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Accuracy of GPS sport watches in measuring distance in an ultramarathon running race

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Abstract

Purpose: The aim of the study was to determine the accuracy of various global positioning system (GPS) sport watches in measuring distance throughout a 56 km running race.

Methods: The measured distance between timing mats was compared to the reported distance of GPS devices at the 2017 Two Oceans Marathon. Runners ($n = 255$) were divided into eight different categories based on GPS sport watch brand and model. The difference between distance measured by GPS and race markers was represented in metres (m) and as a relative error (%).

Results: The Garmin Fenix and cell phone categories had higher errors in measuring distance from the 16 km to finish (56 km) point compared to all other devices, except for activity watches.

Conclusions: The GPS sport watches in this study have an accuracy of $0.6 \pm 0.3\%$ to $1.9 \pm 1.5\%$ (median $\pm$ interquartile range) in reporting distance covered. This indicates that GPS sport watches are a valid and feasible method for sport scientists and coaches to measure performance and track training load. However, the small error associated with each brand needs to be considered when data are interpreted.

Keywords

Devices, endurance, technology, training, validity

Introduction

Wearable technology has, in the last decade, become increasingly popular with endurance runners. Wearables currently represent a $6-billion industry[1] with a projected $25-billion industry by as early as 2019.[2] A large category of wearables give information about distance and speed travelled using Global Navigation Satellite Systems such as GPS.[3,4] To obtain the best possible GPS readings, a high-sampling frequency, open areas free from obstructions such as tall buildings and clear skies are required.[3,5] Endurance runners have several GPS sport watch brands to choose from such as Garmin®, Polar®, Suunto® and TomTom®. Within these brands, there are several existing models, e.g. Garmin Forerunner® 620, Suunto Ambit® 3. It is important to evaluate the reliability and accuracy of these GPS sport watches for coaches and sport scientists to accurately measure performance and track training load. To date, most research regarding the accuracy of GPS devices is related to team sports such as rugby and football, and primarily focus on the accuracy in measuring high intensity changes in speed.[6–11] The GPS devices used in team sports are unique in their specifications and cannot be directly compared to GPS sport watches used in endurance running. There has also been research regarding the validity and reliability of consumer-wearable devices to measure heart rate,[12]

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step counts, energy expenditure and sleep.[13,14] However, only one study in a systematic review[15] reported on the validity of a consumer-wearable in measuring distance.[16] There is currently a lack of research on the accuracy of GPS sport watches in the field of endurance running. With these gaps in mind, the aim of the current study was to determine the accuracy of various GPS sport watches in measuring distance throughout a hilly 56 km running race.

Methods

Race data

The Two Oceans Marathon is a 56 km road race held in Cape Town, South Africa. The course includes variation in terrain including straight open road sections and a windy mountain pass (Figure 1(a)) and includes approximately 800 m of cumulative vertical gain (Figure 1(b)). The 2017 race was held on 15 April. The weather during the allotted race time ranged from 14°C to 24°C with sunny and clear skies (www.timeanddate.com). Participants in the study were recruited from the Two Oceans Marathon list of registered runners (approximately 10,000 entrants). Upon registering for the race, runners have the option to tick 'yes' or 'no' in terms of being contacted for possible research studies. Approximately one month before the race, study personnel sent an e-mail to approximately 10,000 registered runners who consented 'yes' inviting them to participate. All study participants provided informed consent for their race results and GPS files to be accessed for the research study. Race results and segment times of study participants (n = 255) in the 2017 race were accessed via the public website (www.twooceansmarathon.org.za). GPS device files from participants were accessed via the SmartBeat Technologies research database (https://www.smartbeatlabs.com), which runners joined by linking their Strava (www.strava.com) account to the database. The Two Oceans Marathon and SmartBeat Technologies databases are registered with the Human Research Ethics Committee at the University of Cape Town. Segment times were recorded when runners crossed timing mats at the 16 km, 28 km, 42.2 km, 50 km and finish (56 km) points. The segment from the start to the 16 km mat was excluded from analysis since runners ran various distances in this segment depending on their assigned starting batch (batches A–E; with a time range of 1 min 24 s to 6 min 32 s to cross the first timing mat).

