GNSS Positioning Performance Analysis of Smartwatches

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Abstract

Regular physical activities such as walking, running, cycling, swimming, exercising and others are very important for human health. Today, such physical activities have become one of the priorities of both individuals and public administrations within the scope of preventive medicine. The measurement of many parameters related to the physical activities of people, athletes, sports scientists and coaches is very important for performance analysis and management, training planning and program optimization, reliable monitoring of health and performance goals and implementation of correct exercise practices. Typically, Global Navigation Satellite System (GNSS) and other sensors (including altimeter, compass, gyroscope, accelerometer, thermometer, and so on) in smartwatches are used to obtain mainly position, altitude/height, total distance travelled, instantaneous/average/min-max speeds, distance travelled at different speed ranges, pace, frequency/intensity of acceleration/deceleration, pauses, direction, number of steps, biological information, pulse/heart rate, respiration rate, amount of stress, sleep rhythm and hydration and others. The accuracy and reliability of the information provided by GNSS and other sensors on the smart devices is of paramount importance and, in some cases, even vital, to the users. In this study, the positioning accuracy of an embedded GNSS receiver in the Garmin Fenix 7X Solar Sapphire smartwatch has been tested with realistic field measurements under different satellite configurations and different conditions.

Keywords: GNSS, Positioning, Smartwatches, Wearable Technology, Sport.

1. Introduction

Health is of great importance both for people and for public administrations at government level. In this context, for a healthy life, people perform many different physical activities, such as walking, jogging, running, swimming, cycling using their muscles and joints in their daily lives at the level of amateur or professional athletes, in indoor/outdoor places and for different periods. From a public perspective, public administrations are developing policies for preventive health services that prioritize physical activity for communities of healthy individuals and to reduce the high cost of health services. In particular, regular physical activities have positive effects not only on physical health but also on mental and social health. A report by the World Health Organization (WHO) states that physical inactivity is an important factor in many diseases. In Europe, for example, it is estimated that around 10% of total deaths (around 1 million people per year) are caused by physical inactivity. It is also estimated that physical inactivity is the cause of 5% of coronary heart disease, 9% of breast cancer and 10% of colon cancer (WHO, 2016). In fact, the World Health Organization recommends that all adults (aged 18-64 years) should do at least 150 to 300 minutes (2.5 hours to 5 hours) of moderate-intensity aerobic physical activity or at least 75 to 150 minutes vigorous- intensity aerobic physical activity or an equivalent combination throughout the week; children and adolescents (aged 5-17 years) should do at least 60 minutes of moderate- to vigorous- intensity aerobic physical activity per day on average (WHO, 2020). However, in a report published by the European Statistical Office (Eurostat) in 2017, which examines how much time Europeans spend on sports, it is stated that in 2014, 49.8% of the population aged 18 and over in European Union countries, did not do any sports, but 29.9% spent at least two and a half hours a week on physical activities. The proportion of people, who do physical activity for 2.5 hours or more per week, as recommended by the World Health Organization, remains around 5% in Türkiye. The same report also states that 88.2% of the population in Türkiye do not do any sports (Eurostat, 2017). In 2019, a study conducted in Europe found very similar findings to those in the Eurostat 2017 report (Figure 1).

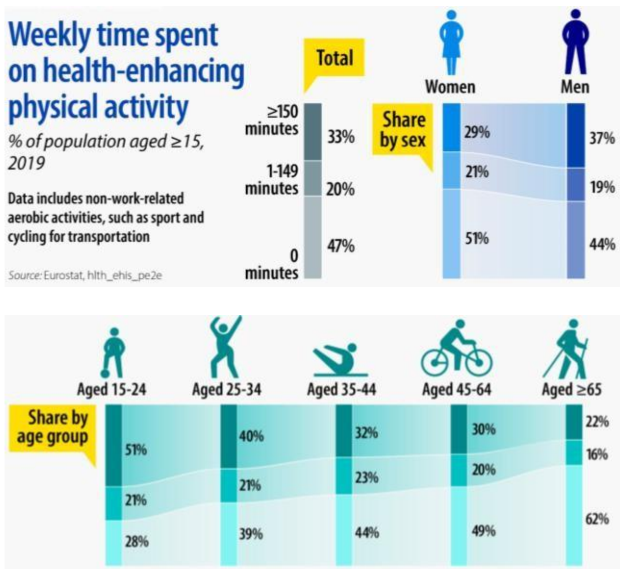

Figure 1. Proportion of weekly time spent on health-promoting physical activities (Eurostat, 2024).

