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VALIDITY AND RELIABILITY OF TITAN2 GLOBAL NAVIGATING SATELLITE SYSTEMS IN TWO DIFFERENT PROTOCOLS

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Abstract GNSS systems are widely used in many sports. Lastly observed increase of popularity of this kind of monitoring is observed by new equipment appearing on the market. Our aim in this study was to assess validity and reliability of TITAN2 GNSS equipment. Two protocols were used: protocol one consisted of 9 laps of 400(m) long athletes track where the devices were carried on an electric car with constant velocity, protocol two was using gold standard proposed by Coutts & Duffield (2010) consisting 128,5m track of different move patterns including 20m sprint with photocells which was covered by 19 male adult professional football players. Results: total distance (TD) CV% was ranging from 0.32 to 0.55%, TD at maximum speed CV% was ranging from 0.45% to 0.78%, maximum speed CV% was 0.206% to 0.609%, TD on 128.5(m) track had CV% of 1.4%. These results prove that TITAN2 GNSS is a reliable device providing valid data to the users.

Key words: GPS, GNSS, TITAN2, validity, reliability, HDOP, DOP

Introduction

Devices monitoring the performance of players' movement on the pitch are widely used in many sports disciplines. Their use in everyday work is becoming mandatory at the professional level. Over the last decade, we have observed a rapid increase in Global Navigation Satellite System (GNSS) devices and systems sold. This is related to the growing demand for precise and reliable tools for estimating or assessing athletes' training and match (start) work. Having access to validated numerical information, coaching staff reduce the risk of making mistakes when deciding on the nature and volume of training tasks.

What's more, using live work, they control the implementation of the plan or introduce modifications on an ongoing basis. Using devices based on GNSS technology for monitoring brings many benefits and possibilities, including comparing the results of individual people in the team with each other over a more extended period of work. Observing the dynamics of changes in specific parameters allows you to observe the progress or regression of the athlete's motor performance. All this is combined with the game context (tactical aspect) to effectively design and individualize the training process corresponding to real game conditions and measuring its effectiveness (Padulo et al., 2019), (Aughey, 2011; Heishman et al., 2018; Pino-Ortega et al., 2022; Seshadri et al., 2019; Varley et al., 2014). Literature confirms the usefulness of observing key indicators in injury prevention, enabling monitoring of load and avoiding situations that increase the risk of injury (Buková et al., 2024; Gabbett, 2016; Gabbett & Ullah, 2012). There are already works confirming the use of, for example, raw data to build predictive models, the task of which is to predict future possible scenarios. We are talking here precisely about the ability to estimate the load value after which the athlete significantly reduces their performance, and the risk of making incorrect decisions will increase dramatically, or calculating the peak value in competitions in individual sports (Nowak et al., 2024).

Generally, the GNSS deliver good validity and reliability for assessing distance and speed in linear motion (Barbero-Álvarez et al., 2010; Kim et al., 2023; Portas et al., 2010) and simulated motion of team sport disciplines. However, the validity can be affected by different conditions, and reliability decreases during motion with a change of direction (COD) (Bloomfield et al., 2007; Duffield et al., 2010; Jennings et al., 2010). The validity and reliability of the obtained results are crucial because these numbers serve as the basis for assessing training progression, evaluating players, and determining the starting point in training program design for many conditioning coaches (Beato et al., 2018; Padulo et al., 2018).

Due to the undoubted advantages of GNSS, many practitioners, such as head coaches, assistants, strength and conditioning coaches, physiotherapists, and scientists, use various models of such devices in their work. The growing popularity, better availability, and falling prices of equipment often go hand in hand with a decrease in its quality. Moreover, these devices, being very mobile, are often used in different and imperfect conditions.

Monitoring movement performance provides coaches and analysts with a lot of data. Unfortunately, some of them, especially those without the appropriate experience, overly trust the information provided. The lack of a critical approach to its validity and reliability increases the risk of misinterpretation and, consequently, this translates into training intervention with a human. There is a lack of practical indications on how quickly and easily it is possible to pre-filter, standardize the method of data collection to reduce the level of error. A good example would be the different working times of the device versus the different training times. Some devices do not display raw data to the end user but instead use algorithms to calculate data, presenting the user with ready-made reports or even charts – thus drawing the user's attention even more, distracting them from considering the obtained results. Manufacturers acting in good faith constantly work on improving the software so that each update can result in a difference in the data generation (Kim et al., 2023). This makes it difficult to compare data over time. One approach to solving this problem is to introduce a parameter commonly referred to as signal quality. Unfortunately, manufacturers do not provide a definition, scale of magnitude, or interpretation of the unit generated in the system.

