

Monitoring Explosive Performances in Relation to Training Load Accumulation in Adolescent Female Soccer Players

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

The Faculty of Graduate and Postdoctoral Studies

(Kinesiology)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

August 2018

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ABSTRACT

Athlete monitoring provides valuable insight into the balance of an athlete's stress and adaptation from training. Many methods exist to quantify athletes' allostatic state, with a physical performance measure a primary link to sport performance. However, little research has focused on a critical aspect of field sport performance, sprinting. Therefore, the purpose of this thesis was to investigate the utility of sprint monitoring using in-depth kinematic analysis. Training load was measured daily, as the product of session duration and rating of perceived exertion, in 32 adolescent female soccer players, comprising a U-15 and U-18 team. Measures of 7-day and 28-day cumulative training loads and 7-day to 28-day exponentially weighted moving average (EWMA) and rolling average (RA) acute to chronic workload ratios (ACWR) were calculated. Players performed a countermovement jump (CMJ) on a contact mat and a 30 m sprint bi-weekly, and completed a daily wellness questionnaire to assess training load response over 14 weeks. From the 30 m sprint, 10 and 30 m times were measured using timing gates, and maximal acceleration, maximal velocity, and time to maximal velocity were measured using a radar gun. Linear mixed models were used to assess the influence of training load on CMJ, 30 m sprint performance variables, and athlete wellness. Cumulative training load over 7 days had a likely small positive effect on 30 m sprint time ($d = 0.14$; 90% CL: -0.01 to 0.28), while 28-day cumulative training load had a likely small positive effect on 30 m sprint time ($d = 0.14$; 0.00 to 0.28), a very likely small negative effect on maximal sprint velocity ($d = -0.19$; -0.03 to -0.35), and a likely moderate negative effect on athlete wellness ($d = -0.35$; -0.02 to -0.68). EWMA and RA ACWRs had possibly small ($d = 0.18$; -0.14 to 0.49) and likely moderate ($d = 0.33$; 0.00 to 0.66) positive effects on wellness. All other relationships were unclear. Monitoring sprint performance should be considered to evaluate response to training loads, with sprint time indicative of acute and chronic loads, while maximal sprint velocity and athlete wellness were more suggestive of chronic loads.

LAY SUMMARY

Many methods exist to measure the balance between increasing fitness and minimizing fatigue in athletes, but a physical performance test is closely related to sport performance. However, little research has focused on a critical aspect of field sport performance: sprinting. Therefore, the purpose of this thesis was to investigate the utility of longitudinally tracking sprint performance in relation to training volume and difficulty. A rating of perceived exertion was used to quantify training difficulty, while countermovement jump, 30 m sprint, and subjective wellness questionnaire were used to assess athlete fatigue. Various methods used to calculate the difficulty of training showed that the more difficult or longer the training, the slower athletes ran over 30 m and lower maximal velocity achieved, and overall athlete wellness was impacted. Therefore, the coaching staff should plan training difficulty accordingly when trying to maximize physical performance.

PREFACE

This dissertation is an original, unpublished, independent work by the author, R. Poehling. The fieldwork reported in this thesis was covered by the University of British Columbia Clinical Research Ethics Board [certificate # H17-01318] approved August 2nd, 2017. The research was identified by Dr. César Meylan (Canadian Women's National Soccer Team Sport Scientist; Senior Strength and Conditioning Coach, Canadian Sport Institute Pacific) and proposed to the Vancouver Whitecaps F.C. Girls Elite Super Regional EXCEL Team. All testing was performed by me, with the assistance of Hélène Maystre (M.Sc. student from the University of Lausanne, Switzerland). All daily team monitoring was performed by me, with the assistance of Jamie Johnson (Athletic Therapist, Vancouver Whitecaps F.C. Girls REX).

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LIST OF ABBREVIATIONS

ACWR: acute to chronic workload ratio
ATP: adenosine triphosphate
AU: arbitrary units
CMJ: countermovement jump
cm: centimetres
CNS: central nervous system
Cohen's *d*: standardized mean difference
CR-10: Borg category ratio 10 scale
CV: coefficient of variation
DJ: drop jump
ES: effect size
EWMA: exponentially weighted moving average
F-v: Force-velocity
 F_0 : theoretical maximal force (N)
FT: flight time
FT:CT: flight time:contact time
GPS: global positioning system
GRF: ground reaction force
HR: heart rate
HS: high school age
Hz: hertz
kg: kilogram
km/h: kilometres per hour
LASSO: least absolute shrinkage and selection operator
LIST: Loughborough Intermittent Shuttle Test
m: metres
m/s: metres per second

min: minutes

NCAA: National Collegiate Athletic Association

NFL: National Football League

NM: neuromuscular

pH: power of hydrogen

P_{MAX} : maximal power (W)

PNS: peripheral nervous system

RA: rolling average

RPE: rating of perceived exertion

s: seconds

SAFT⁹⁰: 90-minute soccer-specific aerobic field test

SAS: Statistical Analysis Software

SBC: Schwarz Bayesian information criterion

SD: standard deviation

SJ: squat jump

sRPE: session rating of perceived exertion

sRPE_{mus}: local-muscular session rating of perceived exertion

SRSS: Short Recovery and Stress Scale

SWC: smallest worthwhile change

TE: typical error

TRIMP: training impulse

U-17: under 17 years old age group

UBC: University of British Columbia

UN: university age

V_0 : theoretical maximal velocity (m/s)

y: years

Yo-Yo IE2: Yo-Yo intermittent endurance test level 2

Yo-Yo IR2: Yo-Yo intermittent recovery test level 2

ACKNOWLEDGEMENTS

I would like to thank all of my previous athletes, coaches, colleagues, mentors, and my fellow students who constantly push me to question everything and try to find answers. Without this continual dialogue, I would not be where I am today and would not have formed the relationships I have to this point.

Thank you to Dr. Michael Koehle for originally putting faith in me and bringing me to Canada. I appreciate your guidance and support through the academic system, welcoming me into your lab, and supervising my graduate career.

Thank you to Dr. César Meylan for putting the pieces in place for me to do what I love. You have believed in me from day one and have graciously balanced academia, work, and skiing. I still don't know how you do all of it, but I am deeply indebted to the time you have put into me. I hope we can continue our conversations of how to make the best better.

Thank you to Dr. Ben Sporer for your expert opinion in applied sport and your willingness to answer my questions whenever needed.

Thank you to Dr. Jean-Sébastien Blouin for your willingness to find time for me throughout my studies and providing balanced advice to our eager practitioner dreams.

To the study participants and associated coaching staff: I am indebted to your willingness and commitment, especially the early, dark, rainy mornings. Without you there would be no results on which to base this thesis.

Finally, everything I do I owe a special heartfelt thank you to my parents for their unconditional love in everything I do, supporting my dreams whether they happen or not, and pushing me to be my best at whatever I do. I couldn't have done it without you. To my sisters, Katie, Annie, and Krissie, you never failed to add the last push of motivation to finish. You will always have my back, a place to sleep, a nice meal to share, or another bottle of wine to discuss life's dilemmas. Lastly, to my girlfriend, Sarah, you made sure I wouldn't sacrifice anything in my journey to Canada. You heard everything there is to hear about a thesis, while never hesitating to simply listen. I would not have been able to get through the long days in the gym, on the field, and writing without your support or

agreeing to ride with me early in the morning. I hope I can support you and take care of you half as much as you have for me over the last couple of years. Thank you.

1 INTRODUCTION

Athlete monitoring is utilized in high performance sport to regulate the amount of stress imposed on the athletes to optimize future performance. Monitoring can help determine whether an athlete is adapting to a stimulus, how individual athletes respond to a specific training load, gauging athlete fatigue and need for recovery, and help minimize the risk of overtraining, illness, and injury (Bourdon et al., 2017). By implementing a thorough monitoring system, the support staff can help maximize athlete availability, which has been related to team success (Arnason et al., 2004). However, little previous research has investigated the training response through consistent monitoring in female soccer players. The extent of the training load undertaken by adolescent athletes can have a large impact on their future development and participation in the sport. In track and field athletes, those that completed a higher yearly training load and at a higher intensity at 13-14 years old were more likely to sustain an overuse injury, which was also significantly correlated with forced retirement from the sport (Huxley, O'Connor, & Healey, 2014). Additionally on two instances, a higher training load in adolescent soccer players was correlated with increased rate of injury and illness, while decreased wellness was related to increased illness (Brink, Visscher, et al., 2010; Watson, Brickson, Brooks, & Dunn, 2016). An increased injury occurrence has been thought to inhibit consistency in training, which could lead to underperformance (Murray, 2017). This reduced consistency can hinder the gradual progression of increased training loads beneficial to the long-term development of these young athletes.

The stress imposed on the athlete is generally categorized into internal and external training loads (Halson, 2014; Wallace, Slattery, & Coutts, 2009). Internal training load is the physiological and psychological stress imposed on the individual. The corresponding measures of internal training load quantify the body's internal adjustments due to these stressors, such as heart rate (HR), blood lactate, cardiovascular utilization, and endocrine concentrations. These values will be unique to each player,

based on the complex interactions of all biological systems. Meanwhile, external training load is the amount of mechanical work completed irrespective of the internal measures. The corresponding measures of external training load quantify various forms of work the athlete completes during measurement, such as time, distance, velocity, power, and all of the subsequent derivatives.

It is important to use a combination of internal and external measures to get a more complete analysis of stress, fatigue, and recovery in the athlete. The body is an extraordinarily complex specimen with numerous inter-related systems, making the notion improbable that one specific training metric may be able to capture the psycho-emotional, physiological, neurological, immunological, and/or behavioral response to any multitude of combinations of training stimuli (Weaving, Jones, Till, Abt, & Beggs, 2017). Therefore, a useful approach may be to triangulate subjective, objective, and performance measures to produce a holistic measure of athlete fitness and fatigue. Using the triangulation approach, a subjective measure of training response/readiness, an objective response measure to training load, and an objective performance measure could be collected. By balancing these three measures, the sport scientist can more accurately prescribe the ensuing load to further emphasize fatigue or adaptation (Weaving et al., 2017).

In team sport, training load measures must be valid and reliable, but at the same time straightforward. Global positioning system (GPS) parameters are becoming a more routine external training load metric in professional and Olympic sport, but they are still expensive and labour-intensive. Most other ways of measuring distance, speed, and change of direction are inapplicable in team sport due the chaotic nature of player movement. Biochemical/hormonal measures and HR are internal training load measures that are commonly used in higher-level sport (Halson, 2014). Some of these measures may provide more in-depth indices, but many lower-level teams do not have the money or manpower to consistently employ these methods. Therefore, simpler measures are often utilized in amateur or youth sport.

An example of a very simple measure of internal training load is session rating of perceived exertion (sRPE), the product of session duration and rating of perceived exertion (RPE). This measure has been shown to be a valid and reliable indicator of training stress (Haddad, Stylianides, Djaoui, Dellal, & Chamari, 2017; Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004), a key factor in overtraining (Foster, 1998). In addition, sRPE has been shown to be correlated with both Banister's method of calculating training impulse (TRIMP) (Lovell, Sirotic, Impellizzeri, & Coutts, 2013) and Edward's method of calculating TRIMP (Kelly, Strudwick, Atkinson, Drust, & Gregson, 2016). Within the sRPE method, there is some concern in the research about the use of subjective measures in the adolescent population to track training load. Specifically, the Borg rating of perceived exertion scale has had mixed efficacy in adolescent populations (Chen, Chiou, Tzeng, Lu, & Chen, 2017; Eston & Williams, 1986; Impellizzeri et al., 2004; Lupo, Capranica, & Tessitore, 2014; Pfeiffer, Pivarnik, Womack, Reeves, & Malina, 2002; Rodríguez-Marroyo & Antoñan, 2015). Therefore, it may be more useful to use pictorial representations in the Borg scale to receive accurate feedback in training load data in an adolescent population (Chen et al., 2017).

Injury has an obvious impact on individual performance, but it can have further repercussions on team success (Arnason et al., 2004). The consistent and accurate implementation of training load can have profound effects on injury status in many team sport athletes (Eckard, Padua, Hearn, Pexa, & Frank, 2018). With a multitude of ways to measure training load, much of the literature has focused on the use of the sRPE measure previously mentioned. Originally stemming from the Banister fitness-fatigue model (Banister, Calvert, Savage, & Bach, 1975), Hulin et al. (2016) coined the acute:chronic workload ratio (ACWR) to provide an index of fatigue (acute 7-day load) compared to fitness (chronic 28-day load). They subsequently found high workload ratios (> 1.5) to be associated with a greater risk of injury. The ACWR has since been used a multitude of times to demonstrate similar findings in rugby league, Australian rules football, cricket, and soccer (Blanch & Gabbett, 2016; Carey et al., 2017; Collins, Roe, Malone, & Bennett, 2017; Hulin, Gabbett, Caputi, Lawson, & Sampson, 2016; Malone, Owen, et al., 2017).

Since then, there has been debate whether to use a rolling average (RA) calculation, or an exponentially weighted moving average (EWMA) calculation to calculate ACWRs (Drew, Blanch, Purdam, & Gabbett, 2017; Menaspà, 2017). Rolling averages may be more stable through daily variation, while on the other hand, it does not take into account the decaying nature of fitness or how recent a large workload took place. Williams, West, Cross, and Stokes (2017) suggest an EWMA to calculate the ACWR, which assigns a decreasing weighting for progressively older values to take into account the progressive building and/or decaying of fitness and fatigue. Murray et al. (2017) presented evidence from Australian rules football that an EWMA ACWR was more sensitive to risk of injury than the RA method. Meanwhile, a principal component analysis by Williams et al. (2017) of ten derivatives of sRPE found that 4-week cumulative load, RA ACWR, and daily training load represented the closest relationship to injury risk in professional rugby league. Nevertheless, there have been mixed results in adolescent populations whether ACWRs are indicative of future injury risk (Bowen, Gross, Gimpel, & Li, 2017; Rodríguez-Marroyo & Antoñan, 2015). But there is a suggestion that a ACWR may provide a dose-response relationship to countermovement jump (CMJ) performance (Collins et al., 2017).

The prediction of injury prevalence in relation to training load seems to be a topic of particular interest to researchers currently, but training load's association to athletic performance may be more informative, if accurately modelled. Various attempts to forecast future endurance performance have shown promise (Banister et al., 1975; Foster, Daines, Hector, Snyder, & Welsh, 1996; Wallace, Slattery, & Coutts, 2014), but little has been done to predict physical performance in a dynamic team sport environment. Lazarus et al. (2017) is the only study utilizing training load measures to model subsequent match performance, using a unique performance score. Other previous research has also analyzed the association between past training load measures and physical performance tests. Total training duration the week before a monthly submaximal intermittent fitness test significantly related to endurance capacity in youth soccer players (Brink, Nederhof, Visscher, Schmikli, & Lemmink, 2010). Additionally, Los Arcos et al. (2014) found accumulated local-muscular sRPE (sRPE_{emus}) to be negatively

correlated with 15 m sprint velocity, while total training and competition time was negatively correlated with CMJ after nine weeks of soccer training. By tracking measures of training load through time, one can start to associate how different levels of training load can affect overall fatigue in their population.

Athletic Performance Fatigue

Fatigue is an integral aspect of training and competition load which must be monitored to minimize its impact on optimal athletic performance. Fatigue has previously been defined as the failure to maintain the required or expected force (Edwards, 1981) or speed at which a muscle contraction is performed (Bigland-Ritchie, 1981). More holistically, this can be defined as a reduction in performance (Knicker, Renshaw, Oldham, & Cairns, 2011). Fatigue can be broken down into the perception of fatigue and measured decrements in function. Additionally, monitoring of athletes using multiple methods can help differentiate between psychological fatigue and neuromuscular (NM) fatigue (Twist & Highton, 2013). Although, both psychological and NM fatigue can reduce performance, they may have different time-courses for recovery based on the mechanism of fatigue.

Psychological fatigue, or mental fatigue, is the subjective feeling of tiredness, lowered concentration, or lack of energy (Knicker et al., 2011; Marcora, Staiano, & Manning, 2009). Purely psychological fatigue can manifest from any number of sources, from outside life-events and relationships to overloaded school, work, or sport tactical learning and assessments. On the other hand, cognitive function can be impaired from hydration, sleep, and drugs, among others (Knicker et al., 2011; Nédélec, Halson, Abaidia, Ahmaidi, & Dupont, 2015). Athletic performance, including soccer-specific physical, technical, and perceptual–cognitive performances (Smith et al., 2018), can be affected by both psychological fatigue and reductions in cognitive function, but psychological fatigue may be more easily overcome. It does not appear that there is a specific physiological determinant to psychological fatigue unlike reduced cognitive function, instead athlete motivation tends to be the limiting factor (Van Cutsem et al., 2017). The athlete will be

less willing to go farther in an endurance test, therefore HR or blood lactate will be lower at the end of a trial. At the same time, motivation can also be acutely increased and thus, overcoming any performance decrement caused by mental fatigue (Hopstaken, van der Linden, Bakker, & Kompier, 2015). Additionally, it should be noted that it seems that acute exercise does not cause mental fatigue, and in some cases it will actually improve some artificial sport-related decision making tasks (Knicker et al., 2011). Psychological fatigue can simply be monitored through a wellness questionnaire, making tracking of it accessible to any team. Psychological fatigue can outlast objective biochemical and performance markers of fatigue, making it imperative to distinguish between psychological and physiological fatigue (Twist, Waldron, Highton, Burt, & Daniels, 2012). Even more importantly, psychological fatigue is critical in diagnosing overtraining syndrome (Meeusen et al., 2013; Twist, Waldron, Highton, Burt, & Daniels, 2012).

In contrast to psychological fatigue, NM fatigue is rooted in specific physiological origins. It can be thought of as a reduction in the maintenance of force caused by factors between the initiation of electrical activity in the central nervous system (CNS), through the excitation/contraction coupling process, to various metabolic and enzymatic processes providing energy for contractile sites (Bigland-Ritchie, 1981). The fatigue related to the cascade of processes can then be broken down into central and peripheral fatigue, which can be defined as proximal or distal to the neuromuscular junction (Gandevia, 2001). Central fatigue is the failure of neural drive (Edwards, 1981), whereas peripheral fatigue can be classified as the reduction in the ability to produce force through compromised contractile mechanisms and/or depolarization of the muscle fiber membrane (Taylor, Amann, Duchateau, Meeusen, & Rice, 2016).

The central and peripheral fatigue processes combine to affect overall muscle function. Physical output has been shown to decrease throughout a soccer match, and during a congested schedule period (Arruda et al., 2015; Moreira et al., 2016; Russell et al., 2016). The most likely mechanisms for temporary within-match fatigue are changes in intramuscular phosphates and accumulation of potassium, along with a multitude of other changes in biochemical concentrations (Krustrup et al., 2006). Additionally,

accumulated fatigue over the course of an entire match is likely caused by a reduction in muscle glycogen, which can be coupled with low pre-match muscle glycogen to affect overall performance (Datson et al., 2014; Krstrup et al., 2006). Further, fatigue due to either high overall training loads or a congested schedule can be caused by reactive oxygen species muscle damage, and impaired motor drive (Andersson et al., 2008; Rampinini et al., 2011). A combination of central and peripheral fatigue are present during the initial stages of recovery after a simulated soccer match, but it seems that peripheral fatigue compromising skeletal muscle function may predominantly be responsible for reduced NM performance in the 48 to 72 hours (h) post-match (Rampinini et al., 2011; Thomas, Dent, Howatson, & Goodall, 2017). Regulation of muscular performance is crucial to prevent catastrophic damage to the NM junction or other intracellular mechanisms (Gandevia, 2001). These mechanisms would damage the excitation-contraction coupling and actin-myosin interaction, which may prevent further muscle contraction if regulation failed.