According to the Figure 1, 47% of the groups do not allocate any time for physical activities, 20% allocate between 1 and 149 minutes, and 33% allocate 150 minutes or more for health-promoting physical activities (Eurostat, 2024). This situation in the European Union is undoubtedly also true to a considerable extent in the world in general. As can be seen, the time of physical activity recommended by WHO for a healthy life has not yet been reached in many countries of the world.

Although many activities and projects have been carried out which closely concerns societies and public administrations all over the world, international indicators show that most countries still have a lot of work to do on this issue. As outlined above, it is clear that physical activity for healthy living should not be left to the initiative of individuals, but should be considered as a daily routine practice in the lives of societies within the framework of roadmaps determined according to internationally recognized standards. At this point, it is undoubtedly very important to determine whether the activities have achieved their objectives or not, whether they have been carried out as intended or not and in general terms, to monitor (measure) such activities with numerical indicators. It must be remembered that what cannot be measured cannot be managed. Therefore, the information obtained from smartwatches, one of today's most widely used wearable technologies, has an important place and play critical role. In this study, the positioning accuracy of an embedded GNSS receiver in a smartwatch has been analysed and tested with realistic field test measurements under different surveying scenarios.

2. Use of Wearable Technology in Health and Sports

As stated in the previous section, it is clear that there is much work to be done to increase the number of people who engage in regular physical activity below the times recommended by world health authorities and that intensive work on this issue must continue. In this process, the activities to be carried out, whether on a personal or professional level, need to be done within the framework of a specific plan and with concrete goals. As a result of the developments in technology, wearable technologies (or wearable devices), which include hardware such as smartwatches, smart clothing, body sensors, smart glasses, fitness tracking devices, heart rate monitors, blood pressure monitors, electronic devices, jewelry, and video devices, undoubtedly have a critical and important role in this period. With these devices, real-time access to much physical and physiological data/information can be provided.

These devices fulfill an important task by providing support to recreational individuals, athletes, sports scientists, strength and conditioning specialists, performance analysts and coaches in the following areas:

- monitoring and analyzing real-time performance based on training or competition,
- making personal training plans,
- maximizing the potential of athletes, increasing their performance, and developing their technical levels.

The most commonly used wearable technology to obtain the above-mentioned information is undoubtedly smartwatches. These devices with different functions measure and track people's physical activities, various physiological and similar parameters with the help of many different sensors and use this dataset and make various suggestions to users. These different types of information obtained from the devices are extremely important for individual physical activity practitioners, athletes, and all other types of users. These devices are widely used in sports applications such as brisk walking, running, swimming, fitness, and exercise; and provide data on many different types of activities and body functions for athletes, their coaches, and other users, including position, height/altitude, total distance covered, instantaneous speed, average speed, min/max speed, distance covered at different speed intervals, tempo, acceleration/deceleration frequency-intensity, pauses, duration (longest duration of staying above a certain speed, etc.), direction, number of steps, biological information, pulse/heart rate, respiratory rate, amount of stress, sleep rhythm, and hydration, using the Global Navigation Satellite System (GNSS) as well as other sensors (depth, altimeter, compass, gyroscope, accelerometer, thermometer, ambient light sensor, etc.). In addition, it is possible to determine the route of the activity or to determine different alternative routes with the GNSS technique. With the GNSS, people or athletes who do recreational activities not only have information about their own activities and activity routines; they can also examine their physical, technical, and tactical skills, determine their sports performance and observe their development, determine what they need to do to achieve their goals, and monitor whether they have achieved their physical activity goals. The validity, accuracy, and reliability of this information/data/values obtained are of great importance.

