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Accelerometer load: a new way to measure fatigue during repeated sprint training?

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ABSTRACT

Purpose: Prescribing the appropriate dose of repeated sprint training to a large number of players in a team sports environment presents a challenge to practitioners. Players experience fatigue and performance decrements at different rates, and so a means of monitoring this would be of interest to coaches. This study aimed to identify if accelerometer load could be used to detect the performance decrement during repeated sprints.
Materials and Methods: Nine male semi-professional and amateur soccer players performed 25 m sprints (2 × 12.5 m with 180° change of direction) interspersed with 20 s passive recovery until a 5% performance decrement in sprint time was reached. Trunk segmental accelerations were measured at the thoracic spine using a triaxial accelerometer worn in a tight-fitting vest.
Results: Sprint time increased by 8.5% (range 5–13%) from the first to the last sprint. Accelerometer load demonstrated a mean decrease of 15% (range 11–23%) from the first to the last sprint. Least squares linear regression revealed accelerometer decrement to be two to threefold greater than the sprint performance decrement. Additionally, strong within-participant associations between accelerometer load and sprint decrement with very large to nearly perfect correlations were observed (Pearson's $r = 0.84–0.99$, $P < 0.03$).
Conclusion: Practitioners may be able to utilize this concept to monitor the fatigue induced by repeated sprinting or high-intensity efforts in team sports training in order to prescribe sprint training relative to individual fatigue profiles.

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KEYWORDS
Football; monitoring; team sports

Introduction

Training volume, frequency and intensity among other factors are manipulated to bring about desired adaptations and performance enhancements. In the context of team sports where multiple players take part in the same training session, delivering appropriately individualized training stimuli across a squad can be difficult. Coaches will often supplement main sessions with additional training in order to achieve these desired adaptations (Macpherson & Weston 2015; Taylor et al. 2015). As an example, small-sided games may be employed to deliver team-based conditioning and supplemented with additional training. As repeated, high-intensity efforts are required in football (Abt & Lovell 2009; Bradley et al. 2009), supplementing team-based training with repeated sprint training is a common approach. However, a dilemma faced in this scenario is how much training to prescribe in order to deliver an effective stimulus to individual players.

The objective of repeat sprint or high-intensity effort training is to facilitate adaptations in the metabolic and neuromuscular systems such that players are able to recover more quickly between repeated efforts and perform higher speed/intensity efforts more frequently or for a longer time (Buchheit & Laursen 2013a, 2013b). In the field, some practitioners may prescribe an arbitrary number of repetitions, or the coach may use their experience to determine the number of repetitions the player should complete based upon training history and observable technique. Another approach may be to monitor sprint times and have players continue until a certain level of fatigue or performance decrement is observed. In the team sports setting, prescribing an arbitrary number of sprints is certainly the more feasible but risks delivering inappropriate workloads to some individuals (Gaudino et al. 2013). Delivering too great or small, a sprinting stimulus might elevate the risk of injury (Duhig et al. 2016; Silva et al. 2016), with an insufficient stimulus rendering the training ineffective for the stated objective. Monitoring the performance decrement using timing systems might reduce the chances of delivering an inappropriate stimulus as the between-player variance in fatigue is reduced (Gaudino et al. 2013), but this is ultimately unfeasible in the applied environment.

Research studying changes in kinematics and kinetics during sprinting and repeated sprinting has consistently reported increased ground contact time and center of mass (CoM) displacement due to a reduction in the force-generating capacity of the working muscles (Girard et al. 2011a, 2011b; Gaudino et al. 2013; Watari et al. 2016). The increased contact time and CoM displacement result in reduced vertical and leg stiffness, making the lower limbs more compliant during the stance phase. These implications are important to consider when prescribing sprint training in team sports athletes as aside from performance (Maloney et al. 2016), too great reductions in stiffness may increase the risk of injury (Butler et al. 2003; Debenham et al. 2016). Therefore, having

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the ability to measure these changes or surrogates of them in the field would provide useful objective data for coaches to consider.