Recovery from central and peripheral fatigue can span from seconds to days, depending on the mechanism and load producing the given fatigue. Therefore, consistent monitoring and an ability to distinguish between psychological, central, and peripheral fatigue is important to dictate further loading and recovery strategies in high performance sport. Although being able to distinguish various fatigue factors can help influence future activities, ultimately, performance is the main outcome that needs to be assessed and regulated.

Monitoring Fatigue in Sport

As previously mentioned, monitoring in athletes should incorporate a multifaceted approach. Many techniques exist to specifically measure NM function and central versus peripheral fatigue, but these are all but impossible to consistently incorporate in a team environment. A common technique to measure NM fatigue in a lab is to use electrical stimulation and maximal voluntary contractions (Thomas et al., 2017).

However, this process is time consuming, may add unnecessary load and soreness, and may be specific to only one muscle group. Therefore, the focus of the current investigation was only on a physical performance approach where total body function is assessed instead of specific muscle or neural structures. The tests used in a team setting must be fast, efficient, and must not substantially add to the overall load (Thorpe, Atkinson, Drust, & Gregson, 2017). One dimension of this monitoring would be to assess the subjective well-being of the individual, while another dimension would be to assess the physical performance of the athlete.

Athlete self-report measures, or wellness questionnaires, as well as measures of physical performance, can be implemented to assess the relative fatigue of an athlete in relation to training load and to provide an individualized insight into the training-stress response (Saw, Main, & Gastin, 2016). A wellness questionnaire is a subjective measure used in sport to assess athlete well-being and psychological fatigue. The questionnaire can consist of the athlete answering several questions regarding general stress, fatigue, motivation, soreness, sleep, among many others in order to evaluate one or more of the elements of mood, stress, recovery, symptoms, and emotions (Saw, Kellmann, Main, & Gastin, 2017). Wellness questionnaires have been shown to be sensitive to changes in training load in professional soccer players across the training week (Thorpe et al., 2016b). Furthermore, these subjective measures are also associated with previous days high-speed running distance (Thorpe et al., 2016a), making the use of these simple questionnaires very beneficial for teams with fewer staff or technologies to specifically track external load. Wellness questionnaires subjectively assess the athlete's training response, but physical performance measures can be used to objectively assess the athlete's training response. These physical performance measures can include a variety of jumping and sprinting protocols to elicit maximal effort relative to baseline to quantify current fatigue (Twist & Highton, 2013).

Jump protocols are commonly used to aide teams in assessing athlete readiness (Taylor, Chapman, Cronin, Newton, & Gill, 2012). CMJ, squat jump (SJ), and drop jump (DJ) are the most often used jumping techniques in team sports (Marrier et al., 2017). The

CMJ tends to be the preferred choice among practitioners because it does not require a box like the DJ, it may be more reliable compared to the DJ because there is less variation in step-off or drop height, and it is more specific to sport movement utilizing the stretch-shortening cycle instead of a static hold or exaggerated eccentric movement before the concentric phase. Additionally, it tends to be relatively easy to get athletes to perform maximally in vertical jumps because of intra-squad competition and the brief nature of the maximal effort.

Jumps are often completed with an external measurement source (e.g. Vertec™ device or tape measure), a contact mat, or a force plate with or without a linear position transducer. Initially, these sources were only used to measure jump height to assess total physical performance in a maximal action. In an adolescent cohort, CMJ height was sensitive to both post-match fatigue, and accumulated fatigue over a seven-week period (Oliver, Lloyd, & Whitney, 2015). In high-level female soccer players, CMJ height stayed depressed after a match for 69 hours leading into another match (Andersson et al., 2008). Training volume and sRPE_{mus} were found to negatively correlate with single-leg and double-leg CMJ height in young male soccer players (Los Arcos, Martínez-Santos, Yanci, Mendiguchia, & Méndez-Villanueva, 2015). Interestingly, a recent investigation found a z-score of -1 in CMJ height pre-training produced a likely negative inference in GPS performance variables in the subsequent training session (Malone et al., 2017). Therefore, CMJ height may possibly be used as a predictor variable for relative intensity in future training sessions. However, it was noticed that the same jump height can be produced by a multitude of movement techniques (Cormie, McBride, & McCaulley, 2009).

Although jump height has previously been found to be a reliable indicator of fatigue, further analysis has found alternative jump variables to be more strongly related to training load. Jump flight time (FT), used by a contact mat and force plate without a linear position transducer to calculate jump height, may also be sensitive to fatigue. Flight time was moderately correlated with wellness scores during a six-week training period, however peak displacement measured with a linear position transducer was not correlated to wellness or training load (Gathercole, Sporer, & Stellingwerff, 2015).

Gathercole, Sporer, Stellingwerff, and Sleivert (2015b) found specific jump mechanical variables to be more indicative of NM fatigue than jump height alone. Furthermore, a more congested training load of only a seven-day microcycle between rugby league games caused a significant reduction in CMJ relative power compared to a nine-day microcycle between games (McLean, Coutts, Kelly, McGuigan, & Cormack, 2010). Lastly, jump height within 18 h post-soccer match was sensitive to varying degrees of match load, but not at 42 h or more, while a flight time:contact time ratio (FT:CT) tended to be sensitive through 66 h post-match (Rowell, Aughey, Hopkins, Stewart, & Cormack, 2016).

At the same time, CMJ may not be sensitive to changes in training load. During a three-week taper, FT:CT and CMJ height did not change with corresponding changes in metres per minute, high-intensity distance, high-intensity distance per minute, repeated high-intensity effort count, tackle count, and training duration (Gibson, Boyd, & Murray, 2016). CMJ height was not affected 24 h after a soccer match in U-17 males compared to immediately before the match (Buchheit, Mendez-Villanueva, Quod, Poulos, & Bourdon, 2010). Moreover, jump height did not change over a four-day microcycle in youth soccer players before or after the training session (Malone et al., 2015). However, CMJ height tended to increase from pre-training to post-training, meaning the warm-up may have not been sufficient or the athletes did not perform maximally pre-training.

When compiling a regular monitoring system, time of completion and ease of analysis are of the utmost importance. A CMJ would be quicker to complete and analyze depending on the systems and software in place and may be easier to convince athletes to perform maximally. Various forms of jumping may be easily performed, but in many team sports jumping does not make up a large percentage of game time. Sprinting has been shown to be the most prominent action leading to a goal in soccer (Faude, Koch, & Meyer, 2012). Therefore, running or more precisely sprinting, may be a more specific indicator of fatigue. A review of sprint monitoring literature can be found in Appendix A. Maximal velocity was moderately reduced 24 to 72 h post-soccer match (Nédélec et al., 2014). Sprint times over 20 metres (m) were significantly impaired 30 minutes (min) after an intermittent exercise test and a soccer match, and continued to be impaired for 72 h

after both types of exercise (Magalhães et al., 2010). Over a season, 15 m sprint time increased with a corresponding increase in a localized sRPE of respiratory stress during training (Los Arcos, Martínez-Santos, Yanci, & Mendez-Villanueva, 2017), meaning increases in training load could have a detrimental effect on subsequent sprint performance. However, Gathercole et al. (2015) found sprint times to be the most affected variable immediately post-exercise, more so than CMJ and DJ, but then recovered by 24 h post-exercise. Sprint times over 10 and 20 m were reduced immediately after a simulated soccer match, but then were recovered at 24-72 h post-match (Thomas et al., 2017). Also, sprint velocity at 10, 20, and 40 m at four time points over a season were not correlated to related changes in training load (Gabbett & Domrow, 2007). There seems to be conflicting evidence whether sprint times are an effective measure of fatigue, similar to measuring jump height. Therefore, as with jumping analysis, a more in-depth approach may be warranted investigating mechanical variables for sprint performance.

New technologies have been employed to investigate more complex sprint variables beyond time to cover set distances. In recent literature, tools such as instrumented treadmills, optical measurement systems, video analysis, horizontal linear position transducers, and laser/radar guns have been utilized (Debaere, Jonkers, & Delecluse, 2013; Morin & Sève, 2011; Romero-Franco et al., 2017; Samozino et al., 2016; Townsend et al., 2017). All of these technologies have their advantages and disadvantages, but few provide the flexibility for use in the field and are not constrained by a set distance. Radar guns provide an even balance of freedom from a lab setting, with few limitations on distance measures. The advantage to using a radar gun is that instantaneous velocity is recorded throughout the sprint, making analysis more thorough. With the instantaneous data, derivation can provide acceleration data to investigate changes in velocity, which could provide information on different physiological systems compared to velocity alone. Similar to force-velocity (F-v) profiling variables such as theoretical maximum force (F_0) and theoretical maximum velocity (v_0), maximal acceleration and maximal velocity can be utilized from the radar data (di Prampero, 2005;

Roe et al., 2017). This provides information for either bounds of the muscular strength and velocity spectrums, producing a more complete picture of an athlete's abilities.

It has long been known that there needs to be a certain level of specificity in an athlete's physical training (Behm & Sale, 1993; Moffroid & Whipple, 1970). When considering muscular contraction and body segment velocities, physical training needs to encompass a wide range of velocities to improve all aspects of the F-v relationship. At the same time, it is known that training one specific movement velocity will mostly benefit that same area of the F-v curve, so to train maximal sprint velocity one must move at similar velocities (Cormie, McGuigan, & Newton, 2011; Djuric et al., 2016). Using this information, it lends itself to the notion that athletes generally need to sprint to improve sprinting. In addition to improving performance, sprint training can also help reduce injury risk. Using the previously mentioned ACWR, practitioners have been able to prescribe a suitable daily training load which is thought to reduce injury risk. Using the ACWR and similar metrics, accumulating higher chronic training loads, while also regularly reaching above 95% maximum velocity in training can help decrease injury risk (Malone, Roe, Doran, Gabbett, & Collins, 2017). Consequently, providing an arena for athletes to attain maximum velocity during the training week rather than assuming it will be reached within the training session would be recommended.

Relevance and Significance

Athlete monitoring systems provide invaluable insight into the stress and adaptation of individual athletes, with the goal to reduce injury risk and increase performance at key events. The current literature sheds light on utilizing accumulated training load and ACWRs to monitor injury risk in a variety of sports, but its effect on performance is scarce. Further, there are a number of studies demonstrating the relationship between subjective wellness questionnaires and increased risk of injury and illness in adolescents. Additionally, much of the research has focused on the CMJ as a primary means of a performance measure in athlete monitoring, however this is

nonspecific to most field-based team sports. Therefore, with the advance of measuring sprints through the entire motion, more informative variables can be used to assess an athlete's performance. The addition of a sprint monitoring system would thus provide a suitable environment for maximal sprint effort, while simultaneously allowing for collection of valuable information to further individualize training load and strength and conditioning programs. Additionally, across all of the various aspects of the literature, there are an increasing number of publications investigating the effects on youth male soccer players, but there is still a scarcity in the literature on the effects on adolescent females in any sport. We know that men and women have different physical outcomes during a typical training session (Clemente & Nikolaidis, 2016), making inferences from adolescent male research difficult to implement with adolescent females.

Purpose, Hypothesis, and Objectives

The efficacy of CMJ to monitor fatigue has had mixed results and is relatively non-specific to the large majority of team sport movements. Therefore, the proposed study strives to use a more specific measure of fatigue, measuring sprint acceleration kinematic variables in the field as well as the traditional measure of CMJ. The action of sprinting can provide a training stimulus to improve sprint performance, while simultaneously reducing injury risk to some lower-body soft tissue injuries. The information obtained from regular sprint monitoring may provide valuable information regarding the current fatigue status of the athlete and susceptibility to future injury, while also providing specific information for prescription of individualized physical training programs. Further, specific information will be gleaned on the training response in adolescent female soccer players, where little other information currently exists.

We hypothesized increasing training load to have a negative effect on overall sprint performance due to an accumulation in fatigue. As training load increased, sprint performance was predicted to diminish due to a decrease in peak acceleration in the initial 1.0 seconds (s) of the sprint, which would also be observed in an increase in 10 m

sprint time. Furthermore, time to maximal speed was anticipated to increase due to the slower initial acceleration. The accumulation of fatigue shown in diminished sprint performance was also expected to be found in decreased CMJ height and reduced wellness scores. Thus, the major objectives of the current project are as follows:

- To provide insight on the fatigue response of high-level adolescent female soccer players by investigating whether a meaningful relationship exists between sRPE-derived training load and sprint performance kinematics, defined as maximal sprint acceleration, maximal sprint velocity, and time to maximal sprint velocity, along with sprint time.
- To corroborate whether the accumulation in training load also affects CMJ height and wellness scores, as found in previous research.
- To examine the efficacy of 7-day and 28-day cumulative training load measures, and rolling average and exponentially weighted moving average acute:chronic workload ratios in high-level adolescent female soccer players.

2 METHODS

Participants

Thirty-two adolescent female soccer players from a national training centre were recruited. They were part of two separate teams, consisting of an Under-15 [$n = 14$, mean \pm SD age 14.7 ± 0.7 y, mass 54.5 ± 7.6 kg, height 164.7 ± 7.0 cm, maturity offset -0.1 ± 0.7 y] and an Under-18 [$n = 18$, 16.7 ± 0.7 y, 60.3 ± 5.4 kg, 167.9 ± 5.9 cm] team. The players ranged from 13 to 18 years old, and were selected by the coaching staff as part of the pathway to national team programs. A typical training week is shown in Table 1. There was not a defined pre-season period, but the training load was planned to gradually increase over the first three weeks of training before the study period started. The team only played in friendly games during the study period. The team typically completed one strength training session (Table 2), one speed and power session (Table 3), four technical training sessions, and one friendly match per week. The team usually took two successive days off over the weekend. All participants were presented the protocols and relevant information before agreeing to partake in the study. Once the player had agreed to partake in the study, along with their parent/guardians, they provided written informed consent conforming to the UBC Clinical Ethics Board.

Table 1 Typical Training Week with Associated Session Time (min) and sRPE (arbitrary unit - AU)

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM	Speed/Power			U-18 Strength	U-15 Strength	OFF	OFF
	<i>U-15: 66 ±4 min, 4.2 ±0.9 AU</i>			<i>67 ±2 min, 4.2 ±0.8 AU</i>	<i>69 ±2 min, 4.5 ±0.9 AU</i>		
	<i>U-18: 68 ±3 min, 4.3 ±0.9 AU</i>						
PM	Technical Training	Match	Recovery + Technical Training	Technical Training	Technical Training		
	<i>U-15: 96 ±12 min, 5.4 ±1.3 AU;</i>	<i>U-15: 70 min, 7.0 ±1.3 AU;</i>	<i>U-15: 84 ±8 min, 4.5 ±1.1 AU;</i>	<i>U-15: 89 ±16 min, 5.8 ±1.4 AU;</i>	<i>U-15: 82 ±9 min, 4.7 ±1.1 AU;</i>		
	<i>U-18: 91 ±13 min, 5.1 ±1.6 AU</i>	<i>U-18: 90 min, 6.0 ±1.6 AU</i>	<i>U-18: 82 ±9 min, 4.4 ±1.2 AU</i>	<i>U-18: 86 ±4 min, 4.9 ±1.1 AU</i>	<i>U-18: 89 ±11 min, 5.2 ±1.5 AU</i>		

Average training session durations ± SD (minutes) and rating of perceived exertion ± SD (Arbitrary Units) over the study period.

Table 2 Typical Strength Training Session

Group	Exercise	Sets X Reps	Intensity
1	Back Squat		
	Incline Bench Row		
	Anterior Hip Mobility		
2	Single-leg Romanian Deadlift		
	Pull-up		
	Banded Ankle Mobilisation		
3	Dumbbell Bench Press		
	Single-leg Bench Hip Extension		
	Thoracic Spine Rotation		
	Overhead Weighted Carry	2 x 20 m	Medium
	Forward Bear Crawl	2 x 20 m	

1RM 1 repetition maximum, m metres

Protocol

In this descriptive longitudinal study, the teams were monitored over the course of the autumn season, commencing September 11, 2017 and concluding December 15, 2017, lasting 14 weeks. Training load was collected after each training session, wellness was collected every morning, and performance measures were measured once a week. The performance tests were conducted on Monday morning, usually after two consecutive days off from training. The training sessions were always at the same time in the morning, except one session, which was two hours later, and were conducted outside on a sports turf field.

Table 3 Typical Speed and Power Training Session

Group	Exercise	Sets X Reps	Intensity
Speed	Sprint (<i>monitoring protocol</i>)	2 x 30 m	
	Bounding	2 x 15 m	
Plyometrics	Drop Landing (<i>15 cm</i>)	2 x 4	
	Lateral Bound Stabilisation	2 x 3 each leg	
	Banded Lateral Walk	2 x 10 m	
	5 m Square Agility	4 x 20 m	
1	Bulgarian Split Squat Jumps	3 x 6 each leg	30%
	Front Plank/Lateral Plank	3 x 20 s	
	Broad Jump	3 x 5	

m metres, *s* seconds

Daily Protocol

Upon waking each morning, each athlete completed an athlete self-report measure (wellness questionnaire) through an online reporting system. The Short Recovery and Stress Scale (SRSS)(Hitzschke et al., 2015) was used to assess how well the athlete felt they were recovering from the training load, and how well the athlete felt they were enduring stress. The reliability (Cronbach $\alpha = 0.74$ to 0.89) and construct validity ($r_s = -0.64$ to 0.64) of the English translation of the German scale have recently been established (Nässi, Ferrauti, Meyer, Pfeiffer, & Kellmann, 2017). The scale asks the

athletes to rate four items of recovery and four items of stress, on a 0-6 scale (Appendix B).

After every strength training, conditioning, and technical training session, sRPE was recorded for each athlete. The total duration of the session (in minutes), including warm-up, was documented. Each athlete rated the session intensity on a modified Borg Category Ratio 10 scale (CR-10). The scale consisted of various facial expressions as descriptors for numbers from 0 to 10 (Appendix C). The facial RPE scale has been found to be a better indicator of training load in children compared to words alone (Chen et al., 2017). The session duration was then multiplied by the RPE to calculate training load (sRPE).