GNSS precision can be significantly affected by the construction of the stadiums (Shergill et al., 2021), stadium location (Kim et al., 2025), the number of satellites, changes in a satellite's geometry, atmospheric and weather effects, clock inaccuracy, rounding errors (Buchheit et al., 2014; Vickery et al., 2014) and the motion characteristics including lots of COD in team sports bring difficulties to the GNSS to be precise (Brughelli et al., 2008). Currently, it is possible to assess predicted measurement accuracy by knowing the value of the dilution of precision (DOP) (Chen, 2015) and User Equivalent Range Error (UERE) (Don, 2017; Sadman & Hossam-E-Haider, 2019). In practice, the most important parameter is Horizontal Dilution of Precision (HDOP) because it characterizes the accuracy of athletes' position measurements during training. This means that HDOP informs sports analysts how accurately they can determine the route, pace, and distance covered during training or competitions by not providing the value and size of the measurement error, it would be possible to prevent over-interpretation. For athletes who rely on GPS technology to track their activities, such as runners, cyclists, skiers, or triathletes, low HDOP is crucial. A lower HDOP value ensures that the data collected during training is more precise and reliable. This allows athletes to precisely analyze their routes, optimize pace and training efficiency, and monitor progress over time. HDOP enables athletes to make more informed training decisions. For example, athletes can adjust their route or pace in real time to achieve their training goals. Therefore, HDOP is a significant criterion when choosing GPS devices for monitoring physical activities, especially for athletes for whom measurement precision is of paramount importance (Dempster, 2006; Gløersen et al., 2018).

The value of this parameter is classified in the following way: 1 – Ideal – Highest possible confidence level to be used for applications demanding the highest possible precision at all times; 1–2 – Excellent - At this confidence level, positional measurements are considered accurate enough to meet all but the most sensitive applications; 2–5 – Good – Represents a level that marks the minimum appropriate for making accurate decisions. The above HDOP scale and related concepts are part of the GPS-related documentation and technical literature. They are available to those working in satellite navigation and GPS technology. They were developed as part of the work of engineers working in the United States Department of Defense. Positional measurements could be used to make reliable suggestions to the user. Furthermore, the severity of errors may vary depending on the physical location of a device and the time of day. Not all manufacturers provide their users with information that the HDOP value is crucial for precise measurements. A lack of these details may lead to inaccurate measurement and make interpreting data for practitioners and researchers difficult. Moreover, it is recommended to become familiar with the criteria for turning the device on and off, as well as locating it on the body, to ensure the correct data is collected by the device. The time of signal acquisition ranges from 30 seconds to several minutes. Considering the above, the validation procedure is needed (Coutts & Duffield, 2010; Portas et al., 2010). Accuracy, validity, and reliability of the GNSS system, as well as compliance with the procedure for using the equipment, are essential factors in ensuring the quality of the provided information (Aughey, 2011; Malone et al., 2017). Currently, it is recommended to work with GNSS devices that have a sampling frequency greater than 10 Hz, linked with an IMU that has a sampling frequency greater than 100 Hz, to ensure the necessary level of accuracy and precision (Rampinini et al., 2015). Validation of GPS devices usually takes place by performing a standard circuit, linear sprint (Barbero-Álvarez et al., 2010) or with direction change, and it uses particular tasks simulating the game (Beato et al., 2016). Distance measurement accuracy of the GNSS systems decreases during high intensity change of direction (COD) movements, the bigger amplitude of speed changes, the more CODs, and the higher movement speed (Jennings et al., 2010). Fast COD deteriorates the validity of GPS distance measurements, and this effect is independent of movement speed. The distance is overestimated on running circuit tracks and underestimated during pendulum tests (Rawstorn et al., 2014). Buchheit et al. (2014) showed there could be differences even between GPS devices of the same model and manufacturer – in their study, the between-unit variations ranged from 1% (peak speed) to 56% (Dec >4 m/s²) (Buchheit et al., 2014).