Accelerometers and inertial measurement units (IMUs) have emerged as a tool with the potential to measure stride variables and reflect changes in running gait such as postural control and CoM oscillations. Some studies (Rabita et al. 2011; Brocherie et al. 2015; Buchheit et al. 2015) have used IMU to directly estimate stride variables such as contact time, flight time and step length. However, others have found that the root mean square (RMS) of accelerations measured during running can be used to detect fatigue (Cormack et al. 2013; Schutte et al. 2015; Barrett et al. 2016b). Within professional and elite teams, players regularly wear micro-electro-mechanical systems (MEMS) featuring global positioning technology and integrated IMU which report derivatives of accelerometer RMS data such as "Force Load" (Colby et al. 2014) or "PlayerLoad" (Barrett et al. 2016b). As yet, however, it is not known if this technology can be used to detect the fatigue-induced alterations in gait discussed above. Therefore, the aim of this study was to investigate whether a commonly utilized IMU device can be used to track fatigue in team sports athletes during a repeated sprint protocol.

Methods

Participants

Nine male semi-professional football players (age [mean ± SD]: 26.2 ± 3.4 years; height: 1.72 ± 0.06 m; body mass: 70.8 ± 6.8 kg) provided written informed consent to participate in the study. All participants were involved in organized football training (3–4 times per week) with their clubs and were free of injury in the 6 months prior to taking part. The project was approved by the local Scientific and Ethics Committee and all procedures complied with the *Declaration of Helsinki* regarding human experimentation.

Experimental design

Prior to testing, participants were fitted with a MEMS device (Optimeye S5, Catapult Innovations, Australia) located at the thoracic spine between the scapulae housed in a tight-fitting garment to reduce movement artefact. The MEMS device features an integrated IMU with triaxial accelerometer sampling at 100 Hz (measurement range ±16 g). The calibration values for all devices were checked against the manufacturers thresholds prior to each testing session and remained within the correct limits.

After a standardized warm-up, participants performed maximal 12.5 m shuttle sprints with 1 × 180° change of direction (total 25 m per sprint) interspersed with 20 s of passive recovery. Participants were encouraged to perform the fastest sprint possible for each trial and continued until a performance decrement of 5.0% was reached and sustained for two consecutive trials, according to the equation recommended by Buchheit and Laursen (2013a). Five seconds prior to each sprint, participants stood stationary on the start line and provided their perceived recovery status (PRS) (Laurent et al. 2011), and 10 s following each effort, they provided a rating of perceived exertion (RPE) for the recently completed sprint (Foster et al. 2001).

To prevent pacing, participants were blinded to the number of sprints to be performed and the criteria for termination. Feedback on sprint times was not provided and participants were given verbal encouragement to perform maximally for each sprint. All testing was conducted on an indoor sports hall with participants wearing their own running shoes. All participants were familiar with completing maximal sprints with 180° changes of direction on this surface and had completed familiarization trials 1 week prior to testing.

Data acquisition

Sprint times were measured using single-beam photoelectric cells placed at a height of 1 m at the start line, level with the front of the athletes' leading foot (Polifemo, Microgate, Italy). The onset of each sprint was demarcated within the MEMS manufacturer supplied software (Sprint 5.1.7, Catapult Innovations, Australia) via visual inspection of the anteroposterior axis as described previously (Akenhead et al. 2014). The measured sprint time was then added to the onset time to identify the end of the sprint. RMS acceleration for each sprint was downloaded from the MEMS device using the manufacturer's software. Combined triaxial accelerometer data were presented as PlayerLoad (PL_{VM}), which is a modified vector magnitude expressed as the square root of the sum of the squared instantaneous rates of change in acceleration in each of the 3 planes, divided by 100 (Boyd et al. 2011).

