1. The within-match patterns of locomotor efficiency during Professional Soccer match play: Implications for Injury risk?

2. Original Investigation

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Abstract

Objectives: The principle aim of the current study was to examine within-match patterns of locomotor efficiency in Professional Soccer, determined as the ratio between tri-axial accelerometer data (PlayerLoad™) and locomotor activities. Between match variability and determinants of PlayerLoad™ during match play were also assessed. ***Design***: A single cohort, observational study. ***Methods***: Tri-axial accelerometer data (PlayerLoad™) was recorded during 86 competitive soccer matches in 63 English championship players (574 match observations). Accelerometer data accumulated (PlayerLoad Vector Magnitude [PL_{VM}]) from the individual-component planes of PlayerLoad™ (anterior-posterior PlayerLoad™ [PL_{AP}], medial-lateral PlayerLoad™ [PL_{ML}] and vertical PlayerLoad™ [PL_{V}]), together with locomotor activity (Total Distance Covered [TDC]) were determined in 15-min segments. Locomotor efficiency was calculated using the ratio of PL_{VM} and TDC (PlayerLoad™ per metre). The proportion of variance explaining the within-match trends in PL_{VM}, PL_{AP}, AP_{ML}, AP_{v}, and TDC was determined owing to matches, individual players, and positional role. ***Results***: PL_{VM}, PL_{AP}, AP_{ML}, AP_{v} and TDC reduced after the initial 15-min match period (P=0.001; η^2=0.22-0.43, large effects). PL:TDC increased in the last 15 minutes of each half (P=0.001; η^2= 0.25, large effect). The variance in PL_{VM} during soccer match-play was explained by individual players (63.9%; P=0.001) and between-match variation (21.6%; P=0.001), but not positional role (14.1%; P= 0.364). **Conclusions:** Locomotor efficiency is lower during the latter stages of each half of competitive soccer match-play, a trend synonymous with observations of increased injury incidence and fatigue in these periods. Locomotor efficiency may be a valuable metric to identify fatigue and heightened injury risk during soccer training and match-play.

Keywords: Accelerometry, Football, Injury risk, Fatigue

Introduction

Monitoring load in team-sports players during training and match play is common practice within industry settings in order to reduce injury risk and optimise their readiness to perform[1, 2]. Obtaining measures of internal load (e.g. heart rate) during competition can be impractical and often prohibited; hence practitioners tend to rely on external load measures, such as locomotor activities, to monitor training and competition loads. Analyzing locomotor activities during match play has demonstrated within-match patterns, with total distances covered (TDC) and high-speed running distances (HSR) decreasing towards the latter stages of each half[3]. These time periods towards the end of each half have been associated with a high injury incidence rate in professional[4, 5] and elite youth[6] soccer players, perhaps owing to fatigue[7]. Indeed, studies that have simulated soccer matches in laboratory-controlled conditions have observed within-match patterns in lower limb kinematics[8], strength,[8,9] and motor unit recruitment[11] that are synonymous with injury incidence trends. However, monitoring these specific injury risk markers during training and competition is not feasible, and real-time surrogate measures are required to enable practitioners to make informed load-monitoring judgements during matches and training sessions.

Locomotor activities such as TDC and HSR can be monitored real-time with advances in time-motion analysis technology; however these metrics neglect the energetically taxing changes in speed[12, 13]. The change in speed has been determined as the frequency and/or distance covered in different acceleration/deceleration categories[13, 14] or using more complex energetic models to estimate metabolic cost[12, 16]. Whilst these contemporary methods maybe valuable additions to monitoring external load for practitioners, they quantify players' positional change in a single plane of motion, neglecting soccer's three-dimensional nature of movement and impacts.

