adequately through appropriate periodization of their activities, allowing optimal recovery between bouts of activity to

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achieve the desired physiological adaptations of the system [1]. The activities performed by the athlete represent an external load, yet the abovementioned physiological adaptations come about because of internal load, primarily in the form of biochemical stresses.

Besides biochemical stresses, the activities performed by the athlete also lead to mechanical stresses on the different tissues that comprise the musculoskeletal system, i.e. on cartilage, bone, muscle and tendon tissue. Basic tissue engineering science has demonstrated how mechanical stresses are directly related to tissue damage and repair (e.g. Wang et al. [2]), showing that homeostasis is triggered directly through a narrow window of load intensities. This means that as a consequence of the mechanical stresses, structural and functional adaptations of the musculoskeletal system take place. In the applied field of training-load monitoring, this mechanical load-adaptation pathway has been largely overlooked. We therefore propose a novel framework in which the physiological and biomechanical load-adaptation pathways are considered separately, as schematically presented in Fig. 1. Albeit oversimplified, for physiological load adaptations one could seek analogy in the workings of a car engine, where the key focus is on the consumption of fuel and oxygen. Sticking with this car analogy, the biomechanical load adaptations could be represented by the suspension system, where the key focus is on keeping the mechanical properties intact. The aim of this paper was to present how some scientific evidence on measures of external and internal training load could be interpreted according to these separate pathways, in the hope that this may ultimately help resolve a current lack of consensus in measures of training load [3].

2 Monitoring External Load

In the past few years, player monitoring systems based on global positioning systems (GPS) have shown to be reliable and valid for monitoring player activity levels in running-based team sports [4–10]. In particular, kinematic variables such as distance covered or some form of the average running velocity are physiologically relevant as they can be representative of energy consumption through the use of so-called ‘metabolic power equations’. This works reasonably well for constant speed sporting activities [11, 12], however accelerating and decelerating the body involves greater energetic cost than maintaining constant speed [13], which has led to the integration of GPS-based accelerations (second derivative of displacement) into adapted power equations for team sports [14–16]. While this was shown to improve estimates of energetic load [15], the fact that team sports involve non-steady-state locomotion makes it very

