Importance, reliability and usefulness of acceleration measures in team sports

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Journal of Strength and Conditioning Research Publish Ahead of Print
DOI: 10.1519/JSC.0000000000001849

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Brief Running Head: Acceleration in team sports.

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ABSTRACT

The ability to accelerate, decelerate and change direction efficiently is imperative to successful team-sports performance. Traditional intensity-based thresholds for acceleration and deceleration may be inappropriate for time-series data, and have been shown to exhibit poor reliability, suggesting other techniques may be preferable. This study assessed movement data from one professional rugby league team throughout two full seasons and one pre-season period. Using both 5 Hz and 10 Hz global positioning systems (GPS) units, a range of acceleration-based variables were evaluated for their inter-unit reliability, ability to discriminate between positions, and associations with perceived muscle soreness. The reliability of 5 Hz GPS for measuring acceleration and deceleration ranged from good to poor (CV = 3.7-27.1%), with the exception of high-intensity deceleration efforts (CV = 11.1-11.8%), the 10 Hz units exhibited moderate to good inter-unit reliability (CV = 1.2-6.9%). Reliability of average metrics (average acceleration/deceleration, average acceleration and average deceleration) ranged from good to moderate (CV = 1.2-6.5%). Substantial differences were detected between positions using time spent accelerating and decelerating for all magnitudes, but these differences were less clear when considering the count or distance above acceleration/deceleration thresholds. All average metrics detected substantial differences between positions. All measures were similarly related to perceived muscle soreness, with the exception of high-intensity acceleration and deceleration counts. This study has proposed that averaging the acceleration/deceleration demands over an activity may be a more appropriate method compared to threshold-based methods, due to a greater reliability between units, whilst not sacrificing sensitivity to within and between-subject changes.

Key Words: Soreness; deceleration; athlete monitoring; football.

INTRODUCTION

Global positioning systems (GPS) are commonly used in team sports to quantify the movement patterns of athletes during training and competition (6). Team-sport athletes typically run at average intensities of 80-140 $m \cdot min^{-1}$ throughout a match (6), equating to an average speed of 1.3-2.3 $m \cdot s^{-1}$, which by most reported standards would not be considered as high intensity. Therefore, the quantification of an athlete's ability to accelerate, decelerate and change direction quickly and efficiently may be more important for successful field-sport performance (21). These actions are often undertaken at low speeds, and despite not reaching classification as high-speed running, are physically taxing and have important implications for developing training and recovery protocols (23, 30). For example, competition acceleration/deceleration profiles have been associated with indicators of muscle damage (creatine kinase; CK) (30), decreases in neuromuscular performance (22) and increases in perceived muscle soreness (22) amongst team-sport athletes. Using a rolling average technique, Furlan et al. (13) demonstrated a lack of agreement between the peak periods of rugby sevens competition using either relative distance or an acceleration-based metabolic power metric. Intuitively, this would suggest that the most intense periods of match-play for speed and acceleration occur separately from each other, and therefore these metrics represent somewhat independent components of team-sport competition.

The ability of 10 Hz GPS units to accurately assess the acceleration-based requirements of team-sports activity has been validated against a laser device sampling at 2000 Hz (1). It was found that the GPS units possessed acceptable validity for quantifying instantaneous speed during acceleration (coefficient of variation, CV = 3.6-5.9%) (28). However, during deceleration, the ability of these units to assess running speed accurately decreased, due to a greater magnitude of change in speed (CV = 11.3%). The authors concluded that although the ability of GPS to accurately assess the magnitude of an acceleration/deceleration effort is limited, these units possess the ability to accurately determine whether an acceleration or deceleration event has occurred.

During team-sports, it is common practice to assess the acceleration/deceleration demands of an activity using the distance, time spent or the number of efforts performed within discrete acceleration bands (6). Large between-unit variations have been observed using GPS to assess the number of acceleration (CV = 10-43%) and deceleration (CV = 42-56%) efforts during a team-sport simulation protocol _ENREF_7(3), which might be a result of the measurement technique employed. For example, using a 3 $m \cdot s^{-2}$ cut-off threshold, two separate units may measure the same acceleration effort as 3.01 $m \cdot s^{-2}$ and 2.99 $m \cdot s^{-2}$, respectively. In this case, the first unit would classify this effort as an acceleration, however the second unit would not, despite a non-substantial difference between the two. To account for such between-unit variability in a practical setting, each player is often assigned the same unit for the entire season, though this is not always the case. For example, if the number of players in the squad exceeds the number of GPS units available, this becomes logistically difficult (3). Furthermore, it is common practice for researchers to pool data for an entire positional group to describe the different demands of each position (6), which may be inappropriate if large errors between GPS units exist. Therefore, it may be that other methods are preferable for quantifying the acceleration-based demands of team-sports activity.

