BRIEF REVIEW

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Applications of GPS Technologies to Field Sports

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Global positioning system (GPS) technology was made possible after the invention of the atomic clock. The first suggestion that GPS could be used to assess the physical activity of humans followed some 40 y later. There was a rapid uptake of GPS technology, with the literature concentrating on validation studies and the measurement of steady-state movement. The first attempts were made to validate GPS for field sport applications in 2006. While GPS has been validated for applications for team sports, some doubts continue to exist on the appropriateness of GPS for measuring short high-velocity movements. Thus, GPS has been applied extensively in Australian football, cricket, hockey, rugby union and league, and soccer. There is extensive information on the activity profile of athletes from field sports in the literature stemming from GPS, and this includes total distance covered by players and distance in velocity bands. Global positioning systems have also been applied to detect fatigue in matches, identify periods of most intense play, different activity profiles by position, competition level, and sport. More recent research has integrated GPS data with the physical capacity or fitness test score of athletes, game-specific tasks, or tactical or strategic information. The future of GPS analysis will involve further miniaturization of devices, longer battery life, and integration of other inertial sensor data to more effectively quantify the effort of athletes.

Keywords: motion analysis, functional performance, physical performance, sport physiology

A Brief History

The global positioning system (GPS) that is now regularly applied in the sporting sphere is only possible through the work of the 1944 Nobel laureate in physics Isidor Rabi. Rabi and his students invented the magnetic resonance method through their precise measures on the hydrogen atom.[1] The development of the nuclear magnetic resonance method lead directly to the creation of atomic clocks, the precise timepieces that form the basis of satellite navigation.[2] The precise measurement of time from the atomic clock allows for the calculation of the length of time it takes a radio signal to travel from the satellite to the GPS receiver on earth. Thus, the

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distance from the satellite to the receiver can be derived, and, if at least four satellites are in communication with that receiver, accurate location of the receiver can be triangulated.[3] Once the position is known, the displacement over a given epoch can be used to calculate velocity of movement, and this is of interest to scientists, coaches, and athletes engaged with team sports.

The early literature on GPS moved quickly from validation of the precision of GPS for measuring steady-state movement at a range of velocities[4] to widespread adoption of the method to measure locomotion in the field in humans[5–8] and animals.[9] The following section will outline the various methods applied to quantify the reliability and validity of GPS to measure human locomotion with an emphasis on field sports.

The Validity of GPS for the Measurement of Human Locomotion

The first attempt to validate a commercially available GPS device (GPS 45, Garmin) for the measurement of human locomotion able to be located by this author was published in 1997.[4] One participant undertook an unclear number of trials (total of $n = 76$) at each of 19 different walking and 22 different running velocities, with GPS data compared with a Swiss chronometer.[4] The participant was paced with a metronome and the correlation between GPS and chronometer speed of displacement was high ($r = .99$) with a 5% coefficient of variation for the slope line. While promising, this early research was hardly a gold-standard confirmation of the validity of GPS for velocity measurement.

Early study and application of GPS was hindered by the deliberate degradation by the United States Department of Defense of the accuracy of satellite transmission,[10] although this signal degradation was turned off in May 2000. It was possible to correct for this scrambled signal by computing the double difference phase, using two receivers placed close together, thus reducing three-dimensional error from the scrambled signal from 100 m to below 1 cm.[10] This was the approach taken to compare high-precision GPS positional information to accelerometer data on trunk position as a de facto measure of gait parameters at velocities between 2.8 and 6.3 $km \cdot h^{-1}$.[10] The high-precision GPS had a high intraindividual variability for step-to-step variability, but was comparable to other measures of intra-gate velocity variation. The ability of differential GPS to measure to this accuracy would seem to point to great utility for application to team sport; however, in this study, the GPS receiver weighed approximately 4 kg, and thus could not be used in any athletic competition.

The necessity for differential GPS further reduced with the adoption of the Wide-Angle Augmentation System and European Geostationary Navigation Overlay Service .[11] This improved technology enhanced position and velocity measurement during straight-line cycling tasks.[11] The cycle tasks were conducted at a range of velocities from 10 to 35 $km \cdot h^{-1}$, with GPS velocity within 0.2 $m \cdot s^{-1}$ for 57% of values, and 0.4 $m \cdot s^{-1}$ for 82% of values with only 0.11 m deviation from the actual path ridden.

Each of the studies outlined above provides a good starting point for the application of GPS technology to team sports. However, an understanding of the efficacy of GPS when velocity was changing rapidly and the path taken by an athlete involved multiple changes of direction rather than straight-line movement was still missing. Further, any GPS device had to be able to withstand heat, moisture, and potential impact to be applied in the team sport environment. The first commercially available GPS devices designed specifically for sporting application became available in 2003.[12] This device (GPSports Systems, SPI-10) was validated against a computer-based tracking (CBT) system (SportsTec Pty. Ltd, Trakperformance) in the first study to specifically investigate GPS application in team sports.[12] The validity of GPS for distance measurement in a series of predetermined circuits was established via comparison with a calibrated trundle wheel. There was a systematic overestimation of distance by GPS of approximately 5%, despite high correlations (r = .998), and CBT by approximately 6% to trundle wheel distance.

Further validation of GPS for team sport did not occur until 2009–2010, with a series of studies employing slightly different methodology and GPS technology being published (Table 1). Direct comparison across these studies is difficult if the aim is a blanket statement on the validity of GPS in team sport, due to the variety of exercise tasks, GPS devices, sample rates and statistical methods applied (Table 1). The following section will attempt to summarize the literature in this area.