GPS devices

Runners were divided into eight categories depending on their GPS device brand (Table 1). Participants provided their own GPS devices. Eight categories defined by the GPS device brand are included (Table 1). Because approximately two-thirds of the participants had Garmin® devices, they were divided into groups

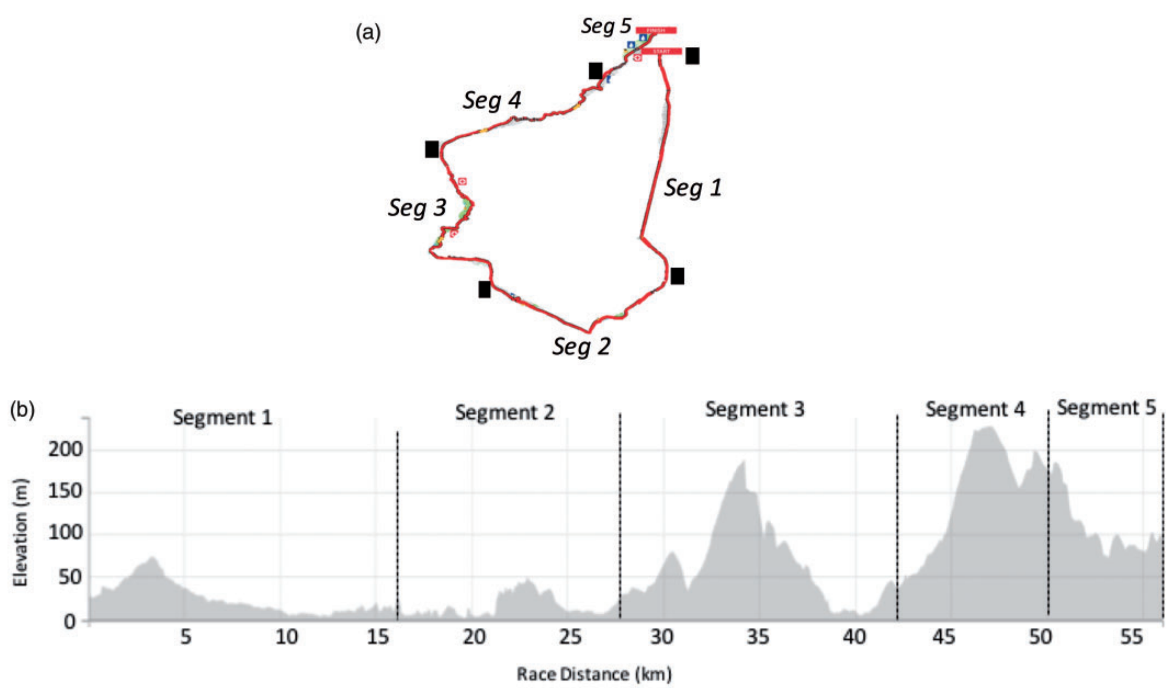

Figure 1. (a) Two Oceans Marathon 56-km race route. (b) Two Oceans Marathon 56-km race profile. Segment 1 (0–16 km), 2 (16–28 km), 3 (28–42.2 km), 4 (42.2–50 km), and 5 (50–56 km) are designated with dashed lines.

Table 1. Number of participants and finishing time of GPS Sport Watch categories.

Device	n	Race time (h:min:s)
GFX	34	5:52:31 ± 44:39
GXT	58	5:42:50 ± 42:28
GFR	67	5:45:04 ± 50:46
ACT	10	6:12:12 ± 35:13
STO	20	5:42:33 ± 40:46
TOM	44	6:02:58 ± 40:24
PLR	8	5:42:38 ± 52:28
CEL	14	6:04:10 ± 36:42
	255	

Note: Data are presented as mean ± SD. GFX series (1, 2, 3); GXT series (305, 310, 735, 910, 920); GFR series (25, 35, 220, 225, 230, 235, 610, 620, 630); ACT (Garmin VivoActive, Fitbit Surge, Samsung Gear 2 and 3, Apple Watch); STO (Ambit 2, 2 R, 2S; Ambit 3 Sport, Peak, Run; Spartan); TOM (Runner 1, 2, 3; Multisport); PLR (M400, V800); CEL (IPhone, Samsung, Sony). GFX: Garmin Fenix® series; GXT: Garmin XT® series; GFR: Garmin Forerunner® series; ACT: Activity watches; STO: Suunto®; TOM: TomTom®; PLR: Polar®; CEL: cell phones.

according to three unique models. The categories include Garmin Fenix® series (GFX), Garmin XT® series (GXT), Garmin Forerunner® series (GFR), Activity watches (ACT), Suunto® (STO), TomTom® (TOM), Polar® (PLR) and cell phones (CEL). All participants in the CEL category used the Strava application to record their race. Eight of the 14 CEL participants used the Strava iPhone app and six used the Strava android app.