In an attempt to overcome the poor reliability of common acceleration measures, a recent study proposed a novel average acceleration/deceleration metric (Ave Acc/Dec; $m \cdot s^{-2}$) (7). This technique involved taking the absolute value of all acceleration/deceleration data, and averaging over the duration of the defined period (match, drill etc.). It may be that such a technique is more appropriate for analyzing time-series data, where all acceleration and deceleration efforts are accounted for, regardless of the magnitude. This is important, as low-intensity acceleration/deceleration work undoubtedly carries some physiological and neuromuscular cost (2), and therefore, warrants inclusion when monitoring these demands. This metric has been shown to be adequately sensitive to detect positional differences in the peak acceleration/deceleration profile of rugby league (7), however no study has yet quantified its reliability between GPS units, or its association with perceived muscle soreness. Therefore, this study aimed to assess the reliability and usefulness of a range of acceleration metrics using GPS technology.

METHODS

Experimental Approach to the Problem

To assess the importance, reliability and usefulness of acceleration variables attained using GPS technology, this study was divided into three sections. 1) The importance of acceleration/deceleration during team sports was determined by establishing the association between the temporal occurrence of the most intense period of match play, for speed and acceleration/deceleration, respectively (7). It was hypothesized that the period of a match where acceleration/deceleration intensity was greatest, would occur separately to the peak period for running speed. 2) Secondly, the inter-unit reliability and interchangeability of acceleration-based metrics was obtained from 38 GPS units from two separate manufacturers (as detailed below), concurrently measuring the same team-sports simulation session. 3) Finally, the usefulness of each of these measures was determined by evaluating their ability to discriminate between positions during team sports competition, and their associations with perceived muscle soreness during a team-sport preparation program.

Subjects

Forty-eight full-time professional rugby league players (24 ± 5 yr; 1.86 ± 0.06 m 99.5 ± 8.9 kg) competing in the National Rugby League (NRL) participated in this study. Permission was granted from a professional rugby league club competing in the NRL to perform analyses on match and training monitoring data across the 2015-16 seasons and the preseason period that divided them. Institutional ethics approval for a retrospective analysis of training load and match data was attained prior to the commencement of this study (HRE16-142).

Procedures

Part 1

To determine the association between the temporal occurrence of the peak periods of both speed and acceleration/deceleration, 742 match files were analyzed, where only files containing at least 35 consecutive minutes of on-field playing time were included. Further, of the 48 matches recorded, six were removed from analysis due to poor satellite connectivity at three separate stadiums, leaving 672 individual files (14 ± 9 per player, range 1-38). Movement data was recorded using portable GPS units that possessed a raw sampling rate of 5 Hz (SPI HPU, GPSports, Canberra, Australia) fitted into a custom-made pouch in their playing jersey, located between the scapulae. Each player was assigned the same unit for the entirety of the collection period to minimize inter-unit variability (3). Throughout this study, all data was downloaded and analyzed by the same member of the research team. Following each match, data were downloaded using the appropriate proprietary software (Team AMS v 2016.1., GPSports, Canberra, Australia), and further analyzed using customized software (R, v R-3.1.3.). Specifically, this software calculated the distance covered per unit of time (speed; $m \cdot min^{-1}$), and a novel average acceleration/deceleration metric (Ave Acc/Dec; $m \cdot s^{-2}$) (7). This technique involved taking the absolute value of all acceleration/deceleration data, and averaging over the duration of the defined period. Finally, a moving average approach was utilized to calculate both the magnitude and temporal location of the peak intensities of each variable, for a range of moving average durations (1 to 10 min). Importance of acceleration was assessed as the disassociation between the occurrence of the peak speed and Ave Acc/Dec intensities.

Part 2

To assess the inter-unit reliability of acceleration-based measures using GPS, this study adapted the methodology of Buchheit et al. (3), where 38 GPS units (5 Hz SPI HPU units, GPSports, Canberra Australia, n = 19; 10 Hz Catapult S5 units, Catapult Innovations, Melbourne, Australia, n = 19) were securely attached to a sprint sled. Units were placed in a vertical position to allow equal exposure of the embedded antennae, with at least 2 cm separating units. The sled was then fixed to a harness, which was attached to one team-sport athlete. The subject performed a 40-min team sport simulation, which involved periods of walking, jogging and running, at a range of speeds and accelerations. Upon completion of the session, files were downloaded and trimmed using proprietary software (Team AMS, GPSports, Canberra, Australia; Openfield, Catapult Innovations, Melbourne, Australia), and further analyzed using customized software (R, v R-3.1.3.). A range of commonly used acceleration-based variables were calculated, including the number of efforts, distance covered and time spent over predefined intensity thresholds (1, 2 and 3 $m \cdot s^{-2}$ for low, moderate and high, respectively). In addition, Ave Acc/Dec was calculated as in Part 1, and further divided into acceleration (Ave Acc; $m \cdot s^{-2}$) and deceleration (Ave Dec; $m \cdot s^{-2}$). Interunit reliability was assessed as the agreement of acceleration-based measures between units.

Part 3a

To establish the usefulness of acceleration-based metrics, the same 672 match files from Part 1 were re-analyzed using customized software (R, v R-3.1.3.). Subjects were classified as either fullbacks, outside backs (centres and wingers), halves (half-backs and five-eighths), hookers, edge forwards (second rowers) or middle forwards (props and locks). Using a 5-min moving average, the peak 5-min period was calculated for each of the acceleration/deceleration metrics outlined in Part 2, and the ability of each metric to discriminate between positions was assessed.