Our study aimed to analyze ranging data generated by a Titan2 sensor (10 Hz, triple GNSS, 1000 Hz accelerometer) using satellite-based regional augmentation systems (SBAS) for location correction during easily repeatable test protocols in the context of differences between individual sensors and their compliance with sample distance (Kim et al., 2025).

Methods

Subjects

Running effort was performed by 19 professional soccer players aged 20.18 ±5.05 (yrs); height of 182.98 ±7.63 (cm); body weight of 76.98 ±7.92 (kg). All of them were informed about the aim and risk of participating in the experiment, and they signed a written consent. The project was approved by the Scientific Research Ethics Committee of Jan Dlugosz University in Czestochowa, no KE-U/2/2021. All the players were healthy during the tests, and they did not report any health issues.

GNSS device

(A) (B)

Figure 1. (A) The unit of GNSS TITAN2 (B), the training west used to place the unit on a player’s body.

In this research the GNSS sensor produced by Integrated Bionics Inc., 2020 (USA) named TITAN2 was used (fig. 1). Its technical parameters were as follows: GNSS ENGINE (U-Blox M8 Concurrent GNSS LCC Module, TCXO, ROM, SAW, LNA); triple GNSS antenna (GPS + GLONASS + GALILEO -SGGP.18A Series Taoglas), sampling at

10 (Hz), inertial measurement (1000 (Hz) accelerometer), battery for 7 (hours), the use of SBAS error correction. The company manufacturing TITAN2 systems claims on their website that many clubs representing a top level in various sports disciplines use their systems. There are also some scientific papers which have used this equipment in their research (Honkanen, 2022; Spornovas, 2022; White et al., 2018).

Procedure

Protocol 1. The first testing protocol used an electric vehicle (model N.CLASSIC 465H, Melex, Poland) moving along a strictly defined track 400 (m) long on an athletic track established at the stadium. The athletic track had IAAF (International Association of Athletic Federation) Class 1 certificate, which enables it for use in National and European Championship events, proving the track's dimensions. To precisely verify and confirm the accuracy of the measurements, its length was tested with an electronic odometer (geo-FENNEL M10, Germany).

In the first testing protocol, the vehicle started generating constant acceleration until reaching maximum speed (22 km/h), which was maintained till it reached the finish line. Final braking was performed after crossing the finish line. GNSS sensors were mounted on a platform placed on the vehicle, in accordance with the manufacturer's guidelines. The test commenced after a 20-minute self-calibration period (acquisition time). The test was repeated 9 times, with a pause of 1 minute between repetitions. All the attempts were filmed and synchronized with the manufacturer's software. The average number of satellites on the test day was 17 ±1, and the HDOP index equalled 1.04 ±0.09. The stadium has an open construction, and there are no high buildings in its vicinity.

Protocol 2. The track of different locomotor activities of various intensities was used for the test according to (Coutts & Duffield, 2010).

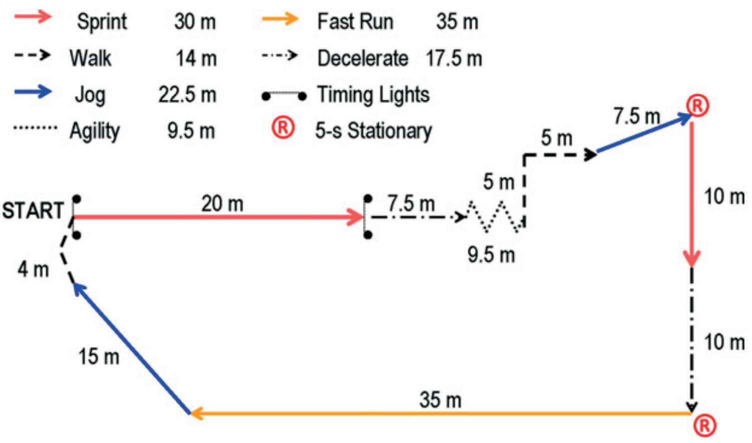

Figure 2. Drawing based on test track from (Coutts & Duffield, 2010).

