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Title
A comparison of displacement and energetic variables between three commercially available team sport GPS devices

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Abstract

This study compared the outputs of three different commercially-available GPS player-tracking devices for a range of commonly used displacement and energetic variables in activities replicating team sport movements. Professional male soccer players (n=7), simultaneously wore three GPS devices (Catapult OptimEye S5, GPExe Pro 1, StatSport ViperPod) whilst completing 4 separate drills, comprising progressively more complex changes in speed and direction. Displacement (distance, speed) and energetic (energy cost, metabolic power, energy expenditure) variables were compared for each device. All three devices tended to under-estimate distance compared to the known value for each drill, with only minor and inconsistent differences between devices. There were no differences between devices for average speed. For energetic variables, substantial differences were found between each device, and these differences magnified as movement tasks became more erratic. Given that energetic variables are derived from measures of instantaneous speed, and also incorporate the magnitude and direction of change between successive data points, these differences may be attributable to disparities in raw data quality, filtering techniques and calculation methods. In order to provide comparable estimates of energetic variables in team sports, player-tracking devices must be capable of accurately recording instantaneous velocity in activities comprising frequent changes in speed and direction.

Introduction

The routine use of player-tracking devices to monitor training and competition loads has become standard practice in many elite international and professional team sports (Cummins, Orr, O'Connor, & West, 2013). Technologies such as global positioning system (GPS), local position measurement (LPM) and camera-based visual recognition systems are commonly used to assess competition demands and determine individual "work rates" (Polglaze, Dawson, & Peeling, 2016). This has been the catalyst for a rapid expansion of team sport research (Coutts, 2014) and a corresponding improvement in the reliability, accuracy and sensitivity of player-tracking devices to detect and quantify activities relevant to team sports (Scott, Scott, & Kelly, 2016).

In comparison to other technologies, GPS devices are generally more portable and do not require installation of additional equipment (Polglaze et al., 2016), and have therefore been widely adopted in a range of team sports. Early GPS devices typically sampled at 1 Hz, which allowed for reliable estimates of total distance over extended periods, but demonstrated poor accuracy in measuring brief, discrete, high-intensity efforts (Jennings, Cormack, Coutts, Boyd, & Aughey, 2010). Frequent changes in both speed and direction caused a further reduction in accuracy and reliability (Jennings et al., 2010). Devices with higher sampling rates (5 and 10 Hz) demonstrated improved accuracy and reliability for the measurement of speed and acceleration, particularly in activities comprising regular changes in direction (Portas, Harley, Barnes, & Rush, 2010). Nevertheless, as movement tasks become more complex, the ability of GPS devices to accurately measure speed and distance is diminished (Rawstorn, Maddison, Ali, Foskett, & Gant, 2014).

Beyond sampling rate, numerous other factors can affect the quality of data obtained by a particular GPS device, by influencing the signal-to-noise ratio. The most familiar of these include the number of satellites connected and their horizontal dilution of precision (HDoP), along with less widely-known attributes such as the method used to determine displacement measures (positional differentiation or Doppler shift), and the particular GPS chipset deployed (Malone, Lovell, Varley, & Coutts, 2017). Furthermore, consideration must be given to whether – and how – raw data is filtered to reduce noise and treat erroneous and/or missing data (Malone et al., 2017). Accordingly, variables which are derived from the raw data can vary greatly between different GPS brands, depending not only on the hardware, but also the firmware within the device, and the software processes and settings once the data is downloaded (Buchheit et al., 2014; Varley, Jaspers, Helsen, & Malone, 2017). Hence, values obtained from different devices, or even the same device with different firmware or software, may not be comparable. Furthermore, studies to assess the reliability and accuracy of a particular device are only applicable to that specific combination of hardware, firmware and software, and cannot be generalised to other devices, even if they have a similar sampling rate.

As our understanding of the physical demands of team sport movements improves, there has been a corresponding requirement for player tracking devices to be more accurate and sensitive to the perpetual changes in speed and direction that characterise this activity. Whereas the traditional approach to quantifying the demands of team sports involved the determination of various displacement variables such as total distance, peak and average speed, and the magnitude and frequency of accelerations (Carling, Bloomfield, Nelsen, & Reilly, 2008), these approaches only consider speed or acceleration in isolation (Polglaze, Dawson, Buttfield, & Peeling, 2018). However, the interaction of speed and acceleration is a key determinant of the energy cost of variable-speed locomotion (Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010). Accordingly, player-tracking devices must be sensitive to these continual changes in speed and direction so that a more comprehensive energetic analysis of team sport activity can be undertaken.