Analysis of GPS device error

Participants were instructed to start their GPS device at the same time as the starting gun. Their race times were recorded as they crossed timing mats at the following race distances: 16 km, 28 km, 42.2 km, 50 km and 56 km. Electronic timing mats and chips were provided by the software company, RaceTec (http://www.racetectiming.com/Default.aspx). RaceTec has a Microsoft SQL server back-end. Timing chips were attached to the runners' shoes using their shoelaces. The race route is measured by an International Association of Athletics Federation (IAAF) accredited course measurer. The times runners crossed the timing mats were used to identify the corresponding time points in the GPS file. For example, the Two Oceans race measures a distance of 12 km in segment 2 of the race (from 16 to 28 km). The Two Oceans database reports runner × crosses the 16 km mat at 1 h 11 min 17 s and the 28 km mat at 2 h 2 min 26 s. These time points were identified in the GPS file and the GPS measured distance between these time points was calculated. Runners who had no split times available in the race results or who failed to complete the 56 km race were excluded from analysis (n = 26).

A relative error was calculated by taking the course distance segment (d_{course}) subtracted from the GPS device segment distance (d_{GPS}) divided by the average of the two values (relative error = $d_{GPS} - d_{course}$/ average d_{GPS}, d_{course}). An error in metres was calculated by taking the course distance segment subtracted from the GPS device segment distance (metres error = $d_{GPS} - d_{course}$). The sign of the error (over or under) was included in both calculations.

Statistical analysis

All statistical analyses were done using GraphPad Prism 7 software (GraphPad Software, La Jolla, CA, USA). Participant race times for each GPS category are expressed as mean ± standard deviation (mean ± SD) and were compared using a Kruskal–Wallis test.

Due to the presence of unequal variances, non-parametric statistical analyses were performed, and all GPS results are expressed as median ± interquartile range (IQR). A Kruskal–Wallis test was used to determine differences in relative and distance errors between GPS device categories for segment 2 (16–28 km), segment 3 (28–42.2 km), segment 4 (42.2–50 km), segment 5 (50–56 km), and the 16–56 km points. Multiple comparisons were corrected by controlling the false discovery rate via the two-stage step-up method of Benjamini et al.[17]

Results

The GPS device categories and mean race times for each category are presented in Table 1. The average finishing times of runners in the different categories were not different between groups ($p = 0.20$; Kruskal–Wallis statistic = 9.76).

The data for segment 1 were not analysed because of the varying time it took participants to cross the start line after the start of the race. For segment 2 (16–28 km), the GXT, GFR, and TOM devices had lower relative ($p = 0.001$; <0.001; <0.001, respectively) and distance errors ($p = 0.001$; $p = 0.001$; $p < 0.001$, respectively) compared to the GFX devices (Figure 2(a), Tables 2 and 3). GXT, GFR, and TOM devices also had lower relative and distance errors ($p < 0.001$) compared to CEL devices (Figure 2(a), Tables 2 and 3).

For segment 3 (28–42.2 km), all device categories except for CEL had lower relative (GXT, GFR, STO, TOM, $p < 0.001$; ACT, $p = 0.024$; PLR, $p = 0.005$) and distance errors (GXT, GFR, STO, TOM, $p < 0.001$; ACT, $p = 0.023$; PLR, $p = 0.004$) compared to the GFX (Figure 2(b), Tables 2 and 3). All device categories except for GFX and ACT had lower relative errors