Tri-axial accelerometers measure three-dimensional movements and have been used to quantify external load in team sports, often determined by a vector magnitude termed PlayerLoad™ (PL_{VM} [17, 18]). In contrast to existing metrics using time-motion analysis, PL_{VM} has an acceptable signal: noise ratio[19] owing to its demonstrated test-retest[20], within- and between-device reliability[19]. The within-match patterns of PL_{VM} were recently examined using standardised soccer simulation under laboratory-controlled conditions in which the volume and intensity of intermittent and multi-directional locomotor activities were fixed in 15-min match segments[21]. In this study PL_{VM} increased in the last 15-min period of each half, mirroring the within match patterns of fatigue[9,11] and injury risk[4,5], indicative of a change in movement strategy[17] and/or a reduced locomotor efficiency[21]. Soccer specific fatigue may manifest in the reduced stiffness of the musculotendon unit[15], owing to a reduced central motor output[11,15], which may compromise the absorption capacity and stability of lower-limb joints[28], increasing the injury risk to passive joint structures. Decreased stability and increased lower-limb vibrations associated with the ground reaction force in a fatigued state[30] may be detected with high-resolution tri-axial accelerometer technology and may explain the reduced locomotor efficiency observed in the latter stages of each half of simulated soccer match-play[21].

However, during competitive games, within-match changes in locomotor efficiency may not be detectable using PL_{VM} alone, given its strong positive association with total distance covered[18]. Hence, PL_{VM} is hypothesised to decrease over the course of each half of match-play synonymous with the decline in locomotor activity[3]. In this study, we primarily aimed to determine the within match-patterns of PlayerLoad™ and locomotor variables in competitive fixtures; however we also attempted to determine match-related changes in players' locomotor efficiency patterns by calculating a ratio of PL_{VM}:TDC (or PlayerLoad™ per meter). Whilst exploratory, we hypothesised that within-match declines in locomotor activities (TDC) would be greater than PlayerLoad™ metrics, an uncoupling which may be identified with the application of PL_{VM}:TDC, and indicative of a reduced locomotor (movement) efficiency. Furthermore, because PL_{VM} is influenced by individual gait patterns[20] and locomotor activities[18], and that match running variables are dictated by positional role[22], our second aim was to quantify the determinants of PL_{VM} together with its between match variability.

Method

The study gained ethical approval from a departmental ethics committee prior to the commencement of the study. As these data reported as part of this retrospective study was collected as part of the routine data monitoring of players in industry practice, informed consent was not deemed necessary[27].

Data was collected during the 2012/2013 and 2013/2014 seasons from three English Championship U21 teams (Age: 20.3 ± 1.6 years; Stature: 1.80 ± 0.07m; Body Mass: 81.2 ± 6.1kg). Official's permission was gained to wear the MEMS devices (Micromechanical Electrical Systems) prior to each match, which were played on natural turf. On match day, players wore a customised tight-fitting neoprene garment underneath their match day shirts, with the unit located between the scapulae. Prior to MEMS device (MinimaxX S4, Catapult Sports, Melbourne, Australia) placement in the players garment, units were taken outside and activated 15 mins beforehand to attenuate erroneous data owing to poor GPS signal quality. All warm-up data was excluded from the study. Match play consisted of two 45 min halves with a 15 min passive half-time interval. Any additional time at the end of each half was excluded from the analysis given the between-match variation in duration. Only players completing three full 90 min games were included in the study, to permit the assessment of between match-variation in our outcome measures. Sixty-four professional soccer players were included in the study, which provided 574 match observations from 86 games (Team 1, n= 221; Team 2, n=196; Team 3, n= 156). These match recordings were then dissected into 15 min periods to assess the within-match patterns of PL_{VM} and the individual accelerometer planes. In accordance with previous time-motion analysis research[14], we used the first 15-minute period as a benchmark from which to identify within-match changes in our outcome measures. Whilst the use of this initial 15-min period as a reference point from which to draw conclusions regarding fatigue from time-motion analysis metrics has been questioned, due to the frantic nature of the opening exchanges in soccer [23]; we adopted this analytical technique to identify within-match patterns of tri-axial accelerometer data and to make inferences in regards to locomotor efficiency, rather than fatigue *per se*.

