Accuracy and reliability of GPS devices for measurement of sports-specific movement patterns related to cricket, tennis and field-based team sports.

ABSTRACT

The aim of this study was to determine the accuracy and reliability of 5, 10 and 15 Hz global positioning system (GPS) devices. Two male subjects (age: 25.5 ± 0.7 yr; height: 1.75 ± 0.01 m; body mass: 74 ± 5.7 kg) completed ten repetitions of drills replicating movements typical of tennis, cricket and field-based (football) sports. All movements were completed wearing two 5 Hz and 10 Hz MinimaxX and two GPS-Sports 15 Hz GPS devices in a specially designed harness. Criterion movement data for distance and speed was provided from a 22-camera VICON system sampling at 100 Hz. Accuracy was determined using one-way analysis of variance with Tukey's post-hoc tests. Inter-unit reliability was determined using intra-class correlation (ICC) and typical error was estimated as coefficient of variation (CV). Overall, for the majority of distance and speed measures as measured using the 5, 10 and 15 Hz GPS devices, were not significantly different ($p>0.05$) to the VICON data. Additionally, no improvements in the accuracy or reliability of GPS devices were observed with an increase in the sampling rate. However, the CV for the 5 and 15 Hz devices for distance and speed measures ranged between 3-33%, with increasing variability evident in higher speed zones. The majority of ICC measures possessed a low level of inter-unit reliability ($r=-0.35$–0.39). Based on these results, practitioners of these devices should be aware that measurements of distance and speed may be consistently underestimated, regardless of the movements performed.

KEY WORDS: validity, movement patterns, movement analysis

INTRODUCTION

An increased interest in quantifying the physical demands of training and competition has developed across a range of sports (6, 7, 10, 15). Advancements in technology have led to the introduction of global positioning system (GPS) devices, which have allowed the concurrent analysis of movement patterns of numerous players to be completed on a routine basis (13). Previously, research has attempted to ensure GPS technology is an accurate and reliable tool for measuring movement patterns; however, this often has been limited to straight line and generic movement protocols rather than unstructured movements typical in sport (1, 12). As the interpretation of training or match-based GPS data is based on an understanding of the accuracy of the devices used, these previous studies may not provide appropriate understanding of GPS accuracy for unstructured, random movements typical of many team sports.

Originally, GPS technology recorded at 1 Hz, which demonstrated limited accuracy for measuring intermittent, multidirectional and fast movements (7, 20). Research has also demonstrated that when sampling at 5 Hz, GPS technology provides an improved and acceptable level of accuracy and reliability for measures of total distance (Coefficient of variation (CV): 2.3-9.8%; intra-class correlation (ICC): 0.17-0.38) (3, 5). In contrast, the same 5 Hz GPS technology has been reported to have lower accuracy and reliability (CV: 0.5-39.5%; ICC: -0.06-0.87) for high-velocity movements or with inclusion of changes of direction typical of court- and field-based team sports when compared to devices of a lower sampling rate over a criterion distance (3, 5, 12). More recently, further technology with increased sampling frequency (10-15 Hz) has become available (2). As yet, few studies report the reliability and accuracy of the newer versions of GPS technology, particularly in non-linear sport-specific movement patterns (2).

To date the majority of data reporting on the quality of GPS technology has focused on the reliability of the systems (3, 7, 12, 16), or have used straight-line drills for criterion distance measures to determine accuracy (12, 18). However, only one data set has determined the accuracy of GPS technology for movements typical of sport, particularly unstructured movements that typify training and competition (5). Duffield et al. (5) reported that in comparison to a high-resolution camera system (VICON system sampling at 100 Hz) both 1 Hz and 5 Hz GPS units underestimated the total distance and speed of specific court-based sport movements. It is therefore possible, that the accuracy of GPS technology is limited by the sampling rate at which they measure. Previous data from Jennings et al. (12) demonstrated that accuracy of the measurements was improved for team sport activities due to an increase in sampling frequency (from 1 Hz to 5 Hz), regardless of distance travelled or speed reached; though these data were still collected from straight-line or simple change of direction movements and without a valid criterion measure of distance or speed.