The first difficulty encountered when investigating GPS validity is the gold-standard criterion measure that GPS has been compared with. The most popular method is to measure a course with a trundle wheel or tape measure, and then set up timing gates at the start and finish. Researchers then estimate the starting point in the GPS data, add the measured length of time to complete the course, and attain distance over that time period from the GPS software.[13–19] There are of course a range of activities that can introduce error using this approach. For example, there is error in the ability of a trundle wheel to accurately measure distance; accurately determining the starting point for movement in the GPS software is extremely difficult; and finally there is some inherent error in the ability of timing gates to accurately measure time over the course. The potential errors mentioned above were overcome in one study using VICON as the criterion measure, as the positional identification error in the VICON system was extremely low (0.0008%).[20] One other study used a theodolite to more accurately measure distance, but still used timing gates, with the inherent limitations outlined above.[21] Thus, the validation of GPS to date has methodological limitations that must be taken into account when assessing results.

It seems on balance that the higher the sample rate, the more valid GPS becomes for measuring distance. If we compare similar high-velocity sprinting tasks across several studies, the error in distance reported for 1 Hz GPS is higher than for 5 Hz,[17,18,20] and 10 Hz is lower again.[13] For example, the standard error of the estimate (SEE) for actual distance was as great as 32.4% for 1 Hz GPS in a standing-start 10 m sprint, with 5 Hz GPS marginally better at 30.9%.[18] In another study, 1 Hz GPS underestimated distance in a high-velocity tennis specific drill by approximately 31%, whereas 5 Hz GPS only underestimated by approximately 6%. In the only published information on 10 Hz GPS to date, the SEM in a 15 m sprint was 10.9%.[13] In conclusion, the higher the sampling rate, the more valid the measure of distance obtained from GPS.

Not surprisingly, the velocity of a task directly influences the validity of distance measured by GPS. Perhaps the best illustrations of this occur in studies

Table 1 Summary of validity studies undertaken on global positioning systems specific to field sports

Ref.	GPS Device	Sample Rate	Sporting Application	Task	Gold Standard	Parameter
14	SpiElite	1 Hz	Hockey	Simulated team-sport circuit	Timing gates	Mean speed Distance
15	MinimaxX v2.0 SPI-10 SPI-Pro	5 Hz 1 Hz 5 Hz	Cricket	Cricket-specific movement	Timing gates	Distance
16	SpiElite	1 Hz	RSA and peak sprint velocity	7 × 30 m sprints	Timing gates	Peak sprint velocity Fatigue index
17	SPI-10 SpiElite WiSPI	1 Hz 1 Hz 1 Hz	Team sport	Simulated team-sport course	Timing gates	Peak velocity Distance
20	MinimaxX v2.0 SpiElite	5 Hz 1 Hz	Tennis	Simulated court-based movement	VICON	Distance Mean velocity Peak velocity
21	SpiElite	1 Hz		Linear 200 m course Nonlinear 200 m course	Theodolite	Distance
18	MinimaxX v2.0	1 and 5 Hz	Team sport	Straight-line course Change-of-direction course Simulated team-sport course	Timing gates	Distance
19	MinimaxX v2.5	1 and 5 Hz	Soccer			
44	MinimaxX v2.0 SpiElite	5 Hz 1 Hz	Soccer	Match running	Video time–motion analysis Amisco	Distance
13	MinimaxX v2.0	10 Hz	Team sport	Linear running	Timing gates	Distance

Note. The manufacturer of SpiElite, SPI-10, SPI-Pro, and WiSPI is GPSports, and the manufacturer of MinimaxX v2.0 is Catapult Innovations.

where the same devices are tested at a range of velocities. For example, the SEE of GPS derived distance ranged from 0.4 ± 0.1 to 3.8 ± 1.4 across walking to striding tasks in one study,[15] and 9.8 ± 2.0 to 11.9 ± 2.5 for 40 m walking through sprinting with 5 Hz GPS in another.[18] Given the low typical length 10–20 m) of high-velocity movements in team sports,[22] the validity of these devices to measure these events seems low.

The longer the duration of a measured task, the more valid GPS measured distance becomes. For example, the standard error is reduced by 2/3 when comparing sprinting 40 m and sprinting 10 m.[18] This is reduced even more dramatically to just 3.8% for 5 Hz GPS over a 140 m modified team-sport running circuit that included a range of tasks of differing velocities and change of direction. Similarly, in a 197 m simulated high-intensity soccer activity, the SEE was just 1.5%.[19] Indeed, over a longer distance, even 1 Hz GPS was capable of valid assessment of locomotive distance.[14,15,17–19]

Thus, in the application of current GPS technology, more confidence is possible in measures of a longer duration, even if they contain periods of high-velocity activity. Further, researchers and practitioners should aim to use GPS with a higher sampling rate to enhance the validity of findings. It is unlikely that studies conducted in team sport matches with 1 Hz GPs can detect anything other than total distance moved by players.

The Reliability of GPS for the Measurement of Human Locomotion

The reliability of GPS to determine human locomotion is influenced by similar factors as outlined in detail above for validity. That is, sample rate, velocity, duration of the task, and the type of task each influence the reliability of GPS.

The effect of an increased GPS sample rate on reliability is at this stage ambiguous. For example, in one study the CV of a 10 m sprint was 77% with 1 Hz GPS, and 39.5% with 5 Hz.[18] However, in linear soccer tasks, the CV was 4.4–4.5% for 1 Hz and 4.6–5.3% for 5 Hz in another study.[19] For longer duration tasks, the CV was reported as 1.4–2.6% for 5 Hz measurement of walking 8800 m, yet only 0.3–0.7% for 1 Hz GPS.[15] However, the CV of 15 and 30 m sprinting with 10 Hz GPS was 0.7–1.3%. It is possible that different models and manufacturers can partially explain these differences in reliability, but it is not yet clear if a higher sampling rate enhances the reliability of GPS.