To factor out the effect of increasing sprint times as the protocol progressed, PlayerLoad_{VM} and the individual planes (anterior–posterior [PL_{AP}], mediolateral [PL_{ML}] and vertical [PL_{V}]) were expressed relative to sprint time. All subsequent analysis was conducted using these relative values and the same percentage decrement method used for sprint times was applied to all PlayerLoad variables as follows: 100 – [greatest PL value × sprints completed (n)/(total PL accumulated)] × 100.

Statistical analysis

Data are presented as mean (95% confidence intervals [CI]) unless otherwise stated. Normal distribution of the data was confirmed using the D'Agostino and Pearson omnibus normality test. Least squares linear regression was used to examine the relationship between decrement scores for sprint times ($\text{Decrement}_{SPRINT}$) and PlayerLoad variables (Decrement_{PLVM}). Regression intercepts and slopes were calculated for each participant individually and using pooled data. Pearson's correlation coefficient (r) was calculated to describe the level of association between $\text{Decrement}_{SPRINT}$ and Decrement_{PLVM} with the following thresholds used for interpretation: trivial (0.0–0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), nearly perfect (0.9–1.0) and perfect (1.0) (Hopkins 2002).

The reliability of sprint times, PL_{VM}, PL_{AP}, PL_{V} and PL_{ML}, was calculated based on four sprint efforts completed by each participant with full recovery between each effort (4 min) conducted on a separate occasion 1 week prior. Reliability was assessed using a custom spreadsheet and the typical error (TE) and smallest worthwhile change (SWC) were calculated in percentage terms (Hopkins 2000; Hopkins et al. 2009).

Pre- and post-protocol values for subjective measures of PRS and RPE were compared using paired *t*-tests with significance accepted at $P < 0.05$. Effect size (0.2 × between-participant SD, *d*) was also calculated and interpreted as trivial (0.0–0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0) and very large (>2.0). Pre-to-post-protocol differences in recorded variables were expressed as factors of the SWC to facilitate comparison. Statistical analysis was undertaken using Prism 6 for Windows (version 6.07, GraphPad Software Inc.).

Results

Mean $\text{Decrement}_{\text{SPRINT}}$ reached at termination was 5.3% (range 4.1–6.1%) with eight of the nine participants reaching the target of 5.0%. Sprint time increased by 8.5% (range 5–13%) from the first to the last sprint. Mean PL_{VM} decrement was 15% (range 11–23%) with PL_{V}, PL_{ML} and PL_{AP} exhibiting similar mean decrements of 15–18%. PlayerLoad from the individual axes (PL_{AP}, PL_{ML}, PL_{V}) all shared very large to nearly perfect correlations with PL_{VM} ($r = 0.87$–0.91, $P < 0.001$) and large to nearly perfect correlations with one another ($r = 0.66$–0.92, $P < 0.001$).

Mean decrease in PL_{VM} from the first to the last sprint was 25% (range 20–40%, $P < 0.001$, $d = 1.9$), 23% (range 12–47%, $P = 0.002$, $d = 1.4$) for PL_{AP}, 29% (range 19–46%, $P < 0.001$, $d = 2.2$) for PL_{ML} and 24% (range 14–34%, $P < 0.001$, $d = 1.3$) for PL_{V}. The number of sprints required to achieve the 5% performance decrement ranged from 7 to 20, with a variance (CV%) of 30%. The mean performance decrement in all participants following sprint number 7 (the highest common number of sprints for comparison) was 4.1% (range 1.7–5.3%) with a variance of 29%. The variance in $\text{Decrement}_{\text{SPRINT}}$ following attainment of the 5% threshold was 7%.

$\text{Decrement}_{\text{SPRINT}}$ was significantly correlated with $\text{Decrement}_{\text{PLVM}}$ for all participants (Table 1). The mean slope of the pooled regression was −2.9 (individual 95% CI for slopes −0.3 to −7.0) for $\text{Decrement}_{\text{PLVM}}$ and −3.0 (individual 95% CI for slopes −0.1 to −8.1%) for PL_{AP}, PL_{ML} and PL_{V} (Figure 1). No within-participant changes were observed for percentage contribution of the three accelerometer axes during the protocol.