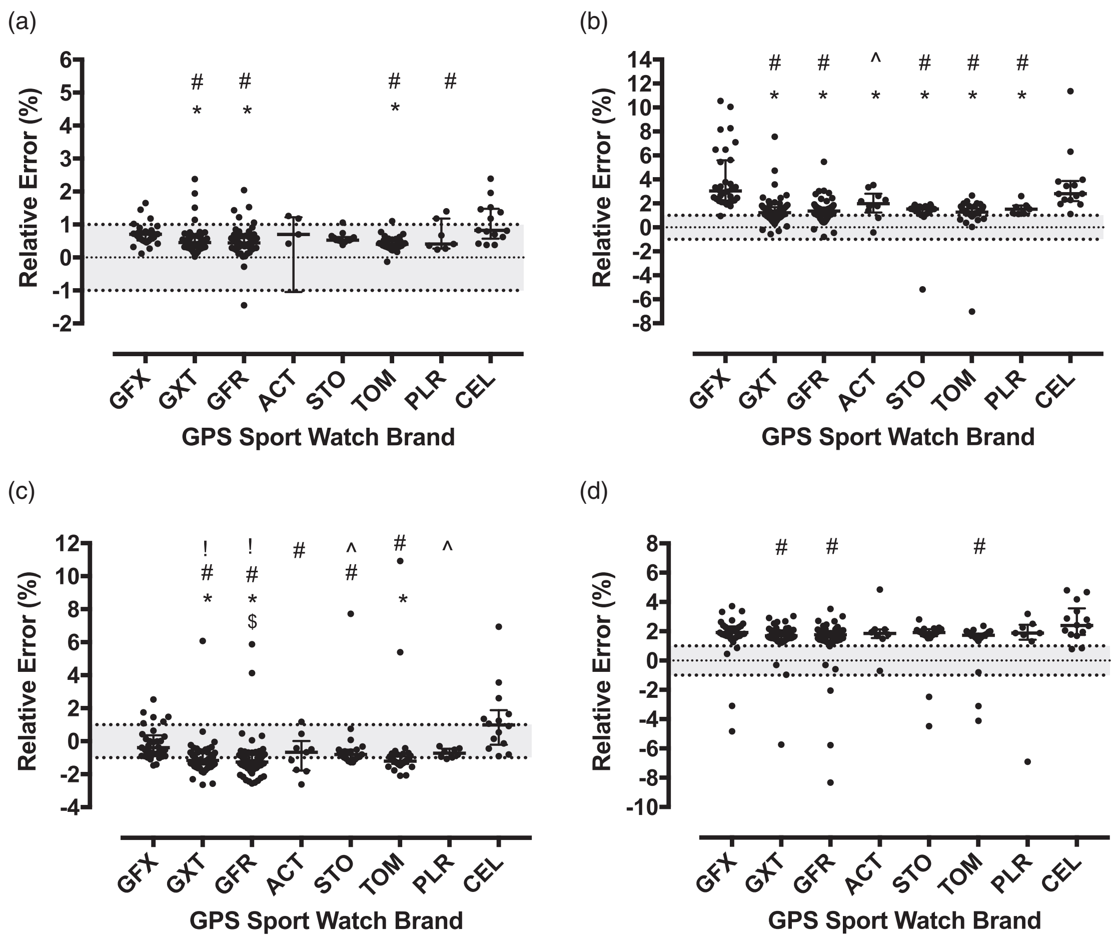

Figure 2. (a) Relative error of GPS measured distance versus IAAF measured distance for segment 2 (16–28 km). *$p < 0.05$ versus GFX. #$p < 0.05$ versus CEL. (b) Relative error of GPS measured distance versus IAAF measured distance for segment 3 (28–42.2 km). *$p < 0.05$ versus GFX. #$p < 0.05$ versus CEL. ^$p < 0.05$ versus TOM. (c) Relative error of GPS measured distance versus IAAF measured distance for segment 4 (42.2–50 km). *$p < 0.05$ versus GFX. #$p < 0.05$ versus CEL. ^$p < 0.05$ versus TOM. !$p < 0.05$ versus STO. $$p < 0.05$ versus PLR. (d) Relative error of GPS measured distance versus IAAF measured distance for segment 5 (50–56 km). #$p < 0.05$ versus CEL.

(GXT, GFR, TOM, $p < 0.001$; STO, $p = 0.001$; PLR, $p = 0.017$) and distance errors (GXT, GFR, TOM, $p < 0.001$; STO, $p = 0.001$; PLR, $p = 0.017$) compared to CEL (Figure 2(b), Tables 2 and 3). TOM had a lower relative error ($p = 0.030$) versus ACT (Figure 2 (b), Table 3).