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The MinimaxX S4 (Catapult Innovations, Scoresby, Victoria) contains a tri-axial piezoelectric linear accelerometer (Kionix: KXP94) sampling at a frequency of 100 Hz, as part of an inertial sensor suite in the micromechanical system. The output of the accelerometer measures ±13g, with each device containing its own microprocessor with a 1GB flash memory and USB interface in order to store and download data. The device is powered by an internal lithium ion battery with 5h of life, weighing 67g and is 88x50x19mm in dimension. Vector Magnitude PlayerLoad™ (PL_{VM}) and individual-component planes of PlayerLoad™ (anterior-posterior PlayerLoad™ [PL_{AP}], medial-lateral PlayerLoad™ [PL_{ML}] and vertical PlayerLoad™ [PL_{V}]) were recorded. The calculation for PL_{VM} is the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (x, y and z) and divided by 100[19]. PL_{AP}, PL_{ML} and PL_{V} were calculated with the same equation, using only the relevant axis in the equation. Expressed in arbitrary units (au), PlayerLoad™ data were recorded using the Catapult software (Sprint 5.0.9.2, Catapultsports, Melbourne, Australia). Prior to the start of each season units were calibrated using the manufacturers jig to comply with the manufacturers guidelines. The device was orientated and placed stationary in each plane of movement and recordings were set at 1g for that position to reduce any bias or drift. Every four weeks calibration values were monitored. All units remained within the manufacturer’s calibration tolerance limits throughout the testing period.

The MEMS device (MinimaxX, S4, Firmware version- 6.88) contains a 10Hz global positioning satellite (GPS) chip in order to record the time motion analysis data. Total Distance Covered (TDC) was used as a measure of the time motion analysis data (TMA). Data were included if the number of satellites exceeded 6 and a horizontal displacement of positioning (HDOP) was less than 1.5. Two match files were excluded as a result. To assess the within-match patterns of PlayerLoad™ and its individual planes in comparison to the locomotor activities, PL_{VM} was made relative to TDC as a measure of players locomotor efficiency (PlayerLoad™ per metre covered; PL:TDC).

Prior to the analysis, both Q-Q plots and stem and leaf charts were monitored to check for normal distribution. Assumptions of normality were further assessed by plotting boxplots of the residuals and a scatterplot of the predicted values. A linear mixed model was then used to assess the differences of PL_{VM}: TDC, PL_{VM}, PL_{AP}, PL_{ML}, PL_{V} and TDC, between each 15-min match period. Linear mixed models were able to account for the different samples between teams. Post-hoc pairwise comparisons, with Sidak adjusted p values, were conducted in the event of a statistically significant F-ratio. A spline model was then fitted to assess the relative change of the aforementioned variables across the first and second half. For all players included in the study, an individual coefficient of variation (CV) was calculated for each outcome variable, by dividing standard deviation (SD) by the individual mean from each game. To explain the variance within the model playing positions, individual player and each competitive fixture were included as random factors within the linear mixed model. The team for which the player represented was also encompassed in the model to account for any variation in tactical or physical approaches to match-play, however no effect was observed (data not shown). Analyses were completed using IBM SPSS Statistics for windows software (release 20; SPSS Inc., Chicago, IL, USA) and all values are reported as mean ± SD. Two-tailed statistical significance was accepted as $p \leq 0.05$ and measures of effect size were calculated using partial eta-squared (η^2). Magnitude of the effect sizes were small (>0.02), medium (>0.13) and large (>0.26)[25].

Results

The initial 0-15 mins of match play incurred a significantly higher PL_{VM} (η^2=0.36-0.43), PL_{AP} (η^2=0.25-0.38), PL_{ML} (η^2=0.22-0.38) and PL_V (η^2=0.29-0.42) in comparison to all other time periods (See Figure 1). During the second half, the absolute accelerometer indices progressively decreased in successive 15 min match periods (see Figure 1), whereas there were no within-match changes in the relative contributions (%) of each accelerometer plane.

TDC showed significant decreases in each 15 min phase in comparison to the initial 0-15 min period (0-15: 1788 ± 252; 75-90: 1516 ± 224; η^2= 0.35, p=0.001). TDC showed similar significant changes across 15 min time periods during match play as was observed for PL_{VM}. Significant increases were observed for PL:TDC towards the end of each half (See **Figure 2;** η^2= 0.11-0.29**)**. The rate of increase for PL: TDC was significantly greater in the first half (0.14 ± 0.02 au) compared to the second half (0.06 ± 0.3 au; p = 0.04).