A growing number of studies have used GPS devices to report on the movement patterns of athletes during both match-play and training activities (4, 9, 15, 19). Despite the body of literature on GPS validity (1, 3, 5, 12, 14), there is little similarity between the unstructured, random movement patterns often present in field-based data and the linear and structured movements used in GPS validity studies. Accordingly, a more comprehensive understanding of the accuracy of the GPS devices used for these movement patterns is required, particularly with higher sampling frequency technology (12). Therefore, the aim of this research was to determine the reliability and accuracy of 5 Hz and 10 Hz MinimaxX as well as 15 Hz SPI GPS systems during straight line running, multi-direction movement patterns, and unstructured movements typical of court- and field-based team sports. It was hypothesized that there would be a reduced accuracy of the GPS technology when compared to VICON. However, it was also hypothesized that both the accuracy and reliability of the GPS technology would be improved with an increase in sampling frequency.

METHODS

Experimental Approach to the Problem

Currently, it is unclear whether the accuracy and reliability of GPS devices is improved with an increase in sampling frequency during movements more representative of those performed in the field. To test the hypothesis this study compared the accuracy and reliability of three varieties of GPS devices with varying sampling rates (5, 10 and 15 Hz) to that of a criterion measure VICON motion analysis system (100 Hz). Ten repetitions of 10 respective drills typical of court- and field-based sports (cricket, tennis and football) were completed whilst concurrently wearing GPS devices to ensure simultaneous VICON and GPS measurements. The same subject completed all 10 repetitions of each drill to eliminate between-subject variability, although the subject themselves were inconsequential to the process as the respective individual movements were time aligned and treated as discrete trials.

Subjects

Two moderately trained males (age: 25.5 ± 0.7 yr; height: 1.75 ± 0.01 m; body mass: 74.0 ± 5.7 kg) participated in the study. Both subjects provided written informed consent prior to undertaking the testing session. The Ethics Committee of the University of Newcastle granted approval for the study.

Procedures

One subject completed all data collection for drills which replicated movement patterns typical of tennis and cricket, with the second subject completing drills typical of field-based team sports (FBTS). This was to ensure residual fatigue from repeated efforts did not result in slower movement velocities that would not appropriately replicate higher velocities. All testing was performed on a plexicushion outdoor court at the Australian Institute of Sport. During data collection, the subjects wore two 5 Hz (MinimaxX Team Sport v2.5, firmware: v6.59) and two 10 Hz (MinimaxX S4, firmware: v6.72) (MinimaxX, Catapult Innovations, Melbourne, Australia), and two 15 Hz (SPI Pro X, GPSports Systems, Canberra, Australia) GPS devices in a customised harness. Each device was housed in a separate pocket across each subjects back, spaced at least 6 cm apart, with the antenna of each unit exposed to allow a clear satellite reception. All devices were activated 15 minutes prior to data collection in a clear open area to allow the acquisition of satellite signals. Data collection occurred at night, with an 'open' sky present at all times and minimal environmental lighting. Each device ran continuously across the entire testing period.

Furthermore, during the testing period, a 22 camera VICON motion analysis system (Oxford Metrics, Oxford, UK) operating at 100 Hz was used to determine criterion movement distance and speed data during each drill. The three-dimensional (3D) position of a single reflective marker attached to the centre of the GPS carrying harness was tracked during each drill. Relevant static and dynamic calibration was undertaken to accurately determine the 3D space in which the simulation drills were completed. The VICON system was calibrated to an accuracy of less than 1 pixel for each camera, with camera resolutions of 12 megapixels, representing an error of 0.0008% (8). For the purpose of analysis, the duration (s) of each drill repetition was calculated from the VICON data and used in the GPS data analysis.

Following the testing session, each device was downloaded to the customised software specific to each GPS model (MinimaxX: Logan Plus 4.6.0, Catapult Innovations, Melbourne, Australia; SPI: Team AMS 5.1, GPSports Systems, Canberra, Australia). Distance and mean and peak speeds were calculated *post hoc* for each respective drill repetition. Measures collated from respective GPS devices were synchronised using GPS time. The duration of each movement was matched to that of the collected VICON data prior to statistical analysis. Initially each repetition was identified using the functioning 10 Hz unit and standardised across all other GPS devices. The highest speed value using this method was classified as peak speed, while mean speed was calculated from each repetition of each drill. During post hoc analysis it was apparent that one 10 Hz MinimaxX unit technically malfunctioned and was therefore removed from all analysis. The accuracy but not reliability of the remaining 10 Hz unit was calculated and reported.