The route consisted of various movement exercises: walk, jog, fast run, sprint and two places where the competitor stood and rested for 5 seconds. The track was marked on a pitch with an artificial surface using a measuring wheel (geo-FENNEL M10, Germany) and a Bosch GLM 40 laser rangefinder (with an accuracy of ±1.5 (mm). Colored cones separated each area. Additionally, the sprint time for the first 20 m was measured using photocells (FITLIGHT Sports Corp, Canada). The total track distance was 128.5 (m). The average number of satellites on the test day was 18 ±1, and the HDOP index was 1.35 ±0.08. The football pitch has an open structure, and there are no tall buildings in its vicinity. GNSS devices were placed on the backs of competitors wearing a tight-fitting vest provided by the manufacturer.

Statistical analysis

The data submitted for statistical analysis was processed using the manufacturer's web software (TITAN2), enabling access to raw data. Statistical analysis was performed using the R programming language (Gentleman et al., 2004; Ihaka & Gentleman, 1996). There were four separate measurements developed, presented in subsequent sections. Reliability was measured in two procedures – constant speed over 400m track (section 1) and different locomotor activities at various intensities over a gold standard track 128.5 (m) long (section 4). Additionally, we measured the variability of the measured speed for a given repetition (section 3), and the variability of each transmitter at the distance of 400 (m) covered in the speed qualified as a sprint (>19.0 km/h; 5.3 m/s; manufacturer settings) (section 2). In this case, we dealt with two diverging observations, respectively, in the first and the sixth lap for transmitter nine (this measurement constituted 1.17% of all the data collected). To avoid the influence of two extreme observations, we decided to remove them from the set and measure appropriate values for particular laps without taking these measurements into account.

To statistically analyze the results of tests from sections one, three and four, non-parametric tests were used. Only in test two, where we could use data from a 128.5 m run analysis, we assumed that the test assumptions were fulfilled and, as a result, we used a parametric test t with different variances. Thus, for the variance analysis of repeatable measurements, we used Friedman's rank test, a non-parametric equivalent of the ANOVA test. That allowed us to run a 9-lap test compared to the gold standard, which was 400 (m). The size of these differences was tested with the help of the effect size for a non-parametric test, which can be calculated as follows (Tomczak & Tomczak, 2014).

$$W = \frac{\chi_w^2}{N\left(k-1\right)}$$

W – W value of Kendall's test

χ_w^2 – statistical value of Friedman's test

N – sample size

k – number of measurements for a particular sample

To interpret the result, the coefficient W uses Cohen's interpretation guidelines(Cohen, 1992): $|d| < 0.2$ – trivial, $|d| < 0.5$ – small, $|d| < 0.8$ – medium and $|d| \geq 0.8$ – large. To obtain reliability between two coupled samples, and, in this way, to obtain reliability between measurements and a real distance, we used the t-test (this test was conducted in section two, where we assumed that the test assumptions were fulfilled). The effect size for this test can be interpreted with the help of Cohen's criterion d: $|d| < 0.2$ – trivial, $|d| < 0.5$ – small, $|d| < 0.8$ – medium and $|d| \geq 0.8$ – large. In our test, we also compare the standard error of estimate, which can be expressed as: $\sqrt{\left(\frac{1}{n}\right)\sum\left(y-y'\right)^2}$, where y refers to a real known value, and y' to a value obtained from measurement. We also took into account percentage differences expressed as $100 \cdot \frac{\text{measured parameter} - \text{ accurate parameter}}{\text{accurate parameter}}$.

To visualize the obtained results, our measurements were presented on a Bland-Altman plot, where axis X represents the difference between the measured distance and a known distance, whereas axis Y represents the average of this difference. In order to determine the variability of one distance shown by one transmitter in total lap time, we used the intraclass correlation coefficient (ICC). The parameters of this coefficient are as follows: two-way mixed effects, absolute agreement, and single rater/measurement. Based on the 95% confidence interval of assessing ICC, values smaller than 0.5, between 0.5 and 0.75, between 0.75 and 0.9 and bigger than 0.9 show weak, average, good and excellent reliability accordingly. The variability for each repetition for a distance shown by all the transmitters was measured with the help of the coefficient of variation (CV). Statistical significance for all the calculations was verified by $p < 0.05$. All the tests were two-tailed. While determining confidence intervals (except for ICC), we used the method of multiple draws with sample returning (bootstrap technique). The final formula is as follows:

$$\left(2t_0 - \theta_{1-\frac{1-\alpha}{2}}, 2t_0 - \theta_{\frac{1-\alpha}{2}}\right).$$