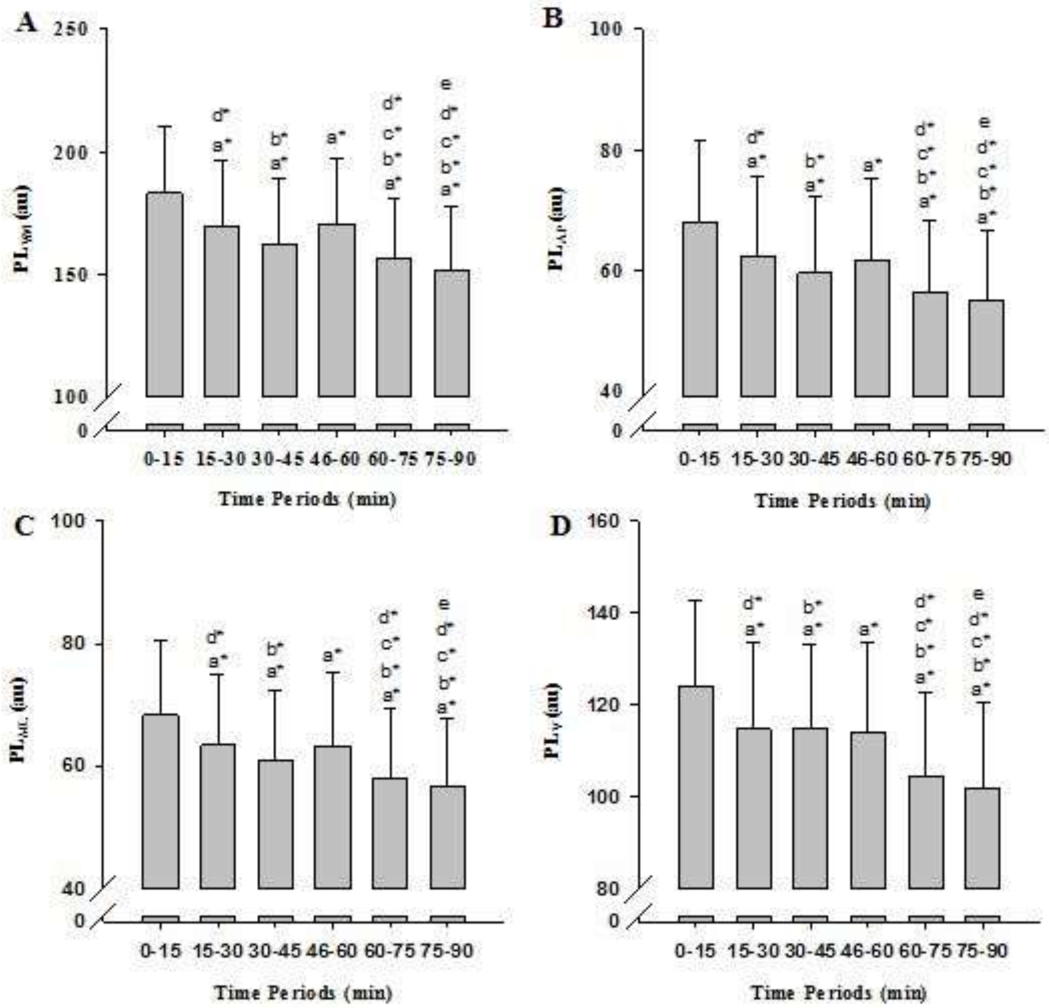

Figure 1. The within-match changes in 15 min match segments for A) PL_{VM}; B) PL_{AP}; C) PL_{ML}; D) PL_V during soccer match play. Dashed line represents 15min half-time period. ^{a} = difference versus 0-15 min; ^{b} difference versus 15-30 min; ^{c} difference versus 30-45 min; ^{d} difference versus 45-60 min;* denotes a significant difference of $p \leq 0.01$. PL_{VM}- PlayerLoad™ vector magnitude; PL_{AP}- PlayerLoad™ in the anterior-posterior plane; PL_{ML}- PlayerLoad™ in the medial-lateral plane; PL_V- PlayerLoad™ vertical plane.