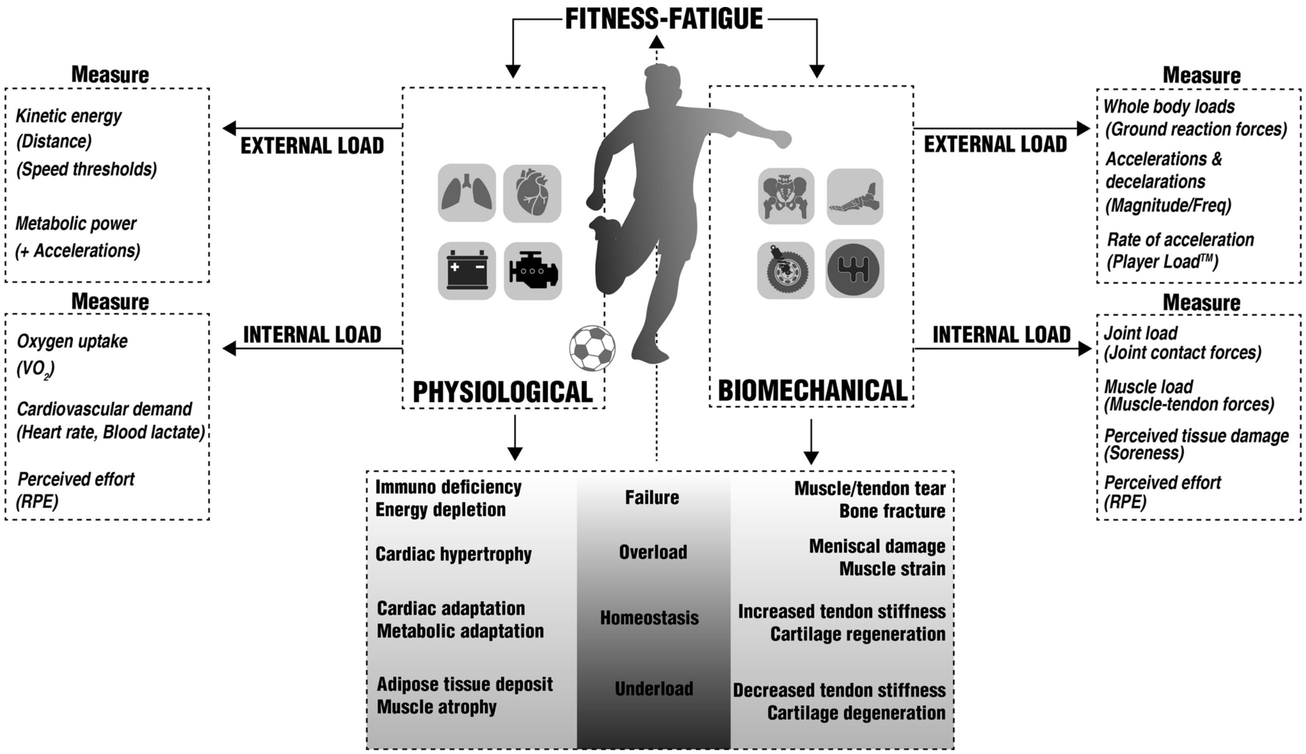


Fig. 1 A new player load monitoring framework outlining the cyclical nature in which physiological and biomechanical load leads to adaptation of the biological system as a whole. *RPE* rating of perceived exertion, *Freq* frequency

difficult to accurately estimate metabolic power, added to the fact that reliability and validity of velocity-based measures is lower for movements with higher accelerations [10, 17], and the accuracy of GPS-based acceleration signals is known to be limited [18].

The biomechanical component of training load (Fig. 1, right-hand side) depends largely on propulsive and breaking forces against the ground. It has been recognized that players in team sports undertake some 500 rapid accelerations and decelerations in a single match [19]. The mechanical stresses on soft tissues (internal load) come from these external kinetic demands of absorbing high forces from the impact with the environment and generating high forces to push off against the ground (remember the car suspension analogy). Directly measuring these external forces is possible but difficult outside of a laboratory. Instead, measuring the accelerations based on Newton's second law (with a certain mass, accelerations are proportional to the external forces acting on the body) is more feasible. The availability of low-cost inertial sensors has led to the integration of accelerometers in commercially available GPS units, and this in turn has led to an expansion of the literature towards evaluating the reliability of accelerometry-based variables [20–23] and their utility to assess training load in various situations [24–27] and sporting populations [23, 24, 28–30].

Accelerometers provide a continuous signal at a high measuring frequency (currently 100 Hz in most commercially available units) and, therefore, providing a summative measure of this signal is needed to represent the extent to which the body has been 'shaken up'. A number of these summative measures have been proposed, such as 'Dynamic Stress Load' [31], 'New Body Load'[32] or 'Force Load' [33], yet arguably the most commonly reported measure has been Player Load$^{\mathrm{TM}}$ [20, 28]. The premise of these summative measures is that an estimate of the external biomechanical load can be provided through accumulating the rates of acceleration. Recent studies have used PlayerLoad$^{\mathrm{TM}}$ values to monitor training load in season and between matches [34, 35], and some studies determined typical profiles in various team sports [34, 36–39]. Scientists have attempted to relate this to the physiological load (external or internal measures), similar to what is commonly done in physical activity monitoring (as reviewed by Chen and Bassett [40] and Yang and Hsu [41]). For example, one study demonstrated moderate to high relationships between PlayerLoad$^{\mathrm{TM}}$ and distance covered [29, 42], while other studies demonstrated a moderate to high relationship between PlayerLoad$^{\mathrm{TM}}$ and ratings of perceived exertion (RPE) [42–44] and a trivial to moderate relationship between PlayerLoad$^{\mathrm{TM}}$ and oxygen uptake ($\dot{V}O_2$) or heart rate (HR) data, respectively [20, 42, 45]. These relationships between measures of physiological and biomechanical loads lack a solid foundation, except for the fact that in running-based team sports the variations in both types of loads are generally experienced together. In fact, this was recognized in three papers where, based on the poor relationship, it was suggested that accumulated accelerometer-based outcomes such as PlayerLoad$^{\mathrm{TM}}$ measure a different construct of the training process than internal physiological load measures such as RPE or HR [35, 38, 42]. Rather, these measures are valuable to estimate the extent to which the player, through their activities, experiences accelerations and hence biomechanical load of the body as a whole. Considering that the trunk is the body segment with the highest mass, attaching an accelerometer to the trunk provides the closest measure of the accelerations of the whole body. The relationship between trunk and whole-body accelerations is not perfect but at least offers a starting point for measuring external load from a biomechanical perspective [46].