Weekly Protocol

Once a week on Monday morning, CMJ and 30 m sprint were performed to assess explosive performance and possible fatigue. The CMJ is when the athlete jumps using a common dip-then-explode technique, which utilizes a longer ground contact time and shorter eccentric phase, making the CMJ more specific to the acceleration component of sprinting. The two teams alternated between the monitoring session and a speed technique session, therefore athletes completed the monitoring protocol every two weeks. Athlete body mass was recorded before each weekly monitoring session. Athlete height was measured every four weeks to ensure accurate stature measures were utilized in the calculations. For athletes under 15 years old, maturity offset from peak height velocity was calculated to determine their stage of maturation (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). During the monitoring session, athletes were reminded of their last sprint time/jump height and their personal best time/height to increase the weekly motivation. A standardized warm-up (Appendix D) was conducted to prepare the athletes for sprinting. Two trials of the 30 m sprint and CMJ were averaged to increase the reliability of the measure. After each sprint, the athletes were given 2 minutes of passive rest while they changed from soccer cleats to flat-soled athletic shoes. After this rest

period, they performed two CMJs with 30 seconds of rest between the jumps. The athlete then changed footwear again, back to their soccer cleats to complete the second sprint. The CMJ height was measured using a contact mat (Just Jump System, Probotics Inc, Huntsville, AL), and performed with the participant's hands on her hips to exclusively assess lower limb power. Jump height was recorded for each jump.

Data Processing

The eight SRSS values were summed to provide a total wellness score. This entailed inverting the stress scale, making a higher number correspond to less stress and vice-versa. Therefore, a maximal score of 48 was the most recovered. A z-score of the total wellness score for each individual was then used for analysis to consider the individual's absolute average and normal variation during the study.

Training load was calculated for each training session using sRPE. On days where multiple sessions were completed, the training load was summed for a daily total. Cumulative training loads were calculated by summing the daily training loads over a 7-day period and a 28-day period. Additionally, ACWR ratios were calculated using 7-day acute and 28-day chronic periods, with the 7-day period overlapping and consisting of the most recent 7-days of the 28-day period. Although recently there has been concern with the spurious correlation of overlapping ratios, there has not yet been sufficient evidence utilizing an uncoupled ratio to warrant its use (Lolli et al., 2017; Windt & Gabbett, 2018). The EWMA was calculated as

$$EWMA_{today} = Load_{today} \times \lambda_a + ((1 - \lambda_a) \times EWMA_{yesterday})$$
$$\lambda_a = 2/(N + 1)$$

where N was chosen as 7 days for the acute load and 28 days for the chronic load (Williams et al., 2017). The results from the first four testing sessions were not considered in the analysis until a complete 7:28-day ratio could be calculated.

To assess 30 m sprint performance, the athlete started in a stationary crouched position, 0.3 m behind the start line. The sprint was measured using dual-beam electronic

timing gates (Swift Performance Equipment, Lismore, Australia) at 10 and 30 m and a radar gun (Stalker ATS II, Applied Concepts, Dallas, TX, USA) set up 3 m behind the start line, 1.0 m above the ground corresponding to roughly the height of the center of mass, acquiring velocity data at 46.9 Hz during the sprint acceleration. The radar gun was mounted via a bracket to a tripod and connected to a laptop computer to reduce any reliability issues with handheld operation. The data were collected without any data processing filter, then plotted in Microsoft Excel and cut at the first increase above 0.44 m/s (baseline). To determine the sprint acceleration variables, a 10 Hz Butterworth filter was applied using a Microsoft Excel add-in (Erer, 2007; Van Wassenbergh, 2007), followed by a 0.597 s rolling average, which corresponds to the time for the fastest athlete to cover 5 m. The rolling average was calculated for any given time point as an average velocity of the previous 0.278 s and the preceding 0.298 s. A 10 Hz filter was used to smooth irregularities in the data while minimizing the loss in sensitivity through reduced frequencies. Additionally, a rolling average was used to further smooth the data, while considering the time to cover a 5 m distance to be the smallest practically significant timeframe that would meaningfully impact soccer performance. Figure 1 depicts a sprint acceleration in the raw format and using the previously mentioned smoothing techniques. Maximal acceleration (derivative of velocity data) in the first 1.0 s was used to determine initial maximal acceleration ability (Inter-day Coefficient of Variation (CV) from first three weeks = 12.2%), maximal velocity during the entire effort was used to determine maximal velocity (CV = 2.1%), and time to maximal velocity was used to determine how quickly an athlete can reach maximal velocity (CV = 20.0%). Ambient weather variables (temperature, humidity, barometric pressure, and wind speed) were recorded during each session using a Kestrel 5400 handheld weather meter (Nielson-Kellerman Co., Boothwyn, PA, USA).

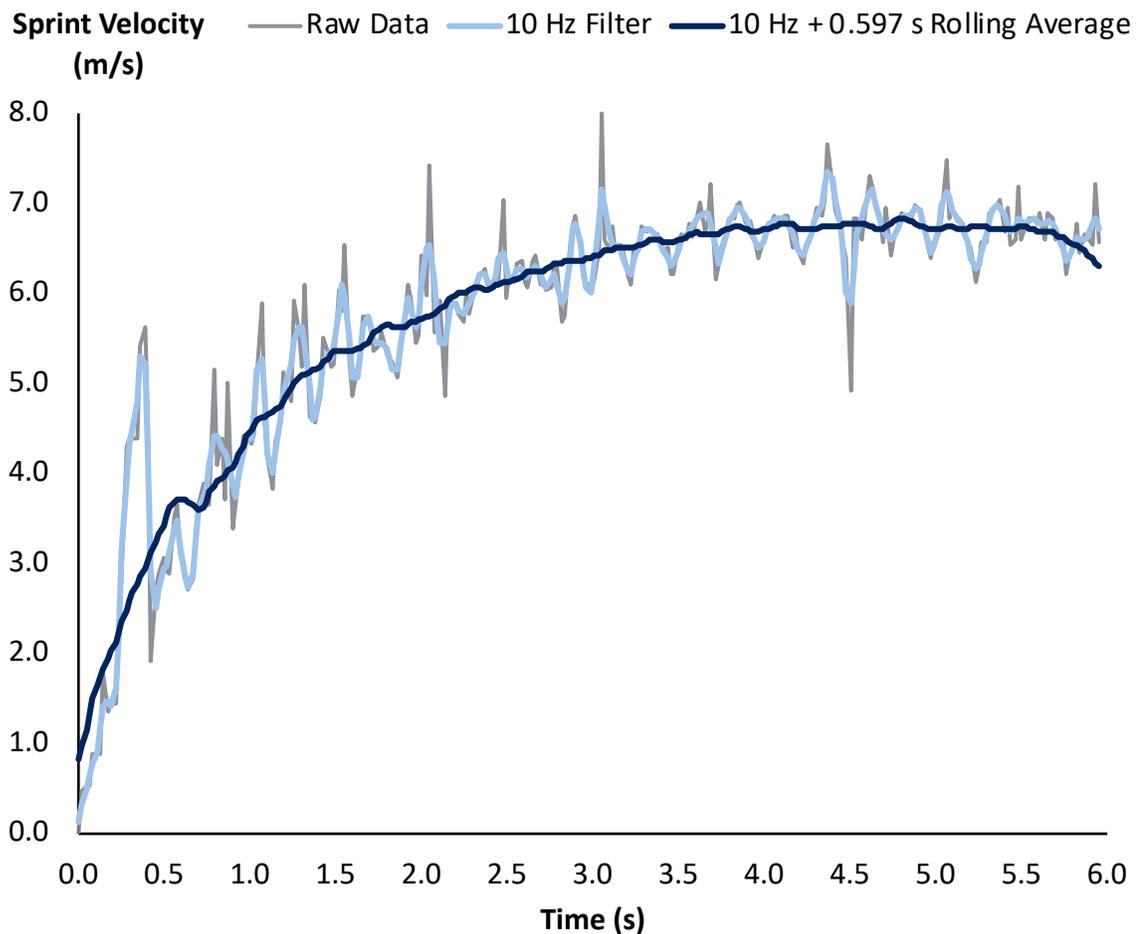


Figure 1 Filtering of Raw Sprint Velocity

A single subject's raw sprint acceleration velocity data from a 46.9 Hz radar gun over 30 m (silver), after using a 10 Hz Butterworth filter (light blue), and after using a 10 Hz Butterworth filter plus a 0.597 s rolling average (navy).

Statistical analysis

Data were analyzed using SAS University Edition via the Proc Mixed function (SAS Institute, Cary, NC). A linear mixed model approach was used to analyze the data due to the repeated measures design and missing data points. Before the mixed model analysis was conducted, a least absolute shrinkage and selection operator (LASSO) regression was used to select the covariates that significantly contributed to the model design. The covariates considered were date, team (U-15, U-18), age, position (outfield, goalkeeper), height, weight, maturity offset, temperature, and wind speed and direction. The LASSO was specified using the Schwarz Bayesian information criterion (SBC), with the entry criteria set to stop selection when the next step would yield a model with an SBC value 2 units greater than the current model. Team was the only covariate deemed meaningful to the model. Therefore, within the mixed models, the performance variables were considered the dependent variables, training load measures were the fixed effects, team was a covariate, and each player was considered a random effect. The dependent variables were log transformed to homogenize the residuals, and consisted of 10 m sprint time, 30 m sprint time, CMJ height, maximal sprint acceleration, maximal sprint velocity, time to maximal sprint velocity, and wellness z-score. The training load measures were all mean-centred by individual, and consisted of 7-day cumulative training load, 28-day cumulative training load, RA ACWR, and EWMA ACWR.

Results were then assessed based on magnitude-based inferences (Hopkins, Marshall, Batterham, & Hanin, 2009). The effect of the fixed effects were calculated by assessing a two standard deviation (2 SD) difference in the fixed effect, due to the difficulty of calculating a correlation coefficient from mixed effects models (Roy, 2006). A 2 SD difference can be considered as the difference between a typically high and typically low training load, and 'ensures congruence between Cohen's threshold magnitudes for correlations and standardized differences' (Hopkins et al., 2009). The magnitude of the 2 SD difference was then expressed as a standardized mean difference (Cohen's *d*), using the pooled standard deviation (Cohen, 1988). The likelihood that the changes in the

dependent variables were greater than the smallest worthwhile change (SWC) and therefore practically important were assessed as 0.2 x observed between-participant SD, based on Cohen's *d* effect size (ES) principle. Threshold values for Cohen's *d* statistic were set as: <0.2 *trivial*, 0.2-0.59 *small*, 0.6-1.19 *moderate*, 1.2-1.9 *large*, >2.0 *very large*. The threshold values were doubled to evaluate the random effects, instead of halving the ES thresholds (Smith & Hopkins, 2011). Confidence intervals (90%) for the (true) mean relationship in the training response were estimated (Hopkins et al., 2009). Based on 90% confidence intervals, the thresholds used for assigning qualitative terms to chances were as follows: <0.5% *almost certainly not*; 0.5-5% *very unlikely*; 5-25% *unlikely*; 25-75% *possibly*; 75-95% *likely*; 95-99.5% *very likely*; >99.5% *almost certainly*. If the chance of having a positive and negative relationship were both >5%, the true relationship was assessed as unclear (Hopkins et al., 2009). Descriptive data are reported as means \pm SD or median \pm interquartile range (IQR), and effect sizes are reported as ES; 90% confidence intervals.

3 RESULTS

The mean weekly training load for each team is shown in Figure 2. The mean weekly training load for the U-15 team was 2384 ± 585 arbitrary units (AU) and the U-18 team was 2547 ± 477 AU. The mean 28-day cumulative training load for the U-15 team was 8078 ± 749 AU and the U-18 team was 8142 ± 690 AU. The mean RA ACWR and EWMA ACWR for the U-15 team was 1.03 ± 0.25 and 0.92 ± 0.22 , and the U-18 team was 0.98 ± 0.14 and 0.91 ± 0.16 , respectively. The average daily response rate of the wellness questionnaire was $83.1\% \pm 13.3\%$. Median values of all of the performance variables are shown in Table 4.

Table 4 Performance Variables by Team

	U-15	U-18
CMJ (cm)	40.8 ± 7.4	44.3 ± 5.3
10 m Sprint (sec)	2.10 ± 0.11	2.02 ± 0.10
30 m Sprint (sec)	4.99 ± 0.19	4.75 ± 0.22
Maximal Acceleration (m/s ²)	7.74 ± 0.76	8.20 ± 0.52
Maximal Velocity (m/s)	7.12 ± 0.27	7.53 ± 0.35
Time to Maximal Velocity (sec)	3.02 ± 0.29	2.84 ± 0.39

Median \pm Interquartile Range

The LASSO analysis stopped after the first step for all dependent variables, applying team as a significant covariate. All further variables did not provide a significant effect on model fit. Therefore, all models used team as a covariate to account for part of the variance in the model. Figure 3 shows the relationships between the training load measures and the performance variables. The between-participant variation was near identical across the training load measures for a specific performance measure. There was small between-participant variation in the relationship between training load and CMJ ($d = 0.08$; 0.04 to 0.12), 10 m sprint ($d = 0.03$; 0.02 to 0.05), 30 m sprint ($d = 0.03$; 0.02 to 0.04), and maximal velocity ($d = 0.03$; 0.02 to 0.04). Training load showed trivial variation between participants in its relationship with maximal acceleration ($d = 0.03$; 0.01 to 0.04), time to maximal velocity ($d = 0.005$; -0.01 to 0.02), and wellness ($d = 0.13$; -0.05 to 0.31).

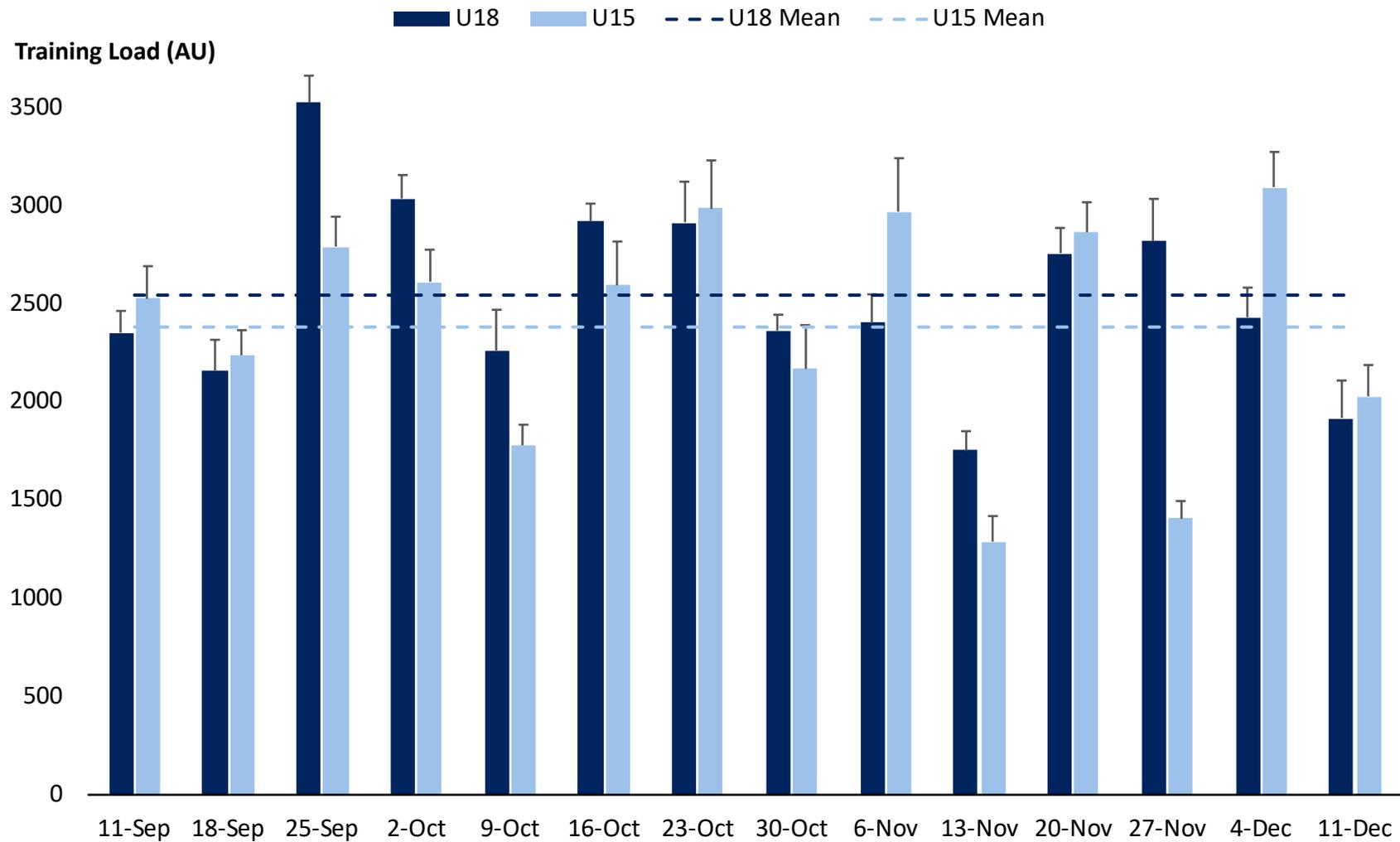


Figure 2 Mean Weekly Cumulative Training Load for the U-18 and U-15 Teams
 Mean \pm SD. Dashed lines are the mean team weekly training loads over the entire study period.

