Acceleration intensity is an important contributor to the external and internal training load demands of repeated sprint exercises in soccer players

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Abstract

The aim of this study was to evaluate the effect of acceleration on the external and internal load during repeated sprint exercises (RSE). This study used a cross-over design. Sixteen soccer players were included (mean ± SDs: age 21 ± 1 years; weight 71.1 ± 7.7 kg). RSE was 3 sets of 7 x 30 m sprints with 25 s and 3 min recovery between sprints and sets, respectively. RSE was performed using two protocols requiring either 10 m maximal acceleration (2.12 $m \cdot s^{-2}$ [RSE-MA]) or 10 m submaximal acceleration (1.66 $m \cdot s^{-2}$ [RSE-SA]). Global positioning systems (10 Hz; STATSports, Viper) were utilised to collect: high speed running (HSR), dynamic stress load (DSL), Heart Rate (HR) peak, time > 85% HR peak, respiratory (RPEres) and muscular (RPEmus) rating of perceived exertion. RSE-MA induced higher load than RSE-SA in HSR ($p = 0.037$, ES = 0.20), DSL ($p = 0.027$, ES = 0.43), HR peak ($p = 0.025$, ES = 0.47), Time > 85% HR peak ($p = 0.028$, ES = 1.11), RPEres ($p = 0.001$, ES = 1.10), and RPEmus ($p = 0.001$, ES = 0.73). This study shows that a different acceleration intensity in a RSE (MA vs. SA) impacts external and internal training load parameters.

Keywords: football, team sports, performance, training, GPS.

Introduction

The physical activities performed by soccer players in games and training are generally quantified by locomotor categories based on preselected speed thresholds (Beato, Jamil, & Devereux, 2018; Mohr, Krustrup, & Bangsbo, 2005). This approach based on fixed speed thresholds, while attempting to represent the diversity of actions and the players' intermittent activity pattern, does not account for power-related activities (*e.g.* accelerations). Therefore, it does not fully quantify the soccer players' training load demands (di Prampero & Osgnach, 2018; Hoppe, Baumgart, Polglaze, & Freiwald, 2018). The quantification of accelerations have been used to overcome the limitations of speed-based monitoring. For instance, players' accelerations have been categorised based on intensity thresholds (such as the number of accelerations > 2 $m{\cdot}s^{-2}$) (Buchheit et al., 2014). Although training load based on accelerations is common practice for sport science practitioners (Richard Akenhead & Nassis, 2016), the physiological impact of accelerations (with different intensities) has not been completely understood (Zamparo, Bolomini, Nardello, & Beato, 2015).

It is well recognised that accelerations are crucial physical components of soccer performance (Hader, Mendez-Villanueva, Palazzi, Ahmaidi, & Buchheit, 2016; Zamparo et al., 2015) that can generate a very high metabolic load even at low speed (Buglione & di Prampero, 2013; Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010). Recent evidence has reported that the energetic cost of intermittent activities is from 3.1 to 6.3 times greater than the energy cost during linear running at constant speed (Zamparo et al., 2015). Moreover, intermittent running exercises (*e.g.* shuttle running or repeated linear sprinting) involving near maximal acceleration have higher internal load demands than linear running, as reflected by energy cost, heart rate (HR), and rating of perceived exertion (RPE) (Fessi, Farhat, Dellal, Malone, & Moalla, 2018; Zamparo, Zadro, Lazzer, Beato, & Sepulcri, 2014). However, the specific contribution of accelerations (*e.g.* maximal intensity vs. submaximal) to the physiological demands has not been clearly understood, as few researchers up to now have tried to compare accelerations with different intensities (Hatamoto et al., 2013; Zamparo et al., 2014). This would suggest that further research is needed to better understand the internal and external load of such activities and the subsequent increment in physiological responses that have been reported in previous studies (Osgnach et al., 2010; Zamparo et al., 2015, 2014).