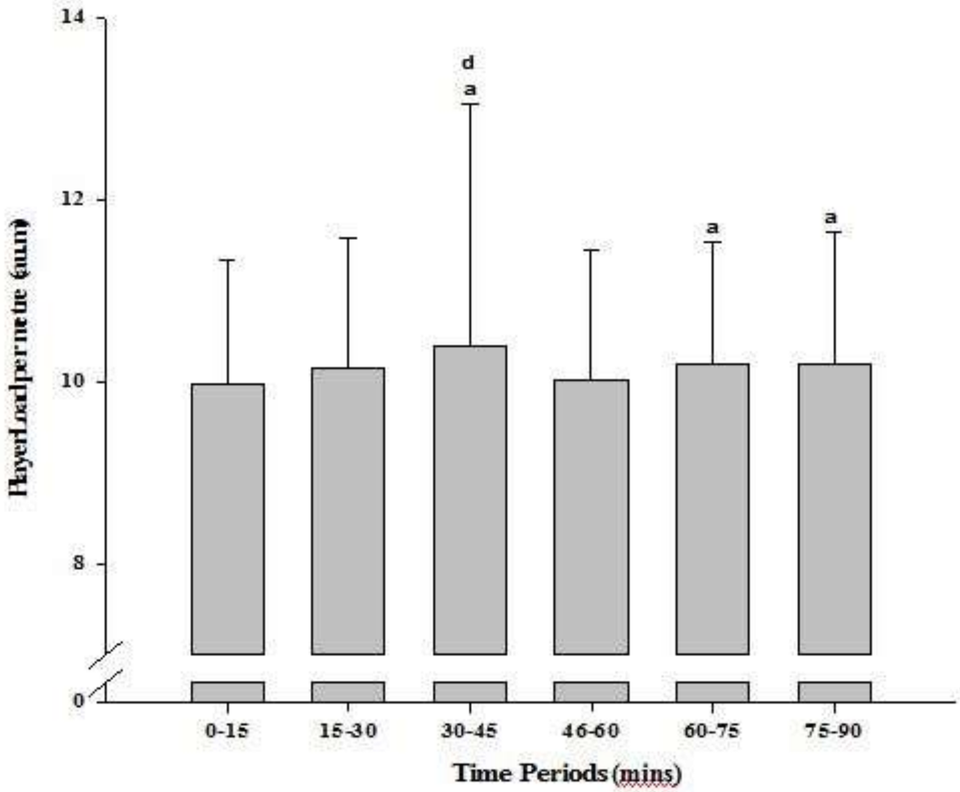

Figure 2. The within-match patterns of PL: TDC during soccer match play. Dashed line represents 15min half-time period. a- is significantly greater than the 0-15 mins, d- is significantly greater than the 46-60 mins. * denotes a significant difference of p ≤ 0.01.

The variance of PL_{VM}, the individual accelerometer planes and locomotor efficiency (PL: TDC) are illustrated in **Table. 1**. Significant findings were identified for both games and the individual player in the current model, however, no significant associations were found for position *per se*.

Table 1. The individual coefficient of between-match variation and the contribution of the variance in soccer match play for PL_{VM}, the individual accelerometer planes, TDC, and locomotor efficiency.

	Coefficient of Variation (95% CI's)	Game (%)	Player (%)	Positions (%)
PL_{VM} (au)	6.6 ± 2.4 (6.0 to 7.2)	21.6*	63.9*	14.1
PLAP (au)	8.8 ± 4.0 (7.4 to 10.4)	27.9*	40.5*	5.7
PLML (au)	9.0 ± 4.1 (6.9 to 11.0)	44.8*	36.8*	12.9
PLV (au)	7.3 ± 2.5 (5.7 to 8.9)	37.1*	36.6*	13.5
TDC (m)	6.6 ± 2.8 (3.5 to 9.5)	10.3	48.3*	8.4
PL_{VM}: TDC (au)	6.4 ± 2.9 (2.0 to 10.8)	21.0*	32.1*	3.6

PL_{VM}- PlayerLoad Vector Magnitude; PL_{AP}- PlayerLoad Anterior-Posterior; PL_{ML}- PlayerLoad Medial-Lateral; PL_{V}- PlayerLoad Vertical; *represents significant determinant of variance within the linear mixed model ($p \leq 0.01$).