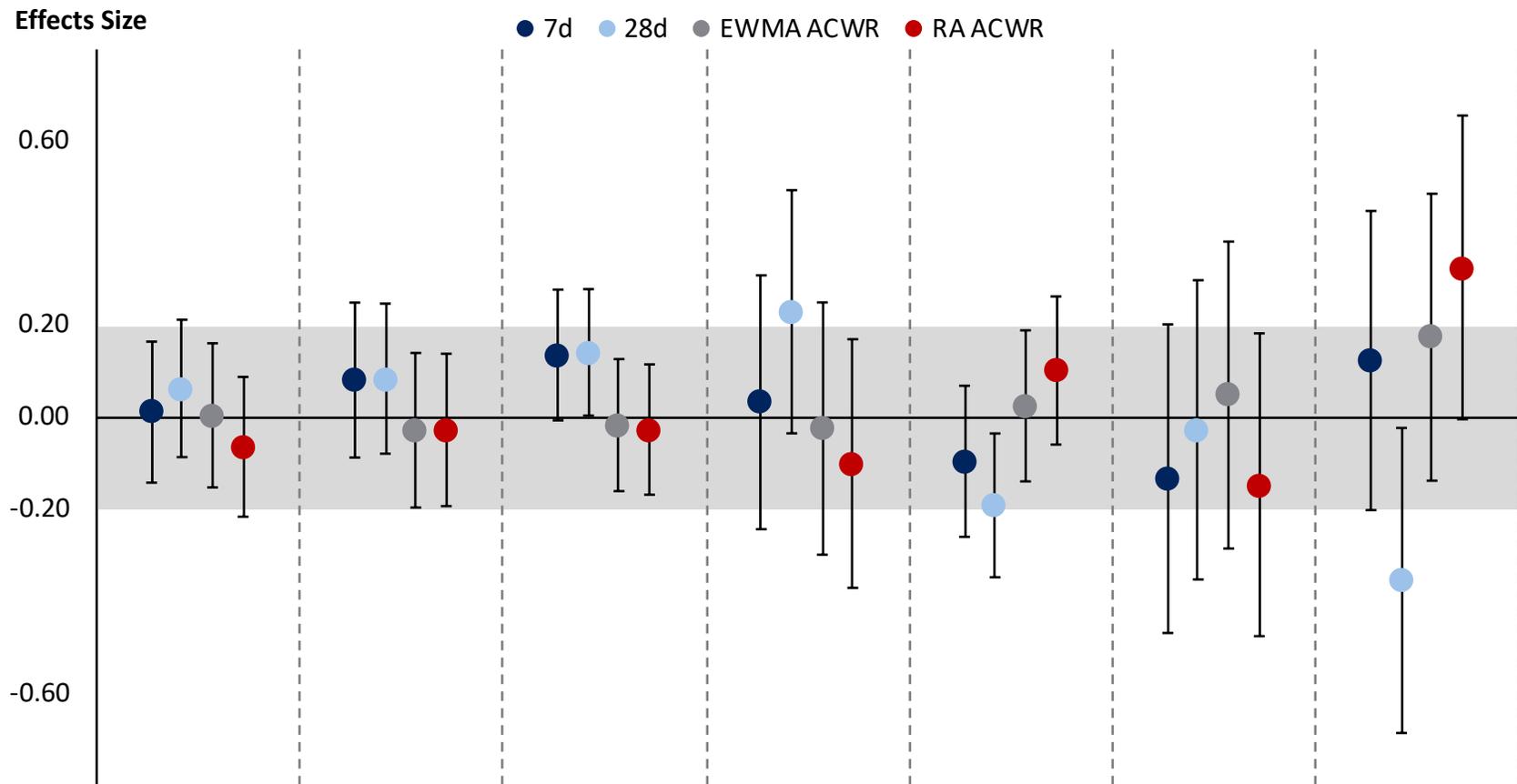


Figure 3 The Relationship Between Training Load Measures and Performance and Wellness Measures

The relationship between 7-day cumulative training load, 28-day cumulative training load, exponentially weighted moving average (EWMA) acute:chronic workload ratio (ACWR), and rolling average (RA) ACWR and various performance and wellness measures. Data are presented as effect size with 90% confidence intervals, shaded area denotes smallest worthwhile change. All effects are unclear and trivial, unless noted. (P = Possibly, L = Likely, VL = Very Likely; S = Small Effect, M = Moderate Effect).

4 DISCUSSION

This is the first study, to our knowledge, that has longitudinally monitored sprint time, velocity, and acceleration variables over multiple weeks in relation to training load, while also adding to the scarce literature on sprint times and underlying kinematics in adolescent female soccer players. The ability to monitor athletic performance measures over time has the ability to provide clear evidence of change in actions specific to field sport. The current literature tends to only use CMJ as a monitoring tool, however, the full scope of sprint performance variables has previously not been investigated. The main findings of the current study were likely small positive relationships between 30 m sprint time and 7-day and 28-day cumulative training loads and a very likely small negative relationship between maximal sprint velocity and 28-day cumulative training load. All other sprint performance measures, and CMJ height, showed trivial relationships with training load measures. Additionally, there was a likely moderate negative relationship between wellness z-score and 28-day cumulative training load, and possibly small and likely moderate positive relationships between 28-day cumulative training load and EWMA ACWR and RA ACWR, respectively, but no relationship with 7-day cumulative training load.

The mean values for the 10 m sprint times of the current cohort seem to be slightly slower than similar groups in the literature, while 30 m sprint time appears to be slightly faster. In the previous literature, 13-17 year old female soccer players have sprinted 10 m in 1.96-2.06 s, versus 2.03-2.11 s for the current group (Emmonds et al., 2018; Hoare & Warr, 2000; López et al., 2006). Meanwhile, the mean values for 30 m sprint times in the current group are 4.77-4.99 s compared to 4.89-5.01 (Emmonds et al., 2018; López et al., 2006).

The mean weekly cumulative training load (U-18: 2547 AU; U-15: 2384 AU) was comparable to the previous literature. Only two other studies have presented weekly cumulative training load in female soccer players. McLean et al. (2012) found NCAA Division I female soccer players (19.9 ± 1.2 y) completed 2247 AU for starters and 1585

AU for nonstarters during the competition season. Meanwhile, female soccer players more similar in age (15.5 ± 1.6 y) to the current teams accomplished 3167 AU but this was self-reported online (Watson et al., 2016). However, it was unclear in the preceding study whether any strength and conditioning was performed in addition to the technical training which would account for some of the additional load, similar to the current teams. The RA ACWR in the present study was very similar to what was found in Watson et al. (2016), around 1.0, while the EWMA ACWR was below others. This ratio corresponds to the “sweet spot” from 0.8 to 1.3 described by Gabbett (2016), which minimizes training load-related injury risk. Furthermore, performance may also be maximized in Australian rules football players just below a similar 1.0 ratio of a unique performance measure (Lazarus et al., 2017).

Sprint Performance and Training Load

The small positive relationship between 30 m sprint time and 7-day and 28-day cumulative training loads contrasts with the previous research. Gabbett and Domrow (2007), Lesinski et al. (2017), and Mara et al. (2015) found no relationships between training load measures and changes in sprint performance. However, all of these analyses only had one or two sprint measurements in the same 14-week time period as the current study. Therefore, fluctuations in training load and sprint performance would not be able to be ascertained based on the infrequent monitoring in these previous studies.

Maximal sprint velocity produced a very likely small negative relationship with 28-day cumulative training load. This is relatable to the increase in sprint time found in university soccer players playing two games per week compared to one game per week over six weeks, but no change over only three weeks (Rollo, Impellizzeri, Zago, & Iaia, 2014). These decreases in sprint performance can be a consequence of repetitive muscle fibre damage with incomplete recovery, which can result in decreased power output (Fitts, 1994; McLean et al., 2010). Mechanical power output has previously been shown to be correlated to v_0 of a sprint acceleration, making a loss in power output a meaningful

contributor to decreased sprint velocity (Morin et al., 2012). Additionally, a decrease in wellness z-score corresponded to decreased maximal sprint velocity in soccer players, possibly corresponding to the repetitive muscle damage and increased soreness (Malone et al., 2018). The decrease in maximal velocity found in the current study coincides with the positive relationship found between 30 m sprint time and training load. The corresponding associations of 30 m time and maximal velocity are in agreement with previous literature stating maximal velocity is correlated to 36.6 m sprint time ($r^2 = 0.94$) in NFL combine athletes (Clark, Rieger, Bruno, & Stearne, 2017). Similarly, maximum velocity yielded significant correlations (Female: $r = -0.74$, Male: -0.90) to 100 m sprint performance in professional sprinters (Slawinski et al., 2017).

Unexpectedly, maximal sprint velocity was not meaningfully related to 7-day cumulative training load, like 30 m sprint time. From this, it appears that 7-day training load may have a larger impact on force-biased qualities, compared to velocity-biased qualities. During the 30 m sprint, the cumulative time will be dependent on the initial acceleration abilities, along with maximal velocity abilities, as the total time will include the entire acceleration. Meanwhile, maximal sprint velocity will be more dependent on the qualities specific to maximal velocity, such as stretch-shortening cycle and limb stiffness (Nagahara, Mizutani, Matsuo, Kanehisa, & Fukunaga, 2018; Nagahara & Zushi, 2016). Therefore, if one were to have a poor acceleration but fast maximal velocity, the 30 m time would be slower due to the poor acceleration whereas the maximal velocity would still be fast as it does not necessarily depend on the acceleration time. However, 10 m sprint time was not related to any training load measure, perhaps due to a slightly larger variance in measurement. The coarse measurement of three sprint time points over 30 m versus 47 Hz maximal velocity measurements could also lead to differences in the ability of maximal velocity to relate to 28-day training load.

Low-frequency fatigue may be a critical factor in the difference in relationships between sprint time and maximal velocity, and 7-day and 28-day cumulative load. Fowles (2006) defines low-frequency fatigue as 'a multifactorial fatigue resulting from high-intensity, moderate- to high-force, repetitive eccentric or stretch-shortening cycle

activities'. It is generally thought to be a result of mechanical damage to the sarcoplasmic reticulum, which may result in decreased calcium release into the intracellular space at low-frequency stimulation, but can be masked at high-frequencies (Fitts, 1994). This reduction in intracellular calcium is thought to diminish force generating capacities (Fowles, 2006). Low-frequency fatigue was present after a soccer match, as demonstrated by single and paired 10 Hz quadriceps muscle peak torque and rate of maximal torque development (Rampinini et al., 2011). This diminished function corresponded with a decrease in 25-40 m sprint time, but not initial 15 m sprint time, similar to the current study finding a lack of relationships with 10 m sprint time. This long-lasting low-frequency fatigue was also accompanied by increased muscle soreness and decreased maximal voluntary contractions, which may recover after acute fatigue, but with inadequate rest and recovery, could gradually build in respect to a 28-day cumulative training load (Rollo et al., 2014).

Maximal acceleration and time to maximal velocity did not show any meaningful relationships with the various training load measures. These two measures have not previously been investigated in the literature, although they share similar traits to other previously investigated variables, such as theoretical maximum force (F_0). Both F_0 and maximal acceleration would be measuring the initial components of sprint acceleration, comprised of a maximal strength element. However, F_0 did not seem to be acutely affected from intense rugby training or a soccer match (Marrier et al., 2017; Nagahara, Morin, & Koido, 2016), making the current findings anticipated. Meanwhile, F_0 was decreased after return from hamstring injury, meaning it may be more affected by trauma rather than residual fatigue (Mendiguchia et al., 2014). Additionally, typically in the sprint literature, it is mentioned that when time to maximal velocity is prolonged, it allows the athlete to achieve a higher maximum velocity and increase performance in track and field races (Slawinski et al., 2017). However, in team sport, favorable outcomes are often won by being the first to the ball, so the ability to reach a higher speed sooner would be of a greater benefit and may be reinforced in team sport training. Therefore, time to maximal

velocity may be a more important consideration in team sport compared to track and field athletes.

No meaningful relationship was established between ACWRs and any sprint performance variables. Although the majority of previous research investigating ACWR is in the context of injury risk management (Gabbett, 2016; Malone, Owen, et al., 2017; Williams, Trewartha, et al., 2017), there does seem to be potential for a relationship between ACWR and performance measures (Collins et al., 2017; Lazarus et al., 2017). In one example, ACWR showed a moderate negative association with CMJ performance, with ratios above 1.0 resulting in likely larger reduction in CMJ performance compared to ratios below 1.0 (Collins et al., 2017). Meanwhile, Lazarus et al. (2017) also found performance to increase when the ACWR ratio was below 1.0. Considering these two findings, perhaps the RA ACWR stayed too consistently around the 1.0 ratio, so no change in performance could be observed due to the consistency of training load across the season. The EWMA ACWR in the present study was lower than expected, but this may have been primarily due to the two consecutive days off (i.e. weekends) each week. This break allowed the EWMA ACWR to drop drastically, unusual to other sporting environments. Therefore, although the EWMA ACWR may have provided a more appropriate loading ratio to experience performance gains (< 1.0), the ratio from the current study may have been artificially low due to the consecutive days of recovery. With this finding, it may not be recommended to use an EWMA ACWR to monitor training load in situations where athletes consistently have two consecutive days off, as it may exaggerate meaningful changes in training load.

Countermovement Jump and Training Load

The CMJ did not show any meaningful relationships with any of the training load measures. The CMJ heights recorded in the current study were consistent with previous literature, if not slightly above normal jump heights. Vescovi et al. (2011) found adolescent female soccer players (14-17 y) jumped 38.7 ± 5.0 cm, compared to 40.1 ± 4.6

and 45.0 ± 3.8 cm for the current U-15 and U-18 teams, respectively. Another group of female soccer players (HS: 15.1 ± 1.6 y, UN: 19.9 ± 0.9 y) jumped (HS) 39.6 ± 4.7 cm and (UN) 40.9 ± 5.5 cm (Vescovi & McGuigan, 2008). Caution must be given when comparing these results with other CMJ heights from differing contact mats or measuring devices, as this particular device may give skewed data compared to reference methods (Dobbin, Hunwicks, Highton, & Twist, 2016).

Although the CMJ has been used in previous literature as a marker of fatigue, there have also been numerous instances where jump height was not sensitive to training load. In youth rugby players, CMJ height was sensitive to post-match fatigue and accumulated fatigue over seven weeks (Oliver et al., 2015). Similarly, youth male soccer players showed a possibly small correlation between CMJ height and sRPEmus training load and training volume (Gil-Rey, Lezaun, & Los Arcos, 2015). However, CMJ height indicated no meaningful relationship with training load in female rugby sevens players (Gathercole, Sporer, & Stellingwerff, 2015). CMJ height also did not change after four consecutive soccer training sessions in youth soccer players (Malone et al., 2015). Other, more sensitive variables have been utilized in the current literature, but also require force plates and necessary software to analyze the data, making them impractical or inaccessible in many environments. CMJ height may not be a sensitive measure of fatigue because athletes can use alternative movement characteristics to produce the same output, therefore making a singular output such as jump height less valuable (Cormack, Newton, & McGuigan, 2008; Gathercole, Sporer, Stellingwerff, et al., 2015b).

Wellness and Training Load

The athlete wellness z-score showed a likely moderate negative association with 28-day cumulative training load. These results are comparable to the previous literature. Sawczuk et al. (2018) found youth athletes exhibited a moderate negative association between training load and muscle soreness and perceived recovery, and small associations between training load and overall wellbeing and fatigue. Additionally, in

youth female soccer players, training load and sleep duration were significantly associated with fatigue (Watson & Brickson, 2018). However, a similar cohort found monthly chronic training load to significantly predict illness, but did not have a significant correlation with any aspect of wellness (Watson et al., 2016). Much of the previous research uses wellness subscales within their analyses which helps depict where associations can be made, however the current study only used a single overall measure of wellness as it was not a primary variable, and to reduce the chance of multiple comparison inflation.

Athlete wellness z-score revealed likely moderate and possibly small positive relationships with EWMA ACWR and RA ACWR, respectively. Although 28-day cumulative load showed a negative relationship, 7-day cumulative training load was not related to wellness z-score. With the average ACWRs below 1.0, the 28-day cumulative training load (chronic load) would be higher than the 7-day cumulative training load (acute load), which would minimize acute fatigue from the 7-day cumulative training load. Low 7-day training loads and ACWRs, and thus minimal acute fatigue, may have produced the positive relationships between wellness and 7-day cumulative training load, EWMA and RA ACWRs. Meanwhile, since the 28-day cumulative training load was higher than the acute load, this corresponded with more fatigue and a negative relationship with wellness. Additionally, the changes in wellness measures may be coming from a number of areas, with some potentially affecting performance such as soreness or sleep quantity and quality (Watson & Brickson, 2018), while others may not necessarily have immediate detrimental effects on performance, such as increased stressed or lack of motivation (Rollo et al., 2014).

Monitoring sprint performance measures may be a useful tool to help measure fatigue in athletes. Sprint time over 30 m, maximal sprint velocity, and wellness measures were found to be the most relevant measures related to training load. Future athlete monitoring systems and research should consider the use of sprint performance measures to further determine the efficacy of fatigue management via sprint performance.

Limitations

Due to the unique environment of team sport training, various aspects of the training environment are not able to be practically controlled. Although the current research provides valuable insight on adolescent female soccer players, caution should be exercised when trying to extrapolate these results to other populations as the demands of training and competition can vary drastically, which may produce varying fatigue patterns. The sprint monitoring took place early Monday morning before school, making it the first activity of the week for the players. Although this prevented other same-day training loads from having an impact on overall performance, it may have also decreased motivation after a weekend. Ultimately, these monitoring methods are largely influenced by athlete motivation, so this could have a confounding impact on performance.

The environmental conditions of the monitoring sessions were documented as well as possible, however they were still completed outside. A number of monitoring sessions included light rain or dew on the turf field which could affect sprint performance, although the athletes wore soccer cleats to minimize any changes in traction, while other weather variables were recorded to be incorporated into the statistical model. The specific attire worn during the monitoring sessions varied significantly over the course of the study due to the large changes in ambient temperature, however the athletes were instructed not to wear large rain or insulated jackets during the protocol.

The accuracy of the training load accumulated over the study period provided additional variability. The athlete's activity over the weekend was not documented unless it was an organized team activity, therefore there could have been large variations in the amount of extracurricular activity they completed over the weekend. Further, private off-site training sessions were not accounted for during the study period, which would have added to specific athlete's overall training load and likely monitoring performance. The bi-weekly monitoring of the athletes provided a larger sample size, but also produced

fewer samples per individual and windows of acute load unaccounted for on the monitoring days.

Limitations stemming from the study design make further inferences difficult. The monitoring period included in the statistical analysis did not align with the beginning of the training season due to differences in athletes' schedules and the need to build a 28-day training load, which would have unaccounted for some acute training loads. The team utilized in the current research did not consistently play meaningful league games, therefore the weekly cycle of fatigue may not be comparable to other teams that may have weekly league games. Additionally, the overall variation in weekly training load was minimal so there may not have been a strong overload or unloading stimulus through the duration of the study period, making it difficult to separate variations in training load and performance measures. With this, the mean and range of the ACWRs were relatively low, also indicating there was not a strong overload stimulus during the study period. The concern for coupled ACWR ratios has recently been published (Lolli et al., 2017; Windt & Gabbett, 2018). These arguments may be mathematically sound, however, there is still an absence of any research utilizing an uncoupled ratio. Therefore, the ACWR ratios should be considered in relation to the current evidence until further literature is available to demonstrate similar utility in uncoupled ratios.

The measure of training load was completely based on a subjective rating, which can be influenced by a number of factors. Although the sRPE method is well documented, it has also been found to only account for 56% and 49% of the variance within Banister's method and Edward's method of calculating training impulse (Kelly et al., 2016; Lovell et al., 2013). The current group of adolescent athletes tended to report the same RPE score for every strength and conditioning session even with large variations in exercise content and intensity, making the sRPE method difficult to ascertain changes in training. Additionally, a primary benefit of the sRPE method is the ease of use, however use of a HR and GPS to track training load would have provided more robust evidence of changes in training load.

The sprint measurements using a radar gun provide more thorough analysis of sprint performance, but it is still susceptible to capturing arm or leg velocity, making filtering of the raw data necessary. This process can be labour-intensive, introduce uncertainty to the true velocity measurements, and make it impractical for frequent use in team sport. It also does not provide immediate feed-back for the athlete, making it impossible to provide additional incentive on sprint measures. Also, a contact mat was used to measure CMJ, only providing jump height. This process made for simple data collection in an applied setting, but limited further analysis of alternative jump variables, such as force, impulse, or timing variables.

The questionnaire used had been recently developed and validated (Hitzschke et al., 2015; Nässi et al., 2017). The questionnaire was originally developed in German, and although it has been validated in English, some of the phrasing was found to be abstract to some of the participants. Therefore, they may have either misinterpreted some of the questions or not answered them with full intent. However, the participants did use the questionnaire for thirty days before the analysis period started as the 28-day cumulative training load was building to its full duration, which makes it less likely that the participants were not familiar with the questions. Additionally, the average daily response rate of the wellness questionnaire was 83.1%, while the average response rate on testing days analyzed was 94.1%, which corresponded to 6 missed wellness scores out of 102. Therefore, there should have been relatively little effect of missing values. Additionally, previous literature has used wellness subscales to determine what has caused changes in wellness. However, in the current study, subscales were not utilized because there was already an increasing number of models for the statistical analysis, so to minimize this number, subscales were not used.