Movement Protocols

Ten repetitions of each of the 4 respective court-based sports drills and 6 respective field-based sports drills were completed. As outlined above, one participant completed all repetitions of the court-based and cricket-based drills, whilst the second participant completed all FBTS drills.

Court-Based Sports

The court based sports protocol as reported by Duffield et al. (5) was used to replicate the movement demands of tennis and consisted of:

(1) a 2 m side-to-side movement pattern from the centre line of the baseline of the tennis court;

(2) a 4 m side-to-side movement pattern from the same position in the previous drill;

(3) a run in a rectangle pattern around the lines of the baseline, singles sideline and service line of a standard tennis court and;

(4) a 10 s random movement pattern around the baseline which replicated tennis match-play movements.

Field-Based Sports

Cricket Protocol

(1) The batting protocol consisted of a typical run-a-three test (16). Due to space restrictions the length of the simulated pitch was restricted to 16 m instead of 17.68 m.

(2) The bowling protocol consisted of 15 m straight line run. The 15 m was separated into 5 m of jogging followed by 10 m of high acceleration. The subject then stopped sharply on a marked spot to replicate the start of a bowling delivery.

(3) The fielding protocol was based upon previously published cricket movement patterns (15). The protocol consisted of three discrete activities:

    (a) walk 3 m, split step, sprint forward 5 m and then walk back to the start;

(b) walk 3 m, split step, sprint right perpendicularly 5 m and then walk back to the start;

(c) walk 3 m, split step, sprint backward on right hand side on 45° angle 5 m and then walk back to the start (Figure 1a).

Completion of the three fielding directions in succession (forwards, perpendicular, backwards, respectively) counted as one repetition.

***** INSERT FIGURE 1 ABOUT HERE*****

Field-Based Team Sports

The FBTS protocol was similar to that used in Jennings et al. (12)and consisted of:

(1) 40 m efforts with seven 90° changes of direction (COD), turning 180º after 20 m and returning to the starting position at sprinting speeds (Figure 1b);

(2) 21 m efforts with seven 45° COD at sprinting speeds (Figure 1c) and;

(3) Further, a 10 s random movement pattern which replicated FBTS match-play movements i.e. forward and backward motion, side-stepping and random change in directions.

Statistical Analysis

Data is reported as mean ± standard deviation (SD). Data (individual variables within each trial e.g. distance, mean speed, peak sped) not within two SD of the mean for each separate movement was considered an outlier and removed prior to data analysis. The difference between each measurement device for distance and speed within each simulation was analysed using a one-way analysis of variance (ANOVA) with Tukey's post hoc tests ($p<0.05$). Intra-class correlation (ICC) were used to assess inter-unit reliability, whilst typical error was expressed as a coefficient of variation (CV).Statistical analyses were performed using the software package IBM SPSS (version 19, IBM Corporation, Somers, New York, USA) and a customised spreedsheet in Microsoft Excel 2003® (Microsoft, Redmond, USA) (11).

RESULTS

GPS Signal Quality

The quality of the signal received by the GPS devices was assessed prior to determining the reliability and accuracy of the devices. A combined horizontal dilution of position (HDOP) for both 5 Hz MinimaxX devices was 1.5 ± 0.4 and 1.0 ± 0.2 for the 10 Hz device. The HDOP was not reported by the manufacturer software of the 15 Hz devices. The mean number of satellites acquired for the 5 Hz, 10 Hz and 15 Hz GPS devices were 8 ± 1, 11 ± 1 and 8 ± 1, respectively.

Measures of Accuracy

Court-Based Sports

Table 1 shows the total distance covered and mean and peak speeds for each device during each court based movement. During the majority of court-based movements the distances measured using the GPS devices were not significantly different ($p>0.05$) to that as measured by VICON. Similarly, the mean and peak speed as measured using the GPS devices were not significantly different ($p>0.05$) to VICON. Regardless of sampling rate, no GPS device reported a more accurate ($p<0.05$) measure for the distances covered or speeds achieved. As evidence, Figure 2 shows a representative trace of the measurement of distance and mean speed during a random movement tennis drill. Furthermore, as presented in Figure 1 and Table 2, the variability in the distance covered and speed reached during court-based movements between devices suggests no one GPS device was more accurate in the measurement of distance or speed compared to VICON.