Part 3b

Training load data was collected across an entire preseason period, which lasted 16 weeks. During this phase, subjects typically completed four-to-five field-based sessions, four strength sessions, and two recovery/hydrotherapy sessions per week. Running loads were recorded using GPS units that possess a raw sampling rate of 5 Hz (SPI HPU, GPSports, Canberra, Australia), and downloaded and analyzed using the same protocol as Parts 1 and 2. For the three average metrics (Ave Acc/Dec, Ave Acc and Ave Dec), each drill value was multiplied by duration to convert to a load measure. Next, a 7-day exponentially-weighted moving average (EWMA) (17) was calculated for each metric, and converted to a Z-score. Perceived muscle soreness was assessed using a one-to-ten Likert scale for five major muscle groups (hamstrings, calves, quadriceps, groins and gluteal), which were then averaged and converted to a Z-score for comparisons with training load data.

Statistical Analyses

The association between the temporal occurrence of the peak periods of running speed and acceleration/deceleration was assessed using chi-squared test, where statistical significance was set at $p < 0.05$. For example, if the peak periods for speed and acceleration/deceleration (for each moving average duration) overlapped, a “Yes” value was recorded. Conversely, if these phases of play did not overlap, this instance was classified as a “No”, indicating that the peak periods of each metric occur independently of each other. Inter-unit reliability was calculated using the coefficient of variation (CV; ±90% confidence intervals [90% CI]), which was rated as good (CV <5%), moderate (CV = 5-10%) or poor (CV >10%) (12). Differences between manufacturers were described using a magnitude-based approach, where differences were considered real if the likelihood of the effect exceeded 75% (15).

To assess differences between the peak periods of competition by position, a linear mixed effects model was used, specifying individual athletes as a random effect, as to account for different within-subject standard deviations, that were nested within individual match files. Positional groups were specified as a fixed effect, describing the relationship between that and of the dependent variables. Pairwise comparisons between positional groups were assessed using the Least Squares mean test, that were further assessed using a magnitude based inference network (15). Differences were described using standardized effect sizes (ES), categorized using the thresholds of; <0.2 trivial, 0.21-0.60 small, 0.61-1.20 moderate, 1.21-2.0 large and >2.0 very large (15). Quantitative chances of real differences in variables were assessed as: <1%, almost certainly not; 1-5%, very unlikely; 5-25%, unlikely; 25-75%, possibly; 75-97.5%, likely; 97.5-99% very likely; >99%, almost certainly (15).

Associations between training load and perceived muscle soreness were also evaluated using linear mixed models, by converting the models’ *t* statistics to ES correlations

(r) and the associated 90% CI (25). Effect size correlations were interpreted as <0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; 0.9-0.99, almost perfect; 1.0, perfect (15). Descriptive statistics are presented as mean ± standard deviation (SD), while all other data are reported as ES ± 90% CI, unless otherwise stated. All statistical analyses were performed using R statistical software (R, v R-3.1.3.).

RESULTS

Figure 1 demonstrates a significant effect of moving average duration on the association between the peak periods of speed and acceleration/deceleration during professional rugby league competition (χ^2 = 943, df = 9, p < 0.001). Interunit reliability statistics for both 5 Hz and 10 Hz GPS are presented in Table 1. The reliability of 5 Hz GPS for measuring acceleration and deceleration ranged from good to poor (CV = 3.7-27.1%). With the exception of high-intensity deceleration efforts (CV = 11.1-11.8%), 10 Hz units exhibited moderate to good inter-unit reliability (CV = 1.2-6.9%). Reliability of average metrics (Ave Acc/Dec, Ave Acc and Ave Dec) ranged from good to moderate (CV = 1.2-6.5%). Units from the two manufactures were not comparable on any acceleration-based metric.

Sensitivity of acceleration-based measures for discriminating positional demands can be found in Table 2. Differences were detected between positions using time spent accelerating and decelerating for all magnitudes, but these differences were less clear when considering the count or distance above acceleration/deceleration thresholds. The Ave Acc/Dec, Ave Acc and Ave Dec techniques all detected substantial differences between positions.

Associations between acceleration/deceleration and perceived muscle soreness are illustrated in Figure 2. There were at least *likely* small positive relationships between perceived soreness and all acceleration and deceleration counts (ES [*r*] = 0.16-0.23), *very likely* small positive relationships with distance covered accelerating/decelerating (ES [*r*] = 0.20-0.23) and *most likely* small positive relationships with time spent accelerating and decelerating (ES [*r*] = 0.20-0.23). There were *most likely* small positive associations between muscle soreness and Ave Acc (ES [*r*] = 0.23, 90% CI = 0.17 to 0.29), Ave Dec (0.23, 0.17 to 0.29) and Ave Acc/Dec (0.23, 0.17 to 0.29).

DISCUSSION

The ability to accelerate, decelerate and change direction effectively is vital for team sports, commonly due to spatial constraints imposed by opposition players or field dimensions (19). Whilst GPS technology represents a method for quantifying these capacities during team-sports training and competition, due to the rapid nature of these movements, they are often difficult to capture effectively with these devices (28). In agreement with the study hypothesis, the novel method of averaging acceleration and deceleration data over select temporal periods was determined to be a more robust technique for capturing the intensity of these movements during team-sports activity, and may be more appropriate when compared to using threshold-based methods. Furthermore, this increase in stability does not result in a substantial decrease in sensitivity, and therefore presents as a preferable method for quantifying the acceleration/deceleration intensity of team-sports competition using GPS technology.