The GNSS positioning method, which consists of the United States' Global Positioning System (GPS), Russia's GLObalnaya NAvigatsionnaya Sputnikovaya Sistema or Global Navigation Satellite System (GLONASS), the European Union's Galileo, and the People's Republic of China's BeiDou Navigation Satellite System (BDS), is used extensively for obtaining information about personal or professional physical activities for recreational purposes and for performance monitoring in addition to many different areas of use; it is also widely used in team sports such as football, rugby, hockey, triathlon, netball, lacrosse and individual sports such as tennis, cycling, ski jumping, athletics, and skiing.

According to the “EO and GNSS Market Report 2022” report published by the EU Agency for the Space Programme (EUSPA), it is estimated that the annual sales of GNSS receivers will reach 2.5 billion in 2031; more than 9 billion GNSS receivers will be used worldwide (EUSPA, 2022). While approximately 65 million of the annual sales on a device basis were sports and wearable devices in 2020, this number exceeded 100 million in 2022. As of 2023, the number of sports and wearable devices with GNSS has approached almost 300 million, and this number is expected to reach 700 million in 2033 (Figure 2) (EUSPA, 2024).

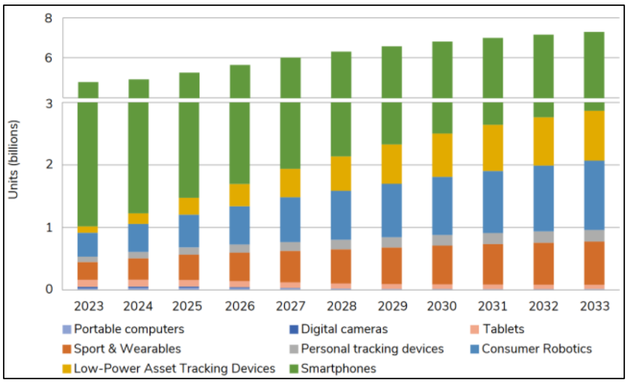

Figure 2. Number of GNSS receivers used in the positioning sector by type (EUSPA, 2024).

Since the position (coordinates), speed (instant, average, min/max), distance covered, number of steps, altitude values, and many other information derived from those obtained from GNSS receivers found in smartwatches used in different sports fields are of critical importance, these values need to be determined reliably and with sufficient accuracy. Because this information is used in most sports planning and analysis. However, almost no information is shared by the manufacturers regarding the positioning accuracy and performance of the GNSS receiver in the smartwatches, and it is not possible to obtain any information about the performance of such devices other than the information provided in the limited number of studies in the literature (Supej and Čuk, 2014; Ciećko et al., 2017; Gløersen et al., 2018; Lee et al., 2020; Johansson et al., 2020; Gilgen-Ammann et al., 2020; Szot et al., 2021; Vorlíček et al., 2021; Dumas 2022; Mikoś et al., 2024; Szot and Sontowski, 2024). The most widely used smart sports watches on the market currently perform real-time 3D point positioning with Single Point Positioning (SPP), an absolute positioning method based on code measurements (Mikoś et al., 2024). In addition to affecting the accuracy of the GNSS technique, atmospheric errors originating from the ionosphere and troposphere, satellite orbit and clock errors, and receiver-related errors, there are also some other error sources (such as electromagnetic noise in the device, antenna size and its structure, high dynamic motion, body/clothes partially or completely blocking healthy GNSS signal reception, and high multipath and noise) originating from the usage patterns and nature of smartwatches (wearable technologies). Due to all these negative factors, position and other position-related information can be determined with low accuracy and even incorrectly in some cases. In this case, for example, the distance covered may be calculated incorrectly, and the practitioners' training development may be misinterpreted, or it may not be possible to realistically achieve the goals set based on distance. Similarly, inaccuracies in the information obtained from the GNSS receiver of smartwatches may lead to misinterpretation of a runner's post-run performance, changes in tempo, and altitude changes on the route, which may result in incomplete/incorrect/inaccurate identification of improvement areas and incorrect organization of training regimes. However, considering that there is very limited literature on the subject, it would be coclude that there is a lot of work to be done to reveal the accuracy performance of such devices with scientific approaches.