TE calculated for sprint times and PlayerLoad variables based on the four trials conducted with complete recovery was similar. The mean TE for all PlayerLoad variables was 6.8–7.2% (95% CI 5.5–9.8%) and the SWC was 4.9–7.2% (95% CI 3.5–12.2%). The mean TE for sprint time was 6.6% (95% CI 5.3–9.0%) and the SWC was 5.2% (95% CI 3.8–8.7%).

Mean PRS immediately before the protocol began was 8.3 (95% CI 6.8–9.8) and decreased to 3.8 (95% CI 1.8–5.8) following the final sprint ($P = 0.004$, $d = 1.9$). Mean RPE increased from 2.3 (95% CI 1.4–3.3) to 7.1 (95% CI 5.2–9.0) at the same time points ($P = 0.004$, $d = 2.5$). The magnitude of pre–post differences in all PL and subjective variables is shown in Figure 2.

Discussion

The main finding of this study is that during a fatigue-inducing repeated sprint protocol, large decrements were observed in PlayerLoad measured at the upper thoracic region. These decrements had very large to nearly perfect correlations with the sprint time performance decrement and could potentially be used to monitor individual fatigue responses to repeated sprint training.

PlayerLoad variables and sprint time demonstrated similar test–retest reliability (SWC and TE), but decrements in PL variables were on average threefold greater than sprint performance decrements. These initial data suggest that PL variables may provide a reliable and sensitive means of monitoring fatigue during standardized sprinting activities within the team sports setting. The greater change in PL variables compared to performance (sprint times) may be comparable to the greater changes in kinetics and kinematics versus changes in sprint performance that has been reported to date (Girard et al. 2011a, 2011b; Gaudino et al. 2013; Watari et al. 2016). Indeed, a disproportionate relationship between alterations to movement strategy and task performance outcomes has also been demonstrated in vertical jumping by Gathercole et al. (2015). It may be that the body's adaptive movement strategies in response to fatigue are more appropriate to monitor than performance in some circumstances. For instance, rather than prescribing repeated high-speed running exercise based on times, objective measures of technique maintenance could instead be used to safely progress training volumes and intensities whilst ensuring quality.

This is the first study to date to examine the effect of repeated sprinting fatigue on PlayerLoad variables and so, direct comparison with other data is not possible. However, the observed reductions in PlayerLoad with increasing fatigue are consistent with previous work examining the kinetic and kinematic changes elicited by overground repeated sprints which reported reduced peak vertical and anteroposterior ground reaction forces, increased ground contact times and CoM vertical displacement, reduced step lengths and reduced vertical and leg stiffness (Girard et al. 2011a, 2011b; Brocherie

Table 1. Pearson correlation coefficient values between sprint performance decrement and PlayerLoad variables for individual participants.

Participant	Sprints (*n*)	$\text{Decrement}_{\text{SPRINT}}$ (%)	$\text{Decrement}_{\text{PLVM}}$ (%)	Pearson's *r*	*P*-value
1	20	5.1	15.4	−0.99 (−1.00 to −0.97)	<0.001
2	9	6.2	12.8	−0.87 (−0.98 to −0.33)	0.011
3	11	5.2	18.5	−0.95 (−0.99 to −0.74)	<0.001
4	7	5.3	13.2	−0.81 (−0.97 to −0.14)	0.028
5	10	5.5	12.5	−0.94 (−0.99 to −0.77)	<0.001
6	13	5.2	11.0	−0.97 (−0.99 to −0.88)	<0.001
7	14	5.0	13.7	−0.97 (−0.99 to −0.92)	<0.001
8	12	4.1	15.5	−0.91 (−0.98 to −0.71)	<0.001
9	13	5.4	22.0	−0.88 (−0.96 to −0.65)	<0.001

PL_{VM}: PlayerLoad vector magnitude (all three axes combined); $\text{Decrement}_{\text{SPRINT}}$: decrement scores for sprint times.