The physiological demands in a repeated sprint exercise (RSE) are considered to be mainly affected by acceleration intensity when running distance has been maintained constant (Buglione & di Prampero, 2013; Zamparo et al., 2015, 2014). During the acceleration phase, both high force and power production are developed to overcome the initial body inertia, which have an important acute impact to neuromuscular functions (*e.g.* activation of fast twitch fibers) (Lockie, Murphy, Schultz, Jeffriess, & Callaghan, 2013). Previous evidence has reported that faster accelerations involve higher metabolic (*e.g.* lactate, RPE, and HR) and mechanical (*e.g.* dynamic stress load [DSL]) demands than less intense accelerations (R. Akenhead, French, Thompson, & Hayes, 2015; Lockie et al., 2013). For instance, mechanical work resulted in more high speed activities (around 4.4 J m^{-1} kg^{-1}) compared to low (2.9 J m^{-1} kg^{-1}) and medium (3.4 J m^{-1} kg^{-1}) speed activities (Zamparo et al., 2016). However, such demands have not been clearly described in the literature and, therefore, a lack of data examining this topic exists.

Training load in soccer is evaluated using external and internal parameters (Akubat, Barrett, & Abt, 2014; Thorpe, Atkinson, Drust, & Gregson, 2017). It has been recognised that the integration of both external and internal training load parameters may offer a better comprehension of the players' training load (Akubat et al., 2014; Vanrenterghem, Nedergaard, Robinson, & Drust, 2017). The most common instrumentations utilised to quantify external training load parameters in team sports are global positioning systems (GPS) (Beato, Coratella, Stiff, & Dello Iacono, 2018; Beato, Devereux, & Stiff, 2018; Cummins, Orr, & Connor, 2013; Young, Mourot, Beato, & Coratella, 2018). GPS are utilised to collect and analyse sport specific metrics such as total distance, number of sprints, accelerations, peak speed, and high speed running (HSR) (Beato, Devereux, et al., 2018; Castillo, Raya-González, Manuel Clemente, & Yanci, 2019; Thorpe et al., 2016; Varley, Fairweather, & Aughey, 2012). Instead, internal load represents the physiological body responses to external stimuli (Impellizzeri, Marcora, & Coutts, 2019; Impellizzeri, Rampinini, & Marcora, 2005). HR is the most common cardiovascular parameter used as indicator of aerobic demands in sports (Svensson & Drust, 2005), while RPE is another internal load parameter, which has been proposed as a valid alternative used to measure the exercise intensity (Fanchini et al., 2016).

To date, no study has evaluated the effect of accelerations with different intensities (*e.g.* maximal and submaximal) on external and internal load parameters in soccer. Considering the limited evidence about this argument, which has a critical importance in team sports, the aim of this study was to compare the acceleration contribution to training load indicators during a standardised RSE protocol in soccer players. Authors hypothesised that acceleration intensity will have a significant role in determining both internal and external load demands in soccer players. The findings of this study may offer important insights to acceleration and sprint training design in soccer and be used to explain the increased physiological demands reported in previous research.

Methods

Participants

Sixteen male amateur soccer players were enrolled in this study (mean ± SDs; age 21 ± 1 years, body weight 71.1 ± 7.7 kg, height 1.79 ± 0.08 m). All participants were informed about the potential risks and benefits of the study and signed an informed consent. Inclusion criteria were the absence of any injury or illness (Physical Activity Readiness Questionnaire) and regular participation in soccer training (minimum 2 sessions per week) and competition (once per week) and to be an outfield player (2 goalkeepers were excluded). Players were amateurs (> 8 years of soccer experience). The protocol was performed during the official season. The Ethics Committee of the School of Health and Sports Sciences, University of Suffolk (Ipswich, UK) approved this study. All procedures were conducted according to the Declaration of Helsinki for human studies.

Experimental design

In this cross-over design, each player was involved in three testing sessions. During the first session, players' anthropometric data were recorded and familiarisation of the two RSE protocols was performed. During the second and third session, participants performed one of the RSE protocols in a random order. The randomisation was performed according to a computer-generated sequence. Each session was separated by at least 72 h and was performed at the same time of day to avoid circadian rhythm interference. Before each RSE, participants performed a standardised warm-up consisting of 5 min of running at a self-selected pace, 5 min of joint mobilisation (passive stretching was not permitted), and 3 submaximal 30 m sprints. Researchers required participants to maintain their normal nutritional intake during the experimental period. Alcohol and caffeine were not permitted prior to the experimental sessions but hydration was allowed during the sessions.