Whilst extensive research has assessed the validity and reliability of various player-tracking systems to report distance, speed and acceleration (Akenhead, French, Thompson, & Hayes, 2014; Varley, Fairweather, & Aughey, 2012), and determine the comparability between systems (Randers et al., 2010), validation studies for energetic parameters are scarce (Rampinini et al., 2015) and the variability between devices is not known. In situations where players may be monitored with different devices (e.g. between club and national team), knowledge of discrepancies between devices is potentially useful information for coaches and conditioning staff. Therefore, the aim of this study was to evaluate three different commercially-available GPS player-tracking devices and compare their outputs for a range of commonly used displacement and energetic variables in activities replicating team sport movements.

Methods

Experimental Approach to the Problem

Participants wore three different GPS devices simultaneously whilst completing four different running drills. The drills were designed to progressively increase movement complexity by incorporating changes in both speed and direction, and thus compare the sensitivity of each device in detecting and quantifying these movement patterns. Raw data from each device were processed in the corresponding proprietary software, and then compared to the known distance. Comparisons between devices were made for displacement and energetic variables.

Participants

Seven male professional soccer players (age 17.7 ± 1.4 y, body mass 78.7 ± 5.4 kg, stature 179.1 ± 5.0 cm) participated in this investigation. All participants were members of the reserve team for a European first division club. Testing was conducted 'in-season'. As part of their contract with the club, participants provided signed informed consent acknowledging that any data collected during testing, training or competition may be de-identified and used for research purposes. Institutional ethical approval was obtained for this study, and all procedures conformed with the Declaration of Helsinki.

Global Positioning System (GPS) Devices

Three brands of commercially-available team sport GPS player-tracking devices were compared in this study; the Catapult OptimEye S5, (Catapult, Australia, firmware version 7.27), GPExe Pro 1, (Exelio srl, Udine, Italy, firmware version 1.7.7) and StatSport ViperPod, (StatSports Newry, Ireland, firmware version 9R), with two separate units of each device used alternately in this study. The Catapult and StatSport devices both sampled at 10 Hz, whilst the GPExe device sampled at 18.18 Hz. All three devices accessed the US-based GPS satellite array, whilst the Catapult device could also access the Russian-based Global Navigation Satellite System (GloNaSS) to provide full GNSS capability. One unit of each device was placed in separate pockets of a customised harness, each 10 cm apart in a line across the participants' upper back to optimise GPS signal quality and minimise interference and antenna obstruction between devices. Manufacturers advise that interference is unlikely with this configuration (Jackson, Polglaze, Dawson, King, & Peeling, 2018). To minimise bias, GPS devices were randomly re-allocated to different pockets at the beginning of each drill. Participants used the same units for all four drills.

Drills

Participants completed four discrete drills in standardised order, with successive drills increasing in movement complexity with respect to changes in speed and direction. All drills were conducted on a regulation grass soccer pitch. To ensure signal integrity and minimise interference from surrounding infrastructure (Williams & Morgan, 2009), testing occurred in an open field (Larsson, 2003), although there was a low-standing spectator stand along one side of the pitch. For Catapult and GPExe devices, the average number of satellite signals was 14.7 ± 1.8 and 10.3 ± 1.5 respectively, while HDoP was 0.61 ± 0.04 (Catapult) and 0.95 ± 0.11 (GPExe). This information could not be retrieved from the StatSport device. For each drill, distance was measured manually using a verified field tape and demarcated using existing pitch markings and/or training cones.

Drill 1 comprised a circuit around the marked boundary lines of the playing pitch, although to avoid the goal nets, participants followed the perimeter of the penalty area rather than staying on the goal line. Hence, each lap consisted of 12 linear segments (Figure 1a), with a combined measured distance of 410.9 m. To allow clear delineation between segments, participants were required to pause briefly at each turning point before commencing the next segment. Participants completed three separate circuits – one each at walking, jogging and running pace, for an overall total of 1232.7 m. Drill 2 comprised four separate maximal straight-line accelerations over distances of 10 m, 20 m, 30 m and 40 m, each followed by a 20m deceleration (Figure 1b). Three trials were performed over each distance (12 repetitions in total), resulting in an overall distance of 540 m. For each repetition, participants were required to start and finish with both feet placed on the demarcated line, and to pause for a few seconds to signify the end of the trial. Drill 3 was adopted from a previous study (Rampinini et al., 2015) and consisted of 2 sets of 4 × 70 m repetitions (i.e. 35 m ‘out’ and 35 m ‘back’) completed at varying speeds to simulate the most intense phases of a soccer match (Figure 1c). The ‘out’ phase comprised 5 m of walking followed by 5, 10 and 15 m of ‘elastic running’ (accelerations and decelerations without stopping), while the ‘back’ phase consisted of 25 m of jogging followed by 10 m of walking. This process was completed three times and on the fourth repetition, participants performed a 35 m run before turning and sprinting maximally back to the starting point. Participants were required to start and finish each 35 m segment (‘out’ and ‘back’) with both feet on the demarcated line, and then pause for a few seconds before turning 180° and commencing the next segment. Total distance for Drill 3 was 560 m. Drill 4 required participants to perform three repetitions each of three separate shuttle sprints over distances of 10 m (5 m out and 5 m back), 20 m (10 m out and 10 m back), and 40 m (20 m out and 20 m back) (Figure 1d). Participants commenced with their feet astride the start line, sprinted maximally to reach a point marked by a cone, performed a 180° change in direction and sprinted back as quickly as possible to the start line, finishing again with both feet on the line. Participants were not required to pause before changing direction, and instead had to straddle the turning cone (i.e. one foot either side) and touch it with both hands before turning. This was done to ensure the participants’ trunk remained in line with the cone as much as possible. Total distance for Drill 4 was 210 m.