In support of our hypothesis, the present study observed that the peak periods of acceleration/deceleration often occurred separately to the peak periods of speed (Figure 1), particularly for moving average windows of shorter durations (<5 min). In the context of the cohort used within the present study (i.e., rugby league players), it may be that the acceleration/deceleration demands might be highest when defending the try-line, whilst the peak speed-based intensities might occur when a line break is made, resulting in a greater distance to be covered per unit of time. Although somewhat related, the correlation between acceleration and maximal sprinting speed (r = 0.56-0.87) (14, 20, 29) suggests that these are independent qualities (5). _ENREF_21 Moreover, it would seem that these events are equally as important to the match outcome, and therefore, should be prepared for appropriately. However, an interesting finding of the present study was that for moving averages of longer durations (>5 min), the peaks in either speed or acceleration/deceleration more commonly occurred at the same time, suggesting that training drills of longer duration should be incorporative of both speed-based and accelerated/decelerated running.

When considering the reliability of GPS technology, the majority of literature has concentrated on the intra-unit reliability of the unit, or the repeatability of measures taken from the same device on repeat occasions (26). This is vital for the accuracy of within-individual comparisons, or for calculating accumulated training load over time. However, knowledge of the inter-unit reliability of these units is also important, for differentiating positional demands during training or matches, or for making comparisons with published literature and norms. The present study observed that across all acceleration and deceleration measures, there was a clear, inverse relationship between the magnitude of the change in speed, and the accuracy of the units. This is a well-known limitation of GPS, which is a result of a limited sampling rate of these devices (1, 3, 18). These findings are in line with others (28), where an increase in sampling rate resulted in a greater stability of acceleration-based measures, and therefore, a minimum sampling rate of 10 Hz is recommended for comparing threshold-based acceleration measures between players and/or position groups. However, of all measures assessed within this study, the average metrics possessed the greatest inter-unit reliability, particularly with 10 Hz devices. This is not surprising, as small differences between units can be magnified using intensity bands, as two non-substantially different efforts could quite easily be classified into different zones (4). Although none of the acceleration-based measures reported within this study were comparable between manufacturers, the stability of several of these within the same manufacturer allows coaches and practitioners to compare the acceleration-based demands of athletes within the same session, or relate to published literature.

Whilst knowledge of the reliability of a measure is important, an increase in stability may come at the cost of a decrease in sensitivity. If a particular metric is not able to detect subtle differences between sessions, players or positions, the reliability of the measure becomes redundant. Within the present study, the usefulness of each acceleration-based metric in a team-sport setting was assessed in two ways. Firstly, the ability of each measure to discriminate between the peak intensities of competition for different positions was examined. Across all methods, there seemed to be an increase in the acceleration/deceleration profile for hookers and halves when compared to all other positions, though this difference was clearer for some methods compared to others. This is in agreement with other research, where inter-positional differences in acceleration and deceleration profiles have been reported (2, 7, 27). Though the present study cannot attest to the validity or accuracy of these metrics in such a chaotic environment, it would seem that the average acceleration/deceleration metrics proposed by this study are equally as sensitive to positional differences as threshold-based methods.

Lastly, this study evaluated the association between accumulated acceleration-based training loads and self-reported perceived muscle soreness. The present study observed that most acceleration and deceleration measures were similarly related to perceived muscle soreness (ES = ~0.20-0.25), with the exception of high-intensity acceleration and deceleration counts and distances. Both time spent above each intensity threshold and acceleration/deceleration averaged over the duration of each drill exhibited small but consistent relationships with perceived muscle soreness. Objective markers of muscle damage (CK) have been linked to high-intensity decelerations (30), possibly due to the high eccentric force production involved during deceleration. The concentration of CK and the time course of muscle function recovery following sport-specific repeated sprint efforts has been examined (16). Specifically, CK and muscle function, as measured by maximal isometric voluntary contractions, were impaired 24 hr post-exercise when compared to pre-exercise, and perceived muscle soreness was elevated 24 hr following the protocol (16). Taken together, it would seem that monitoring the time spent accelerating/decelerating, or the density of accelerated and/or decelerated running (i.e. Ave Acc, Ave Dec and Ave Acc/Dec) will provide coaches with the useful information as to the training status of their athletes for sessions on upcoming days.

Given that the peak match intensities of various team sports have been quantified (7-10), coaches may utilize these data to optimally periodize a training program that reflects the typical microcycle of their athletes, such as a "multiple peaking" model commonly required of team sports athletes (24). It has been established that compared to constant speed running, acceleration and deceleration at low speed can elicit a substantially different physical and mechanical stress (5, 23). For example, high-speed running relies heavily on stretch-shortening cycle activity, lower-limb stiffness and hip extensor activity to generate greater vertical force production (11). In contrast, acceleration is generally considered a result of concentric force development, impulse and hip and knee extensor activity _ENREF_17(14, 20, 29). As such, performance staff may be interested in the tactical periodization of training drills with these capacities in mind, in collaboration with an appropriate resistance training program, allowing a specificity of both the technical and physical aspects of competition.