*****INSERT TABLE 1 ABOUT HERE*****

*****INSERT FIGURE 2 ABOUT HERE*****

Field-Based Team Sports

Table 2 shows the total distance covered and mean and peak speeds for each device during each cricket- and field-based team sport drills. Similar to court simulated movements, the majority of GPS devices, were not significantly different (p>0.05) to the VICON measures. Similar mean and peak speeds were also evident between most GPS devices and VICON for measures of mean speed and peak speed (p>0.05). As with the court-based movements, and regardless of sampling frequency, no particular GPS device could be considered to be of greater accuracy than the others.. As discussed below, an example of the variability in the distance covered and speeds reached during cricket (fast bowling) and FBTS (90º COD drills) movements is presented in Figures 2b and 2c.

*****INSERT TABLE 2 ABOUT HERE*****

Measures of Reliability

Table 3 shows the ICC and CV for the 5 Hz and 15 Hz GPS devices for both court-based and field-based sports drills. Intra-class correlation analysis values for all drills for the 5 and 15 Hz devices ranged from -0.50 to 0.86 and CV ranged between 3 to 33% for each drill for the 5 and 15 Hz devices. Specifically, ICC values were between r= -0.41 to 0.86 for both devices during the tennis drills, whereas during the cricket and field-based sports drills ICC ranged from r= -0.50 to 0.55 and -0.14 to 0.73, respectively. The CV for the 5

Hz and 15 Hz devices ranged from 3.5 to 32.9%, 5.5 to 27.1% and 6.2 to 33.4% for the tennis, cricket and FBTS drills, respectively.

*****INSERT TABLE 3 ABOUT HERE*****

DISCUSSION

The purpose of this current research was to determine the accuracy and reliability of GPS devices sampling at various frequencies (5, 10 and 15 Hz) compared to a criterion measure (VICON) during simulated court-based and FBTS movements. The current data demonstrates that the increase in the sampling frequency of GPS technology did not provide any significant improvement in the accuracy of distance and speed measures during simulated court-based and FBTS movements. Similarly, past research has reported that GPS devices sampling at a rate of either 1 of 5 Hz underreport distance and speed compared to VICON during court-based movements (5). Furthermore, during repetitive and unstructured movements simulating court-based and field-based sports, GPS measures of distance and speed were similar to criterion measures (VICON). Despite this, current evidence suggests that GPS devices possess an acceptable level of accuracy and reliability when measuring moderate to longer distances whilst running at slow to moderate speeds (16). However, measures of both reliability and accuracy appear largely reduced when travelling at higher speeds over short distances (3, 5, 12). In agreement, the current study highlights a low to moderate level of reliability of the GPS devices regardless of the sampling rate or the movement performed.

Total Distance

The current findings indicate that the total distance measures from the various GPS devices were not significantly different to that of the criterion measure provided from the VICON camera system. Previous comparisons to VICON data demonstrated that GPS devices consistently produce lower distance values. Duffield et al. (5) reported that during movements typical of tennis, 1 and 5 Hz GPS devices underreported the distance covered by as much as 38%. Although not significantly different the results of the current study suggest that GPS devices may underreport distance measures, which affect the practical interpretation of the data. As an example, during the half-court drill, the distance measured using 10 and 15 Hz devices differed to VICON by 13 and 14%, respectively. This is further highlighted within Figure 2, which shows total distance was underreported for the majority of GPS devices during each drill presented. Previous research has suggested that during short sprints involving high accelerations, GPS systems show reduced accuracy compared to longer sprints or slower speeds, which may account for this overestimation (12). The present results also highlight that during unstructured movements typical of match play, all three models of GPS devices underreported the total distance covered (10-28%) when compared to VICON during random, unstructured court-based and FBTS drills. Therefore, practitioners using GPS devices should be aware of the resultant underreporting of measures of external load i.e. total distance during unstructured movements in field-based scenarios, and that this may not be altered due to increased sampling rates, as has been previously reported (5).