3 Monitoring Internal Load

From a physiological perspective, if the external load is increased by running further and faster, then that will lead to increased metabolic energy cost [47, 48]. This metabolic energy is needed to drive muscle contractions, which mainly require the provision of carbohydrates, fats and proteins, and the provision of oxygen in the case of aerobic energy-burning processes. These are primarily challenges to the cardiorespiratory system and therefore measures of internal physiological load are most often related to oxygen consumption and cardiac output. The various techniques and measures of internal load have recently been reviewed elsewhere [49, 50], and here we will focus on some of the most commonly used ones. For example, cardiorespiratory output is easily assessed in the field by recording HRs or related outcome variables (e.g. training impulse [TRIMP], as in Borresen and Lambert [51]), and has seen more interest than oxygen consumption, which needs semi-invasive laboratory-based techniques. Both cardiorespiratory measures ignore the anaerobic contributions, for which blood lactate values have been assessed [52, 53]. Blood lactate values reflect an accumulation of previous efforts rather than a measure of the last bout of anaerobic contribution [23]. Second, a less direct measure of internal physiological load is the subjective RPE. This is seen as an index for training stress and has seen great popularity in the field because of its ease of administration [51, 54, 55]. Despite the subjective nature of RPE, it has been shown to correlate well with a number of HR-based internal load indicators when multiplied by the duration of the session [56], which could justify its use as an estimate of internal physiological load. Altogether, a number of techniques to monitor internal physiological load, albeit indirectly, have become established in running-based team sports, which is not yet the case for monitoring internal biomechanical load.

Monitoring mechanical stresses on the musculoskeletal system requires measurement of variables such as joint contact forces or muscle–tendon forces. Advanced biomechanical work is currently being undertaken to estimate such forces in a laboratory environment through musculoskeletal modelling approaches (e.g. Saxby et al. [57]). At present this is impossible in a field context, and the relationship between the aforementioned measures of external load (e.g. from trunk accelerometry) and tissue-specific mechanical stresses are insufficiently understood; therefore, the question is whether indirect measures of mechanical stresses to musculoskeletal tissue are available. A first candidate is in fact RPE, which was earlier proposed as a measure of internal physiological load. We would argue that the biomechanical load can also lead to a perception of how hard a session was, and that a generic RPE probably reflects both types of internal load (biochemical and mechanical stress). In one study, the session-based RPE (RPE multiplied by the duration of the session) was actually explained by acceleration-based measures, at least to the same extent as by measures of energy expenditure, which would suggest that it veers towards internal biomechanical load [31]. By asking the player to be specific in how much their 'breathing' was affected or how much their 'legs' were affected, one may well be able to separate their perceptions of physiological and biomechanical load. The idea of differential RPEs is not novel, with 'breathlessness' and 'leg exertion' closely reflecting the distinction between physiological and biomechanical load, respectively [58]. Other measures of how mechanically damaging training activities have been for the musculoskeletal system is the rating of muscle soreness [59, 60], the Profile of Moods (POMS) questionnaire, or the Recovery-Stress Questionnaire (REST-Q) [61]. However, important disadvantages of these measures is that these are best measured 1 or 2 days after the session took place rather than immediately after the session, taking into account the principle of delayed onset of muscle soreness (DOMS), and that the repeated bout effect quickly leads to less detectable or absence of muscle soreness [62]. Therefore, a more direct indicator of muscle damage is desired and this is possible through measuring serum creatine kinase (CK) levels [63]. In fact, increased CK levels have been shown to moderately relate to acceleration-based player load in rugby league [60] and Australian rules football [64], evidencing the relationship between accumulated tissue trauma (internal load) and external biomechanical loads. However, a limitation of CK levels as an indicator for accumulated tissue damage is that its measurement is difficult, that a single acute macro trauma likely overrides the measure of accumulated micro trauma, and that there is still a similar repeated bout effect as with measures of muscle soreness. In summary, internal loads can be difficult to measure directly, both from a physiological and biomechanical perspective, but subjective assessments through, for example, differential RPEs may well be a suitable indirect alternative.