3. Materials and Methods

In this study, the accuracy performance of the smart sports watch was investigated within the three stages:

i-) Providing a suitable device and making it ready for measurement,
ii-) Performing static and kinematic field tests,
iii-) Evaluating and analyzing the collected data.

These stages are outlined below:

***i*-) Providing a suitable device and making it ready for measurement:** Within the scope of the study, it was decided to use a Fēnix 7X Sapphire Solar model smart sports watch (hereinafter referred to as the device) recently launched by Garmin Ltd., commonly known smartwatch manufacturer in the world. In the first phase of the study, all the necessary preliminary work to perform the measurements was done, and the software required collecting and export position data was provided. Some of the prominent technical features of the device are given in Table 1 (Garmin, 2025).

General	Physical size: 51 x 51 x 14.9 mm Weight: 89 g (case only: 61 g) Display size: 1.4” (35.56 mm) diameter Display resolution: 280 x 280 pixels Memory: 32 GB GPS Time Sync
Sensors	Multi-band GNSS (GPS, GLONASS, Galileo), SatIQ™ Technology, Garmin Elevate™ wrist heart rate monitor, Pulse Ox Blood Oxygen Saturation Monitor, Barometric altimeter, Compas, Gyroscope, Accelerometer, Thermometer
Connectivity	Bluetooth, ANT+, Wi-Fi
Health & Wellness Monitoring	Wrist-based heart rate, Resting heart rate, Abnormal heart rate alerts, Respiration rate, Fitness age, Body Battery energy monitor, All-day stress, Relaxation breathing timer, Breathwork, Sleep, Sleep coach, Nap detection, Hydration, Women's health, Health snapshot, Jet lag adviser

Table 1. The main specifications of the used smartwatch

***ii*-) Performing static and kinematic field tests:** In order to assess the positioning performance of the smartwatch's GNSS receiver, a series of static and kinematic test measurements were carried out at the ITU Ayazağa Campus with the Garmin Fēnix 7X – Sapphire Solar Smartwatch.

For the static test (referred to as Test 1), measurements were carried out for about 3 hours on December 20, 2024 (GPS Day of Year: 355) with a 1-second sampling rate at a known reference point that was installed on the roof of ITU Faculty of Civil Engineering, where the sky conditions were as clear as possible and the factors that negatively affect the measurements, such as multipath and noise, were minimal (Figure 3).

(a) (b) (c)

Figure 3. Garmin Fēnix 7X – Sapphire Solar Smartwatch used in the study (a); Static test measurement (b&c).

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Since smart sports watches do not allow for providing raw GNSS data, relative positioning is not yet possible. Additionally, it is not possible to perform RTK positioning based on phase measurements. For this reason, as mentioned before, smart sports watches determine 3D point positions using the Single Point Positioning (SPP) method (Mikoś et al., 2024).

In order to investigate the kinematic GNSS positioning performance of the smartwatch, two separate tests were performed at different speeds (normal walking referred to as Test 2 and brisk walking referred to as Test 3) on the track in the stadium located at ITU Ayazağa Campus on December 23, 2024 (GPS Day of Year: 358) for periods ranging from approximately 15 to 30 minutes (Figure 4). Through the test measurements, the 3D geodetic coordinates (geodetic latitude/longitude and height) were recorded in real-time with a 1-second sampling rate.