Mean and Peak Speed

As reported earlier for the measures of total distance, similar outcomes for mean and peak speed were evident from GPS devices compared to VICON. However, there was evidence suggesting the GPS devices underreported measures of mean and peak speed despite not being statistically significant. These results are similar to that of previous research (5), whereby mean and peak speed measured using GPS technology during sport-specific movements were consistently lower than that of the criterion VICON measure. As highlighted by Figure 2, mean and peak speed during unstructured movements typical of court-based and FBTS were underestimated by the GPS devices in comparison to VICON, regardless of the sampling rate. Hence, regardless of the sport or sampling frequency, practitioners should note that regular non-linear motions as noted in most sports may increase GPS error. Further, as with total distance covered, there was evidence of GPS devices underreporting compared to VICON despite not being statistically significant for measures of both mean (13-29% difference) and peak speed (14-29% difference) depending on the drill performed. As such, the use of GPS devices to measure speed during sport-specific movements was not significantly different to a criterion measure, but should be still interpreted with caution in field-based settings given the underreporting reported in earlier research (5) and was evident here.

Reliability of GPS Devices

When compared to the 5 Hz devices, the inter-unit CV for the distance covered and mean and peak speed were greater than that in devices with a higher sampling rate. In the current data, the higher CV in the 5 Hz units may be explained by the lower sampling frequency which led to fewer data points being captured by the lower frequency devices (refer to Figure 2), possibly resulting in a higher proportion of movement not being reported in the lower sensitivity devices. The reported inter-unit CV for the measures included in the present data also differed to previously published data for similar movements (5, 12, 16). Regardless of the shorter distance used in the current study and a higher sampling rate, Petersen et al. (16) reported a smaller measure of error when performing the run-a-3 drill using 1 and 5 Hz GPS devices. Similar discrepancies can be observed between the 5 and 15 Hz devices in the current study, as a greater inter-unit CV was evident during the 90º COD (gradual) and 45º COD (tight) compared to the data published by Jennings et al. (12) (gradual COD: 1 Hz: 10.7%; 5 Hz: 7.9%; tight COD: 1 Hz: 12.0%; 5 Hz: 9.2%). Similar to the court-based drills, the CV was higher when performing the FBTS movements within the 15 Hz devices. However, this trend was not repeated upon observation of the inter-unit reliability with a greater ICC being reported for almost half of the distance and speed measures for the 5 Hz devices during the FBTS drills. In particular, total distance as well as mean and peak speeds during the fielding drill were greater when using the lower frequency devices. Importantly, very few of the measures displayed an ICC value that could be classified as moderately reliable, regardless of sampling frequency. This finding lends itself to the previous finding that the inter-unit reliability of GPS devices may be poor for movements associated with field sports (3).

Previous research has demonstrated that the accuracy of GPS is influenced by the nature of the movements performed (5, 12). In particular Duffield et al. (5) reported that the mean and peak speed of movements similar to those performed during a typical tennis match were underestimated by 1 and 5 Hz

GPS devices. The current study made similar observations not only during court-based movements, but also those typical of FBTS. The results of this study show the accuracy of the GPS technology for distance and speed measures was not improved with an increase in sampling rate regardless of the movements performed, which is in contrast to the findings of previous research (5, 12). It was hypothesized that a greater resolution would result in improved accuracy for determining distance and speed measures, especially during movements such as the 45º COD and the fielding drills. Based on previous suggestions (5, 12) it was assumed that this improvement would be due to an increased number of data points captured with the increase in GPS sampling frequency. However, the results of the current study do not support this hypothesis.

It should be noted that these reported findings of the study might be subject to several limitations. Firstly, the quality of the GPS signal may have influenced the data quality. Importantly, HDOP is the main quality indicator of the GPS signal quality, and values greater than 1 may indicate a poor quality signal. As such, the mean HDOP in the current study were 1.5 ± 0.4 and 1.0 ± 0.2 for the 5 and 10 Hz devices, respectively. However, these figures are similar to that reported in previous studies (5, 12) where increases in the sampling rate improved GPS reliability. Of particular interest, the 10 Hz units in the current study acquired a greater number of satellites than both the 5 and 15 Hz devices. Based on this evidence it is unlikely that any unexpected results in this investigation were due to a poor HDOP or too few a number of acquired satellites. Data quality may also have been compromised by the placement of the devices within the custom harness; however it would be surprising if the quality of the GPS data were compromised with no changes in the highlighted quality indicators. Further, customised harnesses as worn in the current study and specialised equipment are common practice within GPS reliability and accuracy studies (3, 5, 12, 16).