Discussion

The aim of the current study was to determine the within match-patterns of PlayerLoad™ and locomotor efficiency (PL:TDC) in professional soccer. Secondary aims of the study were to quantify the between-match variation and determinants of these external load metrics. The key findings from the present study included: 1) PL:TDC increased in the last 15 min of both the first and second halves in comparison to the initial 0-15 min period; 2) The spline model showed that the PL:TDC rate of increase was significantly greater in the first half compared to the second half, indicative of an uncoupling between PL_{VM} and TDC; 3) Between-player (32.1-63.9%) and between-match (10.3-44.8%) variability statistically explained the variance within the current model for PL:TDC, PL_{VM}, the individual accelerometer planes and TDC.

Increased injury occurrence has been shown to occur towards the latter stages of each half within elite[4] and elite youth[6] players during competitive soccer match play. Soccer specific fatigue has been purported to have an aetiological role in the increased injury incidence observed during these time periods[4,5,7]. Indeed simulated soccer matches have shown alterations in lower limb kinematics[8], strength[8,9] and motor unit recruitment[11]. Monitoring these responses during competitive soccer match play is impractical and contravenes governing body regulations, hence external load indices have traditionally been used to monitor fatiguing trends (TDC, HSR[11]). However, methods utilising changes in two-dimensional coordinates fail to quantify critical three-dimensional aspects of soccer match play, such as tackles, impacts and changes of direction. In the current study, we utilised PlayerLoad^{TM} to assess the within match patterns of competitive match play, identifying reductions in three dimensional loading in the latter stages of each half, a trend synonymous with injury incidence.

However, the locomotor patterns have shown strong relationships to PlayerLoad^{TM} during soccer training, with higher distances covered associated with greater loading[18]. Therefore, the progressive reductions in loading identified in PlayerLoad^{TM} during each half of match play likely reflects the typical within match time-motion patterns of soccer match-play, which arguably represents the match context [29] , rather than fatigue *per se*. Hence, in this study we calculated a ratio of PlayerLoad^{VM} to total distance covered as a measure of locomotor efficiency, in an attempt to identify any uncoupling which may be indicative of player fatigue. We observed a large increase in the PL:TDC during the last 15 min period of each half when benchmarked against the initial 0-15 min period. During a standardised soccer simulation ($SAFT^{90}$), Barrett and colleagues[21] showed PL_{VM} increased towards the end of each half when the locomotor activities were fixed in 15 min segments. Using the same simulation, Small and colleagues[8] observed within match alterations in hip extension and knee flexion during sprinting, which resulted in a decreased stride length in a temporal pattern that corroborates with the decreased locomotor efficiency observed in this study, and that of injury incidence[4, 5, 6].

A fatigue-induced reduction in stride length during running may explain the locomotor efficiency patterns we observed as its reciprocal increase in stride frequency and foot contacts incurs loading detected by the accelerometer. Furthermore, increases in accelerometer metrics in the latter stages of each half may reflect reduced pre-activation of the musculotendon unit associated with fatigue[11,15], leading to an impaired capacity to reduce the vibration amplitudes in lower-limb soft tissue (~20%;[30]) that result from ground reaction forces. However, caution has been advised when interpreting tri-axial accelerometer data collected at the scapulae to assess lower limb movement strategy changes[21]. Whilst this unit positioning is necessary for MEMS devices to enhance the GPS signal quality, laboratory studies have indicated that the position of the unit between the scapulae accrues different magnitudes and planar contributions of tri-axial accelerometer data versus its criterion positioning at the centre of mass during both treadmill running[20] and a soccer match simulation[21]. The upper body movements of the trunk are also non-uniform during the stochastic and combative nature of soccer match-play, and may somewhat mask the lower limb changes in running kinematics[10] and lower limb stiffness[15,17, 30]. The scapulae unit positioning during competitive soccer fixtures did not preclude us from identifying modulations in locomotor efficiency, however future industry-practice using micro-sensor technology positioned at the centre of mass may be warranted to determine lower limb loading, independent of GPS monitoring.