In order to assess the accuracy performance of this receiver, it is necessary to obtain the known coordinates of each measurement epoch. For this purpose, a Garmin smartwatch and CHC i80 geodetic-grade GNSS receiver were connected to the same measurement pole and simultaneous measurements were conducted (see Figure 4). Thus, GNSS measurements could be made under almost identical conditions to the Garmin smartwatch and CHC i80 geodetic-grade GNSS receiver. The coordinates of each measurement epoch with cm-level accuracy were determined with the Network RTK (NRTK) method using the CHC i80 receiver and used as known coordinates.

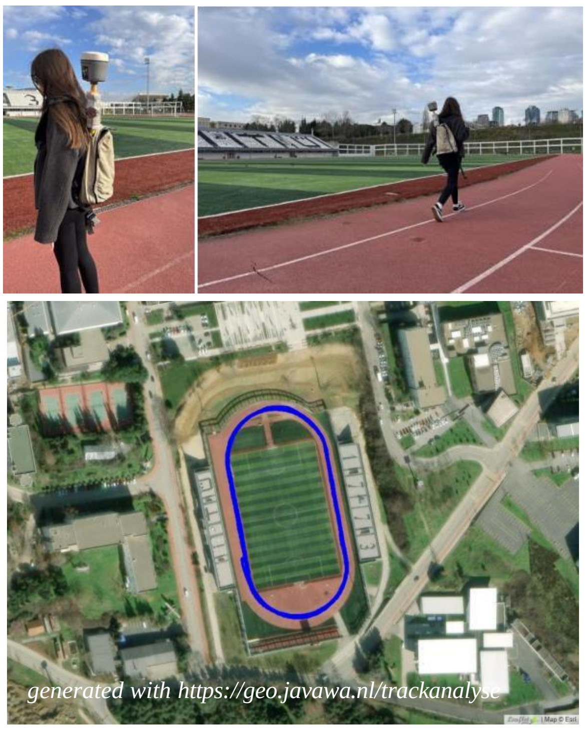

Figure 4. Kinematic test measurements on the track in the stadium.

On the other hand, in order to determine how the use of different satellite systems affects the measurement accuracy, all three-test measurements described above (Test 1-static measurement, Test 2-normal walking and Test 3-brisk walking) were performed twice each with GPS-only and multi-GNSS options.

***iii*-) Evaluating and analyzing the collected data:** The coordinates obtained from the Garmin smartwatch were compared with the NRTK (known) coordinates for each measurement epoch to determine the 2D position and height accuracy of the GNSS receiver in the device. The calculated differences are given in Figure 5 for static test measurement and Figure 6 and Figure 7 for kinematic test measurements.

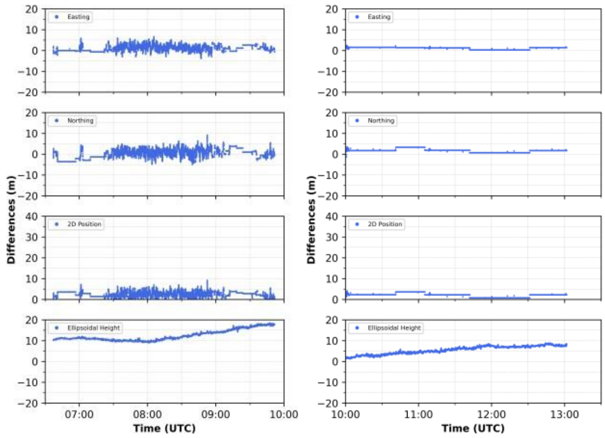

Figure 5. The differences between Static Garmin smartwatch and known coordinates for G-only (*left*); for multi-GNSS (*right*)

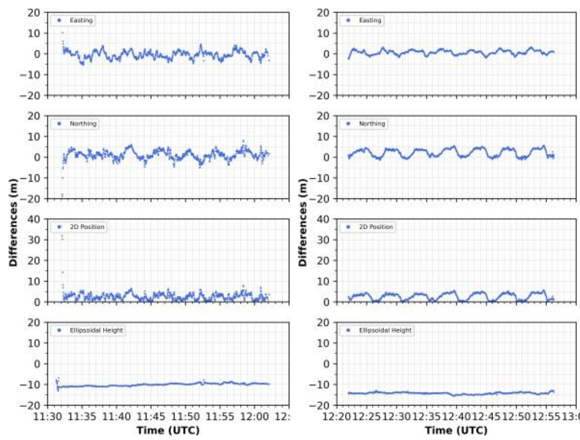

Figure 6. The differences between normal walking Garmin smartwatch and known coordinates for G-only (*left*); for multi-GNSS (*right*)