Data Processing

Data files from each device were downloaded into the associated proprietary software (Catapult – Openfield, version 1.12.0; GPExe – GPExe Web App, version 2.5; StatSports – Viper for StatSports, version 1.2) and trimmed to exclude data outside of the actual drill trials. The proprietary software then provided values for total distance, average speed and average metabolic power for each drill. Total energy expenditure was calculated as the product of metabolic power and duration, whilst energy cost was the quotient of metabolic power and speed (di Prampero et al., 2005). The combined distance across all four drills was also determined for each device.

Statistical Analysis

Prior to analysis, all data were checked for normality and, where necessary, log transformed to satisfy a normal distribution. Statistical analyses were carried out using commercial software (SPSS 24.0, IBM, Chicago, IL, USA). One sample t-tests were used to compare distance measures from each GPS device to the known value, while a one-way ANOVA was conducted to compare displacement and energetic variables between the three devices. Bonferroni’s post-hoc test was used to identify any differences, with statistical significance accepted at $p < 0.05$. Cohen’s effect size (ES) ± 95% confidence interval was calculated to establish the magnitude of difference between devices, which were categorised using the following descriptors: < 0.2 – trivial, 0.2 to 0.6

– small, > 0.6 to 1.2 – moderate, > 1.2 to 2.0 – large, > 2.0 – very large (Hopkins, 2002). Where the confidence interval exceeded the ES, the effect was deemed unclear.

Results

Mean (± SD) displacement (distance, speed) and energetic (energy expenditure, energy cost, metabolic power) variables recorded by each device for each separate drill are presented in Table 1.

Displacement Measures

For Drill 1, compared to the known distance, both GPExe ($p = 0.008$, ES 1.43 ± 0.91, large) and StatSport ($p < 0.001$, ES 1.67 ± 0.68, large) under-estimated distance for WALK, whilst all three devices under-estimated distance for JOG (Catapult: $p = 0.002$, ES 1.61 ± 0.74, large; GPExe: $p = 0.010$, ES 1.40 ± 0.93, large; StatSport: $p < 0.001$, ES 1.68 ± 0.67, large) and RUN (Catapult: $p = 0.007$, ES 1.45 ± 0.89, large; GPExe: $p = 0.017$, ES 1.31 ± 1.00, large; StatSport: $p < 0.001$, ES 1.69 ± 0.66, large). There were no differences between devices for distance in any of the locomotor categories. For Drill 2, Catapult ($p = 0.039$, ES 1.17 ± 1.08, large) and StatSport ($p = 0.017$, ES 1.31 ± 1.00, large) under-estimated distance compared to the known value, and StatSport recorded lower distance than GPExe ($p = 0.025$, large). There was a moderate ES showing a lower distance for Catapult than GPExe. For Drill 3, both Catapult ($p = 0.044$, ES 1.13 ± 1.10, large) and GPExe ($p < 0.001$, ES 1.73 ± 0.60, large) over-estimated distance compared to the known value, and also recorded a higher distance than StatSport (Catapult: $p = 0.036$, moderate; GPExe: $p = 0.002$, large). For Drill 4, GPExe over-estimated ($p < 0.001$, ES 1.34 ± 0.98, large) and StatSport under-estimated ($p = 0.004$, ES 1.51 ± 0.84, large) distance compared to the known value, and StatSport recorded a lower distance than the other devices (Catapult: $p < 0.001$, large; GPExe: $p < 0.001$, large). When all drills were combined, Catapult ($p = 0.022$, ES 1.27 ± 1.02, large) and StatSport ($p < 0.001$, ES 1.74 ± 0.59, large) both under-estimated distance compared to the known value, and StatSport recorded a lower distance than GPExe ($p = 0.040$, large). There were no differences between devices for average speed in any of the drills.