Future Directions

There continues to be a dearth of research on female athletes, especially adolescent female athletes. Therefore, future research in females should investigate the

relationships in training load measures and neuromuscular and hormonal responses using internal and external training load measures to corroborate previous research found in males. Further research in females should also seek to verify changes in mechanical sprint variables over time, as previously shown in males. From the mechanical sprint variable calculations, a F-v relationship can be determined, which provides further information for the practitioner to individualize strength and conditioning programming and may help determine various components of fatigue. Therefore, utilizing this method provides several avenues of information, which can then be utilized for fitness improvements and fatigue monitoring, making further investigation worthwhile.

A wellness questionnaire and sprint performance provide a subjective and performance response measure to training load, therefore an objective response measure should be utilized to determine if this would generate a more complete understanding of the athlete's current fatigue status. Further, specific standards, such as smallest worthwhile change, could be calculated to aid the practitioner in determining the threshold of intervention. Investigation of specific recovery interventions may also help to establish how particular protocols could alleviate or exacerbate performance decrements and perceptions and expressions of fatigue.

The current methods used to extract the sprint variables from the raw sprint velocity data were tedious and impractical for an applied setting. Although the present research used advanced technologies to track sprint velocity and a specific athlete management software to collect wellness questionnaire data, many free and inexpensive alternatives exist that could provide similar data. These alternatives should, therefore, be investigated to determine if they provide the same level of reliability and sensitivity to fatigue as the current measures. Conversely, the negative relationship between maximal sprint velocity and training load yields a worthwhile avenue to pursue for higher-level teams that use GPS during training sessions. If GPS technology is already being utilized to track external training load during training and competition, it would be simple and time-efficient to extract and track maximal sprint velocity during a maximal sprint in the warm-up. The team could conduct a 30 m sprint simultaneously, with maximal velocity being

recorded. Although the current study did not use a GPS system to measure maximal velocity, previous research has found maximal velocity to be comparable between a 20 Hz GPS and the radar gun used in the current study (Nagahara et al., 2017). Therefore, maximal sprint velocity derived from GPS should further be investigated as a monitoring tool to maximize efficiency within the team sport environment.

5 Conclusion

Summary

Athlete monitoring has become an integral component of successful high performance sport departments as coaches try to push their athletes to peak performance. Numerous methods have been utilized to gauge current training and performance status and quantify the fitness and fatigue of athletes, while limitations exist to each method. Ultimately, a multifaceted approach to monitoring should be applied to create a holistic measure of performance preparedness. Previous literature has focused on the CMJ as a measure of performance, but this is not a primary action in many field-based team sports. Meanwhile, sprinting is an integral part of most team sports, such as winning possession, defending opponents, and scoring goals. Therefore, it would be practical to monitor sprinting as it is a more direct component of team performance.

The current findings have added to the previous literature by providing evidence for the use of sprint performance as a viable option to be included in a comprehensive athlete monitoring system. An increase in 30 m sprint time had a positive relationship to 7-day and 28-day cumulative training load, suggesting that both acute and chronic training load affect 30 m sprint performance, potentially due to repetitive muscle fibre damage with incomplete recovery. Concurrently, decreased maximal velocity positively related to 28-day cumulative training load, more indicative of a longer-term low-frequency fatigue with incomplete recovery between training or competition bouts. The 30 m sprint may provide more acute feedback on the previous week's training load, while either 30 m time or maximal velocity can depict the squads' current status in regard to chronic training load. These results demonstrate the utility of monitoring sprint performance in relation to training load to help identify decreased performance and potential areas of focus for strength and conditioning programs and recovery measures. Further, a negative relationship between athlete wellness z-score and 28-day cumulative training load corroborates with the previous literature between athlete wellness and

training load. The current study also provides additional evidence for the use of the SRSS wellness questionnaire in relation to chronic accumulated training loads. Meanwhile, CMJ was not found to be a useful measure of fatigue in the current cohort. Lastly, the present results add to the paucity of research on adolescent female soccer players, providing normative data of training loads and explosive performances.

The current study provided the first evidence that sprint performance may be a viable performance measure to monitor over a season. Two viable options were found to be able to track sprint performance in relation to training load, either 30 m sprint time or maximal sprint velocity. Wellness z-score was also found to be a valuable indicator of previous training load in adolescent female soccer players. Therefore, these measures should be incorporated into a larger holistic athlete monitoring system utilizing subjective, objective, and performance measures to track athlete response to various training load doses.

Practical Applications

The current findings present the first evidence, to our knowledge, of longitudinal monitoring of sprint performance in relation to training load. In addition, the relationship between wellness z-score and 28-day cumulative training load supported the existing literature. Using the current results, one can start to build a multidimensional monitoring system to track fatigue and performance over time.

The present research supports the use of sprint monitoring to help gauge the current fitness and fatigue status of team sport athletes. Sprint time over 30 m may provide the most useful information, being affected by both acute and chronic cumulative training loads. Using sprint performance as a monitoring tool would additionally provide a competitive environment for athletes to maximally sprint, which has previously been shown to increase sprint performance and reduce risk of injury, whereas the CMJ was not supported in the current research and does not provide the additional benefits of maximal velocity sprinting. Additionally, maximal sprint velocity can also be used as an

indicator of chronic training load fatigue. With the increased availability of GPS, this may be a valuable and simple measure to track during the warm-up of team training sessions, however equivalent evidence would be needed using the specific technology. Lastly, wellness measures consistently show susceptibility to training load fatigue, therefore the continued monitoring of these measures should be used to create actionable decision-making processes to prevent decreased performance. Using a statistic such as smallest worthwhile change, thresholds can be defined to determine the point where the practitioners should modify training. Further consultation of the entire breadth of training monitoring information should be studied when considering training modification to estimate the origin of fatigue and the subsequent ability to minimize its effect on performance, with sustained decreases in performance likely the most indicative of true accumulated fatigue.

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APPENDICES

Appendix A: Literature Review

Sprinting is one of the main actions in most field sports, even shown to be a key action in the lead-up to soccer scoring plays (Faude et al., 2012). With the increased utilization of GPS and video tracking systems during training and competition, sprint intensity and volume can easily be tracked daily. From these technologies, a plethora research has demonstrated how training volume and intensity distribution can affect subsequent sprint performance, wellness, and risk of injury or illness. Specifically, regular sprinting was shown to reduce risk of injury (Malone, Roe, et al., 2017). Additionally, sprint performance and sprint mechanics have been shown to change throughout a soccer game and in the lead-up to hamstring injuries, making the monitoring of these variables noteworthy (Mendiguchia et al., 2014; Nagahara et al., 2016). With frequent monitoring, the practitioner can analyze whether their current training methods are appropriate and are producing worthwhile improvements.

Measuring Sprint Performance

Sprint performance is one of the most powerful and dynamic actions in sport, making analysis and measurement difficult. When considered in sport research, sprinting is generally broken down into three phases; the acceleration phase, the maximal speed phase, and the speed maintenance phase (Ross, Leveritt, & Riek, 2001). The acceleration phase generally encompasses from the start of the effort until maximum velocity is achieved (Slawinski et al., 2017). Within the acceleration phase, the individual is producing a high ground reaction force (GRF) but at a relatively slower speed to get their centre of mass up to speed. The maximum speed phase is achieved once acceleration has ceased, thus maintaining constant velocity. At this stage of the sprint, the resultant GRF is vertical and the production of horizontal force is less important (Mero, Komi, & Gregor, 1992). Finally, the objective of the speed maintenance phase of sprint performance is to

maintain the highest possible velocity for as long as possible (Slawinski et al., 2017). Several factors play a role in maintaining maximal velocity, from limiting neural fatigue to metabolic constraints.

Sprint performance can be described as the product of stride rate and stride length. Stride length seems to have the greatest impact on performance when comparing across genders and ages (Hammami et al., 2013; Slawinski et al., 2017). However, in a homogenous cohort, stride length may not be an important factor, but instead more mechanistic variables that come together to make up the stride rate and stride length equation (Morin et al., 2012). These mechanical variables have been shown to be affected throughout a soccer game (Nagahara et al., 2016), and across a season in the lead-up to hamstring injuries (Morin & Samozino, 2018).

Table 5 Common Technologies to Measure Sprint Performance

Method	Common Variables	Advantages	Disadvantages
Sprint Time			
Fully Automatic Timing System (Start gun, pressure-sensitive start blocks, photo-finish)	<ul style="list-style-type: none"> • Time along set distances • Reaction time • Average speed over set distance 	<ul style="list-style-type: none"> • Consistent start procedure (With or without reaction time) • Very accurate finish 	<ul style="list-style-type: none"> • Very time-consuming set-up • Cost
Photocell Timing System	<ul style="list-style-type: none"> • Time along set distance • Average speed over set distance • F_0, v_0, P_{MAX}, D_{RF} 	<ul style="list-style-type: none"> • Ease of set-up • Availability • Ease of processing/data output • Ability to calculate mechanical variables 	<ul style="list-style-type: none"> • Variability in start procedure
- Single Beam		<ul style="list-style-type: none"> • Cost 	<ul style="list-style-type: none"> • Higher error due to arm/leg triggering
- Dual Beam		<ul style="list-style-type: none"> • More reliable triggering than single beam 	<ul style="list-style-type: none"> • More expensive
- Split-beam		<ul style="list-style-type: none"> • More reliable triggering than single beam 	<ul style="list-style-type: none"> • Variability in distance between beams
- Post-processing		<ul style="list-style-type: none"> • Increased reliability compared to single beam 	<ul style="list-style-type: none"> • Defining signal breaks
Hand Timing (i.e. stopwatch)		<ul style="list-style-type: none"> • Should not be used for sprint timing due to high level of error 	
Sprint Velocity/Kinematics			
Radar/Laser Measurement	<ul style="list-style-type: none"> • Instantaneous Velocity • Estimated time over any distance • F_0, v_0, P_{MAX}, D_{RF} 	<ul style="list-style-type: none"> • Not limited to set distances • Ability to calculate mechanical variables • Cost compared to dual beam system 	<ul style="list-style-type: none"> • Time-consuming post-processing • Reliability of start • Loss of position in space (distance) • Error from limbs
Video Analysis		<ul style="list-style-type: none"> • Very little set-up 	<ul style="list-style-type: none"> • Time-consuming post-processing
- Video Camera	<ul style="list-style-type: none"> • Time over any distance • F_0, v_0, P_{MAX}, D_{RF} 	<ul style="list-style-type: none"> • Higher frame resolution 	<ul style="list-style-type: none"> • Video parallax
- Smart Device	<ul style="list-style-type: none"> • Contact and flight times • Stride length and frequency 	<ul style="list-style-type: none"> • Availability • Cost 	<ul style="list-style-type: none"> • Accuracy of phase selection • Video parallax
GPS	<ul style="list-style-type: none"> • Instantaneous Velocity • Estimated time over any distance • F_0, v_0, P_{MAX}, D_{RF} 	<ul style="list-style-type: none"> • Already in use for external load monitoring 	<ul style="list-style-type: none"> • Time-consuming post-processing • Accuracy of measurements • Cost
Linear Position Transducer	<ul style="list-style-type: none"> • Instantaneous Velocity and Force • Time over any distance • F_0, v_0, P_{MAX}, D_{RF} • Estimated limb imbalances 	<ul style="list-style-type: none"> • Ability to use resistance/assistance • Variability of distance measurements 	<ul style="list-style-type: none"> • Cost • Ability to run at zero force • Length of cable

F_0 Theoretical maximal force, v_0 Theoretical maximal velocity, P_{MAX} Maximal power, D_{RF} Decrease in Ratio of force

Sprint timing systems incorporate a vast array of technologies ranging from tens of thousands of dollars for a fully-automated international-level track and field system to less than five dollars for a smart device application. Table 5 outlines the common technologies used to measure sprint performance, common variables collected from each technology, and advantages and disadvantages of each technology. Additionally, Haugen and Buchheit (2016) have written an in-depth review of considerations during sprint testing. With an increase in availability of reliable technologies (e.g. smart devices, applications), hand-timing should no longer be an acceptable practice for consistent monitoring and testing for short sprints (< 100 m). A vast majority of the sprint research uses varying degrees of photocell timing systems, with the most common being single-beam systems (Haugen & Buchheit, 2016). However, single-beam systems are error-prone because arms and legs can also trigger the system, making for early triggers for up to 60% of trials (Yeadon, Kato, & Kerwin, 1999). Laser and radar guns and video analysis can provide much more in-depth information compared to photocells, but also require more detailed processing. A more recent advance in sprint timing has been the use of GPS. They have generally been used in team sport to broadly measure the demands of training and match play but have recently been explored for assessment purposes (Nagahara et al., 2017; Roe et al., 2017).

The current array of methodology to measure sprint performance has made comparisons futile. Sprint performance has been assessed between 2.5-100 m, and 40 yards is common in North America. Although assessments should be specific to the sport and population, having a difference between 20 and 30 m makes comparisons between studies impossible. Additionally, the variables reported can make comparisons cumbersome.

Training Load in Team Sport

Within team sport, fatigue will be caused by a number of different stressors. Acute fatigue can occur within minutes to days after training and competition, first being

realized through an accumulation of potassium, metabolic by-products, reactive oxygen species, and decreases in calcium, ATP, and pH (Allen, Lamb, & Westerblad, 2008). In the ensuing hours and days, muscle damage and subsequent inflammation will be a major contributor to fatigue and reduced performance, most commonly caused by a high number of accelerations and decelerations (Mara et al., 2015; Proske & Morgan, 2001), impact trauma (McLellan, Lovell, & Gass, 2011), and/or prolonged metabolic stress (Tee, Bosch, & Lambert, 2007). Furthermore, glycogen depletion over the course of a soccer match can have detrimental effects on sprint performance as the match progresses, with repletion incomplete for two to three days post-match (Krustrup et al., 2006, 2011). Chronic fatigue, spanning days to months, can be a build-up of the previously mentioned acute biological factors with incomplete recovery, or incremental changes in psychological factors from the stress of accumulated training and competition over large portions of the year (Nédélec et al., 2012; Smith et al., 2018).

Purpose

Jumping is a common method used in high performance sport to monitor the balance of fitness and fatigue in athletes. However, in many field-based team sports, sprinting is a more influential action. Previous literature has shown that sprinting was the most frequent action in goal situations in soccer (Faude et al., 2012). Furthermore, when considering specificity of movement to sporting actions, jumping tends to produce much slower segment velocities compared to sprinting. Sprint training has also been shown to improve sprint performance, while also reducing injury risk (Malone, Roe, et al., 2017; Markovic, Jukic, Milanovic, & Metikos, 2007). Therefore, sprint training and assessment are crucial aspects of team sport preparation. To our knowledge, there has not been a review covering the variation in sprint performance acutely or over the course of a sport season. Additionally, the relationship between sprint performances and training load has not been reviewed. In order to establish whether true adaptation has occurred, or changes are simply the product of fatigue, match stimulus, or training programs, a review

of the literature needs to establish what is normal change in sprint performance and whether it is a useful measure to consider.

Inclusion Criteria

This review focused on team sport athletes, as pure sprint athletes have much different race and training programs focused solely on sprint technique and performance. In this review, changes in sprint performance refers to changes in sprint time and velocity. Acute monitoring was defined as measures in performance over 0-144 h, while repeated-sprint protocols did not fall under the scope of this review. Chronic monitoring was defined as measures in performance over multiple weeks, and the athletes needed to be tested at least two times per year to be included. Monitoring sprint performance in relation to training load was defined as any study comparing changes in maximal sprint performance to changes in training load measures over multiple weeks. Additionally, cohorts affected by novel treatment protocols were not included in any sections.

Changes in Sprint Performance

Acute Monitoring of Sprint Performance

Determining the acute effects and subsequent time-course of recovery of changes in sprint performance helps provide the base knowledge to determine the effect that team sport activities (training or match) has on sprint performance. There is an inclination in the literature toward decreased performance or no change in performance, with very little literature showing an improvement in sprint performance after fatiguing exercise (Table 6). There also does not seem to be a large discrepancy between short-distance acceleration (≤ 10 m) and longer-distance acceleration (≥ 15 m) in acute fatigue (~2-4% increase in sprint time over 0-48 h), albeit there is relatively little research on short-distance acceleration. The type of exercise performed seemed to have an impact on the

effects on sprint performance (competitive vs friendly matches and matches vs simulation), since only a third of the studies had varying performance findings throughout the studies' recovery period.

There appears to be a marginally more rapid recovery of sprint performance after simulated exercise, however with the confounds of each study design, this cannot be a certainty (Silva et al., 2018). Interestingly, only 11 of 37 analyses found a change in sprint performance during the studies' defined range of recovery period, while the remaining studies had a consistent finding across the entire recovery period. Of those eleven, nine found a decrease in sprint performance that then improved to no change (Andersson et al., 2008; Brownstein et al., 2017; Chatzinikolaou et al., 2014; Gathercole, Sporer, Stellingwerff, et al., 2015; Ispirlidis et al., 2008; Rampinini et al., 2011; Thomas, Dent, Howatson, & Goodall, 2017), while two studies found no change in performance that then settled into a decrease in performance (Getto & Golden, 2013; Stone et al., 2016). Of the nine that improved, all but one improved to baseline-levels after 24 h post-match, indicating there may be some evidence that sprint performance may only be sensitive to acute fatigue within 24-48 h. However, since very few studies found progressions or regressions in sprint performance, it seems the specific exercise completed may not have been demanding enough so there was no change in sprint performance, or the exercise was very intense and sprint performance stayed diminished for up to 72 h. This was demonstrated by Magalhães et al. (2010), who found a soccer match to produce a higher HR compared to a simulated match and affected 20 m sprint performance more post-match and 24 h post-activity.