Results

Section 1. – 9x400(m) total distance

The section shall start with showing the reliability of the measurements obtained from each device and the gold standard equalling 400 m. In this case, using Friedman's rank test, we obtained the result showing a statistical difference between the gold standard and the GNSS transmitters. P-value was, in this case, 1.26e–25, where the effect size was 0.82, which points to a large effect size. Bland-Altman plots for each lap were presented in Figure 3. We noticed weak/average variability in the distance one transmitter shows in lap time. The ICC (A, 1) result was 0.439, and the 95% – ICC confidence interval: was $0.211 < ICC < 0.679$. Variability for each repetition in the distance shown by all the transmitters (coefficient of variation CV%) ranged between 0.32% on the 6th lap and 0.55% on the 9th one (Table 1).

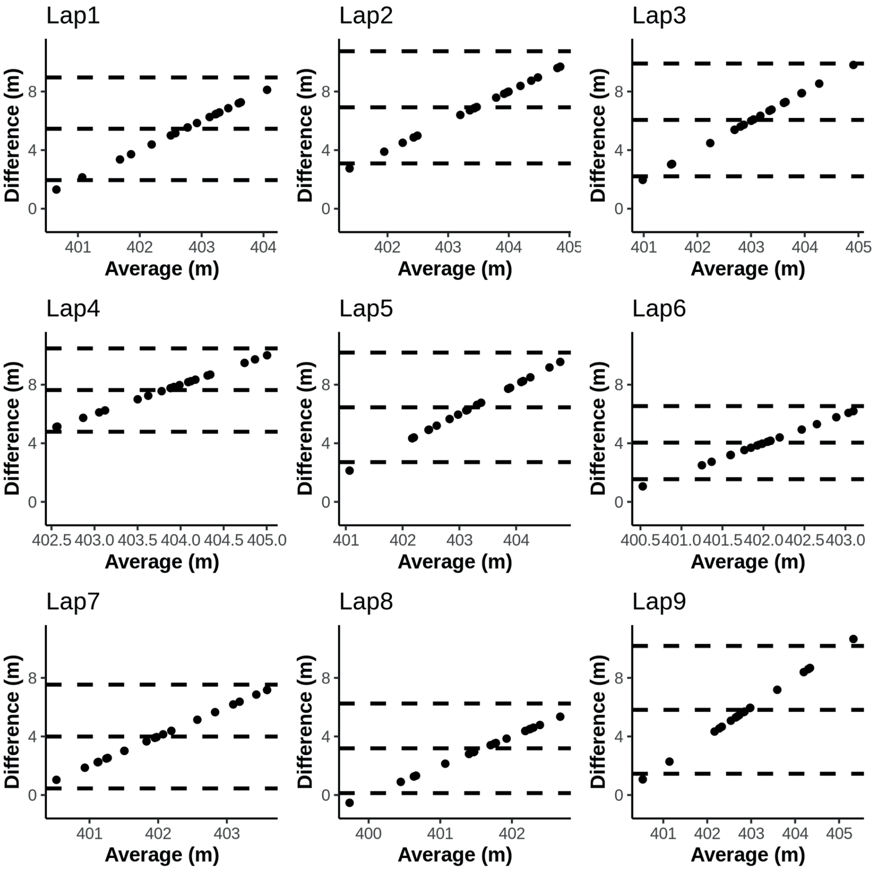

Figure 3. Bland-Altman plots for the total distance registered for each of the nine laps of the 400 m track.

Section 2. 9x400(m) distance at maximum speed

The section tested variability in distance measurement between transmitters for each repetition in the speed qualified as a sprint on the 400 m-long track. Table 2 shows the results obtained. The coefficient of variation ranged between 0.45% for the 8th lap and 0.78% for the 2nd lap.