For segment 4 (42.2–50 km), the GXT, GFR and TOM devices had higher relative ($p < 0.001$) and distance errors ($p < 0.001$) versus GFX (Figure 2(c), Tables 2 and 3). All device categories except for PLR and GFX had significantly different relative (GXT, GFR, TOM, $p < 0.001$; ACT, $p = 0.005$; STO, $p = 0.016$) and distance errors (GXT, GFR, TOM, $p < 0.001$; ACT, $p = 0.004$; STO, $p = 0.013$) versus CEL (Figure 2(c), Tables 2 and 3). The STO and PLR devices had lower relative (STO, $p = 0.005$; PLR, $p = 0.024$) and distance errors (STO, $p = 0.006$; PLR, $p = 0.020$) versus TOM. The GXT and GFR watches had higher relative ($p = 0.012$, $p = 0.001$, respectively) and distance errors ($p = 0.010$, $p = 0.001$, respectively) versus STO. GFR had a higher relative ($p = 0.011$) and distance ($p = 0.010$) error versus PLR (Figure 2(c), Tables 2 and 3).

For segment 5 (50–56 km), GXT, GFR and TOM devices had lower relative ($p = 0.003$; $p = 0.003$; $p = 0.002$, respectively) and distance errors ($p = 0.002$; $p = 0.004$; $p = 0.001$, respectively) compared to the CEL devices (Figure 2(d), Tables 2 and 3).

When relative errors were calculated for 16–56 km, GFX and CEL had higher relative errors compared to all other devices except for ACT (GFX vs. GXT, GFR, TOM, respectively, $p < 0.001$; GFX vs. STO, $p = 0.004$; GFX vs. PLR, $p = 0.012$) (CEL vs. GXT, GFR, TOM, respectively, $p < 0.001$; CEL vs. STO, $p = 0.004$; CEL vs. PLR, $p = 0.009$) (Figure 3, Table 3). GXT, GFR, TOM and STO had errors within the IAAF acceptable course measurement error of 1% (shaded area

Table 2. The absolute distance between the GPS sport watch measurement for a given segment(s) versus the IAAF course measurement.

	GFX	GXT	GFR	ACT	STO	TOM	PLR	CEL
Segment 2 (m)	80 ± 30	50 ± 30[a,b]	50 ± 40[a,b]	80 ± 90	60 ± 10	50 ± 20[a,b]	50 ± 70	100 ± 100
Segment 3 (m)	640 ± 480	370 ± 120[a,b]	390 ± 90[a,b]	480 ± 150[a]	420 ± 80[a,b]	380 ± 60[a,b]	420 ± 80[a,b]	600 ± 210
Segment 4 (m)	−230 ± 90	−290 ± 50[a,b,d]	−300 ± 50[a,b,d,e]	−250 ± 100	−260 ± 40[b,c]	−290 ± 30[a,b]	−260 ± 40[c]	−120 ± 130
Segment 5 (m)	120 ± 40	100 ± 30[b]	110 ± 40[b]	110 ± 30	120 ± 30	100 ± 20[b]	110 ± 40	150 ± 90
Segment 2 – Segment 5 (m)	640 ± 320	240 ± 210[a,b]	240 ± 120[a,b]	380 ± 280	290 ± 70[a,b]	240 ± 80[a,b]	280 ± 160[a,b]	760 ± 510

Note: Data are presented as median ± IQR. Segment 2 = 16–28 km; segment 3 = 28–42 km; segment 4 = 42–50 km; segment 5 = 50–56 km; segment 2–segment 5 = 16–finish (40 km). IQR: inter quartile range; GFX: Garmin Fenix® series; GXT: Garmin XT® series; GFR: Garmin Forerunner® series; ACT: Activity watches; STO: Suunto®; TOM: TomTom®; PLR: Polar®; CEL: cell phones.
[a]Significantly different versus GFX.
[b]Significantly different versus CEL.
[c]Significantly different versus TOM.
[d]Significantly different versus STO.
[e]Significantly different versus PLR.

Table 3. The relative difference between the GPS sport watch measurement for a given segment(s) versus the IAAF course measurement.