Whilst this study has identified modulations in locomotor efficiency that may be used in industry-practice to inform rotation policy by identifying players at an exacerbated risk of injury or to denote the onset of fatigue, we recognise that further work is necessary to confirm our speculation. We also acknowledge the crudity of our measure of locomotor efficiency, considering that total distance covered by players does not represent the intermittent and intensity distribution of soccer and that accelerometer loading rate is influenced by running speed[20]. Furthermore, if observing locomotor efficiency modulations has a role in reducing injury risk and fatigue management, real-time MEMS data capture and processing are necessary, yet the accuracy of live GPS data has been questioned[26]. Accordingly, further work is required in terms of both aetiological research and technological evolution to realise the potential application of tri-axial accelerometer data in professional sports.

To our knowledge, this study is the first to examine the between-match variation in PlayerLoad™ indices during actual soccer match play. We observed low coefficients of variation for the vector magnitude (6.4 ± 2.4%) and its individual planes (7.3-9.0%), which in combination with its sound test-retest[20], within- and between-device reliability[19], suggests that PlayerLoad™ data may be useful for practitioners to detect worthwhile changes in an athlete's external load or changes in locomotor efficiency. Individual gait patterns have been speculated to cause the variation between-athletes PL_{VM} values during incremental treadmill running[20] and during a controlled fixed soccer simulation[21]. Consequently, we suggested that PL_{VM} and the individual planes should be treated and measured within an individual-specific manner as a measure of external load, findings which were corroborated in the current study as the individual player explained more variance in PL_{VM} (63.9%) versus the match (21.6%) and positional role (14.1%) *per* se. Practitioners using accelerometer data on a routine basis are therefore recommended to limit their analyses to within-player contrasts due to the large variability observed between individuals.

Conclusions

PL: TDC, PL_{VM} and the individual component accelerometer planes demonstrated within-match patterns during elite professional soccer match play. Towards the end of each half, the locomotor efficiency (PL:TDC) increased, suggestive of an increase in the loading required for every given metre of distance covered on the pitch. Since these within match patterns are concomitant with match-induced alterations in strength, motor unit recruitment and lower-limb kinetics that have been linked with fatigue and increased injury incidence, locomotor efficiency may be a useful tool to inform substitutions or rotation policy in team sports. The efficacy of accelerometer metrics are further supported by their low signal to noise ratio, but their large between-player variation limits comparisons between individuals.

Practical Applications

- Locomotor efficiency, PL_{VM} and the individual component accelerometer planes detect within-match patterns in soccer.
- The latter stages of each half show an increase in locomotor efficiency, a trend synonymous with observations of increased injury incidence and fatigue.
- Locomotor efficiency may be a useful tool to inform substitutions or rotation policy in team sports.

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References

1. Colby M, Dawson B, Heasman J et al. Training and game loads and injury risk in elite Australian footballers. *J Strength Cond Res* 2014; Ahead of print: 1-8.

2. Rogalski B, Dawson B, Heasman J et al. Training and game loads and injury risk in elite Australian footballers. *J Sci Med Sport* 2013; 16(6): 499-503.
3. Weston M, Drust B, Gregson W. Intensities of exercise during match-play in FA Premier League referees and players. *J Sports Sci* 2011; 29(5),527-532.
4. Ekstrand J, Haggulund M, Walden M. Epidemiology of muscle injuries in professional football (soccer). *Am J Sports Med* 2011; 39(6): 1226-1232.
5. Woods C, Hawkins RD, Maltby S et al. The Football Association Medical Research Programme: an audit of injuries in professional football- analysis of hamstring injuries. *Br J Sports Med* 2004; 38(1): 36-41.
6. Price, RJ, Hawkins RD, Hulse MA et al. The Football Association medical research programme: an audit of injuries in academy youth football. *Br J Sports Med* 2004; 38(4): 466-471.
7. McCall A, Carling C, Nedelec M et al. Risk factors, testing and preventative strategies for non-contact injuries in professional football: current perceptions and practices of 44 teams from various premier leagues. *Br J Sports Med* 2014; 48(18): 1352-1357.
8. Small K, McNaughton L, Greig M et al. The effects of multi-directional soccer-specific fatigue on markers of hamstring injury risk. *J Sci Med Sport* 2010; 13(1): 120-125.
9. Lovell R, Midgley AW, Barrett S et al. Effects of different half-time strategies on second half soccer-specific speed, power and dynamic strength. *Scan J Med Sci Sports* 2013; 23(1): 105-113.
10. Small K, McNaughton LR, Greig M et al. Soccer fatigue, sprinting and hamstring injury risk. *Int J Sports Med* 2009; 30(8); 573-578.
11. Marshall PW, Lovell R, Jeppesen GK et al. Hamstring muscle fatigue and central motor output during a simulated soccer match. *PLos One* 2014; (ahead of print): 1-11.
12. Gaudino P, Iaia FM, Alberti G et al. Monitoring trainng in elite soccer players: systematic bias between running speed and metabolic power data. *Int J Sports Med* 2013; 34(11): 963-968.