Section 3. - 9x400 (m) maximum speed

The section tested the speed registered by each transmitter for nine laps on the 400(m) track. Table 3 shows the results. In this case, the coefficient of variation ranged between 0.206% for the 2nd lap and 0.609% for the 5th lap.

Table 1. The total distance registered for each of the nine laps of the 400 m

	Lap								
Nr	1	2	3	4	5	6	7	8	9
Mean distance (m)	405.456	406.922	406.061	407.633	406.454	404.043	403.994	403.188	405.817
SD (±)	1.788	1.954	1.965	1.451	1.908	1.273	1.808	1.561	2.227
Mean Difference (%)	1.364	1.73	1.515	1.908	1.613	1.011	0.998	0.797	1.454
CV (%)	0.441	0.480	0.484	0.356	0.470	0.315	0.447	0.387	0.549
Standard Error of Estimate	5.727	7.179	6.355	7.763	6.716	4.229	4.364	3.532	6.207
95% CI	(4.72; 6.28)	(6.10; 7.80)	(5.21; 6.94)	(6.998; 8.282)	(5.63; 7.292)	(3.501; 4.598)	(3.207; 4.780)	(2.517; 3.907)	(4.861; 6.797)

Table 2. The total distance covered in the sprint for each of the nine laps of the 400 m

	Lap								
Nr	1	2	3	4	5	6	7	8	9
Mean distance (m)	392.29	393.77	395.07	396.86	400.45	402.53	397.15	400.16	401.71
SD (±)	2.29	3.07	2.84	2.10	2.35	2.31	2.02	1.81	2.43
Mean Difference (%)	-1.93	-1.56	-1.23	-0.79	0.11	0.63	-0.71	0.04	0.43
CV (%)	0.58	0.78	0.72	0.53	0.59	0.57	0.51	0.45	0.61
Standard Error of Estimate	8.03	6.91	5.65	3.75	2.33	3.38	3.46	1.77	2.92
95% CI	(-8.67; -6.65)	(-7.60; -4.9)	(-6.16; -3.70)	(-4.05; -2.19)	(-0.54; 1.5)	(1.51; 3.56)	(-3.72; -1.97)	(-0.6; 0.99)	(0.66; 2.79)

Table 3. Mean of the maximum speed registered for each of nine laps of the 400 m

	Lap								
Nr	1	2	3	4	5	6	7	8	9
Mean (m/s)	5.98	6.01	6.12	6.16	6.19	6.19	6.12	6.17	6.19
SD (±)	0.02	0.01	0.01	0.02	0.04	0.02	0.02	0.02	0.02
CV (%)	0.29	0.21	0.21	0.29	0.61	0.25	0.35	0.36	0.34
95% CI	(5.97; 5.99)	(6.01; 6.018)	(6.12; 6.13)	(6.15; 6.17)	(6.17; 6.21)	(6.19; 6.2)	(6.11; 6.13)	(6.16; 6.18)	(6.19; 6.21)

Section 4. – track of 128.5(m)

The section compared the gold standard distance of 128.5(m) to the measured value, to determine validity between these two values. Table 4 presents average differences, CV (%), standard error, average standard deviation and 95% confidence interval. In this test, the p-value obtained equalled 9.23e-7 (determined with the help of a coupled t-test with different variations), and the effect size value was 2.36. A Bland-Altman plot for analysed data was presented in Figure 4. Additionally, CV% in this case was 1.4%.

Table 4. The total distance of each player registered on the track of 128.5 m

Participants	Distance (m)
1	135.307
2	131.954
3	131.005
4	130.81
5	133.865
6	131.127
7	132.162
8	129.648
9	135.159
10	131.244
11	133.821
12	128.702
13	129.982
14	131.704
15	131.796
16	130.394
17	132.892
18	128.809
19	131.042
Mean	131.654
SD (±)	1.890
Mean Difference (%)	2.454
CV (%)	1.435
Standard Error of Estimate	3.651
95% CI	(2.31; 3.95)