	GFX	GXT	GFR	ACT	STO	TOM	PLR	CEL
Segment 2 (%)	0.7 ± 0.3	0.5 ± 0.3[a,b]	0.4 ± 0.4[a,b]	0.7 ± 2.3	0.5 ± 0.1	0.4 ± 0.2[a,b]	0.4 ± 0.9	0.8 ± 0.9
Segment 3 (%)	3.0 ± 3.4	1.2 ± 0.9[a,b]	1.3 ± 0.7[a,b]	2.0 ± 1.6[a,c]	1.5 ± 0.6[a,b]	1.3 ± 0.5[a,b]	1.5 ± 0.7[a,b]	2.8 ± 1.7
Segment 4 (%)	−0.4 ± 1.3	−1.2 ± 0.7[a,b,d]	−1.3 ± 0.8[a,b,d,e]	−0.7 ± 1.8[b]	−0.8 ± 0.6[b,c]	−1.2 ± 0.4[a,b,e]	−0.7 ± 0.5	−1.0 ± 2.1
Segment 5 (%)	1.9 ± 0.7	1.7 ± 0.5[b]	1.7 ± 0.7[b]	1.9 ± 0.6	1.9 ± 0.5	1.7 ± 0.3[b]	1.9 ± 1.0	2.4 ± 1.8
Segment 2– Segment 5 (%)	1.6 ± 0.9	0.6 ± 0.6[a,b]	0.6 ± 0.3[a,b]	0.9 ± 1.2	0.7 ± 0.2[a,b]	0.6 ± 0.3[a,b]	0.7 ± 0.7[a,b]	1.9 ± 1.5

Note: Data are presented as median ± IQR. Segment 2 = 16–28 km; segment 3 = 28–42 km; segment 4 = 42–50 km; segment 5 = 50–56 km; segment 2–segment 5 = 16 km–finish (40 km). IQR = inter quartile range. GFX: Garmin Fenix® series; GXT: Garmin XT® series; GFR: Garmin Forerunner® series; ACT: Activity watches; STO: Suunto®; TOM: TomTom®; PLR: Polar®; CEL: cell phones.
[a]Significantly different versus GFX.
[b]Significantly different versus CEL.
[c]Significantly different versus TOM.
[d]Significantly different versus STO.
[e]Significantly different versus PLR.

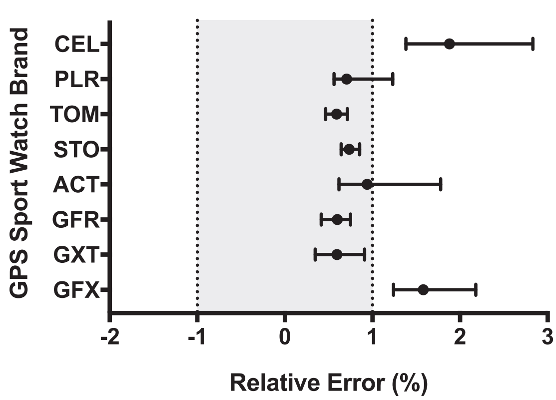

Figure 3. Relative error of GPS measured distance versus IAAF measured distance for segment 2–segment 5 (16–56 km). Note: Data are presented as median +/- IQR.

Figure 3). PLR had 6 of 8 participants that fell within the shaded area; CEL had 2 of 14 participants; and GFX had 2 of 29. When analysed as distance differences, GFX and CEL had higher errors compared to all other devices except for ACT (GFX vs. GXT, GFR, TOM, respectively, $p < 0.001$; GFX vs. STO, $p = 0.004$; GFX vs. PLR, $p = 0.012$) (CEL vs. GXT, GFR, TOM, respectively, $p < 0.001$; CEL vs. STO, $p = 0.003$; CEL vs. PLR, $p = 0.009$) (Table 2).

Discussion

This study has three main findings. Firstly, GPS devices recorded distance within 0.6 ± 0.3% to 1.9 ± 1.5% (median ± IQR) accuracy. Secondly, GXT, GFR, STO, TOM and PLR have lower overall errors compared to CEL and GFX. Thirdly, the errors appear to be greater in the hilly sections of the race with more turns (segments 3, 4 and 5) compared to the flatter and straighter section (segment 2).

When considered in context, the relative error for segment 2 to the finish of the race (i.e. a distance of 40 km) was lower than previous research using a GPS sport watch.[18] Nielsen et al.[18] showed the error in measuring distance using a Garmin Forerunner 110 ranged from 0.8% to 6.2% (mean). The results from our study reflect better accuracy. This could be due to advancements in technology and GPS units since 2013 when the Nielsen paper was published.

The cell phone category displayed a higher error compared to most other categories. Eight participants had iPhones, and six participants had phones with android operating systems. Different brands may have unique GPS units. However, when iPhones were compared to cell phones with android operating systems, there was no difference in relative error for the 16–56 km segment ($p = 0.57$). There has also been research about the accuracy of different running applications on cell phones.[19] All the study participants in the CEL category used the Strava running application (www.strava.com); therefore, this possibility was eliminated. The placement of the GPS device on the body can affect accuracy. GPS sport watches are usually worn on the wrist with a clear view of the sky. In contrast, cell phones can be held or worn on the arm with a case and strap, in a shorts pocket or in a waistband. The placement of the cell phone may have contributed to the large IQR of the CEL category.