One thing that is clear is that the higher the velocity of movement, the lower the reliability of GPS. For example, the CV increased from 30.8% to 77.2% for a 10 m sprint when compared with walking over the same distance measured with 1 Hz GPS. With 5 Hz GPS, the CV increased 23.3% to 39.5% for the same task at the same velocities.[18] Similarly, walking 8800 m had a CV of 1.4–2.6% for 5 Hz GPS, but sprinting 20 m had a CV of 19.7–30.0%.[15]

In tasks that require changes of direction, the reliability decreases. This is true in soccer-specific tasks,[19] planned change-of-direction tasks of different frequencies,[18,23] and in repetitive tasks completed in small court areas.[20]

Interestingly, the variability between two GPS units on the same player for total distance and high-intensity running distance in a hockey match were similar at approximately 10%.[23] The reliability of these GPS units is thus similar to the between-subject standard deviation of elite Australian football (AF) players for high-velocity running,[24] and smaller than that reported for high-velocity running in elite soccer players.[25]

In conclusion, GPS devices have task- and time-dependent reliability that must be considered when reporting differences between or within individual team sport athletes.

The Application of GPS Technology to Match Analysis

Modern GPS devices are small and light; for example, the MinimaxX Team Sport v4.0 is just 88 × 50 × 19 mm and weighs 67 g. Added to their small physical size, these devices typically can store up to 4 h of data, making them suitable to many field sports.

A traditional starting point for the application of a time–motion analysis (TMA) system is in descriptive research on the activity profiles of athletes. It is important to note the use of the term *activity profile* here, as *match* or *movement, demands* is more commonly used in the literature. However, TMA systems such as GPS do not measure the demands of competition, but rather the output of players. We cannot be certain the players have actually met the demands of competition, and indeed, if players fatigue in games, and this is likely,[26–29] then the true demands of competition have not been met. Thus, *activity profile* is a more technically correct term to describe the measures regularly reported.

The widespread application of GPS to field sports in Australian football,[24,26,28–33] cricket,[34–37] hockey,[38,39] rugby,[40–42] and soccer[27,43–45] allows for intriguing comparisons between sports. However, care must be taken when making such comparisons. It is not necessarily that useful to report the total distance that athletes travel in field sports without reference to the time spent engaged in actual match play. For example, total distance traveled measured by GPS from a cricket fast bowler in 1 d international cricket (13,400 m)[36] and an elite AF player (12,939 m)[28] point to cricket being the more demanding sport. However, when that distance is expressed per minute of match time, the cricketer covered approximately 63 $m \cdot min^{-1}$ of the match, and the AF player nearly double that distance (109 $m \cdot min^{-1}$).[28] The expression of distance per minute of match time is even more important in sports where unlimited interchange are allowed, such as AF[26] and hockey.[38,39] Indeed, analysis of periods within AF matches expressing data in meters per minute fails to locate evidence of “fatigue” in matches from lower total distance covered per period.[26] A comparison of approximate meters per minute derived from GPS data from players in various field sports is presented in Figure 1.

The logical extension of distance measures is to break movement into velocity bands (see, for example,[24,26–28,36,42]) or even attempt to locate periods of intense activity during matches, such as repeated sprint sequences.[45] While this type of analysis is common, care must be taken in the application of GPS with its perceived inherent limitations for high-velocity movement.[18,23] It is also possible to measure accelerations undertaken by players using GPS, although this remains controversial to some scientists and practitioners given the literature on the validity of GPS for