Body mass and height were evaluated using a stadiometer (Seca, Italy). To reduce the possible confounding factors, a standardised RSE protocol was designed. This RSE protocol involved running with a prefixed recovery time, recreating the conditions for the assessment of accelerations. Therefore no changes of direction were performed (Zamparo et al., 2015, 2014). RSE during maximal accelerations (MA) used the following protocol: RSE was 3 sets of 7 x 30 m sprints with 25 s and 3 min recovery between sprints and sets, respectively (Bishop, Girard, & Mendez-Villanueva, 2011). Each participant accelerated as fast as possible during each 30 m sprint. After the end of the sprint, participants had 10 m distance in which to decelerate. The recovery was active and participants returned by jogging to the starting point. RSE involving submaximal accelerations (SA) used the same protocol reported above but with a lower acceleration (self-selected) in the first 10 m (Zamparo et al., 2015, 2014). Speed and average acceleration during MA and SA, in the first 10 m sprint, were evaluated by infrared timing gates (Microgate, Bolzano, Italy) placed at the start and end of the mentioned distance. The RSE was conducted on a synthetic outdoor track.

External load variables

External training load parameters were recorded during two sessions by the 10 Hz GPS system and 100 Hz triaxial accelerometer (STATSports, Viper, Northern Ireland). The validity and reliability of these GPS units was: bias was 1.3%, 2.7% during short linear and sport specific activities, respectively, while typical error for peak speed and exercise specific distance was 0.7% and 0.8%, respectively, as previously reported in the literature (Beato, Devereux, et al., 2018). The GPS units were turned on approximately 10 - 15 min before the beginning of the test; meanwhile the subjects familiarised themselves with the equipment and procedures, and performed a warm up. During the experiments, a GPS unit was placed on the back of the participants by means of a harness at the level of the chest (Beato, Jamil, & Devereux, 2017). Number of satellites / horizontal dilution of precision data are not reported in this study because Viper GPS model does not report such information. We used the same GPS unit for all participants to avoid inter-unit variability (a possible confounding factor) (Beato, Coratella, et al., 2018; Beato, Devereux, et al., 2018; Rago et al., 2019). Total distance in metres, HSR > 14.4 $km \cdot h^{-1}$, and relative velocity calculated as the ratio between total distance and the total time were each measured and analysed (Gaudino et al., 2013, 2014). Peak speed ($m \cdot s^{-1}$) was recorded during RSE using the same GPS Viper units; the validity of such variable has been previously reported (Beato, Devereux, et al., 2018).

The indirect estimation of the average metabolic power used the following rationale: the accelerated running on a flat terrain is energetically analogous to uphill running at constant speed (Osgnach et al., 2010):

Energy cost ($J \cdot kg^{-1} \cdot m^{-1}$) = (155.4ES5 - 30.4ES4 - 43.3ES3 + 46.3ES2 + 19.5ES + 3.6)EM

where energy cost of accelerated running on grass, EM is the equivalent mass and ES is the equivalent slope.

DSL is a parameter that summarises the accumulation of the rates of acceleration (mechanical stress) performed by the athletes (Vanrenterghem et al., 2017). DSL was evaluated by a 100 Hz triaxial accelerometer, which summates accelerations in the 3 movement axes (X, Y, and Z planes) to measure a composite magnitude vector (expressed as a G force) (Beato, De Keijzer, Carty, & Connor, 2019).

Internal load variables

Players' internal load was monitored with HR peak, time >85% HR peak and time >75% HR peak. HR peak was recorded during a yo-yo intermittent recovery level 1 test (Krustrup et al., 2003). HR was recorded during RSE using Polar T31 belts (Polar, Oulu, Finland) (Beato, 2018). At the end of each RSE protocol, the RPE has been recorded using the Borg's CR100-scale (Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004). Players were asked individually to provide an RPE score in an attempt to prevent the influence of interaction with other players scores. Players were already familiarised with the RPE scale through used in their soccer training routine, therefore further familiarisation was not needed. RPE was evaluated in term of respiratory (RPEres) and muscular (RPEmus) perceived exertion (Jaspers, Brink, Probst, Frencken, & Helsen, 2017; Los Arcos, Méndez-Villanueva, Yanci, & Martínez-Santos, 2016).