The Garmin Fenix category also displayed a higher error compared to most other categories. The third edition of the Garmin Fenix series (31 of 34 participants in this category had the Garmin Fenix 3) is the first one to offer GPS and Global Navigation Satellite Systems (GLONASS).[20] The recent incorporation of GLONASS into GPS sport watches increases the availability of surrounding satellites. However, there is currently no research comparing the accuracy of GPS versus GPS combined with GLONASS in the devices included in our study. Simply increasing the availability of surrounding satellites does not guarantee improved GPS accuracy. There are many factors to consider such as the quality of the GPS chipset in the device as well as quality of the manufacturer algorithm. Future research should investigate these areas further.

The next finding was that the error appears to change depending on the segment of the race course. For example, the medians in the TomTom category for segments 2, 3, 4 and 5 are 0.4%, 1.3%, −1.2% and 1.7%, respectively. This change in error could be due to changes in course elevation, turns and/or tree cover. Segment 2 is relatively straight and flat with ~100 m of elevation change while segments 3, 4 and 5 include larger changes in elevation (~465 m, 300 m and 150 m, respectively) and more turns. Nielsen et al.[18] tested the accuracy of the Garmin Forerunner 110 in reading distance covered in three different settings. The relative error on a flat path with a clear view of the sky was 0.8%. In an urban area with buildings, the error was 1.2%, and in a covered forest area, the error was 6.2%. Segments 4 and 5 include significant tree cover compared to the other segments which may have affected the accuracy. In addition, segments 3 and 4 include stretches of road surrounded by mountains on one or both sides which can also affect accuracy. A professional product tester found an average GPS sport watch error of 1% on a 1.6 km straight path with a clear view of the sky; 1.7% around a 400 m track and 1.7% on a 0.84 km loop route through a mix of open area and tree cover.[21] In line with this, there is a possibility the turns in segments 3, 4 and 5 (Figure 1(a)) affected the accuracy in reading distance.

Limitations

A limitation of the study is that the distance between course markings can only be guaranteed to 1% according to the IAAF regulations. This limitation was considered in the analysis and interpretation. Consideration should be given to the various software and firmware within devices as both can affect GPS accuracy. Because we do not know which software version participants had on their devices on race day, it is not possible for us to speculate about this. Regardless of whether we categorized by brand, hardware or software, there would have been cross-over between hardware and software. The main aim of our study was to determine if using GPS sport watches are feasible and valid method to measure distance. We feel reporting results by brand has more practical applications for sport scientists, coaches and athletes as firmware is not included in the marketed specifications of the devices. Another limitation of the study includes the lack of control of device settings such as amount of free memory and sampling rate which can affect accuracy. The possibility of runners choosing a low sampling rate is low as the battery life using GPS for 29 of 38 devices is 10 h or more. With a race cut-off time of 7 h, having to alter the sampling rate to extend battery life would not be a likely occurrence in this race. Finally, the lack of control of the placement of the GPS device is a limitation of this study, particularly in the CEL category. GPS sport watches are predominantly worn on the wrist with a clear view of the sky. Cell phones are often worn around the arm in a case or at the waist in a pocket both of which can affect accuracy. While this limitation needs to be considered when interpreting the results, it has practical implications as it is not feasible for runners to carry cell phones without a case and/or strapping it to an arm or placing in a pocket.

Conclusion

The conclusions of the current study are that (1) GPS sport watches are a valid and feasible way to measure performance and track training load; (2) GXT, GFR, STO, TOM and PLR devices have lower overall errors compared to CEL and GFX devices; and (3) the error appears to be greater in segments with more elevation and turns (segments 3, 4 and 5 of the race) compared to the flatter and straighter section (segment 2). The GPS sport watches in this study have an accuracy of $0.6 \pm 0.3\%$ to $1.9 \pm 1.5\%$ (median $\pm$ IQR) in reporting distance covered. This indicates that GPS sport watches are a valid and feasible method for sport scientists and coaches to measure performance and track training load. However, the small error associated with each brand needs to be considered when data are interpreted. Sport scientists, coaches and runners should also consider that error may be influenced by changes in elevation, non-linear movement, tree cover and cloud cover.

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