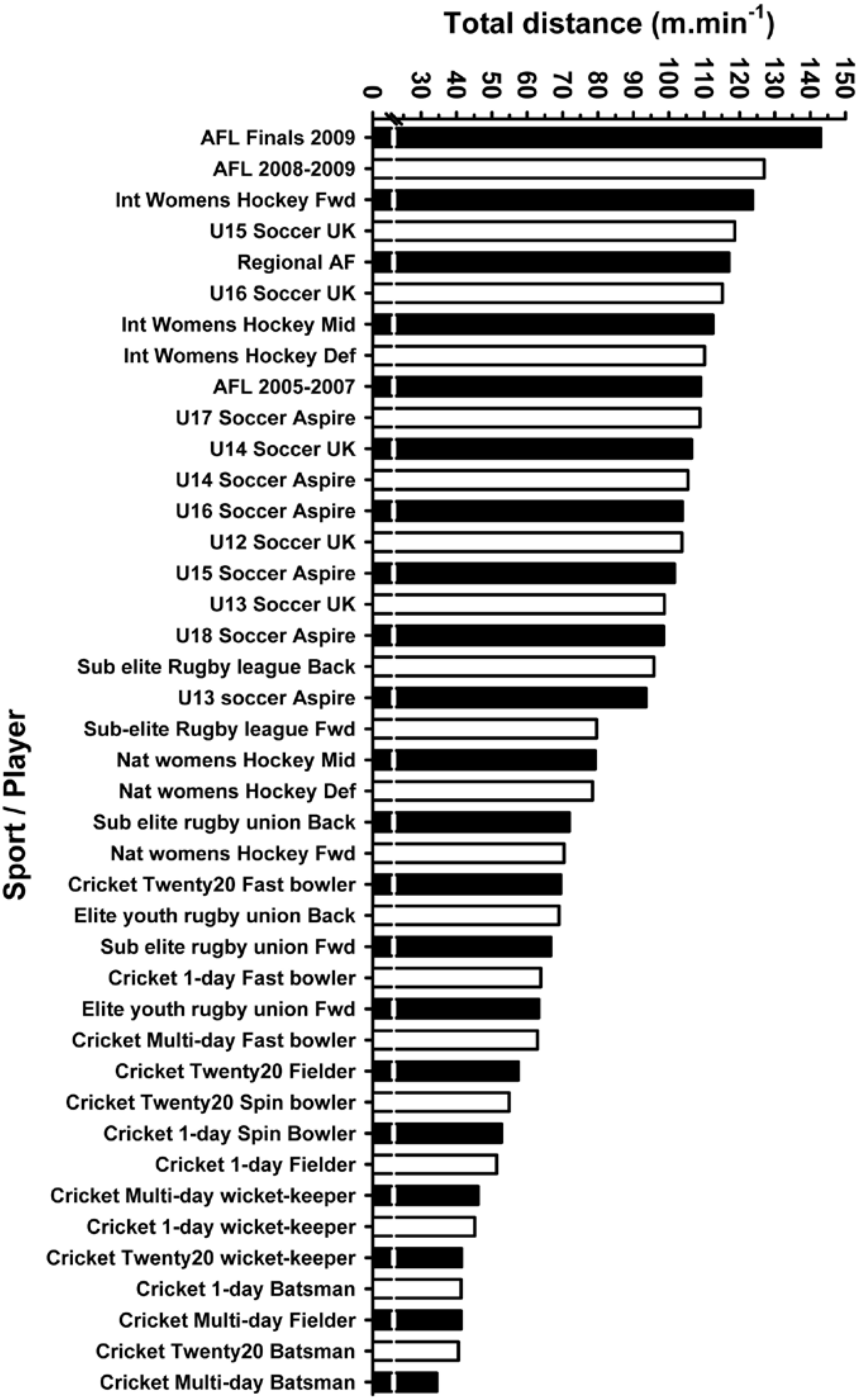

Figure 1 — Total distance per minute of matches (in meters per minute), adapted from[24,26–28,32,36,38–40,42,48,61].

short intense efforts.[18,20,23] However, due to the aforementioned limitations of previous work using timing gates as a gold standard, we have recently piloted validating the ability of GPS to detect instantaneous changes in velocity when accelerating against a laser. The percentage bias of GPS from the criterion measure of the laser was between –5 and –10%, and typical error expressed as a coefficient of variation of between 7 and 14% (Varley, Fairweather, and Aughey, unpublished data). Thus, this measure is as valid as some others regularly reported in match studies. Given the extremely high energetic demand of accelerating,[46] it is not surprising that this quality is reduced during a match, indicative of fatigue.[26] Further, the number of maximal accelerations nearly doubles between AF finals and regular season matches,[24] an elegant quantification of the perceived higher intensity of finals matches in field sports. Finally, the high number of maximal accelerations compared with sprints in AF matches (Figure 2), and the 6-fold higher accelerations than sprints in elite soccer[47] bring into question the importance of repeated-sprint ability in field athletes. The ongoing application of GPS technology for widespread data collection in team sports may allow for a challenge to the dogma that repeated-sprint ability is crucial for team sport athletes in the near future.

Elite AF has possibly the highest uptake rate of GPS use of any sport. Indeed, each elite AF team playing in the Australian Football League (AFL) collects GPS data on some or all players in every competitive match, and the AFL even collects that data for collation in an annual report.[31] The rapid uptake of this technology has led research to move from general descriptive work on player movement in matches[31] to the analysis of fatigue,[24,26,28] comparison of real-time to postgame analysis of data,[33] and comparisons among playing levels[32] in a short period of time.

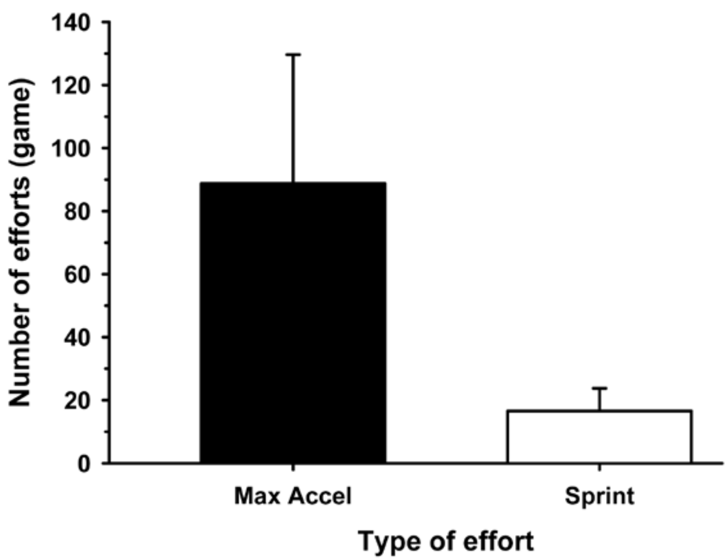

Figure 2 — The average number of maximal acceleration (Max Accel, 2.78–10.00 m·s^{-2}) and sprint (>6.94 m·s^{-1}) efforts per match in elite Australian footballers (Aughey, unpublished observations).

Elite AF players cover between 113[31] and 152[24] m·min^{-1} during matches. With match times of up to 111 min,[31] that equates to nearly 17 km traveled in games. Further, AF players cover up to 30% of this distance as high-intensity or high-velocity running, depending on the definition of this quality used.[24,26,28] Due to the similar GPS technology used in AF, comparisons are able to be made across teams and studies, and inferences made. For example, in one study a team that finished in the bottom 25% of the competition averaged 109 m·min^{-1},[28] whereas a team that finished in the top 25% of the competition players averaged approximately 10% greater distances.[26] There were some differences in GPS technology used in these studies, with 1 Hz GPS used in the former, and 5 Hz in the latter. It is unlikely that this was the sole reason for the different running reported.

The low cost of GPS technology and portability of the system allow for data to be collected easily in any venue used for competition. This is a major advantage compared with sports where the norm is for stadiums rather than players to be instrumented. Further, the size and oval shape of fields in some sports, and the number of players on the field at once (up to 36 players in AF) makes the use semi- or fully automated camera systems difficult. This in turn means that cheap portable technology such as GPS can be employed in elite and subelite competition with relative ease. In one such comparison of players between the national and a regional AF competition, elite players completed approximately 9% greater running, with 21% more high-intensity efforts.[32]

In conclusion, the application of GPS technology has revolutionized the body of knowledge around player movements in elite AF. This technology is valid and reliable enough to detect altered running across a match, between matches, between levels of competition, and between types of matches.