Energetic Measures

In each drill, StatSport reported a higher energy expenditure than both Catapult ($p < 0.001$, large) and GPExe ($p < 0.001$, large). Catapult reported lower energy expenditure than GPExe for each of the three segments of Drill 1 ($p < 0.001$, large), and also Drill 3 ($p = 0.005$, large). There was a moderate ES showing a lower energy expenditure for Catapult than GPExe for Drill 2. For energy cost, StatSport reported higher values in each drill than both Catapult ($p < 0.001$, large) and GPExe ($p < 0.001$, large). Catapult reported lower energy cost than GPExe for each of the three segments of Drill 1 ($p < 0.001$, large), and also Drill 3 ($p = 0.006$, large). For metabolic power, Catapult reported lower values than StatSport for all segments of Drill 1 (Walk: $p = 0.004$, large; Jog: $p = 0.002$, large; Run: $p < 0.001$, large) and for Drills 2, 3 and 4 ($p < 0.001$, large), and a lower value than GPExe for Drill 1 - Run ($p = 0.019$, large). GPExe reported lower metabolic power values than StatSport for Dril1 1 – Walk ($p < 0.001$, large), Drill 2 ($p < 0.001$, large), Drill 3 ($p = 0.005$, large) and Drill 4 ($p < 0.001$, large). Differences in metabolic power between devices across all drills are presented in Figure 2.

Discussion

To the authors’ knowledge, this is the first study to make comparisons between GPS devices for energetic variables. It is important to mention, however, that the accuracy of any particular device in the assessment of energetic variables cannot be ascertained due to the absence of any gold-standard criterion measure in this study. Nevertheless, it is noteworthy that, despite there being only minor differences for total distance, and no differences for average speed, there were substantial and consistent differences between devices for energetic variables. Furthermore, these differences magnified as movement tasks incorporated more frequent changes in speed and direction.

Importantly, each of the devices evaluated here has been independently assessed to some extent for reliability and/or accuracy of displacement measures. Catapult S5 devices demonstrated excellent inter-unit reliability for distance, speed and acceleration in simulated team-sport activity (Jackson et al., 2018). GPExe Pro 1 devices were shown to be reliable and accurate for measures of total distance over a simulation circuit (Hoppe, Baumgart, Polglaze, & Freiwald, 2018), although accuracy was diminished in sections involving higher speeds or changes in direction. StatSport ViperPod devices under-estimated distance and speed in shuttle running, and this bias was amplified for shorter shuttle distances (Beato, Bartolini, Ghia, & Zamparo, 2016). Whilst each of the specific devices used in the current study has been independently assessed against alternative measurement systems, it should be noted that none of these utilised gold-standard methods to capture multi-directional movement (e.g. 3-dimensional motion capture system) as their criterion measure.

Although these aforementioned studies report varying degrees of accuracy and reliability amongst these devices, there were only minor and inconsistent differences for total distance across all drills in the present study. Generally, all three devices under-estimated distance compared to the known value, except in Drill 3 where Catapult and GPExe over-estimated distance. Despite these disparities, all three devices reported similar average speeds across each drill. Therefore, the results from the present study suggest that measures of distance and speed are comparable between the three devices. Of note, the additional satellites available to the Catapult device through GLoNaSS capability did not appear to influence distance and speed measurement in comparison to the other devices.

In contrast to displacement measures, there were few similarities between devices for energetic variables. In fact, across all drills, there were very few instances where differences and/or large effect sizes did not exist between each device. Furthermore, these differences tended to magnify as drills became more complex. This indicates that energetic variables are not comparable between devices even when they report similar displacement measures. Given that energy cost, metabolic power and energy expenditure are derived directly from instantaneous speed over consecutive data points, these findings highlight an important distinction between displacement and energetic analysis of locomotor activity. Whereas displacement measures consider individual data points in isolation to determine cumulative and average characteristics, energetic analysis considers the value of each data point together with the magnitude and direction of change from the previous data point (di Prampero et al., 2005). Hence, the assessment of energetic variables relies on accurate measures of instantaneous speed, irrespective of whether the activity is constant or erratic in nature.

Possible sources for the reported differences between devices for energetic variables found here may include the quality of the instantaneous raw speed data (Varley et al., 2012), how (and even if) the raw data is filtered (Hoppe et al., 2018), and what algorithm is used to calculate energy cost and subsequently metabolic power. Both GPExe and StatSport report that metabolic power is calculated using established equations (di Prampero et al., 2005), whereas Catapult utilise a proprietary algorithm (Catapult, 2013). Since GPExe and StatSport use the same method to calculate energetic variables, and there are no differences for average speed between these devices, it seems apparent that variations exist in the raw data obtained and/or how that data is treated. This highlights another important aspect of energetic analysis, in that the energy costs of acceleration and deceleration of similar magnitude are not reciprocal, and are also dependent on starting speed (Osgnach et al., 2010). Hence, whilst slight errors between successive data points may "cancel each other out" when calculating average speed and total distance, these errors can generate large variations in derived energetic variables.