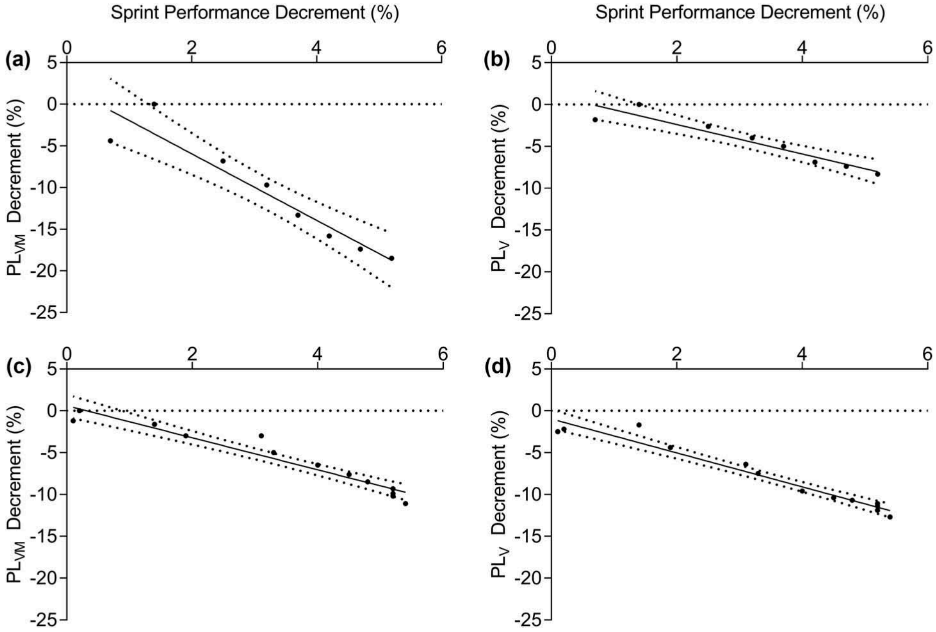

Figure 1. Representative least squares linear regressions between sprint performance decrement ($Decrement_{SPRINT}$), PlayerLoad vector magnitude (PL_{VM}) and PlayerLoad in the vertical axis (PL_V). All player load values are relative to sprint time (e.g., $PL \cdot s^{-1}$). Dotted lines represent 95% confidence intervals of the regression. Participant 3, panels A and C; Participant 7, panels B and D.

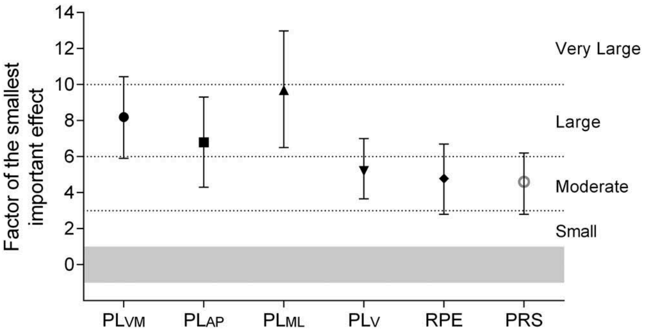

Figure 2. Differences in measured variables from the first to the last sprint expressed as a factor of the variable-specific smallest worthwhile differences (SWD). The SWD was set as 0.2 × between-participant SD for all PL variables and 1 au for RPE and PRS.

PL_{VM}: PlayerLoad vector magnitude (all three axes combined); PL_{AP}: PlayerLoad in the anterior–posterior axis; PL_{ML}: PlayerLoad in the medio-lateral axis; PL_V: PlayerLoad in the vertical axis; RPE: rating of perceived exertion; PRS: perceived recovery status.