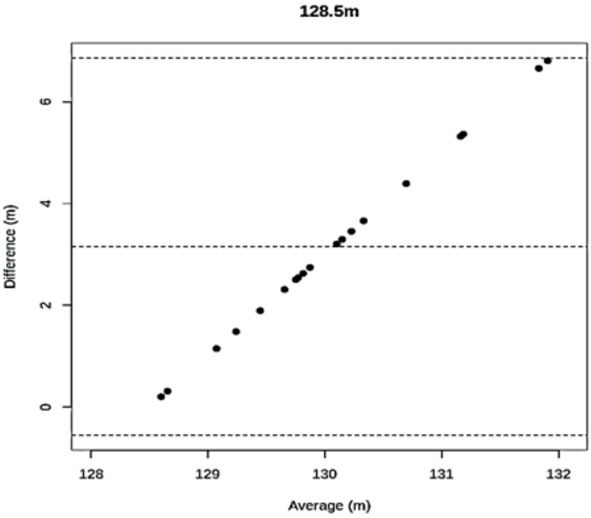

Figure 4. Bland-Altman plot for total distance of each player registered on the track of 128.5(m).

Discussion

The validity and reliability of GNSS TITAN 2 were tested in relation to the gold standard – using tests of 400 (m) and 128.5 (m) in a way proposed by Rawstorn et al. (2014), Muñoz-Lopez et al. (2017), Nikolaidis et al.(2018) in their research. Moreover, we tested variability for maximum speed registered by each transmitter on nine laps on the 400 (m) track and variability between transmitters for each repetition in the distance covered in the sprint on the 400 (m) track. Huggins & Giersch (2020) and Scott et al., (2016) state that the value of the coefficient of variation (CV%) for determining the reliability of the GNSS system in the context of acceptable error admits the following classified values: good (CV < 5%), average (5.1–10%) and weak (CV > 10%). In the test using the electric car, the coefficient of variation for distance obtained by 8 players on the distance of 200(m) in the research by (Nikolaidis et al., 2018) ranged from 1.31% to 2.20%, and in the publication by Rawstorn et al. (2014), the CV value was 2.16%. On the other hand, in the current test, the coefficient of variation for the distance of 400 (m) ranged from 0.32% (the 6th lap) to 0.55% (the 9th lap). Similar results were obtained while determining the distance above the speed classified as a sprint. The coefficient of variation ranged from 0.45% for the 8th lap to 0.78% for the 2nd lap. A similar situation occurred while we tried to determine the peak speed: CV% 0.21 – 0.61. In the research by Nikolaidis et al. (2018), the mean difference (MD) between the GNSS recorded distance, and the reference distance (n = 8.5 laps, distance = 200m) was –0.06 to 1.06% as in the case of the present study the mean difference (%) between the GNSS measurement and 400 (m) distance ranged from 0.79 in the eighth lap to 1.90% in the fourth lap. These results fit the approved accuracy norm below 5% (with small errors, 5%, good) (Huggins & Giersch, 2020). Simultaneously, poor/moderate intra-unit reliability was observed in 400 m (ICC = 0.439, 95% CI 0.211; 0.679). For comparison, a good intra-unit reliability was observed in 200 (m) (ICC = 0.833, 95% CI 0.535; 0.962) in the previously mentioned study of Nikolaidis et al. (2018). During the second protocol, a representative of typical team sport activity profiles during the competition was used according to Coutts & Duffield (2010), to systematically assess the effect of different forms of running and fast change of direction on the validity of distance measurement coming from a previously no validated GNSS device (TITAN2,USA). In article of Huggins & Giersch (2020), the authors demonstrated by measuring total distance (TD) for the Polar Team Pro device, accuracy and reliability measures were below 5% error at all speeds during the 40 m and 100 m line tests and the team sport simulation circuit (TSSC). The mean GPS difference (±SD) for TD during TSSC using extraction methods (a) and (b) was 0.2 ±1.2 and 2.2 ±2.2 m, respectively. Device accuracy in constant velocity (VelC) measurement was significantly different ($p < 0.05$) at all speeds over 40 m and 100 m, with effect sizes ranging from trivial to small. Instantaneous velocity (VelI) during linear running was similar ($p > 0.05$) at all speeds ($p = 0.001$). The device's reliability when measuring VelC at 40 and 100 m was <5% CV, while at a distance of 100 m, VelI ranged from 1.4 to 12.9% (Huggins & Giersch, 2020). However, it is difficult to compare these results due to methodological differences regarding the total distance or the setting of individual test components. They unanimously confirm the need to validate devices of this type. The TITAN2 – GNSS device used in our test was similar to other devices with a sampling frequency of 10 (Hz). This analysis shows that this sensor detects with high accuracy both the maximum speed in the test and the distance in the case of sprint speed. Many research examples show that the effectiveness and reliability of GNSS sensors decrease at speeds above 20 (km/h). Of course, it should be taken into account that the maximum speed of the electric vehicle was only 22 (km/h), so it cannot be definitively stated that there will be no difference at speeds of e.g. up to 35 (km/h). This is a limitation that should be further analyzed in the future. Our tests noted no deviations (maximum test speeds), and the devices worked properly. The reason might be connected to the fact that the manufacturer used the SBAS system cooperating with reference stations of strictly defined locations to generate location correction. What is more, vehicle use may lead to collecting more data in higher speed conditions, in comparison to data collected while testing players during sprint (Jennings et al., 2010; Tomczak & Tomczak, 2014). It results in a probability of obtaining higher accuracy with currently available equipment (Williams & Morgan, 2009). According to Scott et al. (2016) and Malone et al.(2017) it should be underscored that an important element of this test is paying attention to the influence of DOP, and especially HDOP, on the quality of each validation of devices analysing data coming from GNSS. While some researchers describe results obtained from GNSS devices in detail, in the research by Waldron et al. (2011) HDOP was recorded at 1.3 ±0.3 with available satellites ranging between 9 and 12 during the session. The majority of research lacks this information. In our case, this value of HDOP was 1.04 ±0.09 with available satellites 17±1 for the first protocol, and for the second one, HDOP equalled 1.35 ±0.08 with available satellites 18 ±1 and was classified as excellent (Dempster, 2006).