The present study has presented a comprehensive overview of the use of acceleration-based metrics using GPS technology within team sports. Despite the clear importance of acceleration to success in team-sports activity, there remains no consensus to the most appropriate method of quantifying these demands using GPS technology. It is suggested by the current authors that when addressing time-series data, it is inappropriate to classify actions by their intensity, using predefined thresholds. The present study has presented a simple method for the accurate quantification of acceleration and deceleration in a team sport setting, where all changes in speed are included, regardless of their magnitude. Overall this method seems to be equally if not more reliable than threshold-based methods for assessing these demands, and this increased stability did not seem to be detrimental to the sensitivity of the metric. Therefore, averaging the acceleration and/or deceleration profile of an activity seems to be the most appropriate method for the measurement of these demands during team-sports competition and training.

PRACTICAL APPLICATIONS

- Classification of acceleration/deceleration into intensity bands is inappropriate for time-series data, and is primarily poorly reliable, and averaging the demands over select periods is a more stable, equally as sensitive and therefore more appropriate method.
- Coaches may measure acceleration and deceleration independently from each other, or combine as an indication of overall acceleration/deceleration, or multiply by the duration of the drill, reflective of the load imposed through acceleration and deceleration.

- Monitoring the density of these demands during specific training methodologies relative to peak match intensity will assist coaches in ensuring that athletes are prepared to compete at the level required during competition, and furthermore will provide useful information regarding the efficacy of certain training drills for developing acceleration/deceleration capacity.

REFERENCES

1. Akenhead R, French D, Thompson KG, and Hayes PR. The acceleration dependent validity and reliability of 10 Hz GPS. *J Sci Med Sport* 17: 562-566, 2014.
2. Akenhead R, Harley J, and Tweddle S. Examining the external training load of an English Premier League football team with special reference to acceleration. *J Strength Cond Res*, 2016. doi: 10.519/JSC. 0000000000001343.
3. Buchheit M, Al Haddad H, Simpson BM, Palazzi D, Bourdon PC, Di Salvo V, and Mendez-Villanueva A. Monitoring accelerations with GPS in football: time to slow down? *Int J Sports Physiol Perform* 9: 442-445, 2014.
4. Buchheit M, Manouvrier C, Cassirame J, and Morin JB. Monitioring locomotor load in soccer: is metabolic power, powerful? *Int J Sport Med* 36: 1149-1155, 2015.
5. Buchheit M, Samozino P, Glynn JA, Michael BS, Al Haddad H, Mendez-Villanueva A, and Morin JB. Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. *J Sports Sci* 32: 1906-1913, 2014.
6. Cummins C, Orr R, O'Connor H, and West C. Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Med* 43: 1025-1042, 2013.

7. Delaney JA, Duthie GM, Thornton HR, Scott TJ, Gay D, and Dascombe BJ. Acceleration-based running intensities of professional rugby league match-play. *Int J Sports Physiol Perform* 11: 802-809, 2016.

8. Delaney JA, Scott TJ, Thornton HR, Bennett KJ, Gay D, Duthie GM, and Dascombe BJ. Establishing duration specific running intensities from match-play analysis in rugby league. *Int J Sports Physiol Perform* 10: 725-731, 2015.

9. Delaney JA, Thornton HR, and Duthie GM. Modeling peak running intensity in football, in: *Australian Strength and Conditioning Association Conference on Applied Strength and Conditioning*. Melbourne, Australia, 2016.

10. Delaney JA, Thornton HR, Pryor JF, Stewart AM, Dascombe BJ, and Duthie GM. Peak running intensity of international rugby: Implications for training prescription. *Int J Sports Physiol Perform*, 2016. (Publish Ahead of Print).

11. Dorn TW, Schache AG, and Pandy MG. Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. *J Exp Biol* 215: 1944-1956, 2012.

12. Duthie G, Pyne D, and Hooper S. The reliability of video based time motion analysis. *J Hum Mov Stud* 44: 259-271, 2003.

13. Furlan N, Waldron M, Shorter K, Gabbett TJ, Mitchell J, Fitzgerald E, Osborne MA, and Gray AJ. Running intensity fluctuations in elite rugby sevens performance. *Int J Sports Physiol Perform* 10: 802-807, 2015.

14. Harris NK, Cronin JB, Hopkins WG, and Hansen KT. Relationship between sprint times and the strength/power outputs of a machine squat jump. *J Strength Cond Res* 22: 691-698, 2008.

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

16. Howatson G and Milak A. Exercise-induced muscle damage following a bout of sport specific repeated sprints. *The Journal of Strength and Conditioning Research* 23: 2419-2424, 2009.

17. Hunter JS. The exponentially weighted moving average. *J Quality Technol* 18: 203-210, 1986.

18. Johnston RJ, Watsford ML, Kelly SJ, Pine MJ, and Spurrs RW. Validity and interunit reliability of 10 Hz and 15 Hz GPS units for assessing athlete movement demands. *J Strength Cond Res* 28: 1649-1655, 2014.