Statistical analysis

Data were presented as the mean ± SDs. Shapiro-Wilk test was used for checking the normality (assumption). Robust estimates of 95% confidence interval (CI) and heteroscedasticity were calculated using bootstrapping technique (randomly 1000 bootstrap samples). Paired T-Test was used to evaluate between-group differences (MA vs. SA). Significance was set at $p < 0.05$ and reported to indicate the strength of the evidence. Effect size (ES) based on the Cohen d principle was interpreted as *trivial* < 0.2, *small* 0.2 - 0.6, *moderate* 0.6 - 1.2, *large* 1.2 - 2.0, *very large* > 2.0 (Hopkins, Marshall, Batterham, & Hanin, 2009). Statistical analyses were performed in SPSS software version 20 for Windows 7 (Chicago, USA).

Results

Conceptual validity of RSE design

A statistical difference was found between the RSE-MA vs. RSE-SA in 10 m sprint time (2.17 ± 0.12s and 2.45 ± 0.23, $p < 0.001$, ES = 1.47, *large*) and average acceleration (2.12 ± 0.15 $m{\cdot}s^{-2}$ and 1.66 ± 0.20 $m{\cdot}s^{-2}$, $p < 0.001$, ES = 2.03, *very large*). No differences were found between the two protocols in the following variables: Peak speed ($p = 0.164$), total distance ($p = 0.086$), and relative velocity ($p = 0.069$).

External and internal load parameters

RSE-MA reported a higher load compared to RSE-SA in the following variables (Table 1): HSR ($p = 0.037$), DSL ($p = 0.027$), HR peak ($p = 0.025$), Time > 85% HR peak ($p = 0.028$), RPEres ($p < 0.001$), and RPEmus ($p = 0.001$), but no differences were found in Time > 75% HR peak ($p = 0.826$) or metabolic power ($p = 0.519$)

*****Table 1 here please*****

Discussion

The aim of this study was to compare the effect of two RSE using a different acceleration intensity (MA vs. SA) on training load parameters in soccer players. This study found that a RSE-MA protocol resulted in higher external (*e.g.* HSR, DSL) and internal loads (*e.g.* HRpeak, Time >85% HR peak, RPEres, and RPEmus) than RSE-SA. Thus, acceleration intensity is a key contributor to the training load demand of RSE. Such findings underline the importance and contribution of powerful actions to the overall training load of the exercise (*e.g.* sprint and shuttle running), which may add critical insight into soccer training designing.

Conceptual validity of RSE design

Despite the perceived importance of accelerations in sport, there is no conclusive evidence about the external and internal load of such activities (Zamparo et al., 2015). This limitation may be due to the difficulty to accurately quantify the training load of a single acceleration (Buglione & di Prampero, 2013). In this study, we have used two standardised RSE to overcome this limitation (Bishop et al., 2011). The design difference between the protocols was related to a different acceleration intensity (SA intensity was 22% lower than MA, $p < 0.001$). Such design differences were confirmed by the sprint times and acceleration intensities recorded during the initial 10 m sprint ($p < 0.001$, *large*). After the 10 m sprint, each participant tried to reach their own maximum speed in the remaining 20 m. No differences were found between the Peak speed in RSE-MA vs. RSE-SA ($p = 0.164$). Moreover, no significant differences were found in total distance and relative velocity between the protocols, $p = 0.086$ and $p = 0.069$, respectively. These results showed that these protocols had an identical design, with the exception of the acceleration intensity, supporting the conceptual validity of the RSE design. Therefore, this study showed that the training load differences reported between RSE-MA vs

RSE-SA were associated with the acceleration intensity in the initial 10 m and were not related to other factors such as Peak speed or total distance.

External load parameters

RTE-MA was associated with higher external load variables such as HSR (ES = 0.20, *small*) compared to RTE-SA (see Table 1), which may explain the subsequently higher physiological responses (*e.g.* HR and RPE) reported. The difference found in HSR may be explained by the initial higher acceleration performed during RSE-MA by the players, which enabled them to cover more distance at over 14.4 km·h^{-1}. Furthermore, in this study DSL was used to evaluate the mechanical impact on accelerations, which were higher in RSE-MA compared to RSE-SA (ES = 0.43, *small*). The higher acceleration in MA may be related to a higher force and power production. Based on a logical rationale, the higher the DSL in an exercise, the greater the players' mechanical stress (Beato et al., 2019). These findings, for the first time, reported that a difference exists in external load variables recorded by GPS and triaxial accelerometers between maximal and submaximal accelerations. On the other hand, this study has not found a difference (*trivial*) between RSE-MA and RSE-SA in metabolic power. This result is not surprising since average metabolic power is highly correlated to total distance and relative velocity, for which effects are both *trivial* (comparison between the two RSE protocols). The metabolic power analysed in this study is not a direct measurement (*e.g.* by a breath-by-breath metabolic device) of the metabolic requests of the RSE but an indirect estimation by GPS data.