PRACTICAL APPLICATIONS

GPS devices in the current study reported statistically similar distance and speed measures to VICON. However, in agreement with previous research (5) there was a tendency for the GPS devices to underestimate these measures during straight line running, multi-direction movement patterns, and unstructured movements typical of team sports. Further, that the distance and speed measures of the GPS units possess a low to moderate level of inter-unit reliability when performing high-speed straight line running, multi-direction movement patterns, and unstructured movements (3,6,12). However, unlike previous research (5, 12, 17) no improvements in either accuracy or reliability were evident with increases in GPS sampling frequency.

Based on this evidence, it is recommended that practitioners understand the limitations which may arise when using GPS devices for interpretation of training load monitoring during match-play and training. In particular the low accuracy and reliability of high-intensity efforts is again of concern given the proposed importance of such measures to training and performance outcomes. Currently GPS analysis remains the most effective and time-efficient for monitoring workload within the team sport environment. By applying the information of the current study, practitioners should interpret differences in matches or training session based on the accuracy and variability reported here. As others have stated, it would be recommended that subjects wear the same device during training or data collection sessions. Finally, practitioners should be aware that these results are specific to the hardware and software of the units used in this study and may not be applicable to other versions or products.

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FIGURE LEGENDS

Figure 1: Schematic representation of the movements used in the current study (a) cricket fielding protocol; (b) gradual 5 m COD; (c) tight 3 m COD.

Figure 2: Comparison of speed-time and distance-time curves between VICON and GPS devices for the (a) random tennis (b) fast bowling and (c) 90º COD drills.

TABLE LEGENDS

Table 1: Mean ± SD for movement analysis devices for distance covered, mean speed and peak speed during court-based sports movements.

Table 2: Mean ± SD for movement analysis devices for distance covered, mean speed and peak speed during field-based team sports movements.

Table 3: Intra-class correlation analysis (ICC) and co-efficient of variation (CV) within movement analysis devices (within models) for each respective drill.

Table 1: Mean ± SD for movement analysis devices for distance covered, mean speed and peak speed during court-based sports movements.

	VICON	*5 Hz #1*	*5 Hz #2*	*10 Hz #1*	*15 Hz #1*	*15 Hz #2*
2 m Tennis	*n=10*	*n=9*	*n=10*	*n=10*	*n=9*	*n=9*
Distance (m)	23.2 ± 1.3	28.2 ± 4.4[a]	21.3 ± 3.1[b]	17.9 ± 2.0[a,b,c]	22.1 ± 2.0[b,d]	19.7 ± 1.8[b]
Mean Speed ($m \cdot s^{-1}$)	1.4 ± 0.1	1.3 ± 0.2	1.0 ± 0.2[a,b]	1.1 ± 0.1[a,b]	1.4 ± 0.1[c,d]	1.3 ± 0.1[c,d]
Peak Speed ($m \cdot s^{-1}$)	2.9 ± .04	3.9 ± 0.8	3.3 ± 0.8	2.4 ± 0.2	2.3 ± 0.2	2.3 ± 0.1
4 m Tennis	*n=10*	*n=9*	*n=10*	*n=10*	*n=10*	*n=10*
Distance (m)	45.5 ± 3.8	42.6 ± 5.0	38.2 ± 8.4[a]	36.7 ± 3.6[a]	43.1 ± 4.3	38.3 ± 2.4[a]
Mean Speed ($m \cdot s^{-1}$)	2.1 ± 0.1	1.9 ± 0.3	1.6 ± 0.4[a]	1.7 ± 0.1[a]	2.0 ± 0.1[c,d]	1.8 ± 0.2[a]
Peak Speed ($m \cdot s^{-1}$)	3.6 ± 0.2	4.2 ± 0.7	4.7 ± 1.5	3.1 ± 0.1	3.2 ± 0.3	3.9 ± 1.0
Half Court	*n=10*	*n=10*	*n=10*	*n=10*	*n=10*	*n=9*
Distance (m)	25.3 ± 0.8	24.0 ± 4.8	24.3 ± 5.6	21.9 ± 1.6	21.8 ± 1.3	20.9 ± 2.5[a]
Mean Speed ($m \cdot s^{-1}$)	3.0 ± 0.4	2.1 ± 0.6[a]	2.1 ± 0.7[a]	2.6 ± 0.3	2.6 ± 0.4	2.5 ± 0.5
Peak Speed ($m \cdot s^{-1}$)	4.6 ± 0.5	4.1 ± 1.1	4.3 ± 1.4	4.3 ± 0.2	3.9 ± 0.5	4.1 ± 0.5
Random Tennis	*n=10*	*n=10*	*n=9*	*n=9*	*n=10*	*n=10*
Distance (m)	21.6 ± 1.6	25.5 ± 5.4[a]	18.6 ± 2.4[b]	19.0 ± 1.4[b]	19.8 ± 1.5[b]	16.4 ± 2.3[a,b]
Mean Speed ($m \cdot s^{-1}$)	2.1 ± 0.2	1.8 ± 0.3	1.6 ± 0.4	1.8 ± 0.2	1.9 ± 0.2	2.3 ± 0.7[c]
Peak Speed ($m \cdot s^{-1}$)	4.7 ± 2.0	4.3 ± 1.0	4.1 ± 0.6	3.3 ± 0.3	3.3 ± 0.3	2.8 ± 0.3[a]