Although clear differences were found between devices for energetic variables, it is not possible to determine which of these devices was the most accurate due to the absence of a criterion measure. However, given the poor level of agreement between devices, it is clear that data obtained from different devices is not comparable, and results from research utilising these devices need to be interpreted carefully. Future research should assess these (and other) player-tracking devices against an appropriate gold-standard criterion measure which is capable of accurately determining instantaneous speed in activity comprising erratic changes in speed and direction, such as a 3-dimensional motion-capture system. Furthermore, in order to evaluate the influence of proprietary software in deriving energetic variables, future work should compare values provided by the software to those obtained when the raw data is exported, filtered using generic methods, and entered into validated algorithms for the calculation of energy cost and metabolic power. Filtering techniques should aim to retain meaningful accelerations of the centre of mass whilst eradicating fluctuations surrounding single foot contacts within the stride cycle.

Conclusions

Despite there being only minor differences in displacement measures between devices, energetic variables obtained from the different GPS devices are not comparable. Given that energetic variables are derived from measures of instantaneous speed, and also incorporate the magnitude and direction of change between successive data points, these differences may be attributable to disparities in raw data quality, filtering techniques and calculation methods. In order to provide comparable estimates of energetic variables in team sports, player-tracking devices must be capable of accurately recording instantaneous velocity in activities comprising frequent changes in speed and direction, and to filter the data appropriately.

Disclosure Statement

The authors report no conflict of interest.

References

Akenhead, R., French, D., Thompson, K. G., & Hayes, P. R. (2014). The acceleration dependent validity and reliability of 10Hz GPS. *Journal of Science and Medicine in Sport, 17*(5), 562-566

Beato, M., Bartolini, D., Ghia, G., & Zamparo, P. (2016). Accuracy of a 10 Hz GPS unit in measuring shuttle velocity performed at different speeds and distances (5–20 m). *Journal of Human Kinetics, 54*(1), 15-22

Buchheit, M., Al Haddad, H., Simpson, B. M., Palazzi, D., Bourdon, P. C., Di Salvo, V., & Mendez-Villanueva, A. (2014). Monitoring accelerations with GPS in football: time to slow down? *International Journal of Sports Physiology and Performance, 9*(3), 442-445

Carling, C., Bloomfield, J., Nelsen, L., & Reilly, T. (2008). The role of motion analysis in elite soccer: contemporary performance measurement techniques and work rate data. *Sports Medicine, 38*(10), 839-862

Catapult. (2013). Sprint Manual. Melbourne: Catapult.

Coutts, A. J. (2014). Evolution of football match analysis research. *Journal of Sports Sciences, 32*(20), 1829-1830. doi: 10.1080/02640414.2014.985450

Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Medicine, 43*(10), 1025-1042 di Prampero, P.E., Fusi, S., Sepulcri, L., Morin, J., Belli, A., & Antonutto, G. (2005). Sprint running: a new energetic approach. *Journal of Experimental Biology, 208*(14), 2809-2816

Hopkins, W. G. (2002). A scale of magnitudes for effect statistics, in: A New View of Statistics. WG Hopkins, ed. http://www.sportsci.org/resource/stats/effectmag.html, 2002. [Accessed March 15, 2018]

Hoppe, M., 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

Jackson, B. M., Polglaze, T., Dawson, B., King, T., & Peeling, P. (2018). Comparing global positioning system (GPS) and global navigation satellite system (GNSS) measures of team sport movements. *International Journal of Sports Physiology and Performance, 13(8)*, 1005-1010

Jennings, D., Cormack, S., Coutts, A. J., Boyd, L., & Aughey, R. J. (2010). The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *International Journal of Sports Physiology and Performance*, *5*(3), 328-341

Larsson, P. (2003). Global positioning system and sport-specific testing. *Sports Medicine, 33*(15), 1093-1101

Malone, J. J., Lovell, R., Varley, M. C., & Coutts, A. J. (2017). Unpacking the black box: applications and considerations for using GPS devices in sport. *International Journal of Sports Physiology and Performance, 12*(Suppl 2), S2-18-S12-26

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

Polglaze, T., Dawson, B., Buttfield, A., & Peeling, P. (2018). Metabolic power and energy expenditure in an international men's hockey tournament. *Journal of Sports Sciences, 36*(2), 140-148

Polglaze, T., Dawson, B., & Peeling, P. (2016). Gold standard or fool's gold? The efficacy of displacement variables as indicators of energy expenditure in team sports. *Sports Medicine, 46*(5), 657-670. doi: 10.1007/s40279-015-0449-x