A few studies may help us decipher what may cause decreases in sprint performance (Table 6). Generally, it seems that sprint performance was sensitive to acute fatigue immediately post-exercise (~4.6% increase in time over 20 m) and potentially 24 h post (~2.5% over 20 m)(Brownstein et al., 2017; Ispirlidis et al., 2008; Rampinini et al., 2011; Thomas et al., 2017). More than 24 h post-exercise, it was inconclusive whether sprint performance can reliably detect fatigue, as a greater proportion of the studies find small to no change after 24 h (Andersson et al., 2008; Ispirlidis et al., 2008; Silva et al.,

2013). Of the research that did find change after 24 h, it stayed on average to a relatively consistent 2.5% decrement in performance over 20 m, up to 72 h post-activity (Andersson et al., 2008; Fatouros et al., 2010; Magalhães et al., 2010; Stone et al., 2016). Using relevant research, sprint performance was likely most affected by CNS fatigue, but surely peripheral nervous system (PNS) fatigue also plays a part. Previous literature investigating specific indices of CNS or PNS fatigue in relation to soccer have shown CNS fatigue to be prominent in the 24 h post-exercise, similar to the timeline of decayed sprint performance, while PNS fatigue persists up to 72 h (Andersson et al., 2008; Goodall et al., 2017; Rampinini et al., 2011; Robineau, Jouaux, Lacroix, & Babault, 2012; Thomas et al., 2017). In some instances, only CNS fatigue was found, with no corresponding PNS fatigue as measured via peak twitch and M-wave amplitude (Robineau et al., 2012). Rampinini et al. (2011) found a 40 m sprint with change of direction to be significantly correlated to decreases in maximal voluntary activation and maximal voluntary contraction, indicators of CNS fatigue. At the same time, Brownstein et al. (2017) found no correlation between 10 or 20 m sprint and NM fatigue indices after a friendly soccer match, but the players only completed 45% (1211 vs 2664 m) of high-intensity running (> 15 km/h) compared to Rampinini et al. (2011). Reductions in sprint performance have also previously been correlated to the time spent above maximum aerobic speed and time above 90% of maximum HR, making high-intensity running a potentially crucial component of sprint performance fatigue (Castillo, Yanci, Cámara, & Weston, 2016; Marrier et al., 2017). Additionally, during a simulated game with extra-time, PNS fatigue was maximized at 90 min while CNS fatigue kept building through 120 min, showing the intensity and duration of activity was relevant to which system was stressed (Goodall et al., 2017). Again, this can be seen with greater decrements in 20 m sprint performance after a soccer match compared to a Loughborough Intermittent Shuttle Test (LIST) (Magalhães et al., 2010).

Table 6 Acute Change in Sprint Performance

Authors	Subjects	Sprint Variables (Equipment)	Stimulus	Time Points	Results
Chatzinikolaou et al., 2014	24 handball players; Elite; 22.8 y	10 m (s) (Newtest)	2 x 30' handball match	Pre-match, 24, 48, 72, 96, 120, 144 h Post-match	24 h: ↑ 4.7%, 48 h: ↑ 1.6%, 72, 96, 120, 144 h: NS
Brownstein et al., 2017	16 male soccer players; Level 9 of English Football League; 21 y	20 m (s) (Brower); Splits: 10 m	Soccer match	Pre-match, 0, 24, 48, 72 h Post-match	10 m (s) – NS 20 m (s) – 0 h: ↑ 4%, 24, 48, 72 h: NS
Gathercole, Sporer, Stellingwerff, & Sleivert, 2015	11 male team sport athletes; University athletes; 23.0 y	20m (s) (Brower); Splits: 10 m	Modified 3-stage Yo-Yo IR 2/IE 2	Pre-test, 0, 24, 72 h Post-test	0-10 m (s) – 0 h: Large ↑ (ES: 3.1), 24 h: NS, 72 h: Large ↓ (ES: -1.3) 10-20 m (s) – 0 h: Large ↑ (ES: 3.4), 24,72 h: NS 0-20 m (s) – 0 h: Large ↑ (ES: 4.5), 24 h: NS, 72 h: Moderate ↓ (ES: -0.8)
Ronglan, Raastad, & Børgesen, 2006	13 female handball players; NOR National Team; Camp: 23.7 y Tournament: 23.1 y	20 m (s); Splits: 10 m	Regular Team Training and Competition	Camp: Pre-training, 0, 21, 28, 30, 44, 53, 89 h Post-training Tourn: Baseline (0 h), Pre-match 1 (80 h), 2 (104 h), 3 (128 h), Post-match 1 (82 h), 2 (106 h), 3 (130 h)	From baseline: (Camp) 20 m (s) – 0 h: ↑ ~1.2%, 22 h: ↑ ~0.7%, 28 h: ↓ ~0.7%, 30 h: ↑ ~1.9%, 44 h: NS, 53 h: ↓ ~0.5%, 89 h: ↑ ~0.8% (Tournament) 10 m (s) – 80, 82, 104, 106, 128, 130 h: NS 20 m (s) – 80 h: ↑ 2.3%, 82 h: NS, 104 h: ↑ 1.6%, 106 h: ↑ 3.2%, 128 h: ↑ 2.9%, 130 h: NS
Thomas, Dent, Howatson, & Goodall, 2017	15 male soccer players; Level 9 of English Football League; 21 y	20 m (s) (Brower); Splits: 10 m	90' soccer-specific aerobic field test (LIST)	Pre-match, 0, 24, 48, 72 h Post-match	10 m (s) – 0 h: ↑ 2.7%, 24, 48, 72 h: NS 20 m (s) – 0 h: ↑ 3.5%, 24, 48, 72 h: NS
Andersson et al., 2008	22 female soccer players; SWE/NOR top division; Active (n = 8): 22.6 y, Passive (n = 9): 21.6 y	20 m (s)	2 – Soccer matches 74 h apart	Pre-match I: 0, 5, 21, 27, 45, 51 & 69 (Pre-match II); 74 h (Post-match II)	(Active Recovery) 20 m (s) – 0 h: ↑ 2.5%, 5, 21, 27, 45, 51, 69 h: NS, 72 h (Post-match 2): ↑ 2.2% (Passive Recovery) 20 m (s) – 0 h: ↑ 3.5%, 5, 21, 27, 45, 51, 69 h: NS, 72 h (Post-match 2): ↑ 1.9%
Ascensão, Leite, Rebelo, Magalhães, & Magalhães, 2011	20 male soccer players; 2 national league teams; G1 (n = 10): 18.3 y, G2 (n = 10): 18.1 y	20 m (s) (Brower)	Soccer match	Pre-match, 24, 48 h Post-match	20 m (s) – 24, 48 h: NS

Table 6 Acute Change in Sprint Performance

Authors	Subjects	Sprint Variables (Equipment)	Stimulus	Time Points	Results
Ascensão et al., 2008	16 male soccer players; secondary division team; 21.3 y	20 m (s) (Brower)	Soccer match	Pre-match, 30 min Post-match, 24, 48, 72 h Post-match	30 min: ↑ ~9.6%, 24 h: ↑ ~6.5%, 48 h: ↑ ~5.1%, 72 h: ↑ ~5.5%
Djaoui, Diaz-Cidoncha Garcia, Hautier, & Dellal, 2015	10 male soccer players; U-17 French first league academy; 16.3 y	20 m (s) (Microgate)	Soccer match	Pre-match, 24, 48 h Post-match	24 h: ↑ 0.92%, 48 h: NS
Getto & Golden, 2013	13 male, 10 female team sport athletes; University athletes	20 m (s) (Freelap)	Team Strength + Conditioning Sessions	Pre-test, 0, 24 h Post-test	Control – 0, 24 h: NS All groups – 0 h: NS, 24 h: ↑ 26.5%
Ispirlidis et al., 2008	24 male soccer players; Elite; 21.1 y	20 m (s) (Newtest)	Soccer match	Pre-match, 24, 48, 72, 96, 120, 144 h Post-match	24 h: ↑ 2%, 48 h: ↑ 2.5%, 72 h: ↑ 1.6%, 96, 120, 144 h: NS
Magalhães et al., 2010	16 male soccer players; Portuguese 2nd & 3rd Divisions; 21.3 y	20 m (s) (Brower)	90' soccer-specific aerobic field test (LIST) + Soccer match	Pre-match, 30 min, 24, 48, 72 h Post-match	(LIST) 20 m (s) – 30 min: ↑ ~4.4%, 24 h: ↑ ~1.0%, 48 h: ↑ ~1.0%, 72 h: ↑ ~1.4% (Soccer) 20 m (s) – 30 min: ↑ ~9.2%, 24 h: ↑ ~6.8%, 48 h: ↑ ~5.8%, 72 h: ↑ ~5.4%
Sjökvist et al., 2011	14 female soccer players; University athletes; 20.3 y	20 m (s) (Brower)	55' soccer-specific training and conditioning	Pre-test, 24, 48, 72 h Post-test	20 m (s) – 24, 48, 72 h: NS
Wiewelhove et al., 2015	11 male, 11 female team sport athletes; Regional-level athletes; 23.0 y	20 m (s) (Sportronic)	Six-day HIIT Training Program	Pre-training, 0, 72 h Post-training	20 m (s) – 0 h: ↑ 3.7%, 72 h: ↑ 2.6%
Fatouros et al., 2010	30 male soccer players; Greek U-21 Division 1; 20.3 y	30 m sprint (Newtest)	Soccer match	Pre-match, 24, 48, 72 h Post-match	24 h: ↑ ~8.2%, 48 h: ↑ ~5.3%, 72 h: ↑ ~3.9%
Silva et al., 2013	7 male soccer players; Portuguese professional soccer league; 22-31 y	30 m (s) (Brower) Splits: 5 m	Soccer match	Pre-match, 24, 48, 72 h Post-match	5 m (s) – 24, 48, 72 h: NS 30 m (s) – 24, 48, 72 h: NS

Table 6 Acute Change in Sprint Performance

Authors	Subjects	Sprint Variables (Equipment)	Stimulus	Time Points	Results
Castillo, Yanci, Cámara, & Weston, 2016	24 soccer referees; Spanish National 3rd Division; CR (n = 8): 25.6 y, AR (n = 16): 32.3 y	30 m (s) (Microgate); Splits: 15 m	Soccer match	30 min Pre-match, 30 min Post-match	(CR) 15 m (s) – Post-match: Very likely small ↑ (3.7%) 30 m (s) – Post-match: Likely small ↑ (3%) (AR) 15 m (s) – Post-match: Likely small ↑ (2.3%) 30 m (s) – Post-match: Very likely small ↑ (2.4%)
Robineau, Jouaux, Lacroix, & Babault, 2012	8 soccer players; Amateur; 20.4 y	30 m (s) (TELSI + OptoJump) Splits: 10, 20 m	90' soccer-specific aerobic field test	Pre-test, Half-time, 0 h Post-test	0-10 m (m/s) – HT: NS, 0 h: ↓ 3.6% 10-20 m (m/s) – HT: NS, 0 h: ↓ 4.3% 20-30 m (m/s) – HT: ↓ 3.2%, 0 h: ↓ 4.8%
Krustrup et al., 2006	31 male soccer players; Danish 4th Division; 28 y	30 m (s) (Time It)	Soccer match	Pre-match, Post-Intense Period 1 (PI-1), Half-time, Post-Intense Period 2 (PI-2), Post-match	Sprint #1 – PI-1, HT: NS, PI-2: ↑ ~2.9%, Post: ↑ ~3.4%
Krustrup, Zebis, Jensen, & Mohr, 2010	23 female soccer players; Danish top league; 23 y	30 m (s) (Time It)	Soccer match	Pre-match, 0 h Post-match	Sprint #1 – 0 h: ↑ 3.9%
Marrier et al., 2017	13 male rugby sevens players; Elite international; 26.9 y	30 m (s, m/s) (Fusion + Stalker)	Team Training Session	Pre-training, 0 h Post-training	30 m (s) – 0 h: Very likely small ↑ (1.0%) P_{max} – 0 h: NS; F₀ – 0 h: NS v₀ – 0 h: Very likely small ↓ (2.3%)
Mohr et al., 2010	20 male soccer players; Spanish 2nd & 3rd Divisions; 19.3 y	30 m (s) (Alge Timing)	Soccer match (2 x 47.5')	Pre-match, 0 h Post-match	Sprint #1 – 0 h: NS
Nagahara et al., 2016	13 male soccer players; University club; 19.7 y	35 m (m/s) (Jenoptik laser)	Soccer match	Pre-match, End of First Half (FH), Beginning of Second Half (SH), Post-match (PM)	10 m (s) – FH, PM: NS, SH: ↑ (2.4%) 20 m (s) – FH, PM: NS, SH: ↑ (2.4%) P_{max} – FH, PM: NS, SH: ↓ (5.8%) F₀ – FH, SH, PM: NS; v₀ – FH, SH: NS, PM: ↓ (3.9%)
Rampinini et al., 2011	22 male soccer players; Italian Serie A; 19 y	40 m (s) w/ CoD (Microgate) Splits: 15, 25 m CoD at 20 m (i.e. 20 m + 20 m)	Soccer match	Pre-match, 0, 24, 48 h Post-match	0-15 m (s) – 0 h: ↑ 2.5%, 24, 48 h: NS 15-25 m (s) – 0 h: ↑ 4.2%, 24, 48 h: NS 25-40 m (s) – 0 h: ↑ 1.4%, 24 h: ↑ 0.9%, 48 h: NS 0-40 m (s) – 0 h: ↑ 2.8%, 24 h: ↑ 1.2%, 48 h: NS

Table 6 Acute Change in Sprint Performance

Authors	Subjects	Sprint Variables (Equipment)	Stimulus	Time Points	Results
Stone et al., 2016	8 male soccer players; Welsh Division 1; 20.3 y	60 m (s) (Fusion) Splits: 10 m	90' soccer-specific aerobic field test	Pre-test, 0, 24, 48 h Post-test	(Artificial Turf) 10 m (s) – 0 h: NS, 24 h: ↑ 1.8%, 48 h: ↑ 1.8% 60 m (s) – 0 h: ↑ 0.9%, 24 h: ↑ 2.0%, 48 h: ↑ 1.9% (Natural Turf) 10 m (s) – 0 h: NS, 24 h: ↑ 3.0%, 48 h: ↑ 2.4% 60 m (s) – 0 h: ↑ 2.6%, 24 h: ↑ 2.7%, 48 h: ↑ 2.1%
Nédélec, McCall, et al., 2013	13 male soccer players; Professional; 17.7 y	6 s sprint on non-motorized treadmill (Woodway)	90' soccer-specific aerobic field test (SAFT ⁹⁰)	Pre-test, 0, 24, 48 h Post-test	Mean Sprint Power Output – 0, 24, 48 h: NS Mean Sprint Speed – 0, 24, 48 h: NS Peak Sprint Speed – 0, 24, 48 h: NS
Nédélec et al., 2014	10 male soccer players; Professional; 21.8 y	6 s sprint on non-motorized treadmill (Woodway)	Soccer match	Pre-match, 24, 48, 72 h Post-match	Mean Sprint Power Output – 24, 48, 72 h: NS Mean Sprint Speed – 24, 48, 72 h: NS Peak Sprint Speed – 24 h: ↓ 3.8%, 48 h: ↓ 5.0%, 72 h: ↓ 4.8%
Nédélec, Wisloff, McCall, Berthoin, & Dupont, 2013	8 male soccer players; Reserves in Scottish Premier League; 18 y	6 s sprint on non-motorized treadmill (Woodway)	90' soccer-specific intermittent treadmill test	Pre-match, 0, 24, 48, 72 h Post-match	Mean Sprint Power Output – 0, 24, 48, 72 h: NS

Mean ± SD, All results are significant unless otherwise noted, *m* metres, *y* years, *h* hours, *min* minutes, *s* seconds, ↑ increase in sprint time (decreased performance), ↓ decrease in sprint time (increased performance), ↑↑ increase in sprint velocity (increased performance), ↓↓ decrease in sprint velocity (decreased performance), *NS* No significant change, *G1* Group 1, *G2* Group 2, ~ Estimated averages, *CR* Centre Referee, *AR* Assistant Referee, *Yo-Yo IR2* Yo-Yo Intermittent Recovery Test Level 2, *Yo-Yo IE2* Yo-Yo Intermittent Endurance Test Level 2, *LIST* Loughborough Intermittent Shuttle Test, *ES* Effect Size, *SWE* Swedish, *NOR* Norwegian, P_{max} Maximal Power (W/kg), F_0 Theoretical Maximal Force (N), v_0 Theoretical Maximal Velocity (m/s), *SAFT⁹⁰* 90 minute Soccer-specific Aerobic Field Test, *CoD* Change of Direction, *HT* Half-time, *U-17* Under 17 Years Old Age Group, Soccer matches were 2 x 45 minutes unless otherwise noted.

There may be other factors that correspond with decreased sprint performance linked with CNS or PNS contribution. Delayed onset muscle soreness is likely the most well researched factor, with increased soreness corresponding with decreased sprint performance (Andersson et al., 2008; Ascensão et al., 2011; Chatzinikolaou et al., 2014; Djaoui et al., 2015; Getto & Golden, 2013; Ispirlidis et al., 2008; Nédélec et al., 2014; Stone et al., 2016; Wiewelhove et al., 2015). Other factors may be decreased glycogen availability (Krustrup et al., 2006) or decreased hamstrings and/or quadriceps peak torque (Andersson et al., 2008; Ascensão et al., 2008, 2011; Robineau et al., 2012; Ronglan et al., 2006). Finally, sprint performance may be nearly as susceptible to fatigue as jump performance. Sprint performance was more prone to fatigue in 7 out of 22 studies (Castillo et al., 2016; Fatouros et al., 2010; Ispirlidis et al., 2008; Krustrup et al., 2010; Marrier et al., 2017; Robineau et al., 2012; Stone et al., 2016), while jump performance was more inclined to fatigue in nine studies (Andersson et al., 2008; Ascensão et al., 2011; Brownstein et al., 2017; Gathercole, Sporer, Stellingwerff, et al., 2015; Mohr et al., 2010; Nédélec, McCall, et al., 2013; Nédélec, Wisloff, McCall, Berthoin, & Dupont, 2013; Silva et al., 2013; Thomas et al., 2017), and sprints and jumps were equal in six studies when both performance measures were used (Chatzinikolaou et al., 2014; Magalhães et al., 2010; Nédélec et al., 2014; Pliauga et al., 2015; Ronglan et al., 2006; Wiewelhove et al., 2015). Therefore, sprint monitoring may be as useful as jump monitoring when assessing acute fatigue but is more specific to team sport, making it more meaningful to monitor.

Fatigue has also been found to affect specific sprint biomechanical variables, affecting resultant sprint performance. Stride frequency was found to decrease alongside a reduction in 10, 20, and 30 m sprint performance after a simulated soccer match (Robineau et al., 2012), while v_0 was also reduced and significantly correlated to 30 m sprint performance after an intense rugby session and a soccer match (Marrier et al., 2017; Nagahara et al., 2016). Both stride frequency and v_0 are important factors to sprint performance, being strongly correlated to maximum and mean speeds during a 100 m sprint and 4 s distance during a sprint acceleration (Morin et al., 2012), making these two variables perhaps the most worthwhile variables to monitor. Maximal power (P_{MAX}) may

also be an important variable, as it was decreased after half-time in a soccer match, corresponding to a decrease in 10 and 20 m sprint performance (Nagahara et al., 2016).

Considering this evidence, it seems sprint monitoring may be useful for assessing daily acute (0-48 h) fatigue after high-intensity soccer matches, but likely not useful over 72-144 h. If it is not properly utilized, using sprint monitoring daily may progressively add too much additional load to an athlete's weekly load, making the monitoring counter-productive. Over the most common distance (20 m), the practitioners can expect ~4.5% increase in sprint time immediately post-activity, and from 24-72 h a ~2.5% increase in sprint time. These reductions are likely largely caused by CNS fatigue, with additional reductions caused by PNS fatigue and delayed onset muscle soreness. Further, stride frequency and v_0 are the principal components of sprint performance affected by acute team sport fatigue.