All PlayerLoad values are relative to sprint time (e.g., $PL \cdot s^{-1}$).

et al. 2015). Although we did not directly measure these stride variables, resultant accelerations measured on the upper body have been shown to reflect the magnitude and frequency of ground contact events (Brocherie et al. 2015; Schutte et al. 2015). The combination of these adjustments results in a reduction of peak accelerations measured at the trunk during ground contact, meaning the accelerometer oscillates at a reduced amplitude. Although the absolute vertical displacement of CoM may increase, so does the time period over which it occurs. The resultant reduction in vertical stiffness (or increased lower limb compliance) facilitates a smoother oscillation of reduced amplitude, and therefore a reduced rate of loading of the accelerometer.

Barrett et al. (2016a) reported that absolute PlayerLoad values decreased throughout 90 min of soccer match play, but when expressed relative to total distance, the values actually exhibited a significant increase over the course of the match. The same trend was observed during a soccer simulation in which total distance was controlled for (Barrett et al. 2016b). The authors suggested that a fatigue-induced reduction in the capacity to dampen vibrations during running was responsible for the observed increases in load per unit distance. However, as in the current study, the effects of modulated stride length or frequency were not accounted for, limiting the extent of comparison between data. Further, the task-dependent nature of fatigue must be considered, as the fatigue response to maximal sprinting and submaximal running is of course different (Morin et al. 2011a, 2011b).

The PlayerLoad variables reported in the current study are essentially the square root of the sum of the squared instantaneous rates of change in acceleration in the respective axes. It is therefore important to consider the potential impact of gait modification on this value. For instance, during fatigue, consider reduced peak vertical accelerations (reduced stiffness) due to inhibited force production which in isolation would decrease the summated accelerometer values. However, the same mechanism would also slightly reduce step length, potentially increasing the number of steps required to cover a standard distance which would have the effect of increasing the frequency of segmental accelerations (Barrett et al. 2016b). It is therefore possible that the resulting destructive interference would result in a diminished difference in summated accelerations compared to baseline. In the current study, considering the short distance of the sprint efforts (25 m) and the moderate fatigue decrement (≈5%), then the number of steps taken is not likely to have changed although this was not verified.

The 5% decrement threshold used may be considered moderate in comparison to the 10% often used within the literature (Gaudino et al. 2013). However, this was selected based upon the inclusion of a change of direction, and following pilot testing indicating the likely number of sprints needed to achieve this value. Against the context of the moderate performance decrement, the large decrements in PlayerLoad variables highlight the promise of IMU as a feasible means of monitoring fatigue during standardized training sessions. This technology has already been advocated as a means of monitoring fatigue during (Barrett et al. 2016b) and post-team sports activity (Cormack et al. 2013), but this is the first time to our knowledge that it has been used to examine acute responses to sprint training.

Individual subjective ratings of perceived exertion (RPE) and PRS revealed two participants who changed by only 1 point or less from their first sprint to their last. One of these players (participant 8) failed to reach the 5% fatigue decrement (4.1%) before voluntary withdrawal; the other player (participant 4) reached a fatigue decrement of 5.3%. Despite trivial changes in perceived ratings which may be attributed to a poor understanding or experience of the process, both players recorded 14–15% decrements in PL variables. These two cases suggest that objective data can provide useful information that cannot be assumed to be captured using subjective measures.

Future research into the efficacy of this approach is required and several factors may need to be considered. First, the current sprint protocol included sprints with a change of direction. From the current data, the proportion of the observed decrement in PlayerLoad which occurred in the straight line phase versus the turn is not known and limits the scope of our interpretation of the current data. Second, the current study was conducted indoors on a hard surface and it is not known if the current results would be replicated on other surfaces such as natural grass. Third, the current analysis was conducted retrospectively and the methods used (PlayerLoad expressed relative to sprint time) are currently not accessible to practitioners in real time. Manufacturers of these technologies may wish to consider making these functions available to facilitate research in this area. Lastly, we did not examine the effect of a prolonged recovery on the augmentation of accelerometer loading. However, we did consider the inter-trial reliability of all PlayerLoad variables following full recovery and used this data to interpret the current findings.