There had been relatively little investigation into the activity profile of cricketers until the advent of valid reliable GPS devices. The majority of the work in this area has been completed by the group from the Australian Institute of Sport and Centre for Excellence in cricket. A summary of movement category distances by game format and playing position from[36] is presented in Table 2. Interestingly, this group reports in meters per hour rather than meters per minute, so some calculation is required to compare between sports.

It is clear from this recent work that cricketers spend a substantial amount of time, and percentage of total distance, walking. Compared with other field sports, there is relatively little moderate to high intensity running,[26,28,29,39] but a high sprint component. As could be expected, the shorter forms of the game have the highest intensities,[36] and fast bowlers the most intense activity profiles of all positions.[34,36,37]

Hockey is similar to AF in now allowing unlimited interchange during competition. Thus knowledge of the activity profiles of players during games can be used in real time to inform decisions on which players have reduced running, potentially related to fatigue, and thus may need a period of rest off the field of play. To date, there is no published data available on elite men's field hockey activity profiles derived from GPS, although the author is aware of at least two studies currently under review on this area.

There are only two studies available on women's hockey match activity profiles using GPS, one on national-level players in Australia,[39] and one in international players from the United Kingdom.[38] The gap in distance covered per minute of the match between elite and subelite competition is vast compared with other sports.[32]

Table 2 Movement category distances by playing position and game format from Petersen et al.[36] All data are means ± SD.

Game Format and Playing Position	Walking	Jogging	Running	Striding	Sprinting
Twenty20					
Batsmen	1638 ± 352	332 ± 103	97 ± 35	187 ± 70	175 ± 97
Fast bowlers	2634 ± 268	718 ± 276	164 ± 76	249 ± 121	406 ± 230
Fielders	2242 ± 448	737 ± 219	157 ± 71	182 ± 101	129 ± 91
Spin bowlers	2317 ± 282	678 ± 210	107 ± 40	109 ± 53	81 ± 55
Wicketkeepers	1587 ± 139	552 ± 166	138 ± 90	147 ± 77	59 ± 23
One day					
Batsmen	1808 ± 400	279 ± 119	86 ± 37	154 ± 70	149 ± 94
Fast bowlers	2520 ± 362	618 ± 217	157 ± 58	220 ± 81	316 ± 121
Fielders	2117 ± 374	640 ± 193	119 ± 46	124 ± 59	81 ± 51
Spin bowlers	2251 ± 239	621 ± 154	116 ± 43	120 ± 63	58 ± 37
Wicketkeepers	1913 ± 196	558 ± 104	109 ± 16	97 ± 29	34 ± 21
One day					
Batsmen	1604 ± 438	200 ± 90	67 ± 18	107 ± 33	86 ± 28
Fast bowlers	2512 ± 258	614 ± 173	185 ± 89	233 ± 133	230 ± 149
Fielders	1773 ± 339	480 ± 160	88 ± 43	83 ± 55	52 ± 33
Spin bowlers	—	—	—	—	—
Wicketkeepers	2135 ± 151	523 ± 214	51 ± 18	35 ± 24	23 ± 30

There is in fact a 34% difference between these levels.[38,39] Part of this divergence in distance covered might be explained by players being from different countries, strategic and tactical differences in game style, or possibly the time of the year analysis was performed. Importantly, the use of GPS across these levels allows discussion of this difference to occur.

Global positioning system technology has also been applied to rugby union[40,41,48] and league.[42] The literature has included description of activity profiles, but also a comparison of matches to training,[40] an investigation of the effects of a supplement on match running recorded by GPS,[41] and a description of match running and muscle damage and endocrine responses.[42] It is studies like the last-mentioned[42] that provide an insight into the potential expansion of GPS technology in field sports by using GPS as a tool to measure activity in games or training to explain physiological responses, or to assist in determining mechanisms of fatigue in matches.

The Application of GPS Technology to Training Analysis

With the detailed understanding of various field sports made possible largely through the adoption of GPS, we are in a much better position to also measure the activity profile of players in training. A greater understanding of matches and training also allows the tailoring of training to adapt players to the activity profiles required in matches.

In elite AF players from one club, training largely failed to meet the demands of matches.[49] Indeed the high-velocity and high-intensity activities were between 18 and 60% lower in training than matches.[49] Similar results were observed in the comparison of adolescent rugby league training and matches, with greater jogging, striding, and sprinting and total distance in matches versus training.[40] This discrepancy in training stimulus was further highlighted in elite women's hockey players who spent more time in low-intensity, but less time in moderate- and high-intensity activities in training versus matches.[39] Only in cricket did training match or exceed the activity profile of matches.[35] However, this was true only for conditioning drills, and not simulation or skill-based drills.[35] It is also possible that training exceeded match activity in cricket due to the low time spent training compared with playing and the relatively low intensity of matches. The type of drill undertaken is important, as there are clear differences in open and closed drill activity profiles, with open drills more physically demanding than closed drills.[50]

Future Developments in GPS Application to Field Sports?

The future applications of GPS are likely to focus in three key areas: a greater integration of movement data with fitness, physiological, tactical, or strategic data; integration of GPS and inertial sensor data; and further miniaturization with a possible increase in sample rate.