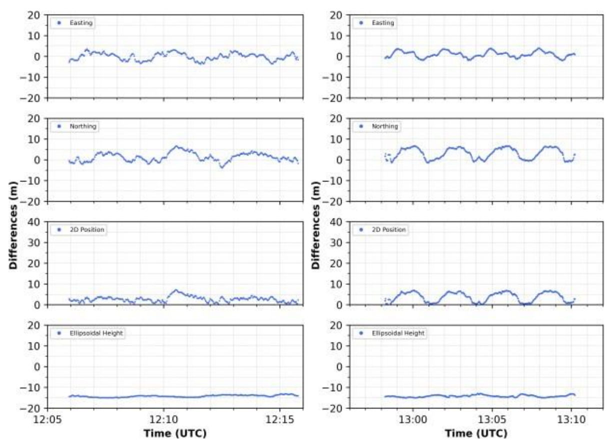

Figure 7. The differences between brisk walking Garmin smartwatch and known coordinates for G-only (*left*); for multi-GNSS (*right*)

The differences were also investigated statistically, including minimum, maximum, and mean values for 2D position and height components with corresponding Standard Deviation (STD) and Root Mean Square Error (RMSE) in Table 2.

Static	**G-only**		**multi-GNSS**	
	2D (m)	**h (m)**	**2D (m)**	**h (m)**
Min.	0.0	9.0	0.8	1.2
Max.	9.2	18.4	4.2	8.8
Mean	2.5	12.4	2.1	5.5
STD	1.2	2.6	0.9	1.9
RMSE	2.8	12.7	2.3	5.9

(a)

Normal Walking	**G-only**		**multi-GNSS**	
	2D (m)	**h (m)**	**2D (m)**	**h (m)**
Min.	0.0	-11.2	0.0	-15.5
Max.	8.0	-7.8	5.7	-12.8
Mean	2.6	-10.0	2.7	-14.2
STD	1.4	0.6	1.5	0.4
RMSE	2.9	10.1	3.1	14.2

(b)

Brisk Walking	**G-only**		**multi-GNSS**	
	2D (m)	**h (m)**	**2D (m)**	**h (m)**
Min.	0.2	-15.0	0.0	-15.0
Max.	7.2	-13.1	7.0	-12.9
Mean	2.7	-14.2	3.7	-14.2
STD	1.3	0.5	2.2	0.5
RMSE	3.0	14.2	4.4	14.2

(c)

Table 2. Statistical analysis of the differences for Test 1-*static measurement* (a), Test 2-*normal walking* (b) and Test 3-*brisk walking* (c)

As a result of all these findings, the following concluding remarks could be stated for the static test:

- According to the comparison results of the static measurements, the Root Mean Square Error (RMSE) of 2D horizontal position was found as 2.8 m for GPS-only and 2.3 m for multi-GNSS. For the height component, the RMSE values were obtained as 12.7 m for GPS-only and 5.9 m for multi-GNSS constellation. The results obtained from the static measurements show that the multi-GNSS satellite configuration improves the horizontal and vertical positioning accuracy in terms of RMSE when compared to GPS-only positioning.

- The standard deviation (STD) of the 2D horizontal position were calculated as 1.2 m for GPS-only, 0.9 m for multi-GNSS, while 2.6 m and 1.9 m for the height component, respectively. When both RMSE and STD values are investigated together, it is seen that there are big mean values. Thus, it is seen that the precision of the position obtained with the smartwatch is high, but its accuracy is low.