Internal load parameters

This study found meaningful differences in internal load variables between the protocols such as higher HR peak (ES = 0.47, *small*) and Time > 85% HR peak in RSE-MA compared to RSE-

SA (ES = 1.11, *moderate*). Moreover, *moderate* differences were found in RPEres (ES = 1.10, *moderate*) and RPEmus (ES = 0.73, *moderate*), which underline the greater perceived cardiovascular and muscular load required during maximal accelerations (Azcárate, Los Arcos, Jiménez-Reyes, & Yanci, 2019). Differences in the external load demands, found in the current study, are large enough to lead to substantial changes in the physiological parameters (*e.g.* HR, *moderate*) and in players' perceived exertion (*e.g.* RPE, *moderate*). These results support the knowledge that internal load variables (*e.g.* blood lactate concentration, energy cost, and HR) are affected by the acceleration intensity during intermittent running activities (Buglione & di Prampero, 2013; Zamparo et al., 2015, 2014). A physiological explanation of such findings can be related to the higher anaerobic demands during the initial acceleration (higher during MA than SA). Such high anaerobic demands (*e.g.* greater utilisation of ATP and PCr) due to MA compare to SA may be associated with higher HR and RPEres responses found in the current study (Jimenez-Reyes et al., 2016; Svensson & Drust, 2005). We may suppose that a higher cardiovascular involvement may be necessary to repay the initial O_2 debt contracted by the anaerobic glycolysis (*e.g.* post-exercise oxygen consumption replenishes the phosphagen system), however further research is needed to verify this statement since this study has not used a metabolic device. These higher anaerobic demands may also be explained by a greater muscular involvement related to higher mechanical requests during the acceleration phase. This study supports this statement since it reported a higher RPEmus, HSR, and DSL in RSE-MA. These findings may be explained considering the difference in biomechanical outputs such as higher initial force production, joint load, power, and momentum necessary to develop a MA compared to SA, which may be related to a higher neuromuscular involvement throughout the RSE (Jimenez-Reyes et al., 2016; Osgnach et al., 2010).

This study is not without limitations: firstly, the energy expenditure of both MA and SA has not been calculated since a metabolic device has not been utilised (Zamparo et al., 2015, 2014). Future studies could use a metabolic device to give additional physiological insights that are not possible using GPS. Secondly, the average metabolic power reported in this study is an indirect estimation by GPS data and cannot be fully used as a substitute for direct measurement. This parameter is affected by some limitations, which have previously been reported in the literature. Lastly, the accuracy of each RSE protocol may be affected by inconsistent participants' movements (*e.g.* total distance, Peak sprint, etc.) and such limitation should be taken into consideration (Beato, Devereux, et al., 2018).

The findings of this study may offer important practical implications to practitioners. Firstly, a clear description of the impact of acceleration intensity on training load variables has been stated, as well as a theoretical explanation of such findings. The second application is relative to the design of RSE protocols in sports setting. RSE is a widely implemented conditioning methodology in team sports and its effectiveness may depend on several training variables such as frequency, volume, and duration, as well as by the intensity of the activities performed within the RSE (*e.g.* MA vs. SA).

Conclusion

This study offers important practical insight into the impact of RSE design and training load monitoring in team sports. The intensity of the initial acceleration, in a RSE protocol, has a significant impact on both external and internal training load parameters. A higher acceleration intensity produces higher mechanical and physiological stress and consequently, induces larger physical stimuli to soccer players than a submaximal acceleration. Practitioners should design

RSE exercises where maximal (all-out) accelerations are requested to generate high external and mechanical load, which can stimulate greater physiological responses and adaptations. Furthermore, this study showed that by the manipulation of specific external training load variables such acceleration intensity, DSL and HSR, is possible to modulate internal training load parameters (*e.g.* HR, RPEres and RPEmus) that may lead to sport specific adaptations. Lastly, practitioners are invited to monitoring both external and internal training load parameters during RSE protocols to verify if the aims of the sessions have been achieved.