A recent AF investigation has provided an elegant mediation analysis of the relationship between Yo-Yo IR2 performance, high-intensity running distance per minute, and total ball disposals in elite AF players.[30] This study provides an excellent example as to how activity profile data from GPS can provide an in-match performance measure, and the determinants of that performance can be understood through fitness testing. Perhaps the most exciting analysis from that study is the connection between physical capacity, fitness, and actual match performance. These relationships have also been investigated in youth soccer players using GPS technology.[27,51,52] Further, GPS data from matches can be used as a pre- and posttest to assess the efficacy of supplementation or dietary intervention.[41] It is important that researchers are aware of the match-to-match variability in activity profiles[25] when studies using GPS data from matches as a pre- and posttest. A recent abstract based on Prozone data has provided excellent insight into the number of match files required in this type of research.[53]

Other factors that might influence match-play activity profiles of athletes are also intriguing. For example, there are clear differences in the running performance of elite soccer players when the match score represents a team being equal, behind, or in front of the opposition.[54] It is of interest if this trend carries over to other football codes with higher scores, such as AF or rugby league or union. The effect of score may be more subtle in these sports.

Intrinsic factors are likely to also be influencing match running. It is extremely likely that field sport athletes pace their efforts and the high-frequency data provided by GPS may be able to quantify this effect.[26,55–57]

Global positioning system devices can of course only be used on outdoor fields. Future developments may include the development of localized "satellites" in stadiums, or the incorporation of inertial sensor data. The two main manufacturers of field sport GPS devices each include accelerometers and other sensors in their devices, although the use of this data is very much in its infancy in field sports. At least one manufacturer has commenced supplementing 10 Hz GPS sampling with accelerometer data to provide in effect a 15 Hz sample rate. This application could be extended even further to rely more on the inertial sensor data as a marker of load in field sports.

We have recently established the reliability of a modified vector magnitude (Player Load) calculated from accelerometer data,[58] and we[59] and others[60] have used this data to establish differences between training drills. A logical extension of this work is to use accelerometer data to measure load in matches. For practitioners wanting a standardized method to report to coaches and athletes, the Player Load relates strongly to total distance measured by GPS devices (Figure 3). Thus, with

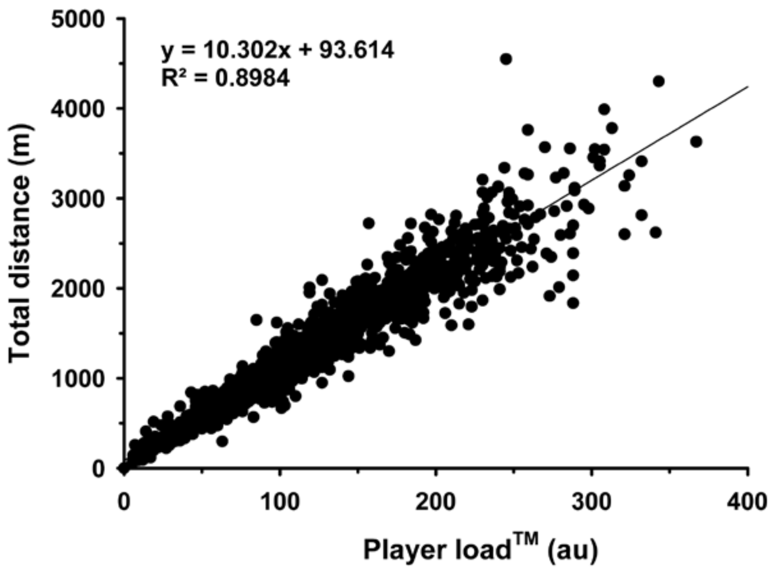

Figure 3 — The relationship between total distance and a modified vector magnitude[58] in elite Australian football players (Aughey and Boyd, unpublished observations).

the use of a regression equation an estimate of total distance can be made with a degree of certainty.

With an increase in the accuracy of GPS, it may be possible in the future to detect changes in gait through trunk movement as attempted in early GPS research with cumbersome GPS receivers.[10] Of course, the chaotic nature of team sports may make this type of analysis difficult to interpret, but the quest to measure fatigue in competition could be aided by more-accurate GPS data. Further, more-accurate GPS data may assist in being able to quantify changes in direction of movement in field sports with confidence. This knowledge would be extremely valuable for strength and conditioning practitioners in designing specific training programs to enhance this quality in field athletes.

To further enhance the usability of GPS in field sports, greater miniaturization, an increase in battery life, and memory storage are required. The smaller the device, the more likely athletes and indeed governing bodies of sports are to allow use in important competitions. Given that the daily duration of some field sports exceeds 6 h, an increase in battery life is also required. Finally, the devices still need to become more robust, so that practitioners and athletes can be confident that data will not be incomplete or lost in those important competitions. Unlike laboratory-based research, field studies in important competitions cannot be repeated, and lost data can be disastrous.

Global positioning systems have rapidly advanced in the past 10 y. During this time, extensive validation and reliability testing have been completed, and the devices applied heavily across many team sports. Sport scientists now have a much deeper understanding of the activity profiles of a range of sports owing to the application of GPS technology. Further, GPS has enabled scientists to investigate relationships between physical capacity and match performance. The integration of this and other data will greatly expand the body of knowledge of activity in field sports in the next few years.

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References

1. Rabi II, Zacharias JR, Millman S, Kusch P. A New Method of Measuring Nuclear Magnetic Moment. *Phys Rev*. 1938;53(4):318.
2. Rigden JS. Rabi, scientist and citizen 2ed. Cambridge, Massachusetts: Harvard University Press; 2000:1–283.
3. Larsson P. Global positioning system and sport-specific testing. *Sports Med*. 2003;33(15):1093–1101.
4. Schutz Y, Chambaz A. Could a satellite-based navigation system (GPS) be used to assess the physical activity of individuals on earth? *Eur J Clin Nutr*. 1997;51(5):338–339.
5. Phillips ML, Hall TA, Esmen NA, Lynch R, Johnson DL. Use of global positioning system technology to track subject's location during environmental exposure sampling. *J Expo Anal Environ Epidemiol*. 2001;11(3):207–215.
6. Terrier P, Ladetto Q, Merminod B, Schutz Y. Measurement of the mechanical power of walking by satellite positioning system (GPS). *Med Sci Sports Exerc*. 2001;33(11):1912–1918.