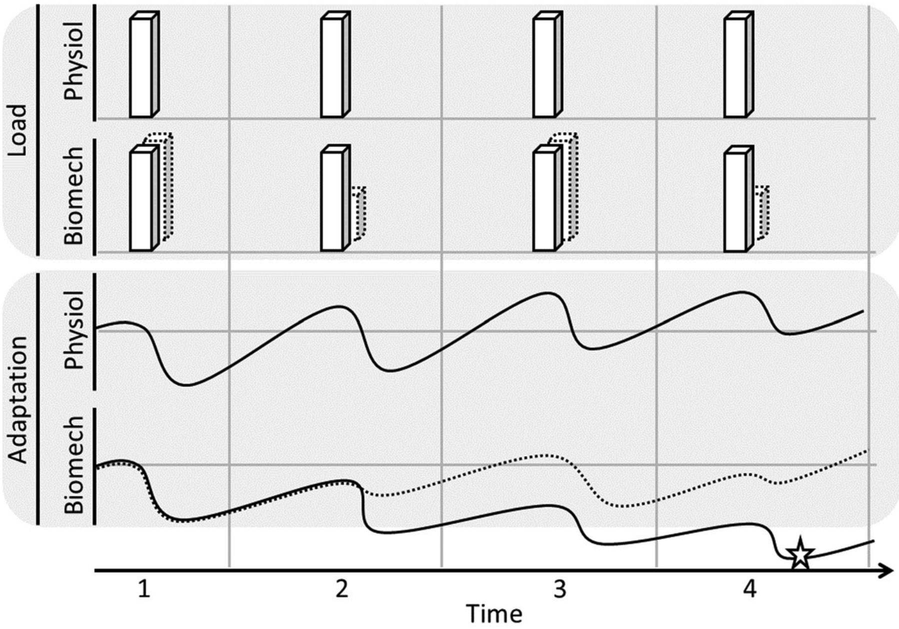
4 Adaptation

Principles of load and the assumed consequent adaptation are generally accepted in a physiological context of training-load monitoring, both centrally (heart, lungs, nervous system) or peripherally (capillarization, fibre subtypes, molecular, oxidative, glycolytic). In the context of team sports, these have been reviewed extensively elsewhere (e.g. Wallace et al. [48], Howatson and Milak [63], and Gamble [65]). However, to our knowledge, this principle has not yet been formulated in an explicitly biomechanical context. While a recent editorial [66] and review [54] have already alluded to this, we believe that with more detailed biomechanical understanding the distinct biomechanical load-adaptation pathway in the proposed framework can be further justified.

Biomechanical adaptations take place through mechanical stresses to the various musculoskeletal tissues. Muscular adaptations are perhaps best known and the most responsive to mechanical stimuli, with considerable adaptations to mechanical properties such as fascicle length, pennation angle, and muscle thickness (for an excellent review on this matter, see Wisdom et al. [67]). Similar to how muscle properties depend on mechanical stimuli, the synthesis of other soft tissues and their molecular turnover depends on the mechanical stresses to which they are exposed. For example, articular cartilage that is regularly exposed to high levels of stress has a higher cell volume [68], a higher content of proteoglycans for better synthesis [69, 70], and is stiffer [71]. Similarly, tendons undergo structural adaptations that change their modulus [72], as well as size adaptations based on habitual loading patterns [73]. While it is commonly known that excessive mechanical load accumulation can generate structural failure in the form of chronic injuries (e.g. stress fractures, tendinitis), the more subtle biomechanical adaptations are often overlooked. This is probably because they are less obvious to observe, and they tend to have a slower response rate than physiological adaptations.