19. Kempton T, Sirotic AC, Rampinini E, and Coutts AJ. Metabolic power demands of rugby league match play. *Int J Sports Physiol Perform* 10: 23-28, 2015.

20. Little T and Williams AG. Specificity of acceleration, maximum speed, and agility in professional soccer players. *J Strength Cond Res* 19: 76-78, 2005.

21. Lockie RG, Murphy AJ, Knight TJ, and Janse de Jonge XA. Factors that differentiate acceleration ability in field sport athletes. *J Strength Cond Res* 25: 2704-2714, 2011.

22. Nedelec M, McCall A, Carling C, Legall F, Berthoin S, and Dupont G. The influence of soccer playing actions on the recovery kinetics after a soccer match. *J Strength Cond Res* 28: 1517-1523, 2014.

23. Osgnach C, Poser S, Bernardini R, Rinaldo R, and di Prampero PE. Energy cost and metabolic power in elite soccer: a new match analysis approach. *Med Sci Sports Exerc* 42: 170-178, 2010.

24. Pyne DB, Mujika I, and Reilly T. Peaking for optimal performance: Research limitations and future directions. *J Sports Sci* 27: 195-202, 2009.

25. Rosnow RL, Rosenthal R, and Rubin DB. Contrasts and correlations in effect-size estimation. *Psychol Sci* 11: 446-453, 2000.

26. Scott MT, Scott TJ, and Kelly VG. The validity and reliability of global positioning systems in team sport: A brief review. *J Strength Cond Res* 30: 1470-1490, 2016.

27. Taskin H. Evaluating sprinting ability, density of acceleration, and speed dribbling ability of professional soccer players with respect to their positions. *J Strength Cond Res* 22: 1481-1486, 2008.

28. Varley MC, Fairweather IH, and Aughey RJ. Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *J Sports Sci* 30: 121-127, 2012.

29. Vescovi JD and McGuigan MR. Relationships between sprinting, agility, and jump ability in female athletes. *J Sports Sci* 26: 97-107, 2008.

30. Young WB, Hepner J, and Robbins DW. Movement demands in Australian rules football as indicators of muscle damage. *J Strength Cond Res* 26: 492-496, 2012.

Figure 1: Temporal association between peak periods of acceleration/deceleration ($m \cdot s^{-2}$) and speed ($m \cdot min^{-1}$), represented as the observed frequency of overlapping periods.

Figure 2: Association between acceleration and deceleration measures and perceived muscle soreness, presented as effect size ± 90% confidence interval.

Table 1. Inter-unit reliability and interchangeability of the global positioning systems (GPS) from two different manufacturers.