7. Larsson P, Burlin L, Jakobsson E, Henriksson-Larsen K. Analysis of performance in orienteering with treadmill tests and physiological field tests using a differential global positioning system. *J Sports Sci*. 2002;20(7):529–535.
8. Larsson P, Henriksson-Larsen K. Combined metabolic gas analyser and dGPS analysis of performance in cross-country skiing. *J Sports Sci*. 2005;23(8):861–870.
9. Hebenbrock M, Due M, Holzhausen H, Sass A, Stadler P, Ellendorff F. A new tool to monitor training and performance of sport horses using global positioning system (GPS) with integrated GSM capabilities. *Dtsch Tierarztl Wochenschr*. 2005;112(7):262–265.
10. Terrier P, Ladetto Q, Merminod B, Schutz Y. High-precision satellite positioning system as a new tool to study the biomechanics of human locomotion. *J Biomech*. 2000;33(12):1717–1722.
11. Witte TH, Wilson AM. Accuracy of WAAS-enabled GPS for the determination of position and speed over ground. *J Biomech*. 2005;38(8):1717–1722.
12. Edgecomb SJ, Norton KI. Comparison of global positioning and computer-based tracking systems for measuring player movement distance during Australian football. *J Sci Med Sport*. 2006;9(1-2):25–32.
13. Castellano J, Casamichana D, Calleja-González J, San Román J, Ostojic SM. Reliability and accuracy of 10 Hz GPS devices for short-distance exercise. *J Sports Sci Med*. 2011;10:233–234.
14. MacLeod H, Morris J, Nevill A, Sunderland C. The validity of a non-differential global positioning system for assessing player movement patterns in field hockey. *J Sports Sci*. 2009;27(2):121–128.
15. Petersen C, Pyne D, Portus M, Dawson B. Validity and reliability of GPS units to monitor cricket-specific movement patterns. *Int J Sports Physiol Perform*. 2009;4(3):381–393.
16. Barbero-Alvarez JC, Coutts A, Granda J, Barbero-Alvarez V, Castagna C. The validity and reliability of a global positioning satellite system device to assess speed and repeated sprint ability (RSA) in athletes. *J Sci Med Sport*. 2010;13(2):232–235.
17. Coutts AJ, Duffield R. Validity and reliability of GPS devices for measuring movement demands of team sports. *J Sci Med Sport*. 2010;13(1):133–135.
18. Jennings D, Cormack S, Coutts AJ, Boyd L, Aughey RJ. The validity and reliability of GPS units for measuring distance in team sport specific running patterns. *Int J Sports Physiol Perform*. 2010;5(3):328–341.
19. Portas MD, Harley JA, Barnes CA, Rush CJ. The validity and reliability of 1-Hz and 5-Hz global positioning systems for linear, multidirectional, and soccer-specific activities. *Int J Sports Physiol Perform*. 2010;5(4):448–458.
20. Duffield R, Reid M, Baker J, Spratford W. Accuracy and reliability of GPS devices for measurement of movement patterns in confined spaces for court-based sports. *J Sci Med Sport*. 2010;13(5):523–525.
21. Gray AJ, Jenkins D, Andrews MH, Taaffe DR, Glover ML. Validity and reliability of GPS for measuring distance travelled in field-based team sports. *J Sports Sci*. 2010;28(12):1319–1325.
22. Spencer M, Bishop D, Dawson B, Goodman C. Physiological and metabolic responses of repeated-sprint activities:specific to field-based team sports. *Sports Med*. 2005;35(12):1025–1044.
23. Jennings D, Cormack S, Coutts AJ, Boyd LJ, Aughey RJ. Variability of GPS units for measuring distance in team sport movements. *Int J Sports Physiol Perform*. 2010;5(4):565–569.
24. Aughey RJ. Increased high intensity activity in elite Australian football finals matches. *Int J Sports Physiol Perform*. 2011;6:367–379.
25. Gregson W, Drust B, Atkinson G, di Salvo V. Match-to-match variability of high-speed activities in premier league soccer. *Int J Sports Med*. 2010;31(4):237–242.
26. Aughey RJ. Australian football player work rate: evidence of fatigue and pacing? *Int J Sports Physiol Perform*. 2010;5(3):394–405.