13. Varley V, Aughey R. Acceleration profiles in elite Australian soccer. *Int J Sports Med*. 2013; 34(1): 34–39.
14. Akenhead R, Hayes PR, French D et al. Diminutions of acceleration and deceleration output during professional football match play. *J Sci Med Sport* 2013; 16(6): 556-561.
15. Oliver JL, De Ste Croix MBA, Lloyd RS et al. Altered neuromuscular control of leg stiffness following soccer-specific exercise. *Eur J Appl Physiol* 2014; 114(1): 2241-2249.
16. Osgnach C, Posner S, Bernadini R et al. Energy cost and metabolic power in elite soccer: A new match analysis approach, *Med Sci Sports Exerc* 2010; 42(1): 170-178.
17. Cormack S, Mooney MM, Morgan W et al. Influence of neuromuscular fatigue on accelerometer load in elite Australian football players. *Int J Sports Physiol Perform* 2013; 8(4): 373-380
18. Scott TJ, Black CR, Quinn J et al. Validity and reliability of the session-RPE method for quantifying training in Australian football: a comparison of the CR10 and CR100 scales. *J Strength Cond*. 2013; 27(1): 270-276.
19. Boyd LJ, Ball K, Aughey R. The reliability of MinimaxX accelerometers for measuring physical activity in Australian Football. *Int J Sports Physiol Perform* 2011; 6(3): 311-321.
20. Barrett S, Midgley AW, Lovell R. PlayerLoad™: Reliability, Convergent Validity and Influence of Unit Position during Treadmill Running. *Int J Sports Physiol Perform* 2014; (Ahead of Print): 1-8.
21. Barrett, S, Midgley AW, Towlson C et al. Within-match PlayerLoad™ patterns during simulated soccer match (SAFT^{90}): Potential implications for unit positioning and fatigue management. *Int J Sports Physiol Perform* In Press: 1-16.
22. Gregson W, Drust B, Atkinson G et al. Match-match variability of high-speed activities in premier league soccer. *Int J Sports Med* 2010; 31(4): 237-242.
23. Lovell R, Barrett S, Portas M et al. Re-examination of the post half-time reduction in soccer work-rate. *J Sci Med Sport* 2012; 16(3): 250-254.

24. Carling C, Le Gall F, Dupont G. Analysis of repeated high-intensity running performance in professional soccer. *J Sports Sci* 2012; 30(4): 325-336

25. Miles J, Shevlin M. (2001) Applying Regression and Correlation: A Guide for Students and Researchers. Sage:London.

26. Aughey R.J, Fallon C. Real-time versus post-game GPS data in team sports. *J Sci Med Sport* 2010; 13(3): 348-349.

27. Winter EM, & Maughan RJ. Requirements for ethics approvals. *J Sports Sci* 2009; *27*(10): 985–985.

28. Hughes G, & Watkins J. A risk-factor model for anterior cruciate ligament injury. *Sports Med* 2006; 36(5): 411-428.

29. Sullivan C, Bilsborough JC, Cianciosi M et al., Factors affecting match performance in professional Australian football. *Int J Sports Physiol Perform* 2014; 9(3): 561-566.

30. Nikooyan AA, & Zadpoor AA. Effects of muscle fatigue on the ground reaction force and soft tissue vibrations during running: A model study. *IEEE Bio Med* 2012; 59(3):