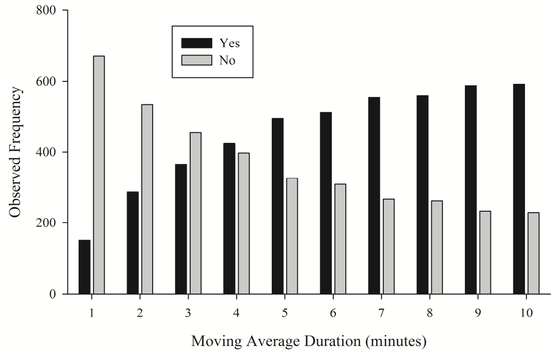
Variable	GPSports HPU (5 Hz)		Catapult S5 (10 Hz)		ES (90% CI)	Likelihood of the Difference
	Mean ± SD	CV% (90% CI)	Mean ± SD	CV% (90% CI)		
Average Acc/Dec (m·s^{-2})	0.72 ± 0.04	5.7% (4.5-7.8%)	0.56 ± 0.01	1.2% (1.0 to 1.7%)	1.18 (0.58 to 1.78)	*likely* moderate
Average Acc (m·s^{-2})	1.16 ± 0.07	6.5% (5.1 to 8.9%)	0.83 ± 0.02	2.8% (2.2 to 3.9%)	1.57 (0.94 to 2.20)	*likely* large
Average Dec (m·s^{-2})	-1.14 ± 0.06	4.9% (3.8 to 6.8%)	-0.61 ± 0.01	2.2% (1.8 to 3.1%)	3.40 (2.63 to 4.17)	*most likely* very large
Low Acc (n)	60 ± 3	5.1% (4.0 to 6.9%)	112 ± 5	4.4% (3.4 to 6%)	1.79 (1.37 to 2.21)	*very likely* large
Moderate Acc (n)	28 ± 1	3.7% (2.9 to 5.0%)	49 ± 3	5.3% (4.2 to 7.3%)	1.63 (1.20 to 2.05)	*very likely* large
High Acc (n)	18 ± 2	13.2% (10.5 to 18.1%)	20 ± 1	5.9% (4.7 to 8.2%)	0.45 (-0.06 to 0.95)	*likely* small
Low Dec (n)	68 ± 3	4.6% (3.7 to 6.3%)	91 ± 3	3.3% (2.6 to 4.5%)	0.97 (0.51 to 1.42)	*likely* moderate
Moderate Dec (n)	22 ± 1	4.8% (3.8 to 6.6%)	33 ± 2	5.2% (4.1 to 7.2%)	1.18 (0.74 to 1.63)	*very likely* moderate
High Dec (n)	12 ± 1	6.5% (5.2 to 8.9%)	16 ± 1	4.8% (3.8 to 6.6%)	0.92 (0.46 to 1.38)	*likely* moderate
Low Acc (s)	6.2 ± 0.3	5.5% (4.4 to 7.5%)	4.3 ± 0.1	2.1% (1.7 to 3%)	1.78 (1.13 to 2.42)	*likely* large
Moderate Acc (s)	2.2 ± 0.3	13.4% (10.7 to 18.4%)	1.4 ± 0.1	3.9% (3.1 to 5.4%)	2.12 (1.39 to 2.84)	*very likely* large
High Acc (s)	0.7 ± 0.2	24.3% (19.3 to 33.3%)	0.5 ± 0	5.6% (4.4 to 7.8%)	1.85 (1.01 to 2.68)	*likely* large
Low Dec (s)	7.1 ± 0.5	7.0% (5.6 to 9.6%)	4.2 ± 0.1	1.6% (1.3 to 2.2%)	2.74 (2.01 to 3.47)	*very likely* very large
Moderate Dec (s)	2.2 ± 0.3	14.8% (11.8 to 20.3%)	0.9 ± 0.1	6.4% (5 to 8.8%)	5.75 (4.65 to 6.84)	*most likely* very large
High Dec (s)	0.6 ± 0.1	17.9% (14.2 to 24.5%)	0.2 ± 0	11.8% (9.3 to 16.3%)	5.76 (4.63 to 6.89)	*most likely* very large
Low Acc (m)	849 ± 38	4.5% (3.6 to 6.2%)	590 ± 10	1.7% (1.4 to 2.4%)	1.75 (1.12 to 2.39)	*likely* large
Moderate Acc (m)	354 ± 47	13.4% (10.6 to 18.4%)	226 ± 10	4.4% (3.5 to 6.1%)	2.22 (1.49 to 2.96)	*very likely* large
High Acc (m)	132 ± 36	27.1% (21.5 to 37.1%)	79 ± 5	6.9% (5.5 to 9.6%)	2.59 (1.63 to 3.55)	*likely* very large
Low Dec (m)	882 ± 65	7.4% (5.9 to 10.1%)	584 ± 11	1.8% (1.4 to 2.5%)	2.03 (1.36 to 2.7)	*very likely* large
Moderate Dec (m)	316 ± 55	17.3% (13.7 to 23.7%)	125 ± 7	5.7% (4.5 to 7.9%)	5.94 (4.77 to 7.11)	*most likely* very large
High Dec (m)	79 ± 18	23% (18.3 to 31.6%)	29 ± 3	11.1% (8.8 to 15.4%)	6.12 (4.82 to 7.42)	*most likely* very large

ES = effect size; m = metres; Acc = acceleration; Dec = deceleration; CV = coefficient of variation; CI = confidence intervals; n = number; s = second; m = metre.

Table 2. Sensitivity of various acceleration-based measures to detect positional differences in team sports using global positioning systems.