Differences in response rates can have important consequences, as demonstrated in Fig. 2. In the top part of Fig. 2, a sequence of physiological and biomechanical

Fig. 2 Theoretical example of how different time frames between physiological and biomechanical adaptation may need different periodization between physiological and biomechanical load. The *dotted blocks* represent an alternative biomechanical load periodization, leading to an improved biomechanical adaptation profile, as shown by the *dotted line*. The *star* indicates a theoretical time point where critical weakness and tissue failure could more likely occur



internal loading is delivered to the system in the form of training sessions with a certain amount of load, for example with 2-day intervals in between sessions. In the bottom part of Fig. 2, the associated changes to the state of physiological and biomechanical systems is shown through the solid lines, which could be glycogen availability within the muscle (physiological), and stiffness of a tendon (biomechanical), to name two. When hypothetically taking a biomechanical response rate that is twice as long as the physiological response rate, the physiological adaptation has reached supercompensation and the next training session comes at the right time to achieve gradual improvement of the system. However, due to its slower response rate, biomechanical adaptation is still incomplete, meaning that the next biomechanical load arrives at a time when the tissue is still weakened, causing gradual degeneration until a critical weakness and tissue failure may be reached (as indicated by the star in Fig. 2). Perhaps the amount of biomechanical load should be reduced at times of weakness (dashed biomechanical load block with dashed biomechanical adaptation line at time point 2), allowing for supercompensation in the tissue properties to take place before a higher biomechanical load is delivered at time point 3. This theoretical example of how periodization could pursue optimal sequencing of load is only possible if one is able to separately control physiological and biomechanical load. In the next section, we will discuss a couple of examples of how this can be achieved in running-based team sports.

5 Differentiating Physiological and Biomechanical Load

Separate modification of physiological and biomechanical load is already common practise in the rehabilitation of lower extremity musculoskeletal injuries. Aqua jogging exercises and, more recently, exercises on an anti-gravity (also called lower-body positive pressure) treadmill have become common practice during the rehabilitation of athletic injuries [74]. Such exercises aim to provide physiological load with reduced biomechanical load, and, for both types of exercises, ground reaction forces are reduced by up to 20% depending on modality [75, 76]. The benefit of these exercises is that despite low biomechanical load, they involve walking or running locomotion that in the case of aqua jogging is only slightly altered due to water resistance [77], therefore these are favoured against cycling exercises, even if tissue loading due to impact is known to be negligible during cycling. Another example of load differentiation can be found in the load alterations, as observed when playing small-sided games. Studies have found that reducing pitch size reduces the physiological load [78, 79] but likely increases the biomechanical load [79, 80]. Another example is the use of high-intensity interval training (HIT) which delivers a high physiological load but with low biomechanical load. As suggested in a recent review on HIT [81], this could therefore be a practical example of the alternative training session that one may wish to schedule at time points 2 and 4 in Fig. 2. A final example is running on sand, where it was found to be possible to perform maximal intensity sprints involving high physiological load but reduce the biomechanical load (impact) considerably compared with what is typically experienced on a harder surface (e.g. concrete or grass) [82].

6 Conclusions

Huge amounts of data can be monitored on a daily basis. Turning these data into relevant information for players, coaches and therapists can be an extremely daunting challenge for a novice sports scientist entering the professional sporting environment. With this paper, we would like to encourage not only sport scientists to pursue further research according to a framework that differentiates physiological and biomechanical load-adaptation pathways, but also the broader coaching and sports medical staff in running-based team sports to venture into some of the biomechanical literature reviewed in this paper and sharpen their views on how monitoring training load can be a valuable tool for improving performance while preventing injury.

Compliance with Ethical Standards

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Conflict of interest Jos Vanrenterghem, Niels Nedergaard, Mark Robinson, and Barry Drust declare that they have no conflicts of interest relevant to the views shared in this article.

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