27. Buchheit M, Mendez-Villanueva A, Simpson BM, Bourdon PC. Match running performance and fitness in youth soccer. *Int J Sports Med*. 2010;31(11):818–825.
28. Coutts AJ, Quinn J, Hocking J, Castagna C, Rampinini E. Match running performance in elite Australian Rules Football. *J Sci Med Sport*. 2010;13(5):543–548.
29. Duffield R, Coutts AJ, Quinn J. Core temperature responses and match running performance during intermittent-sprint exercise competition in warm conditions. *J Strength Cond Res*. 2009;23(4):1238–1244.
30. Mooney M, O'Brien B, Cormack S, Coutts A, Berry J, Young W. The relationship between physical capacity and match performance in elite Australian football: A mediation approach. *J Sci Med Sport*. 2011. doi:10.1016/j.jsams.2011.03.010.
31. Wisbey B, Montgomery PG, Pyne DB, Rattray B. Quantifying movement demands of AFL football using GPS tracking. *J Sci Med Sport*. 2010;13(5):531–536.
32. Brewer C, Dawson B, Heasman J, Stewart G, Cormack S. Movement pattern comparisons in elite (AFL) and sub-elite (WAFL) Australian football games using GPS. *J Sci Med Sport*. 2010;13(6):618–623.
33. Aughey RJ, Falloon C. Real-time versus post-game GPS data in team sports. *J Sci Med Sport*. 2010;13(3):348–349.
34. Petersen CJ, Pyne DB, Portus MR, Dawson BT. Comparison of player movement patterns between 1-day and test cricket. *J Strength Cond Res*. 2011;25(5):1368–1373.
35. Petersen CJ, Pyne DB, Dawson BT, Kellett AD, Portus MR. Comparison of training and game demands of national level cricketers. *J Strength Cond Res*. 2011;25(5):1306–1311.
36. Petersen CJ, Pyne D, Dawson B, Portus M, Kellett A. Movement patterns in cricket vary by both position and game format. *J Sports Sci*. 2010;28(1):45–52.
37. Petersen C, Pyne DB, Portus MR, Karppinen S, Dawson B. Variability in movement patterns during One Day Internationals by a cricket fast bowler. *Int J Sports Physiol Perform*. 2009;4(2):278–281.
38. Macutkiewicz D, Sunderland C. The use of GPS to evaluate activity profiles of elite women hockey players during match-play. *J Sports Sci*. 2011;29:967–973.
39. Gabbett TJ. GPS analysis of elite women's field hockey training and competition. *J Strength Cond Res*. 2010;24(5):1321–1324.
40. Hartwig TB, Naughton G, Searl J. Motion analyses of adolescent rugby union players: a comparison of training and game demands. *J Strength Cond Res*. 2011;25(4):966–972.
41. Minett G, Duffield R, Bird SP. Effects of acute multinutrient supplementation on rugby union game performance and recovery. *Int J Sports Physiol Perform*. 2010;5(1):27–41.
42. McLellan CP, Lovell DI, Gass GC. Creatine kinase and endocrine responses of elite players pre, during, and post rugby league match play. *J Strength Cond Res*. 2010;24(11):2908–2919.
43. Buchheit M, Horobeanu C, Mendez-Villanueva A, Simpson BM, Bourdon PC. Effects of age and spa treatment on match running performance over two consecutive games in highly trained young soccer players. *J Sports Sci*. 2011;29(6):591–598.
44. Randers MB, Mujika I, Hewitt A, et al. Application of four different football match analysis systems: a comparative study. *J Sports Sci*. 2010;28(2):171–182.
45. Buchheit M, Mendez-villanueva A, Simpson BM, Bourdon PC. Repeated-sprint sequences during youth soccer matches. *Int J Sports Med*. 2010;31(10):709–716.
46. Osgnach C, Poser S, Bernardini R, Rinaldo R, di Prampero PE. Energy cost and metabolic power in elite soccer: a new match analysis approach. *Med Sci Sports Exerc*. 2010;42(1):170–178.
47. Varley MC, Aughey RJ, Pedrana A. Accelerations in football: Toward a better understanding of high-intensity activity. In: Proceedings of VIIth Worl Congress on Science and Football, Nagoya, Japan: Japanese Society of Science and Football; 2011:343.
48. Cunniffe B, Proctor W, Baker JS, Davies B. An evaluation of the physiological demands of elite rugby union using Global Positioning System tracking software. *J Strength Cond Res*. 2009;23(4):1195–1203.

49. Boyd L, Ball K. A Profile of Training and Match Demands. In: *Proceedings of Football Australasia 3*. Melbourne, Australia: Aughey RJ Workrate in Australian Football; 2008:29.
50. Farrow D, Pyne D, Gabbett T. Skill and Physiological Demands of Open and Closed Training Drills in Australian Football. *Int J Sports Sci Coaching*. 2008;3(4):489–499.
51. Castagna C, Impellizzeri F, Cecchini E, Rampinini E, Alvarez JC. Effects of intermittent-endurance fitness on match performance in young male soccer players. *J Strength Cond Res*. 2009;23(7):1954–1959.
52. Castagna C, Manzi V, Impellizzeri F, Weston M, Barbero Alvarez JC. Relationship between endurance field tests and match performance in young soccer players. *J Strength Cond Res*. 2010;24(12):3227–3233.
53. Gregson W, Batterham AM, Atkinson G, di Salvo V, Drust B. Estimating sample size for intervention studies involving match activity data as indicators of soccer performance. In: Proceedings of VIIth World Congress on Science and Football, Nagoya, Japan: Japanese Society of Science and Football; 2011:343.
54. Varley MC, Aughey RJ, Pedrana A. Match score influences running intensity in football. In: Proceedings of VIIth World Congress on Science and Football, Nagoya, Japan: Japanese Society of Science and Football; 2011:343.
55. Vleck VE, Bentley DJ, Millet GP, Burgi A. Pacing during an elite Olympic distance triathlon: comparison between male and female competitors. *J Sci Med Sport*. 2008;11(4):424–432.
56. Townshend AD, Worringham CJ, Stewart IB. Spontaneous pacing during overground hill running. *Med Sci Sports Exerc*. 2010;42(1):160–169.
57. Angus SD, Waterhouse BJ. Pacing Strategy from High Frequency Field Data: More Evidence for Neural Regulation? *Med Sci Sports Exerc*. 2011.
58. Boyd LJ, Ball K, Aughey RJ. The reliability of MinimaxX accelerometers for measuring physical activity in Australian football. *Int J Sports Physiol Perform*. 2011;6:311–321.
59. Boyd LJ, Ball K, Gallaher EL, Stepto NK, Aughey RJ. Practical application of accelerometers in Australian football. In: *Proceedings of Asics Conference on Science and Medicine in Sport,* Port Douglas, Australia. Sports Medicine Australia; 2010.
60. Montgomery PG, Pyne D, Minahan CL. The Physical and Physiological Demands of Basketball Training and Competition. *Int J Sports Physiol Perform*. 2010;5:75–86.
61. Harley JA, Barnes CA, Portas M, et al. Motion analysis of match-play in elite U12 to U16 age-group soccer players. *J Sports Sci*. 2010;28(13):1391–1397.