[a] Within each respective drill type: significantly different to VICON; [b] Within each respective drill type: significantly different to 5 Hz #1; [c] Within each respective drill type: significantly different to 5 Hz #2; [d] Within each respective drill type: significantly different to 10 Hz #1; [e] Within each respective drill type: significantly different to 15 Hz #1; [f] Within each respective drill type: significantly different to 15 Hz #2

Table 2: Mean ± SD for movement analysis devices for distance covered, mean speed and peak speed during field-based team sports movements.

	VICON	*5 Hz #1*	*5 Hz #2*	*10 Hz #1*	*15 Hz #1*	*15 Hz #2*
Run-a-3	*n=10*	*n=9*	*n=10*	*n=10*	*n=9*	*n=10*
Distance (m)	46.7 ± 0.3	46.3 ± 7.6	40.7 ± 8.8	41.1 ± 2.5	40.8 ± 1.9	39.5 ± 8.1
Mean Speed ($m \cdot s^{-1}$)	3.5 ± 0.1	3.5 ± 0.1	2.9 ± 0.7	3.1 ± 0.2	3.1 ± 0.2	3.0 ± 0.6
Peak Speed ($m \cdot s^{-1}$)	6.5 ± 1.3	5.9 ± 0.9	5.4 ± 0.5	5.4 ± 0.3	5.1 ± 0.3	5.0 ± 1.1
Fast Bowling	*n=10*	*n=9*	*n=10*	*n=10*	*n=10*	*n=10*
Distance (m)	15.0 ± 0.2	19.7 ± 4.2[a]	18.0 ± 3.2[a]	13.7 ± 1.4[b,c]	14.5 ± 0.7[b,c]	13.5 ± 1.3[b,c]
Mean Speed ($m \cdot s^{-1}$)	3.2 ± 0.1	2.5 ± 0.6[a]	2.5 ± 0.6[a]	2.9 ± 0.4	3.1 ± 0.2[b,c]	2.8 ± 0.2
Peak Speed ($m \cdot s^{-1}$)	5.9 ± 0.8	4.2 ± 0.9	4.3 ± 1.2	4.9 ± 0.2	5.0 ± 0.3	4.5 ± 0.4
Fielding	*n=8*	*n=8*	*n=8*	*n=8*	*n=7*	*n=7*
Distance (m)	39.8 ± 0.4	39.8 ± 0.4	41.2 ± 13.1	35.0 ± 1.5	34.3 ± 1.1	40.3 ± 7.4
Mean Speed ($m \cdot s^{-1}$)	1.5 ± 0.1	1.4 ± 0.4	1.3 ± 0.4	1.3 ± 0.1	1.3 ± 0.1	1.5 ± 0.2
Peak Speed ($m \cdot s^{-1}$)	4.1 ± 0.1	4.1 ± 0.1	4.3 ± 0.7	3.9 ± 0.6	3.4 ± 0.2	4.8 ± 1.0
90º COD	*n=10*	*n=10*	*n=10*	*n=9*	*n=10*	*n=9*
Distance (m)	34.7 ± 1.0	34.6 ± 3.7	31.0 ± 6.5	29.2 ± 0.4[a,b]	29.9 ± 1.81[a,b]	29.3 ± 1.9[a,b]
Mean Speed ($m \cdot s^{-1}$)	3.1 ± 0.1	2.4 ± 0.3[a]	2.2 ± 0.5[a]	2.5 ± 0.1[a]	2.7 ± 0.1[a,c]	2.7 ± 0.3[a,c]
Peak Speed ($m \cdot s^{-1}$)	4.2 ± 0.1	4.9 ± 1.3	4.9 ± 1.4	3.6 ± 0.1	3.8 ± 0.3	4.3 ± 0.8