References

Akenhead, R., French, D., Thompson, K. G., & Hayes, P. R. (2015). The physiological consequences of acceleration during shuttle running. *International Journal of Sports Medicine*, *36*(4), 302–307. https://doi.org/10.1055/s-0034-1389968

Akenhead, Richard, & Nassis, G. P. (2016). Training load and player monitoring in high-level football: current practice and perceptions. *International Journal of Sports Physiology and Performance*, *11*(5), 587–593. https://doi.org/10.1123/ijspp.2015-0331

Akubat, I., Barrett, S., & Abt, G. (2014). Integrating the internal and external training loads in soccer. *International Journal of Sports Physiology and Performance*, *9*(3), 457–462. https://doi.org/10.1123/ijspp.2012-0347

Azcárate, U., Los Arcos, A., Jiménez-Reyes, P., & Yanci, J. (2019). Are acceleration and cardiovascular capacities related to perceived load in professional soccer players? *Research in Sports Medicine (Print)*, 1–15. https://doi.org/10.1080/15438627.2019.1644642

Beato, M. (2018). Reliability of internal and external load parameters in 6 a-side and 7 a-side recreational football for health. *Sport Sciences for Health*, *14*(3), 709–714. https://doi.org/10.1007/s11332-018-0466-x

Beato, M., Coratella, G., Stiff, A., & Dello Iacono, A. (2018). The validity and between-unit variability of GNSS units (STATSports Apex 10 and 18 Hz) for measuring distance and peak speed in team sports. *Frontiers in Physiology*, *9*(September), 1288. https://doi.org/10.3389/FPHYS.2018.01288

Beato, M., De Keijzer, K. L., Carty, B., & Connor, M. (2019). Monitoring fatigue during intermittent exercise with accelerometer-derived metrics. *Frontiers in Physiology*, *10*(June), 780. https://doi.org/10.3389/fphys.2019.00780

Beato, M., Devereux, G., & Stiff, A. (2018). Validity and reliability of global positioning system units (STATSports Viper) for measuring distance and peak speed in sports. *Journal of Strength and Conditioning Research*, *32*(10), 2831–2837. https://doi.org/10.1519/JSC.0000000000002778

Beato, M., Jamil, M., & Devereux, G. (2017). Reliability of internal and external load parameters in recreational football (soccer) for health. *Research in Sports Medicine (Print)*, *26*(2), 244–250. https://doi.org/10.1080/15438627.2018.1431532

Beato, M., Jamil, M., & Devereux, G. (2018). The reliability of technical and tactical tagging analysis conducted by a semi-automatic VTS in soccer. *Journal of Human Kinetics*, *62*(1), 103–110. https://doi.org/10.1515/hukin-2017-0162

Bishop, D., Girard, O., & Mendez-Villanueva, A. (2011). Repeated-sprint ability - part II: recommendations for training. *Sports Medicine*, *41*(9), 741–756. https://doi.org/10.2165/11590560-000000000-00000

Buchheit, M., Haddad, H. Al, Simpson, B. M., Palazzi, D., Bourdon, P. C., Salvo, V. Di, & Mendez-villanueva, A. (2014). Monitoring accelerations with GPS in football: Time to slow down ? *International Journal of Sports Physiology and Performance*, *9*, 442–445.

Buglione, A., & di Prampero, P. E. (2013). The energy cost of shuttle running. *European Journal of Applied Physiology*, *113*(6), 1535–1543. https://doi.org/10.1007/s00421-012-2580-9

Castillo, D., Raya-González, J., Manuel Clemente, F., & Yanci, J. (2019). The influence of youth soccer players' sprint performance on the different sided games' external load using GPS devices. *Research in Sports Medicine (Print)*, 1–12. https://doi.org/10.1080/15438627.2019.1643726