All GNSS devices can read information on the number of satellites and HDOP (Padulo et al., 2018), although not all manufacturers provide their final users with such data, which may result in the above-mentioned situation that not all researchers report the number of satellites and HDOP values.

Conclusions

Based on the analysis of the conducted tests, we came to the conclusion that GNSS devices (TITAN 2; 10-Hz using SBAS system) implemented in this experiment provide accurate and reliable information on the total distance covered during various movement patterns within different speed zones. It concerns especially a distance covered at a speed of ≥19 km/h, defined as a sprint in our case by the device manufacturer. Practitioners and researchers require accurate and reliable athlete tracking data. Our results with TITAN2 demonstrate that the GNNS technology is reliable and trustworthy.

GNSS system manufacturers should introduce information on the signal quality and its potential impact on the error in the final calculations. We can expect this, for example, based on HDOP and vertical dilution of precision VDOP. Additionally, it is suggested to introduce a uniform scale in this area. Recommendation – Average HDOP values from training sessions for a single device from the entire session and all devices should be < 1.00.

Limitations of the study

The main limitation we can identify is that the validity and reliability of other variables associated with accelerations generated by an accelerometer have not been tested.

Future research

Future studies may aim to analyze the use of GNSS sensors in tests resembling small-pitch games, medium-sized games, and large-pitch games in different pitch locations. Furthermore, the influence of cloud cover or rainy weather should be analyzed to increase the usability of the tested GNSS equipment. As technological possibilities are developing we recommend evaluation of hybrid systems – combining GNSS data with VIDEO from stationary cameras with the projection of fixed objects on the pitch and the recognition of the movement trajectories of players, referees, and the ball during match competition and training sessions. Since the artificial intelligence is more popular we recommend testing the use of algorithms based on extreme values to build predictive models estimating the value of e.g., max, and using them in live work in daily training, as well as estimating the level of player performance after which the quality of making correct decisions significantly decreases.

Practical application

A given device's accuracy and validity encourages its users to use it not only in professional but also in amateur sport. It is especially useful in outdoor individual sports and team games for monitoring training consisting of linear movements and direction changes in larger areas. To assess the quality of collected geometric data, one should use the HDOP coefficient, which is a standard tool to quantify the positional precision of the Global Navigation Satellite System, its value should equal ≤ 2, and the authors suggest lowering that value to ≤ 1 while working with professionals. The devices should have the possibility to be coupled with SBAS or other systems enabling communication with referential stations, improving GNSS accuracy and reliability of information, and correcting mistakes.

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