45º COD	*n=10*	*n=10*	*n=10*	*n=10*	*n=10*	*n=9*
Distance (m)	21.2 ± 0.6	22.4 ± 5.6	20.2 ± 3.9	17.9 ± 0.7[b]	17.1 ± 2.0[a,b]	18.6 ± 2.0
Mean Speed ($m \cdot s^{-1}$)	1.8 ± 0.1	1.5 ± 0.3[a]	1.3 ± 0.4[a]	1.5 ± 0.1[a]	1.5 ± 0.2[a]	1.6 ± 0.1
Peak Speed ($m \cdot s^{-1}$)	2.8 ± 0.5	3.2 ± 0.4	3.2 ± 0.9	2.5 ± 0.1	2.4 ± 0.4[c]	3.7 ± 1.0[a,d,e]
Random FBTS	*n=10*	*n=9*	*n=10*	*n=10*	*n=10*	*n=10*
Distance (m)	34.2 ± 4.1	31.9 ± 3.7	33.1 ± 6.5	24.5 ± 3.0[a,b,c]	28.4 ± 3.5	29.3 ± 4.8
Mean Speed ($m \cdot s^{-1}$)	2.2 ± 0.3	1.7 ± 0.3[a]	1.8 ± 0.7	1.6 ± 0.2[a]	1.8 ± 0.2	1.9 ± 0.3
Peak Speed ($m \cdot s^{-1}$)	4.2 ± 0.5	4.3 ± 0.9	5.0 ± 2.1	3.2 ± 0.4	3.5 ± 0.3	3.7 ± 0.7

[a] Within each respective drill type: significantly different to VICON; [b] Within each respective drill type: significantly different to 5 Hz #1; [c] Within each respective drill type: significantly different to 5 Hz #2; [d] Within each respective drill type: significantly different to 10 Hz #1; [e] Within each respective drill type: significantly different to 15 Hz #1; [f] Within each respective drill type: significantly different to 15 Hz #2

Table 3: Intra-class correlation analysis (ICC) and co-efficient of variation (CV) within movement analysis devices (within models) for each respective drill.

	5 Hz ICC	*15 Hz ICC*	*5 Hz CV*	*15 Hz CV*
Distance (m)				
2 m Tennis	0.41	0.46	12.0	5.4
4 m Tennis	0.72	0.10	9.1	8.5
Half Court	-0.41	0.46	29.0	6.9
Random Tennis	0.24	0.02	18.4	12.1
Run-a-3	0.06	-0.17	22.1	17.9
Fast Bowling	0.06	0.53	21.2	5.5
Fielding	0.33	-0.16	20.6	17.0
90º COD	0.41	0.46	17.7	6.2
45º COD	0.24	0.02	22.7	12.4
Random FBTS	0.72	0.10	22.8	8.2
Mean speed ($m \cdot s^{-1}$)				
2 m Tennis	-0.14	0.73	19.7	3.5
4 m Tennis	0.39	0.01	14.9	8.6
Half Court	0.49	0.86	26.2	7.4
Random Tennis	-0.02	0.20	21.0	22.8
Run-a-3	-0.50	-0.10	27.1	16.3
Fast Bowling	0.50	-0.22	20.2	8.8
Fielding	0.55	-0.35	21.3	15.2
90º COD	-0.14	0.73	19.8	7.8
45º COD	-0.02	0.20	28.1	10.9
Random FBTS	0.39	0.01	33.4	7.5
Peak speed ($m \cdot s^{-1}$)				
2 m Tennis	0.03	0.25	22.5	6.4
4 m Tennis	0.15	-0.08	22.9	20.6
Half Court	0.05	0.61	32.9	8.2
Random Tennis	0.13	0.67	20.0	5.4
Run-a-3	-0.16	0.05	14.2	14.1

Fast Bowling	0.36	0.03	23.6	8.4
Fielding	0.49	-0.05	16.2	16.9
90º COD	0.03	0.25	26.3	14.5
45º COD	0.13	0.67	20.9	20.0
Random FBTS	0.15	-0.08	31.5	11.9