Cummins, C., Orr, R., & Connor, H. O. (2013). Global Positioning Systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Medicine*, *43*, 1025–1042. https://doi.org/10.1007/s40279-013-0069-2

di Prampero, P., & Osgnach, C. (2018). Metabolic power in team sports - part 1: an update. *International Journal of Sports Medicine*, *39*(08), 581–587. https://doi.org/10.1055/a-

0592-7660

Fanchini, M., Ferraresi, I., Modena, R., Schena, F., Coutts, A. J., & Impellizzeri, F. M. (2016). Use of CR100 scale for session rating of perceived exertion in soccer and Iis interchangeability with the CR10. *International Journal of Sports Physiology and Performance*, *11*(3), 388–392. https://doi.org/10.1123/ijspp.2015-0273

Fessi, M. S., Farhat, F., Dellal, A., Malone, J. J., & Moalla, W. (2018). Straight-line and change-of-direction intermittent running in professional soccer players. *International Journal of Sports Physiology and Performance*, *13*(5), 562–567. https://doi.org/10.1123/ijspp.2016-0318

Gaudino, P., Iaia, F., Alberti, G., Strudwick, A., Atkinson, G., & Gregson, W. (2013). Monitoring training in elite soccer players: Systematic bias between running speed and metabolic power data. *International Journal of Sports Medicine*, *34*(11), 963–968. https://doi.org/10.1055/s-0033-1337943

Gaudino, P., Iaia, F. M., Alberti, G., Hawkins, R. D., Strudwick, a. J., & Gregson, W. (2014). Systematic bias between running speed and metabolic power data in elite soccer players: Influence of drill type. *International Journal of Sports Medicine*, *35*(6), 489–493. https://doi.org/10.1055/s-0033-1355418

Hader, K., Mendez-Villanueva, A., Palazzi, D., Ahmaidi, S., & Buchheit, M. (2016). Metabolic power requirement of change of direction speed in young soccer players: Not all is what it seems. *PloS One*, *11*(3), e0149839. https://doi.org/10.1371/journal.pone.0149839

Hatamoto, Y., Yamada, Y., Fujii, T., Higaki, Y., Kiyonaga, A., & Tanaka, H. (2013). A novel method for calculating the energy cost of turning during running. *Open Access Journal of Sports Medicine*, *4*, 117–122. https://doi.org/10.2147/OAJSM.S39206

Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine and Science in Sports and Exercise*, *41*(1), 3–13. https://doi.org/10.1249/MSS.0b013e31818cb278

Hoppe, M. W., Baumgart, C., Polglaze, T., & Freiwald, J. (2018). Validity and reliability of GPS and LPS for measuring distances covered and sprint mechanical properties in team sports. *PLOS ONE*, *13*(2), e0192708. https://doi.org/10.1371/journal.pone.0192708

Impellizzeri, F. M., Marcora, S. M., & Coutts, A. J. (2019). Internal and external training load: 15 years on. *International Journal of Sports Physiology and Performance*, *14*(2), 270–273. https://doi.org/10.1123/ijspp.2018-0935

Impellizzeri, F. M., Rampinini, E., Coutts, A. J., Sassi, A., & Marcora, S. M. (2004). Use of RPE-based training load in soccer. *Medicine and Science in Sports and Exercise*, *36*(6), 1042–1047. https://doi.org/10.1249/01.MSS.0000128199.23901.2F

Impellizzeri, F. M., Rampinini, E., & Marcora, S. M. (2005). Physiological assessment of aerobic training in soccer. *Journal of Sports Sciences*, *23*(6), 583–592. https://doi.org/10.1080/02640410400021278

Jaspers, A., Brink, M. S., Probst, S. G. M., Frencken, W. G. P., & Helsen, W. F. (2017). Relationships between training load indicators and training outcomes in professional soccer. *Sports Medicine*, *47*(3), 533–544. https://doi.org/10.1007/s40279-016-0591-0

Jimenez-Reyes, P., Pareja-Blanco, F., Cuadrado-Peñafiel, V., Morcillo, J. A., Párraga, J. A., & González-Badillo, J. J. (2016). Mechanical, Metabolic and Perceptual Response during Sprint Training. *International Journal of Sports Medicine*, *37*(10), 807–812. https://doi.org/10.1055/s-0042-107251