Conclusion

In conclusion, these preliminary data suggest that segmental accelerations measured using an integrated IMU may provide a practical estimate of neuromuscular fatigue for practitioners in the field. Although the decrement in sprint performance was moderate, the observed reductions in PlayerLoad were much greater. This approach has the potential to be used by practitioners in the field to monitor player responses during standardized repeat sprint training of multiple athletes in real time. Further work is required to fully understand the determinants of accumulated accelerometer load, how to maximize the usefulness of the data and how best to control for confounding factors such as reduced vertical acceleration magnitude and increased stride frequency.

Practical implications

Practitioners have the potential to monitor standardized sprint training of multiple athletes in the field using integrated IMUs. Access to real-time estimates of fatigue may facilitate the individualization of training on the field.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Author contributions

All authors participated in the conception and design of the study, the analysis and interpretation of data and the drafting of the manuscript. The manuscript has been read and approved by all the listed co-authors and meets the requirements of co-authorship.

References

Abt G, Lovell R. 2009. The use of individualized speed and intensity thresholds for determining the distance run at high-intensity in professional soccer. J Sports Sci. Jul;27:893–898. Epub 2009/07/25.

Akenhead R, French D, Thompson KG, Hayes PR. 2014. The acceleration dependent validity and reliability of 10 Hz GPS. J Sci Med Sport. 17:562–566.

Barrett S, Midgley A, Reeves M, Joel T, Franklin E, Heyworth R, Garrett A, Lovell R. 2016a. The within-match patterns of locomotor efficiency during professional soccer match play: implications for injury risk? J Sci Med Sport. Oct;19:810–815.

Barrett S, Midgley AW, Towlson C, Garrett A, Portas M, Lovell R. 2016b. Within-match PlayerLoad™ patterns during a simulated soccer match: potential implications for unit positioning and fatigue management. Int J Sports Physiol Perform. Jan;11:135–140.

Boyd LJ, Ball K, Aughey RJ. 2011. The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. Int J Sports Physiol Perform. Sep;6:311–321. Epub 2011/09/14.

Bradley PS, Sheldon W, Wooster B, Olsen P, Boanas P, Krustrup P. 2009. High-intensity running in English FA Premier League soccer matches. J Sports Sci. Jan 15;27:159–168. Epub 2009/01/21.

Brocherie F, Millet GP, Girard O. 2015. Neuro-mechanical and metabolic adjustments to the repeated anaerobic sprint test in professional football players. Eur J Appl Physiol. May;115:891–903.

Buchheit M, Gray A, Morin JB. 2015. Assessing stride variables and vertical stiffness with GPS-embedded accelerometers: preliminary insights for the monitoring of neuromuscular fatigue on the field. J Sports Sci Med. 14:698–701.

Buchheit M, Laursen PB. 2013a. High-intensity interval training, solutions to the programming puzzle. Part II: anaerobic energy, neuromuscular load and practical applications. Sports Med. Oct;43:927–954.

Buchheit M, Laursen PB. 2013b. High-intensity interval training, solutions to the programming puzzle: part I: cardiopulmonary emphasis. Sports Med. May;43:313–338.

Butler RJ, Crowell 3rd HP, Davis IM. 2003. Lower extremity stiffness: implications for performance and injury. Clin Biomech. Jul;18:511–517.

Colby MJ, Dawson B, Heasman J, Rogalski B, Gabbett TJ. 2014. Accelerometer and GPS-derived running loads and injury risk in elite Australian footballers. J Strength Cond Res. Aug;28:2244–2252.

Cormack SJ, Mooney MG, Morgan W, McGuigan MR. 2013. Influence of neuromuscular fatigue on accelerometer load in elite Australian football players. Int J Sports Physiol Perform. Jul;8:373–378. Epub 2012/11/22.