Portas, M. D., Harley, J. A., Barnes, C. A., & Rush, C. J. (2010). The validity and reliability of 1-Hz and 5-Hz global positioning systems for linear, multidirectional, and soccer-specific activities. *International Journal of Sports Physiology and Performance, 5*(4), 448 - 458

Rampinini, E., Alberti, G., Fiorenza, M., Riggio, M., Sassi, R., Borges, T., & Coutts, A. (2015). Accuracy of GPS devices for measuring high-intensity running in field-based team sports. *International Journal of Sports Medicine, 36*(1), 49-53

Randers, M. B., Mujika, I., Hewitt, A., Santisteban, J., Bischoff, R., Solano, R., . . . Mohr, M. (2010). Application of four different football match analysis systems: A comparative study. *Journal of Sports Sciences, 28*(2), 171-182

Rawstorn, J. C., Maddison, R., Ali, A., Foskett, A., & Gant, N. (2014). Rapid directional change degrades GPS distance measurement validity during intermittent intensity running. *PLoS One, 9*(4), e93693

Scott, M., Scott, T., & Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport: A brief review. *Journal of Strength and Conditioning Research, 30*(5), 1470-1490

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

Varley, M. C., Jaspers, A., Helsen, W. F., & Malone, J. J. (2017). Methodological considerations when quantifying high-intensity efforts in team sport using global positioning system technology. *International Journal of Sports Physiology and Performance, 12*(8), 1059-1068

Williams, M., & Morgan, S. (2009). Horizontal positioning error derived from stationary GPS units: A function of time and proximity to building infrastructure. *International Journal of Performance Analysis in Sport, 9*(2), 275-280

Table 1. Displacement and energetic variables from Catapult (CAT), GPExe (GPE) and StatSport (STS) devices for each drill.