Chronic Monitoring of Sprint Performance

Although acute fatigue may help explain how or why there are changes in sprint performance, chronic monitoring over many weeks would help decipher fluctuations in sprint performance as predominantly fatigue-related or performance changes. Sprint time over 5 m had the lowest percent of studies (~13%) showing improvement in performance over a season (Table 7)(Taylor, Portas, Wright, Hurst, & Weston, 2013). This lack of change compared to other distances could be attributed to the large variation in measurements at this distance, having a typical error (TE) of ~5% (Haugen & Buchheit, 2016), possibly due to changes in trunk angle during acceleration (Simperingham, Cronin, & Ross, 2016). The lack of improvement in 5 m sprint time could additionally be attributed to a decrease in strength training during the season, as 5 m sprint times have been correlated to thigh muscle volume, lower body power, and back squat strength (Chelly et al., 2010). Ultimately, 5 m sprint time may not be an effective tool to measure change over a season.

Table 7 Chronic Change in Sprint Performance

Authors	Subjects	Sprint Variables (Equipment)	Time Points	Results
Lesinski, Prieske, Helm, & Granacher, 2017	19 female soccer players, Junior Bundesliga, 15.3 y	10 m (s) (Microgate)	44 weeks; Pre-PreS (0 wk), Post-PreS (+5 wk), Mid S (+17, 21, 29 wk), End S (+44 wk)	NS
Gorostiaga, Granados, Ibáñez, González-Badillo, & Izquierdo, 2006	15 male handball players, European Champions League, 31.0 y	15 m (s) (Newtest) Splits: 5 m	41 weeks; Pre-PreS (0 wk), Post-PreS (+4 wk), Mid S (+25 wk), End S (+41 wk)	5 m (s) – NS 15 m (s) – NS
Caldwell & Peters, 2009	13 male soccer players, English Nationwide Conference North League, 24 y	15 m (s) (Newtest)	52 weeks; End S (0 wk), Pre-PreS (+13 wk), Post-PreS (+17 wk), Mid S (+43 wk), End S (+52 wk)	From previous time point: 13 wk: ↑ 3.3%, 17 wk: ↓ 0.8%, 43 wk: ↓ 2.0%, 52 wk: NS
Taylor et al., 2013	19 female soccer players, English FA Girls Centre of Excellence, U-13 (n = 10): 11.8 y U-15 (n = 9): 13.4 y	20 m (s) (Fusion) Splits: 5 m	36 Weeks; Pre-PreS (0 wk), Mid S (+17 wk), End S (+39 wk)	From baseline (BL) and a previous time point (PT): (U-13) 5 m (s) – 17 wk: Most likely ↑ (8.0%)(BL), 39 wk: Very likely ↑ (5.0%)(BL), 17-39 wk: Likely ↓ (2.8%)(PT) 20 m (s) – 17 wk: Likely ↑ (3.1%)(BL), 39 wk: NS, 17-39 wk: Likely ↓ (2.7%)(PT) (U-15) 5 m (s) – 17 wk: Likely ↑ (3.6%)(BL), 39 wk: Possibly ↑ (2.0%)(BL), 17-39 wk: Possibly ↓ (1.6%)(PT) 20 m (s) – 17 wk: Likely ↑ (1.5%)(BL), 39 wk: NS, 17-39 wk: Likely ↓ (1.4%)(PT)
Thomas, Mather, & Comfort, 2014	11 male lacrosse players, National, 24.5 y	20m (s) (Brower) Splits: 5, 10 m	24 weeks; PreS (0 wk), Mid S (+6, 15 wk), End S (+24 wk)	From baseline (BL) and a previous time point (PT): 5 m (s) – 6 wk: ↓ 0.01% (BL), 15 wk: NS, 24 wk: ↓ 0.03% (BL), 6-15 wk: ↑ 0.01% (PT), 15-24 wk: ↓ 0.03% (PT) 6-24 wk: ↓ 0.02% (PT) 10 m (s) – 6, 15 wk: NS, 24 wk: ↓ 0.02% (BL), 6-15 wk: NS, 15-24 wk: ↓ 0.02% (PT) 6-24 wk: ↓ 0.01% (PT) 20 m (s) – 6 wk: ↓ 0.01% (BL), 15 wk: NS, 24 wk: ↓ 0.02% (BL), 6-15 wk: NS, 15-24 wk: ↓ 0.01% (PT), 6-24 wk: ↓ 0.01% (PT)

Table 7 Chronic Change in Sprint Performance

Authors	Subjects	Sprint Variables (Equipment)	Time Points	Results
Till et al., 2014	75 male rugby league players, Profession club academy, 13.1 – 19.9 y	20 m (s) (Brower) Splits: 10 m	43 weeks; PreS (0 wk), End S (+43 wk)	(U-14) 10 m (s) – NS, 20 m Time – NS (U-16) 10 m (s) – NS, 20 m Time – NS (U-18) 10 m (s) – ↓ 1.7%, 20 m Time – ↓ 1.6% (U-20) 10 m (s) – ↓ 2.2%, 20 m Time – ↓ 1.9%
Hammami et al., 2013	24 male soccer players, Tunisian U-16 National Team, 14.5 y	30 m (s) (Brower) Splits: 5, 10 m	34 weeks; PreS (0 wk), End S (+34 wk)	5 m (s) – 34 wk: NS 10 m (s) – 34 wk: ↓ 5.0% 30 m (s) – 34 wk: ↓ 2.2%
Jastrzębski, Rompa, Szutowicz, & Radzimiński, 2013	19 male soccer players, 16.6 y	30 m (s) (TAG Heuer) Splits: 5 m	45 weeks; Pre-PreS (0 wk), End S (+45 wk)	5 m (s) – 45 wk: ↑ 1.8% 30 m (s) – 45 wk: NS
Silva et al., 2011	18 male soccer players, Portuguese Championship, 25.7 y	30 m (s) (Brower) Splits: 5 m	47 weeks; Pre-PreS (0 wk), Post-PreS (+5 wk), Mid S (+30 wk), End S (+47 wk)	From previous point: 5 m (s) – 5, 30, 47 wk: NS 30 m (s) – 5, 47 wk: NS, 30 wk: ↓ 1.9%
Silva et al., 2014	14 male soccer players, Portuguese professional league, 25.7 y	30 m (s) (Brower) Splits: 5 m	52 weeks; Pre-PreS (0 wk), Mid S (+30 wk), End S (+47 wk), Pre-PreS (+52 wk)	5 m (s) – 5, 30, 47 wk: NS 30 m (s) – 5, 30, 47 wk: NS
Fessi et al., 2016	22 male soccer players, Stars League, 23.7 y	30 m (s) (Microgate) Splits: 10 m	12 weeks; Pre-PreS (0 wk), Post-PreS (+5 wk), Mid S (+12 wk),	From baseline: 10 m (s) (ES) – 5 wk: Moderate ↓ 5.6%, 12 wk: Large ↓ 5.6% 30 m (s) (ES) – 5 wk: Moderate ↓ 4.1%, 12 wk: Moderate ↓ 4.1%
López, Moro, & Aldazabal, 2006	12 female soccer players, Atletico Madrid, 16.6 y	30 m (s) (Unspecified timing gates) Splits: 10, 20 m	34 weeks; Post-PreS (0 wk), Mid S (+14 wk), End S (+34 wk)	From previous time point: 10 m (s) – 14 wk: ↑ 1.0%, 34 wk: ↑ 2.0% 20 m (s) – 14 wk: ↓ 1.1%, 34 wk: ↓ 1.1% 30 m (s) – 14, 34 wk: NS

Table 7 Chronic Change in Sprint Performance

Authors	Subjects	Sprint Variables (Equipment)	Time Points	Results
López-Segovia, Palao Andrés, & González-Badillo, 2010	37 male soccer players, U-19 Spanish First Division, G1: 18.4 y, G2: 18.1 y	30 m (s) (Unspecified timing gates) Splits: 10, 20 m	16 weeks; Post-PreS (0 wk), End S (+16 wk)	(G1 – Strength Training) 10 m (s) – 16 wk: NS 20 m (s) – 16 wk: ↑ 2.3%, 30 m (s) – 16 wk: ↑ 2.3% 10-20 m (s) – 16 wk: ↑ 3.2%, 20-30 m (s) – 16 wk: ↑ 2.6% 10-30 m (s) – 16 wk: ↑ 3.3% (G2 – No Strength Training) 10, 20, 30 m (s) – 16 wk: NS 10-20, 10-30 m (s) – 16 wk: NS 20-30 m (s) – 16 wk: ↓ 1.0%
Williams, Oliver, & Faulkner, 2011	200 male soccer players, English professional club, U-12 – U-16	30 m (s) (Brower) Splits: 10 m	3 years x 26 weeks; PreS (0 wk), End S (+26 wk)	10 m (s) – NS 20 m (s) – NS
Dragijsky, Maly, Zahalka, Kunzmann, & Hank, 2017	28 male soccer players, Czech highest youth league, 11.7 y	30 m (s) (Brower)	22 weeks; Pre-PreS (0 wk), Post-PreS (+10 wk), Mid S (+16 wk), End S (+22 wk)	From baseline: 10 wk: NS, 16 wk: ↓ 3.1%, 22 wk: ↓ 3.3%
Gravina et al., 2008	66 male soccer players, Best players in Spanish region, 10-14 y	Fly 30 m (s) (Seiko)	24 weeks; PreS (0 wk), End S (+24 wk)	(First Team) – 24 wk: ↓ 5.3% (Reserve Team) – 24 wk: NS
Ingebrigtsen, Shalfawi, Tønnessen, Krusturup, & Holtermann, 2013	19 male soccer players, High-level, 16.9 y	35 m (s) (Unspecified timing gates) Splits: 10 m	6 weeks; PreS (0 wk), Post-PreS (+6 wk)	(Control group) 10 m (s) – NS 35 m (s) – NS
Haugen, 2018	44 male soccer players, Norwegian professionals	40 m (s) (Brower) Splits: 5, 10, 20, 30 m	Variable length; PreS (Jan-Mar), Mid S (Apr-Oct), End S (Oct-Dec)	20 m (s) (ES) – Mid S: Possibly small ↓ 0.7%, End S: Most likely small ↓ 1.8%, Mid S-End S: Most likely small ↓ 1.1% 40 m (s) (ES) – Mid S: Likely small ↓ 0.8%, End S: Most likely small ↓ 1.6%, Mid S-End S: Most likely small ↓ 0.8%

Table 7 Chronic Change in Sprint Performance

Authors	Subjects	Sprint Variables (Equipment)	Time Points	Results
Gabbett & Domrow, 2007	183 rugby league players, New South Wales Country Rugby League, 21.4 y	40 m (s) (Swift) Splits: 10, 20 m	2 years x 34 weeks; Pre-PreS (0 wk), Post-PreS (+13 wk), Mid S (+21 wk), End S (+34 wk)	From baseline (BL) and a previous time point (PT): 0-10 m (m/s) – 13 wk: NS 21 wk: ↑ 4.0% (BL), 34 wk: ↑ 2.0% (BL), 13-21 wk: ↑ 3.6% (PT) 10-20 m (m/s) – 13 wk: ↑ 1.6%, 21 wk: ↑ 0.5% (BL), 34 wk: ↑ 0.9% (BL), 13-21 wk: ↓ 1.1% (PT) 20-40 m (m/s) – 13, 21, 34 wk: NS
Silvestre et al., 2006	25 male soccer players, University, 19.9 y	40 yd (s) (Brower) Splits: 10 yd	17 weeks; Pre-PreS (0 wk), End S (+17 wk)	10 yd (s) – 17 wk: NS 40 yd (s) – 17 wk: NS
Waldron, Gray, Worsfold, & Twist, 2016	13 male rugby league players, Profession club U-19, 18.2 y	40 m (s) (Brower) Splits: 10 m	34 weeks; Pre-PreS (0 wk), Mid S (+5 wk), End S (+34 wk)	From baseline (BL) and a previous time point (PT): 10 m (s) – 5 wk: ↓ 2.0% (BL), 34 wk: ↓ 1.5% (BL), 5-34: NS 40 m (s) – 5 wk: ↓ 1.2% (BL), 34 wk: ↓ 0.9% (BL), 5-34: NS
Kraemer et al., 2004	25 male soccer players, University, Starters: 19.9 y Nonstarter: 18.7 y	40 yd (s) (Hand) Splits: 20 yd	11 weeks; PreS (0 wk), Mid S (+3, 7, 8, 9 wk), End S (+11 wk)	From baseline: (Starters) 20 yd (s) – 3, 7, 8, 9, 11 wk: NS 40 yd (s) – 3, 7, 8, 11 wk: NS, 9 wk: ↑ 4.4% (Nonstarters) 20 yd (s) – 3, 7, 8, 9, 11 wk: NS 40 yd (s) – 3, 7, 8, 9, 11 wk: NS
Gabbett, 2005	68 male rugby league players, Queensland Rugby League	40 m (s) (Swift)	39 weeks; Pre-PreS (0 wk), Post-PreS (+13 wk), Mid S (+21 wk), End S (+39 wk)	13, 21, 39 wk: NS
Ostojic, 2003	30 male soccer players, 1st National league, 23.5 y	50 m (s) (Brower)	42 weeks; Pre-PreS (PS1), Post-PreS (PPS), Mid S (MS), End S (ED), Pre-PreS (PS2, 42 wk)	From baseline: PPS: ↓ 2.7%, MS: ↓ 4.0%, ED: ↓ 5.3%, PS2: ↑ 1.3% From a previous time point: PPS-PS2: ↑ 4.1%, MS-PS2: ↑ 5.6%, ED-PS2: ↑ 7.0%, PPS-ED: ↓ 2.7%

Mean ± SD, *m* metres, *y* years, *wk* week, *h* hours, *min* minutes, *s* seconds, *m/s* metres per second, ↑ increase in sprint time (decreased performance), ↓ decrease in sprint time (increased performance), ↑ increase in sprint velocity (increased performance), ↓ decrease in sprint velocity (decreased performance), *G1* Group 1, *G2* Group 2, ~ Estimated averages, *ES* Effect Size, *Pre-PreS* Before the Pre-Season Phase, *Post-PreS* After the Pre-Season Phase, *PreS* During the Pre-Season Phase, *Mid S* Middle of the Season, *End S* End of the Season, *U-13* Under 13 Years Old Age Group

Sprint performance in team sport athletes of 10-50 m assessed over the course of a season does not provide a clear picture of improvement or decay (Table 7). Over all of the studies evaluated, consistently about 30% of the time points showed an improvement in sprint performance. Meanwhile, the remaining 70% of the time points were split between no change (33-63%) or a decrement in performance (5-33%). When considering the most researched distances (10, 20, 30, and 40 m), which made up 73% of the time points, it was very consistently about 8% of the points showed decay, 60% found no change, and 32% showed improvements in performance over 5- to 52-week seasons. When considering the first five to ten weeks of monitoring, relatively few studies found a decay in performance. Only studies over 35 m found a decay in performance (Kraemer et al., 2004; Ostojic, 2003), while all others at all distances in the first ten weeks found no change or improvements. Therefore, this could be a function of increased sprint training volume and added speed stimulus through the beginning of the season, and therefore enhanced strength and power capabilities, or short sprints (< 30 m) are less sensitive to fatigue in the first five to ten weeks. Generally, these first weeks are a large portion of the pre-season training phase and returning from the off-season with little high velocity activity. When considering phase specific changes in sprint performance, the pre-season phase showed mostly no change, while a few studies found improvements. A possible explanation is the balance between increased sprint volume through increased on-field training and thus improvements in sprinting, but also a fatiguing aspect of increased training loads through pre-season training (Mara et al., 2015). This change in sprint performance was demonstrated in Caldwell & Peters (2009), with a large decay in performance over the off-season, but then a gradual return to the same sprint performance levels by the end of the following season. The training load accomplished during the pre-season phase would likely be a determining factor whether the players build fatigue or adapt to the increased training stimulus. Meanwhile, sprint performance through the middle and end phases of the season provided inconclusive results.

Although no conclusion can likely be drawn from the analysis of all of the sprint times over a season, other information can be highlighted. Two studies showed a

significant correlation between sprint performance and body fat percentage (Caldwell & Peters, 2009; Ostojic, 2003). Both of these studies assessed the players before and after their off-season, with the highest measurements of body fat percentage and sprint performance occurring just before pre-season. This shows that without a structured training program, athletes will likely decrease in performance and body composition. Additionally, all three female studies showed a decay in shorter-sprint performance (< 15 m) over the course of a season, while longer-distances were equivocal (López, Moro, & Aldazabal, 2006; Mara et al., 2015; Taylor et al., 2013). This may demonstrate the additional importance of female team sport athletes consistently performing a physical preparation plan to optimize maximal speed characteristics. As a whole, the research showed inconclusive relationships between sprinting and jumping abilities, with nine studies displaying similar changes in sprint and jump performance (Caldwell & Peters, 2009; Fessi et al., 2016; Gabbett & Domrow, 2007; Gorostiaga et al., 2006; Hammami et al., 2013; Ingebrigtsen et al., 2013; Kraemer et al., 2004; López-Segovia et al., 2010; Waldron et al., 2016) and seven studies showing dissimilar changes (Gabbett, 2005; Gravina et al., 2008; Lesinski, Prieske, Helm, & Granacher, 2017; López et al., 2006; Silva et al., 2011; Silvestre et al., 2006; Thomas, Mather, & Comfort, 2014). However, when comparing changes in strength and sprint performance, five studies showed similar improvements in strength and sprinting (Kraemer et al., 2004; López-Segovia et al., 2010; Silva et al., 2011; Till et al., 2014; Waldron et al., 2016), while one study showed increased strength but not improved sprint performance (Silvestre et al., 2006). This is consistent with previous research demonstrating the importance of muscular strength in sprint performance (Chelly et al., 2010; Seitz, Reyes, Tran, de Villarreal, & Haff, 2014).

Monitoring sprint performance irregularly over a season may not be able to depict changes in fatigue or performance, but it likely depends on a number of factors, including whether specific sprint training is conducted. With all of the literature only utilizing sprint monitoring after long training phases, it is difficult to determine what causes changes in sprint performance. Additionally, sprint performance tends to decrease over the off-season. Therefore, the physical performance coach should be aware and plan for such

changes over the season, including blunting the decrease during the off-season to increase performance in the early stages of the competition phase. This can be achieved through specific sprint training, and maintenance of maximal strength training, especially in the female population.

Monitoring of Sprint Performance and Training Load

Irregular monitoring of sprint performance times may not provide a clear picture of changes in fatigue or performance but investigating its relationship with training load may help establish rational for changes in sprint performance. To our knowledge, no study has consistently investigated the direct relationship between training load and sprint performance over a longer period of time (> 6 days). A few studies have used a simple before and after change in sprint performance over one defined period, but none have investigated the progression of sprint performance in relation to training loads. One investigation used before and after measures over three time periods during a season, but each test was two to three months apart, more similar to seasonal testing protocols (Gabbett & Domrow, 2007). However, some guidance may still be generated from this literature.