Debenham J, Travers M, Gibson W, Campbell A, Allison G. 2016. Eccentric fatigue modulates stretch-shortening cycle effectiveness–a possible role in lower limb overuse injuries. Int J Sports Med. Jan;37:50–55.

Duhig S, Shield AJ, Opar D, Gabbett TJ, Ferguson C, Williams M. 2016. Effect of high-speed running on hamstring strain injury risk. Br J Sports Med. Dec;50:1536–1540.

Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, Doleshal P, Dodge C. 2001. A new approach to monitoring exercise training. J Strength Cond Res. Feb;15:109–115. Epub 2001/11/16.

Gathercole R, Sporer B, Stellingwerff T, Sleivert G. 2015. Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. Int J Sports Physiol Perform. Jan;10:84–92.

Gaudino P, Gaudino C, Alberti G, Minetti AE. 2013. Biomechanics and predicted energetics of sprinting on sand: hints for soccer training. J Sci Med Sport. May;16:271–275.

Girard O, Micallef J-P, Millet GP. 2011a. Changes in spring-mass model characteristics during repeated running sprints. Eur J Appl Physiol. Jan;111:125–134.

Girard O, Racinais S, Kelly L, Millet GP, Brocherie F. 2011b. Repeated sprinting on natural grass impairs vertical stiffness but does not alter plantar loading in soccer players. Eur J Appl Physiol. Oct;111:2547–2555.

Hopkins WG. 2000. Measures of reliability in sports medicine and science. Sports Med. 30:1–15.

Hopkins WG. 2002. A scale of magnitude for effect sizes. Available from: http://www.sportsci.org/resource/stats/

Hopkins WG, Marshall SW, Batterham AM, Hanin J. 2009. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. Jan;41:3–13.

Laurent CM, Green JM, Bishop PA, Sjökvist J, Schumacker RE, Richardson MT, Curtner-Smith M. 2011. A practical approach to monitoring recovery: development of a perceived recovery status scale. J Strength Cond Res. Mar;25:620–628.

Macpherson TW, Weston M. 2015. The effect of low-volume sprint interval training on the development and subsequent maintenance of aerobic fitness in soccer players. Int J Sports Physiol Perform. Apr;10:332–338.

Maloney SJ, Richards J, Nixon DG, Harvey LJ, Fletcher IM. 2016. Do stiffness and asymmetries predict change of direction performance? J Sports Sci. Apr;30:1–10.

Morin J-B, Dupuy J, Samozino P. 2011a. Performance and fatigue during repeated sprints: what is the appropriate sprint dose? J Strength Cond Res. Jul;25:1918–1924.

Morin J-B, Samozino P, Edouard P, Tomazin K. 2011b. Effect of fatigue on force production and force application technique during repeated sprints. J Biomech. Oct;44:2719–2723.

Rabita G, Slawinski J, Girard O, Bignet F, Hausswirth C. 2011. Spring-mass behavior during exhaustive run at constant velocity in elite triathletes. Med Sci Sports Exerc. Apr;43:685–692. Epub 2010/10/01.

Schutte KH, Maas EA, Exadaktylos V, Berckmans D, Venter RE, Vanwanseele B. 2015. Wireless tri-axial trunk accelerometry detects deviations in dynamic center of mass motion due to running-induced fatigue. PLoS One. 10:e0141957.

Silva JR, Brito J, Akenhead R, Nassis GP. 2016. The transition period in soccer: a window of opportunity. Sports Med. Mar;46:305–313.

Taylor J, Macpherson T, Spears I, Weston M. 2015. The effects of repeated-sprint training on field-based fitness measures: a meta-analysis of controlled and non-controlled trials. Sports Med. Jun;45:881–891. Epub 2015/03/21.

Watari R, Hettinga B, Osis S, Ferber R. 2016. Validation of a torso-mounted accelerometer for measures of vertical oscillation and ground contact time during treadmill running. J Appl Biomech. Jun;32:306–310.