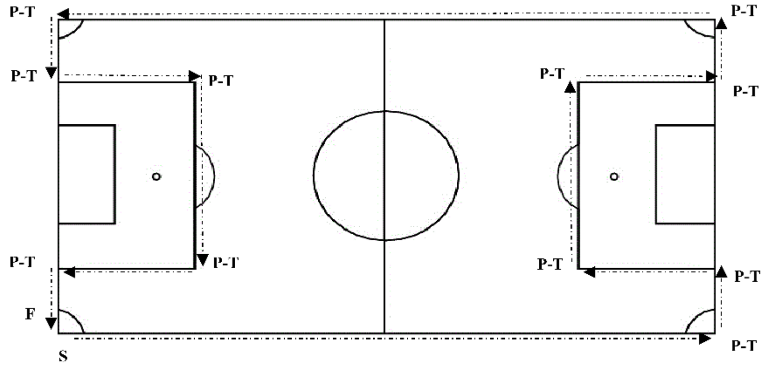
		Mean ± Standard Deviation			Effect Size ± 95% Confidence Interval			ANOVA	
		Catapult	GPExe	StatSport	CAT V GPE	CAT v STS	GPE V STS	Main Effect	Post Hoc
Distance (m)	Drill 1-Walk	404.5±7.2	403.4±5.2[a]	401.6±4.0[a]	0.19±1.23	0.49±1.21	0.38±1.20	0.635	CAT=GPE=STS
	Drill 1-Jog	398.2 ±6.2[a]	401.6 ±6.7[a]	400.5±4.4[a]	0.52±1.17	0.44±1.20	0.18±1.23	0.557	CAT=GPE=STS
	Drill 1-Run	401.2±6.4[a]	403.6 ±6.0[a]	401.3 ±4.0[a]	0.40±1.19	0.02±1.24	0.46±1.20	0.660	CAT=GPE=STS
	Drill 2	533.9±6.1[a]	541.3±4.5[d]	532.4±6.2[ac]	1.15±0.98	0.26±1.21	1.28±0.91	0.019	CAT=(GPE>STS)
	Drill 3	564.3±4.5[ad]	566.6±2.5[ad]	559.1±3.2[bc]	0.62±1.19	1.13±0.99	1.57±0.70	0.002	(CAT=GPE)>STS
	Drill 4	212.6±3.1[d]	213.3±2.6[ad]	204.6±3.2[abc]	0.25±1.21	1.56±0.70	1.63±0.64	0.001	(CAT=GPE)>STS
	All Drills Combined	2514.7±24.4[a]	2529.8±21.0[d]	2499.5±15.6[ac]	0.65±1.15	0.72±1.15	1.28±0.91	0.043	CAT=(GPE>STS)
Average Speed $(m \cdot s^{-1})$	Drill 1-Walk	1.4±0.1	1.4±0.1	1.4±0.1	0.05±1.22	0.12±1.22	0.06±1.22	0.947	CAT=GPE=STS
	Drill 1-Jog	2.4±0.2	2.4±0.2	2.4±0.2	0.11±1.22	0.08±1.22	0.03±1.22	0.988	CAT=GPE=STS
	Drill 1-Run	3.1±0.1	3.2±0.1	3.1±0.1	0.17±1.22	0.01±1.22	0.18±1.22	0.969	CAT=GPE=STS
	Drill 2	4.0±0.3	4.1±0.3	4.0±0.2	0.20±1.22	0.04±1.22	0.25±1.21	0.851	CAT=GPE=STS
	Drill 3	2.6±0.1	2.6±0.2	2.5±0.1	0.08±1.22	0.18±1.22	0.26±1.21	0.841	CAT=GPE=STS
	Drill 4	3.1±0.1	3.1±0.1	3.0±0.1	0.08±1.22	0.87±1.09	0.96±1.05	0.068	CAT=GPE=STS
Energy Expenditure $(J \cdot kg^{-1})$	Drill 1-Walk	1694±40[cd]	1852±51[bd]	1959±16[bc]	1.70±0.55	1.88±0.26	1.60±0.73	0.001	CAT<(GPE<STS)
	Drill 1-Jog	1728±54[cd]	1916±82[bd]	2145±55[bc]	1.60±0.67	1.87±0.28	1.67±0.60	0.001	CAT<(GPE<STS)
	Drill 1-Run	1879±71[cd]	2076±52[bd]	2390±84[bc]	1.66±0.62	1.86±0.30	1.79±0.43	0.001	CAT<(GPE<STS)
	Drill 2	2970±140[d]	3138±85[d]	3892±133[bc]	1.19±0.98	1.86±0.31	1.86±0.30	0.001	(CAT=GPE)<STS
	Drill 3	3054±122[cd]	3276±73[bd]	3713±134[bc]	1.47±0.80	1.81±0.39	1.76±0.47	0.001	CAT<(GPE<STS)
	Drill 4	1704±175[d]	1759±87[d]	2437±208[bc]	0.46±1.24	1.75±0.49	1.79±0.44	0.001	(CAT=GPE)<STS
Energy Cost $(J \cdot kg^{-1} \cdot m^{-1})$	Drill 1-Walk	4.18±0.12[cd]	4.59±0.12[bd]	4.88±0.05[bc]	1.69±0.57	1.87±0.29	1.63±0.65	0.001	CAT<(GPE<STS)
	Drill 1-Jog	4.34±0.16[cd]	4.77±0.15[bd]	5.35±0.14[bc]	1.61±0.66	1.85±0.33	1.75±0.50	0.001	CAT<(GPE<STS)
	Drill 1-Run	4.69±0.20[cd]	5.14±0.12[bd]	5.96±0.25[bc]	1.60±0.70	1.83±0.35	1.78±0.48	0.001	CAT<(GPE<STS)
	Drill 2	5.56±0.23[d]	5.79±0.16[d]	7.31±0.31[bc]	1.04±1.04	1.86±0.30	1.85±0.32	0.001	(CAT=GPE)<STS
	Drill 3	5.41±0.20[cd]	5.78±0.12[bd]	6.64±0.24[bc]	1.47±1.81	1.83±0.36	1.80±0.43	0.001	CAT<(GPE<STS)
	Drill 4	8.01±0.82[d]	8.24±0.37[d]	11.90±0.98[bc]	0.43±1.25	1.78±0.45	1.83±0.39	0.001	(CAT=GPE)<STS
Metabolic Power $(W \cdot kg^{-1})$	Drill 1-Walk	6.0±0.4[d]	6.6±0.6	6.9±0.5[b]	1.06±1.02	1.48±0.77	0.71±1.13	0.005	(CAT<STS)=GPE
	Drill 1-Jog	10.3±0.8[d]	11.4±1.2	12.7±1.2[b]	0.99±1.04	1.54±0.72	1.02±1.03	0.002	(CAT<STS)=GPE
	Drill 1-Run	14.7±0.8[cd]	16.3±0.9[bd]	18.7±1.1[bc]	1.37±0.84	1.77±0.46	1.57±0.69	0.001	(CAT<GPE)<STS
	Drill 2	22.3±2.2[d]	23.5±1.6[d]	29.1±2.3[bc]	0.63±1.17	1.64±0.64	1.63±0.64	0.001	(CAT=GPE)<STS
	Drill 3	13.9±1.0[d]	14.9±0.9[d]	16.9±1.1[bc]	1.00±1.04	1.63±0.63	1.41±0.82	0.001	(CAT=GPE)<STS
	Drill 4	25.1±3.0[d]	25.9±1.9[d]	35.9±3.8[bc]	0.37±1.21	1.68±0.58	1.71±0.55	0.001	(CAT=GPE)<STS