Krustrup, P., Mohr, M., Amstrup, T., Rysgaard, T., Johansen, J., Steensberg, A., … Bangsbo, J. (2003). The yo-yo intermittent recovery test: physiological response, reliability, and validity. *Medicine and Science in Sports and Exercise*, *35*(4), 697–705. https://doi.org/10.1249/01.MSS.0000058441.94520.32

Lockie, R. G., Murphy, A. J., Schultz, A. B., Jeffriess, M. D., & Callaghan, S. J. (2013). Influence of sprint acceleration stance kinetics on velocity and step kinematics in field sport athletes. *Journal of Strength and Conditioning Research*, *27*(9), 2494–2503. https://doi.org/10.1519/JSC.0b013e31827f5103

Los Arcos, A., Méndez-Villanueva, A., Yanci, J., & Martínez-Santos, R. (2016). Respiratory and muscular perceived exertion during official games in professional soccer players. *International Journal of Sports Physiology and Performance*, *11*(3), 301–304. https://doi.org/10.1123/ijspp.2015-0270

Mohr, M., Krustrup, P., & Bangsbo, J. (2005). Fatigue in soccer: a brief review. *Journal of Sports Sciences*, *23*(6), 593–599. https://doi.org/10.1080/02640410400021286

Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R., & di Prampero, P. E. (2010). Energy cost and metabolic power in elite soccer: a new match analysis approach. *Medicine and*

Science in Sports and Exercise, *42*(1), 170–178. https://doi.org/10.1249/MSS.0b013e3181ae5cfd

Rago, V., Brito, J., Figueiredo, P., Costa, J., Barreira, D., Krustrup, P., & Rebelo, A. (2019). Methods to collect and interpret external training load using microtechnology incorporating GPS in professional football: a systematic review. *Research in Sports Medicine (Print)*, 1–22. https://doi.org/10.1080/15438627.2019.1686703

Svensson, M., & Drust, B. (2005). Testing soccer players. *Journal of Sports Sciences*, *23*(6), 601–618. https://doi.org/10.1080/02640410400021294

Thorpe, R. T., Atkinson, G., Drust, B., & Gregson, W. (2017). Monitoring fatigue status in elite team-sport athletes: Implications for practice. *International Journal of Sports Physiology and Performance*, *12*, 27–34. https://doi.org/10.1123/ijspp.2016-0434

Thorpe, R. T., Strudwick, A. J., Buchheit, M., Atkinson, G., Drust, B., & Gregson, W. (2016). Tracking morning fatigue status across in-season training weeks in elite soccer players. *International Journal of Sports Physiology and Performance*, *11*(7), 947–952. https://doi.org/10.1123/ijspp.2015-0490

Vanrenterghem, J., Nedergaard, N. J., Robinson, M. A., & Drust, B. (2017). Training load monitoring in team sports: A novel framework separating physiological and biomechanical load-adaptation pathways. *Sports Medicine (Auckland, N.Z.)*, *47*(11), 2135–2142. https://doi.org/10.1007/s40279-017-0714-2

Varley, M. C., Fairweather, I. H., & Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of Sports Sciences*, *30*(2), 121–127. https://doi.org/10.1080/02640414.2011.627941

Young, D., Mourot, L., Beato, M., & Coratella, G. (2018). The match heart rate and running profile of elite under-21 hurlers during competitive match-play. *Journal of Strength and Conditioning Research*, *32*(10), 2925–2933. https://doi.org/10.1519/JSC.0000000000002558

Zamparo, P., Bolomini, F., Nardello, F., & Beato, M. (2015). Energetics (and kinematics) of short shuttle runs. *European Journal of Applied Physiology*, *115*(9), 1985–1994. https://doi.org/10.1007/s00421-015-3180-2

Zamparo, P., Pavei, G., Nardello, F., Bartolini, D., Monte, A., & Minetti, A. E. (2016).

Mechanical work and efficiency of 5 + 5 m shuttle running. *European Journal of Applied Physiology*, *116*(10), 1911–1919. https://doi.org/10.1007/s00421-016-3443-6

Zamparo, P., Zadro, I., Lazzer, S., Beato, M., & Sepulcri, L. (2014). Energetics of shuttle runs: The effects of distance and change of direction. *International Journal of Sports Physiology and Performance*, *9*(6), 1033–1039. https://doi.org/10.1123/ijspp.2013-0258