Variable	Edge Forwards	Fullbacks	Halves	Hookers	Middle Forwards	Outside Backs
Average Acc/Dec ($m \cdot s^{-2}$)	0.89 ± 0.08	0.84 ± 0.06	0.92 ± 0.07[abef]	0.90 ± 0.09[abef]	0.84 ± 0.09	0.85 ± 0.08
Average Acc ($m \cdot s^{-2}$)	0.44 ± 0.04	0.41 ± 0.03	0.45 ± 0.04[abef]	0.44 ± 0.04[abef]	0.40 ± 0.04	0.42 ± 0.04
Average Dec ($m \cdot s^{-2}$)	0.46 ± 0.04	0.44 ± 0.03	0.48 ± 0.04[abef]	0.47 ± 0.05[abef]	0.44 ± 0.04	0.44 ± 0.04
Low Acc (n)	33.7 ± 4.0[f]	31.0 ± 4.8	37.6 ± 5.4[abef]	37.2 ± 5.5[abef]	31.6 ± 4.7	30.4 ± 6.4
Moderate Acc (n)	16.1 ± 2.5	15.6 ± 2.5	18 ± 3.2[abef]	16.7 ± 3.1[abef]	14.8 ± 2.7	15 ± 3.3
High Acc (n)	7.3 ± 1.7	7.6 ± 2.3	7.4 ± 2.2	7.0 ± 2.2	7.2 ± 2.2	7.0 ± 2.0
Low Dec (n)	32.9 ± 3.3[b]	30.1 ± 4.5	37.9 ± 4.5[abef]	35.6 ± 4.3[abef]	31.0 ± 4.1[b]	30.7 ± 5.5[b]
Moderate Dec (n)	12.6 ± 2.2[bf]	11.1 ± 2.1	11.5 ± 2.3	11.1 ± 2.1	11.2 ± 2.8	10.3 ± 2.5
High Dec (n)	4.4 ± 1.2e	4.3 ± 1.1	3.5 ± 1.3	3.1 ± 1.3	3.5 ± 1.4	3.9 ± 1.1
Low Acc (s)	47.8 ± 6	45.0 ± 4.6	50 ± 5.9[abef]	48.3 ± 6.3[abef]	44.0 ± 6.1	44.6 ± 5.9
Moderate Acc (s)	17.9 ± 2.9[b]	15.9 ± 1.7[f]	17.8 ± 2.4[bef]	18.4 ± 3.1[abef]	16.5 ± 2.7	15.9 ± 2.9
High Acc (s)	8.4 ± 1.6[b]	7.6 ± 1.3	7.8 ± 1.0	8.7 ± 1.3[abcef]	8.0 ± 1.5	7.6 ± 1.2
Low Dec (s)	51.1 ± 5.6	48.0 ± 4.7	54.8 ± 4.8[abe]	52.9 ± 6.7[abef]	48.3 ± 5.6	48.6 ± 5.3
Moderate Dec (s)	19.6 ± 2.5[a]	16.4 ± 3.1	19.4 ± 2.6[af]	18.9 ± 3.1[af]	17.8 ± 3[a]	16.9 ± 3[a]
High Dec (s)	7.9 ± 1.4[cdf]	6.2 ± 1.2	7.0 ± 1.5	7.2 ± 1.6[bcef]	6.6 ± 1.5[a]	6.2 ± 1.5[a]
Low Acc (m)	109.8 ± 51.3[e]	109.5 ± 13.2	106.8 ± 14.9[e]	103.4 ± 16.2[e]	93.8 ± 19.3	96.4 ± 16.1
Moderate Acc (m)	35.2 ± 8.4	35.6 ± 5.5	33.4 ± 5.1[e]	33.4 ± 7.6[e]	30.2 ± 6.6	31.8 ± 7.1
High Acc (m)	12.1 ± 4.3	11.1 ± 2.6	10.6 ± 2.4	10.8 ± 3.1	9.7 ± 3.1	10.8 ± 2.8
Low Dec (m)	123.3 ± 49.6	121.3 ± 11.1	124.3 ± 15.5	121.4 ± 19.1	108.7 ± 22.6	109.7 ± 17.1
Moderate Dec (m)	50.0 ± 9.1	45.5 ± 6.3	46.9 ± 7.4[ef]	45.7 ± 8.9[ef]	43.3 ± 9.2	42.8 ± 8.4
High Dec (m)	22.3 ± 4.3[cf]	20.2 ± 3.8	19.1 ± 4	19.3 ± 4.3	18.5 ± 4.4	18.7 ± 4.2

ES = effect size; m = metres; Acc = acceleration; Dec = deceleration; n = number; s = second; m = metre. [a] = greater than edge forwards, [b] = greater than fullbacks, [c] = greater than halves, [d] = greater than hookers, [e] = greater than middle forwards, [f] = greater than outside backs. All differences considered real if likelihood of effect exceeding 0.2 × between-subject SD was greater than 75%.



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6
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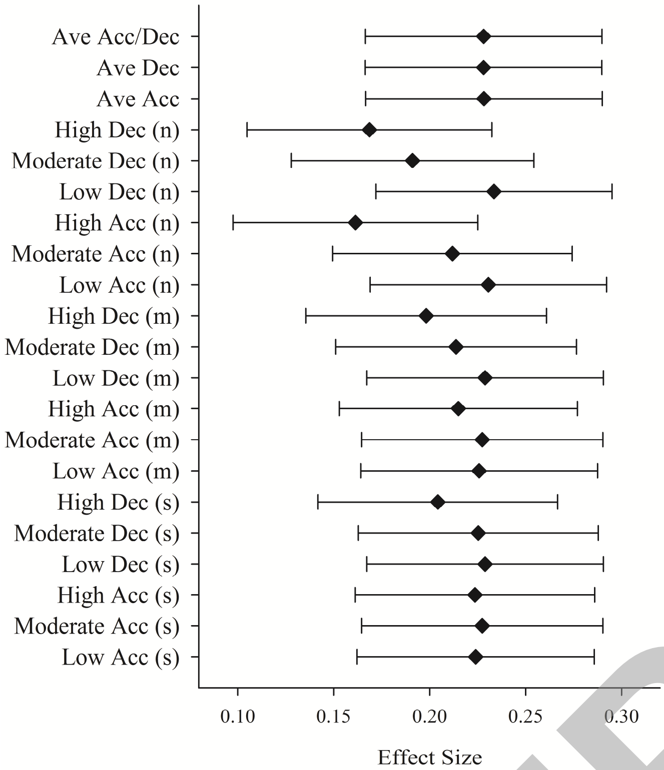
Moving Average Duration (minutes)


Ave Acc/Dec
Ave Dec
Ave Acc
High Dec (n)
Moderate Dec (n)
Low Dec (n)
High Acc (n)
Moderate Acc (n)
Low Acc (n)
High Dec (m)
Moderate Dec (m)
Low Dec (m)
High Acc (m)
Moderate Acc (m)
Low Acc (m)
High Dec (s)
Moderate Dec (s)
Low Dec (s)
High Acc (s)
Moderate Acc (s)
Low Acc (s)
0.10
0.15
0.20
0.25
0.30
Effect Size