[a] significantly different to known value (Drill 1 - 410.9 m, Drill 2 - 540 m, Drill 3 - 560 m, Drill 4 - 210 m, Combined - 2542.7 m)
[b] significantly different to Catapult, [c] significantly different to GPExe, [d] significantly different to StatSport

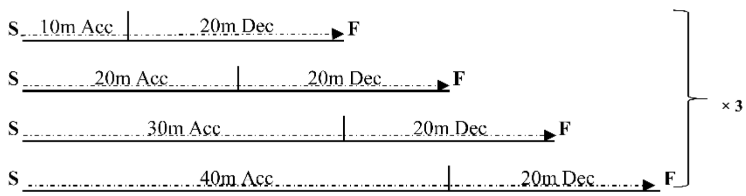
Figure 1. Layout and sequence for each drill. S - start, F - finish, P-T - pause-turn, Acc - acceleration, Dec - deceleration.

Figure 2. Differences in metabolic power between devices across all drills: a) Catapult vs GPExe, b) Catapult vs StatSport, c) GPExe vs StatSport. CAT – Catapult, GPE – GPExe, STS – StatSport.

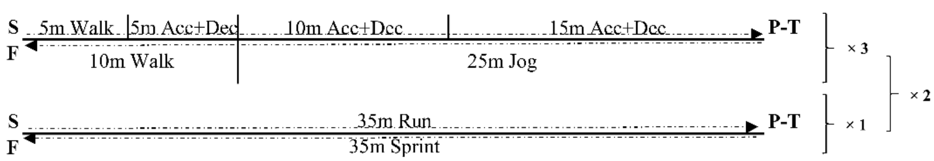
a) Drill 1



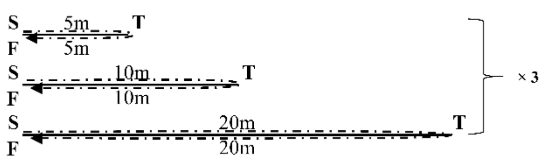
b) Drill 2

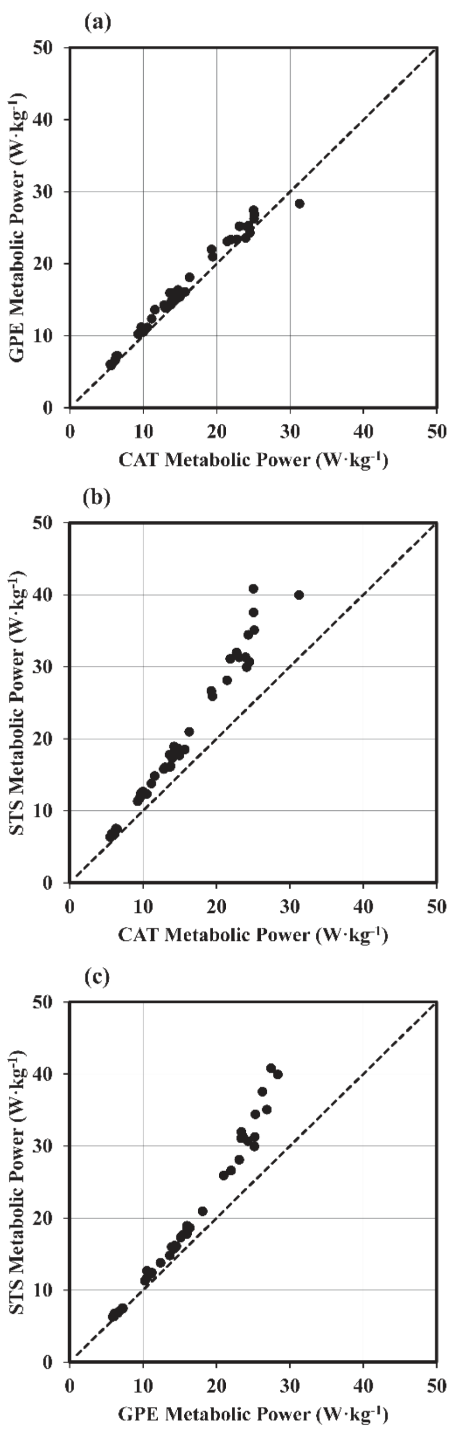


c) Drill 3



d) Drill 4




(a)
GPE Metabolic Power (W·kg-1)
CAT Metabolic Power (W·kg-1)
0
10
20
30
40
50
(b)
STS Metabolic Power (W·kg-1)
CAT Metabolic Power (W·kg-1)
(c)
STS Metabolic Power (W·kg-1)
GPE Metabolic Power (W·kg-1)