Table 8 Sprint Performance and Training Load

Authors	Subjects	Sprint Variables (Equipment)	Mean Weekly Training Load (sRPE)	Time Points	Results
Mara et al., 2015	17 female soccer players, National league	5, 15, 25 m (s) (Fusion)	(5 sessions/wk)	18 weeks; Pre-PreS (0 wk), Post-PreS (+6 wk), Mid S (+12), End S (+18 wk)	From baseline (BL) and a previous time point (PT): 5 m (s) – 6, 12, 18 wk: NS, 6-18 wk: \uparrow ~3.3% (PT) 15 m (s) – 6 wk: \downarrow ~2.9% (BL), 12, 18 wk: NS 25 m (s) – 6, 18 wk: NS, 12 wk: \downarrow ~3.1% (BL), 12-18 wk: \uparrow ~4.5% (PT)
Gil-Rey, Lezaun, & Los Arcos, 2015	28 male soccer players, Junior Spanish 1st Division, Elite (n = 14): 17.6 y Non-elite (n = 14): 17.5 y	15 m (s) (Microgate) Splits: 5 m	(Elite) sRPEres – 1460 AU sRPEmus – 1548 AU (Non-elite) sRPEres – 1223 AU sRPEmus – 1318 AU (4 sessions + 1 match/wk)	9 weeks; Mid S (0, +9 wk)	(Elite) 5 m (s) (ES) – 9 wk: Possibly small \uparrow 1.3% 15 m (s) (ES) – 9 wk: NS (Non-elite) 5 m (s) (ES) – 9 wk: Possibly small \uparrow 1.1% 15 m (s) (ES) – 9 wk: Likely moderate \uparrow 1.9%
Los Arcos et al., 2017	14 male soccer players, Spanish La Liga reserve team, 20.6 y	15 m (s) (Newtest) Splits: 5 m	sRPEres ~ 1385 AU sRPEmus ~ 1422 AU (4-8 sessions + 1-2 matches/wk)	32 weeks; Pre-PreS (0 wk), End S (+32 wk)	5 m (s) – NS 15 m (s) – NS
Los Arcos et al., 2015	19 male soccer players, Spanish La Liga reserve team, 20.2 y	15 m (s) (Newtest) Splits: 5 m	sRPEres ~ 1807 AU sRPEmus ~ 1852 AU (4-8 sessions + 1-2 matches/wk)	9 weeks; Pre-PreS (0 wk), Mid S (+9 wk)	5 m (s) (ES) – 9 wk: Very likely moderate \downarrow 2.3% 15 m (s) (ES) – 9 wk: Likely small \downarrow 1.0%
Los Arcos et al., 2014	21 male soccer players, Spanish 3rd Division, 21.0 y	15 m (s) (Newtest) Splits: 5 m	sRPEres – 1515 AU sRPEmus – 1576 AU (4-6 sessions + 1 match/wk)	9 weeks; Mid S (0, +9 wk)	5 m (s) – NS 15 m (s) – NS

Table 8 Sprint Performance and Training Load

Authors	Subjects	Sprint Variables (Equipment)	Mean Weekly Training Load (sRPE)	Time Points	Results
Miloski, de Freitas, Nakamura, de A Nogueira, & Bara-Filho, 2016	12 male futsal players, Brazilian National League, 24.3 y	20 m (s) (Cefise) Splits: 5 m	~3113 AU (10.5 sessions + 1-2 matches/wk)	22 weeks; Pre-PreS (0 wk), Post-PreS (+6 wk), Mid S (+13 wk), End S (+22 wk)	From baseline: 5 m (s) – 6 wk: Possibly ↓ 1.8%, 13 wk: Very likely ↓ 5.5%, 22 wk: Almost certainly ↓ 9.1% 20 m (s) – 6 wk: Likely ↓ 1.6%, 13 wk: Very likely ↓ 3.5%, 22 wk: Almost certainly ↓ 4.5%
Murphy, Duffield, Kellett, & Reid, 2015	20 male/10 female tennis players, High-performance, 17 y	20 m (s) (Swift) Splits: 5, 10 m		4 weeks; Pre-tour (0 wk), Post-tour (+4 wk)	5 m (s) (ES) – 4 wk: Moderate ↑ 3.6% 10 m (s) (ES) – 4 wk: Moderate ↑ 3.3% 20 m (s) (ES) – 4 wk: Moderate ↑ 2.2%
Murphy, Duffield, Kellett, Gescheit, & Reid, 2015	20 male/10 female tennis players, High-performance, 17 y	20 m (s) (Swift) Splits: 5, 10 m	~6531 AU	4 weeks; Pre-tour (0 wk), Post-tour (+4 wk)	5 m (s) (ES) – 4 wk: Moderate ↑ 3.6% 10 m (s) (ES) – 4 wk: Moderate ↑ 3.3% 20 m (s) (ES) – 4 wk: Moderate ↑ 2.2%
Nakamura, Pereira, Rabelo, Ramirez-Campillo, & Loturco, 2016	10 male futsal players, Professional Brazilian team, 19.1 y	20 m (s) (Fusion) Splits: 5, 10 m	~4000 AU (8 sessions/wk)	9 weeks; Pre-PreS (0 wk), Post-PreS (+9 wk)	5 m (m/s) (ES) – 9 wk: Likely small ↓ ~4.2% 10 m (m/s) (ES) – 9 wk: Very likely moderate ↓ ~3.5% 20 m (m/s) (ES) – 9 wk: Very likely moderate ↓ ~3.5%
Rollo, Impellizzeri, Zago, & Iaia, 2014	30 male soccer players, University club, 20 y	20 m (s) (Brower) Splits: 10 m	1 vs 2 matches (M) per week (2 sessions + matches/wk)	6 weeks; Mid S (0, +3, 6 wk)	From baseline (BL) and previous time point (PT): (1 M) 10 m (s) – 3 wk: NS, 6 wk: ↓ 3.2% (BL)/ ↓ 2.5% (PT) 20 m (s) – 3 wk: ↓ 0.3% (BL), 6 wk: ↓ 2.8% (BL)/ ↓ 2.5% (PT) (2 M) 10 m (s) – 3 wk: NS, 6 wk: ↑ 2.8% (BL)/(PT) 20 m (s) – 3 wk: ↑ 0.3% (BL), 6 wk: ↑ 3.6% (BL)/ ↑ 3.3% (PT)
Coutts, Reaburn, Piva, & Murphy, 2007	7 male rugby league players, Queensland Cup, 25.7 y	40 m (s) (Swift) Splits: 10 m	2316 AU (5-7 sessions/wk)	7 weeks; Pre-PreS (0 wk), Post-PreS (+6 wk), Post-taper (+7 wk)	10 m (s) – 6 wk: NS, 7 wk: MCID ↓ 2.1% from previous point 40 m (s) – NS
Gabbett & Domrow, 2007	183 rugby league players, New South Wales Country Rugby League, 21.4 y	40 m (s) (Swift) Splits: 10, 20 m	~345 AU (2-3 sessions/wk)	2 years x 34 weeks; Pre-PreS (0 wk), Post-PreS (+13 wk), Mid S (+21 wk), End S (+34 wk)	From baseline (BL) and a previous time point (PT): 0-10 m (m/s) – 13 wk: NS, 21 wk: ↑ 4.0% (BL), 34 wk: ↑ 2.0% (BL), 13-21 wk: ↑ 3.6% (PT) 10-20 m (m/s) – 13 wk: ↑ 1.6%, 21 wk: ↑ 0.5% (BL), 34 wk: ↑ 0.9% (BL), 13-21 wk: ↓ 1.1% (PT) 20-40 m (m/s) – 13, 21, 34 wk: NS

Table 8 Sprint Performance and Training Load

Authors	Subjects	Sprint Variables (Equipment)	Mean Weekly Training Load (sRPE)	Time Points	Results
Gabbett, 2005	68 male rugby league players, Queensland Rugby League	40 m (s) (Swift)	~500 AU (2 sessions + 1 match/week)	39 weeks; Pre-PreS (0 wk), Post-PreS (+13 wk), Mid S (+21 wk), End S (+39 wk)	13, 21, 39 wk: NS
Roe, Darrall-Jones, Till, & Jones, 2016	14 male rugby union players, Professional senior academy, 19.1 y	40 m (s) (Catapult GPS)	1810 AU (8 sessions/ wk)	10 weeks; Pre-PreS (0 wk), Post-PreS (+10 wk)	40 m (m/s) – 10 wk: Very likely ↑ 5.5%

Mean ± SD, *m* metres, *y* years, *wk* week, *h* hours, *min* minutes, *s* seconds, *m/s* metres per second, ↑ increase in sprint time (decreased performance), ↓ decrease in sprint time (increased performance), ↑ increase in sprint velocity (increased performance), ↓ decrease in sprint velocity (decreased performance), ~ Estimated averages, *ES* Effect Size, *Pre-PreS* Before the Pre-Season Phase, *Post-PreS* After the Pre-Season Phase, *PreS* During the Pre-Season Phase, *Mid S* Middle of the Season, *End S* End of the Season, *U-13* Under 13 Years Old Age Group, *sRPE* Session Rating of Perceived Exertion (Session Duration x RPE), *AU* Arbitrary Units, *MCID* Minimal Clinically Important Difference, *sRPEres* Central-respiratory Session Rating of Perceived Exertion, *sRPEmus* Local-Muscular Session Rating of Perceived Exertion

The available literature on linear sprint performance in relation to training load may indicate, from youth tennis to professional soccer, a positive correlation exists between increasing sprint times (i.e. diminished sprint performance) and increasing training load and volume (Table 8). This relationship is found at 5 m (Los Arcos et al., 2015; Murphy, Duffield, Kellett, Gescheit, et al., 2015; Murphy, Duffield, Kellett, & Reid, 2015), 10 m (Murphy, Duffield, Kellett, Gescheit, et al., 2015; Murphy, Duffield, Kellett, & Reid, 2015), 15 m (Gil-Rey et al., 2015; Los Arcos et al., 2017, 2015, 2014), and 20 m (Murphy, Duffield, Kellett, Gescheit, et al., 2015; Murphy, Duffield, Kellett, & Reid, 2015). Additionally, faster players over 20 m tended to sustain higher training loads over the first two weeks of pre-season in male futsal players (Nakamura et al., 2016). However, in the same players, there was no meaningful correlation between sprint velocity and training load over the entire nine-week pre-season. A lack of association between training load and sprint performance was similarly found in sub-elite rugby league players over three distinct time periods of the season (Gabbett & Domrow, 2007). Yet, much of this research used very few longitudinal time points to create these relationships, making fluctuations in training load difficult to decipher from overall changes over months. Although there was evidence of decayed sprint performance with increased training load, it was difficult to draw strong conclusion because the previous research only used two or three sprint measures. Therefore, more consistent longitudinal sprint monitoring needs to be analyzed to draw specific conclusions.

Accumulated chronic fatigue pertaining to sport performance, lasting over weeks, can lead to functional and non-functional overreaching. The mechanisms of this long-term fatigue are yet to be fully investigated and are likely too complex to fully ascertain. They likely stem from a multiplicity of factors, ranging from direct physiological and biological factors (e.g. muscle fiber damage, neural excitability, stretch reflex inhibition), in addition to psychological, nutritional, social, and behavioural factors (Meeusen et al., 2013; Ross et al., 2001; Twomey et al., 2017). Although acute fatigue from soccer matches predominately show CNS fatigue, there are signs of low-frequency fatigue in the PNS (Rampinini et al., 2011). Over one week, there may not be significant changes in

performance due to low-frequency fatigue, but as the season progresses and the games and fatigue build on each other, the fatigue could perpetuate to create decreases in performance as seen in McLean et al. (2012) and Rollo et al. (2014). McLean et al. (2012) found maximal power during a cycle ergometer test to decrease throughout the season for university female soccer starters, versus no change for nonstarters. Additionally, Rollo et al. (2014) found 10 and 20 m sprint time increased by 2.8 and 3.5% after six weeks of university soccer players playing two matches per week. Comparatively, players from the same team who trained the same amount, but only played one match per week, significantly improved their sprint times by 3.3 and 2.9%. The researchers suggest that the competition load associated with one match per week was more effective and allowed for improvement, while the two matches per week gradually exacerbated fatigue levels and affect physical performance.

Team sport athletes must concurrently undertake a large amount of strength training and conditioning. Therefore, small changes in sprint performance may initially be nullified due to large volumes of conditioning. When thorough strength and power programs are implemented in-season in team sports, there may be improvements (4.5-9%) in jump and sprint performance throughout a season, even with spikes in training load (Miloski et al., 2016). Additionally, these programs may help keep jump and sprint performance consistent in light of fatigue and injury in the later stages of a season (Gabbett, 2005).

The pre-season training phase can produce mixed results due to the unknown training demands completed in the off-season. One study has shown the presence of fatigue through decreases in CMJ power, while simultaneously achieving very likely (5.5%) improvements in 40 m sprint velocity in senior academy rugby union players over a pre-season period (Roe et al., 2016). Another study showed 10 m sprint time did not significantly change with intentional overreaching through pre-season, but equaled the smallest worthwhile change in improvement following a seven-day taper in rugby players at the end of pre-season (Coutts et al., 2007). This may show that the specific training over a pre-season period likely leads to greater improvements in sprint performance than

decreases stemming from fatigue, but the athletes may be more susceptible to performance improvements coming off of an off-season due to lack of fitness. A major factor often unaccounted for is the training volume and content over the off-season period, which can make athletes more susceptible to benefits of training programs. Additionally, sprint performance may be more greatly affected by longer-term fatigue as demonstrated by Rollo et al. (2004) compared to even three weeks of fatigue, the length of some pre-seasons. Mara et al. (2015) found an improvement in 5, 15, and 25 m sprint performance through a pre-season period, and then decayed through the season, potentially because of accumulated fatigue, similar to McLean et al. (2012). However, much of this is speculative because almost all testing is only carried out before and after training phases, instead of consistent monitoring of sprint performance, making the source of improvement or decay in performance difficult to isolate.

With no long-term consistent monitoring of sprint performance in relation to training load, it is difficult to evaluate the association. From the little research available, it can be reasoned that large changes in training load do cause impairments in sprint performance. This is likely due to low-frequency accumulated fatigue over multiple weeks, versus acute fatigue over a week or two. In some shorter pre-season training phases, the accumulated fatigue may not out-weight the benefits of increased sprint training after an off-season phase, consequently showing overall improvements in sprint performance. Therefore, the applied practitioners must be aware of the state of the athletes going into a pre-season phase.

Conclusions

It is difficult to create specific sprint performance criteria due to the variability in methodologies and subjects throughout the research. From the available research, sprint performance appears to be most affected during the first 24 h post-exercise, which results from a higher degree of CNS fatigue compared to PNS fatigue. Sprint performance covering 5 m rarely detects change in acute fatigue or over a season, while 10-50 m sprint

performance measures appear to be more susceptible to change. Furthermore, athlete body composition and leg strength are specific factors that may have a large influence on changes in sprint performance over the course of a season. Additionally, female athletes may be more prone to losses in strength over a competition season, resulting in negative effects in sprint performance. High chronic training load and training volume likely play a role in diminished sprint performance, which may be more affected by the accumulation of low-frequency fatigue over many weeks. Meanwhile, off-season training likely has a large effect on whether improvements in sprint performance are observed during the early season period.

Practical Applications

The current evidence suggests simple timing of sprint performance provides a varied representation of fatigue and changes in sprint performance. It has been established that sprint performance is a critical component of team sport, hence regular sprint training is vital. However, further investigation into macroscopic biomechanical sprint variables may provide further reason to explore the use of sprint monitoring.

Currently, daily monitoring of sprint performance would not make empirical or practical sense, and high volumes of maximal speed sprinting should be minimized in the 24-48 h post-match. Sprint training should also be considered over the off-season training phase to keep sprint performance more consistent entering the pre-season and early competition phases. But more thorough investigations need to take place to consider consistent weekly monitoring of sprint performance, especially in relation to training load. The acute and chronic loading of the current training phase likely has a large influence on current sprint ability, so these variables are essential to consider when examining changes in sprint performance. Meanwhile, from comparisons of the susceptibility of CMJ and sprint performance to fatigue, it may be reasonable to replace CMJ height monitoring with sprint performance monitoring due to the specificity of the

activity for team sport athletes, along with the training and injury prevention outcomes associated with regular maximal sprint training.

Appendix B: Short Recovery and Stress Scale

Short Recovery Scale

Below you find a list of expressions that describe different aspects of your current state of recovery. Rate how you feel right now in relation to your best ever recovery state.

Physical Performance Capability

e.g. strong, physically capable, energetic, full of power

○ ○ ○ ○ ○ ○ ○
does not

Mental Performance Capability

e.g. attentive, receptive, concentrated, mentally alert

apply at 0
○ ○ ○ ○ ○ ○ ○
does not

1

Emotional Balance

e.g. satisfied, balanced, in a good mood, having everything under control, stable, pleasant

apply at 0
○ ○ ○ ○ ○ ○ ○
does not

1

Overall Recovery

e.g. recovered, rested, muscle relaxation, physically relaxed

apply at 0
○ ○ ○ ○ ○ ○ ○
does not

1

apply at 0
all 1

1

Short Stress Scale

Below you find a list of expressions that describe different aspects of your current state of stress. Rate how you feel right now in relation to your highest ever stress state.

Muscular Stress

e.g. muscle exhaustion, muscle fatigue, muscle soreness, muscle stiffness

○ ○ ○ ○ ○ ○ ○
does not

Lack of Activation

e.g. unmotivated, sluggish, unenthusiastic, lacking energy

apply at 0
○ ○ ○ ○ ○ ○ ○
does not

1

Negative Emotional State

e.g. feeling down, stressed, annoyed, short-tempered

apply at 0
○ ○ ○ ○ ○ ○ ○
does not

1

Overall Stress

e.g. tired, worn out, overloaded, physically exhausted

apply at 0
○ ○ ○ ○ ○ ○ ○
does not

1

apply at 0
all 1

1

Appendix C: Facial RPE Scale

0	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	

Appendix D: Standardized Warm-up

WARM-UP		
	Sets	Distance
Dynamic Movement - work between a 20-m line		
Easy Forward Skipping	1	20
Easy Backward Skipping	1	20
Skipping with arm circles - both direction	2	20
Skips with cross body arm swings	2	20
Side Shuffle	2	20
Alternating Side Shuffle	2	20
Carioca - with high front side kick	2	20
Backwards running - low + high kicks	2	20
Mobility		
10 x Leg Swings, 10 x Hip Circles, 10 x Leg out Rock Backs 10 x Leg Out Thread the needle, 10 x Cat Camel, 10 x Hip Collapser		
Activation		
5 x SL Glute Bridge 3 x 10 sec Side Plank 10 x Mini Band Lateral Walks 5 x Bird Dog		
Sprint Mechanics & Plyo - work between a 20-m line		
RDL into Walking A	1	10
A skip	2	10
Dribbling Ankle height	2	10
Straight Leg Bounds	2	20
Skip for Height	1	20
Skip for Distance Bleed	2	5+20-m (90%)
Broad Jump to Accel 20-m (95%)	2	1 + 20-m
Familiarization in the gates		
10-m Acceleration (95%)	2	10-m
20-m Sprint (95%)	1	20-m
30-m Sprint (hit top speed by the end)	1	30-m