- Looking at Figure 5, the maximum differences in the 2D position were reached at 9.2 m for G-only while 4.2 m for multi-GNSS. For the height component, the maximum differences were reached at 18.4 m for G-only positioning while 8.8 m for multi-GNSS positioning.

According to these static results, it has been observed that the multi-GNSS satellite constellation improved positioning accuracy. However, it was observed that the smartwatch performed lower than expected even in measurements made under very good environmental and atmospheric conditions.

The following evaluations were made regarding the results of kinematic measurements made at two different walking speeds:

- When we looked at the 2D RMSE values calculated from the differences between the coordinates obtained from kinematic measurements and the known coordinates, the accuracy value for G-only was found to be 2.9 m for normal walking and 3.0 m for brisk walking. For multi-GNSS, these values were obtained as 3.1 m and 4.4 m, respectively. For the height component, the RMSE value was found to be 10.1 m for G-only and 14.2 m for multi-GNSS in normal walking, while the height accuracy was obtained as 14.2 m for both satellite configurations in brisk walking.

- When the STD values calculated from the differences obtained from the normal walking evaluation results were investigated, the STD value of approximately 1.5 meters in the horizontal position (2D) and approximately 0.5 m in height was obtained for both G-only and multi-GNSS. According to the comparison results of the coordinates obtained from brisk walking with the reference coordinate value, a STD value of 1.3 m for G-only and 2.2 m for multi-GNSS was obtained in 2D position. The STD value of the height component was obtained as 0.5 m for both satellite constellations.

- Looking at Figure 6 and Table 2b, the maximum differences in the 2D position reached 8.0 m for G-only positioning and 5.7 m for multi-GNSS for normal walking. For the height component, the maximum differences were 11.2 m for G-only positioning and 15.8 m for multi-GNSS positioning. Concerning brisk walking (please look at Figure 7 and Table 2c), the maximum differences in the 2D position reached 7.2 m for G-only positioning and 7.0 m for multi-GNSS constellations. For the height component, the maximum differences were found to be 15.0 m for both satellite configurations.

- The kinematic tests' results showed that the horizontal and vertical position accuracy slightly decreases as the walking speed increases. This situation indicates that the kinematic measurements made at different walking/running speeds affect the positioning accuracy (accuracy decreases as the movement speed increases). It was also observed that the option to use the multi-satellite system available in the smartwatch did not improve the kinematic positioning accuracy.

When the results obtained from the study were investigated, it was seen that the tested device provided horizontal positioning accuracy in the order of meters and height accuracy several times worse. It was seen that the positioning accuracies obtained with these smartwatches, which have their own hardware limitations, antennas with low measurement performance and size, and observations with higher multipath and noise, are very similar to the accuracies expected from the classical SPP method. In this case, it has been shown that sports watches can be easily used for many activities, especially performance analysis and management, training planning, training program optimization, reliable monitoring of health and performance goals, and implementation of correct exercise practices by sports scientists and coaches.

4. Conclusions

In this study, the static and kinematic positioning performances of the embedded GNSS receiver in Garmin's Fenix 7X Solar Sapphire smartwatch are investigated under different measurement conditions (static and kinematic) and for different satellite configurations (GPS-only and multi-GNSS). According to the results of the study, it was seen that horizontal and vertical positioning accuracy at the several meters level can be achieved with this smart device. It was also revealed that the positioning performance is affected by different motion speeds, measurement conditions and satellite configurations.

In general, having realistic and reliable information about the accuracy of positioning obtained from embedded GNSS in smart devices, which plays an important role in monitoring and analysing real-time performance based on training or competition, making personal training plans, maximizing the potential of athletes, increasing their performance and improving their technical level, is critical for more realistic programming and analysis of exercises/workouts and achieving health and sports goals more effectively. From this point of view, it was evaluated that the results obtained from the study will guide those who are engaged in personal or professional recreational activities, sports, exercise, sports scientists, experts, performance analysts and coaches and will also provide support for their analysis.

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