Electronics Letters

LETTER OPEN ACCESS

Implementation and Performance Analysis of RTK-GNSS in Wearable Devices for Athletes in Harsh Environments

Mingu Kim[1] | Bit Kim[2] | Chulwoo Park[2] | Jinsung Yoon[2]

[1]Division of Mechanical and Electronics Engineering, Hansung University, Seoul, Republic of Korea | [2]Fitogether Inc., Seoul, Republic of Korea

Correspondence: Mingu Kim (mingukim@hanusung.ac.kr)

Received: 4 June 2024 | **Revised:** 26 March 2025 | **Accepted:** 29 April 2025

Funding: This research was financially supported by Fitogether Inc. This is part of Fitogether's ongoing work as a "FIFA Preferred Provider for Live Player Tracking".

ABSTRACT

This study presents the performance analysis of RTK-GNSS (real-time kinematic global navigation satellite system) mounted on wearable devices for athletes in harsh environments. GNSS signal can deteriorate by obstacles, i.e. stadium roofs, due to the high GDOP (geometric dilution of precision). RTK-GNSS is used to overcome harsh environment problems in this study. Hardware experiments are performed to analyse the performance of RTK-GNSS in sports wearable devices in harsh environments. The full pitch tracking test results of a wearable device equipped with RTK-GNSS demonstrate the best performance among three different wearable devices in a harsh environment; the maximum positioning error of 1.56 m is approximately 3–30 times smaller than that of wearable devices equipped with stand-alone GNSS. The distance test results of the wearable device equipped with RTK-GNSS validate the most accurate performance, 98.97%, compared to the true value in harsh environment.

1 | Introduction

Performance analysis of professional sports players has become increasingly critical. High quality athlete data is essential for accurate performance evaluation. GNSS (global navigation satellite system) can provide data to track the position and velocity of athletes in outdoor sports, and RTK-GNSS (real-time kinematics global navigation satellite system) has been widely studied in various fields, for instance, industrial geodesy for surveying and mapping, precision agriculture, and aerospace systems.

RTK-GNSS has been successfully applied to formation flight of high Earth orbit spacecraft [1], swarm flight of UAV (unmanned aerial vehicles) [2], and precise landing for a reusable rocket [3]. Additionally, RTK-GNSS has been utilized for autonomous farm tractors and ground vehicles for precision agriculture [4, 5], studying the dynamic behaviour of high buildings [6], improving performance in harsh urban environment using three-dimensional mapping databases [7], and robust positioning method based on the existence of non-line-of-sight signals in challenged environments [8].

Despite the wide range of RTK-GNSS applications, the utilization of RTK-GNSS in the sports field remains relatively unexplored, with only a few studies [9–12]. Although there have been some cases of RTK-GNSS technology being used in the sports field, mostly hardware tests have been performed using large equipment. In sports, the accuracy of position and velocity data is important to evaluate player performance. In particular, many football players engage in football matches and training sessions in outdoor stadiums, some of which have roofs. However, the GNSS signal can be degraded by roofs or obstacles in stadiums, making the collecting of highly accurate position and velocity data of athletes challenging.

In this study, we investigate the implementation of RTK-GNSS technique in wearable EPTS (electronic performance and tracking system) for football players to obtain highly accurate position and velocity data, even in harsh environments. EPTS is one of the devices that provide athletes with movement data and performance metrics, i.e. speed, acceleration, and heart rate. To address the challenges posed by harsh environments, we propose the implementation of RTK-GNSS in wearable EPTS for football players in this study. We perform hardware experiments to validate the performance of the proposed RTK-GNSS mounted on wearable devices. We compare the performance of the proposed RTK-GNSS-mounted wearable device with that of the stand-alone GNSS-mounted wearable devices in an open stadium without roofs, a half-closed stadium, and a fully-closed stadium with roofs.

2 | Proposed Method

The relative positions of GNSS satellites affect GNSS positioning accuracy due to errors in distance measurements from GNSS signals. The positioning accuracy can be quantified using the concept of GDOP (geometric dilution of precision) and the measurement errors.

Many stadiums have roofs, and therefore, visible satellite distribution geometry is restricted. It means that poor GDOP values are observed in stadiums with roofs, and the presence of stadium roofs can cause GNSS positioning accuracy to be lower. Accurate positioning of football players during matches or training sessions is crucial for analysing and improving players' performance. To enhance the positioning accuracy in harsh environments, RTK-GNSS is adopted for wearable EPTS for football players in this study.

GDOP can be calculated by using the location information of visible GNSS satellites. The line-of-sight matrix, $\mathbf{H}$, is represented using the location information of satellites as

$$\mathbf{H} = \begin{bmatrix} a_{x,1} & a_{y,1} & a_{z,1} & 1 \\ a_{x,2} & a_{y,2} & a_{z,2} & 1 \\ a_{x,3} & a_{y,3} & a_{z,3} & 1 \\ a_{x,4} & a_{y,4} & a_{z,4} & 1 \end{bmatrix} \tag{1}$$

where the $a_{x,i}$, $a_{y,i}$, and $a_{z,i}$ represent the x, y, z-axis unit vector components of the ith satellite, respectively.

The covariance matrix and GDOP can be calculated as follows.

$$\mathbf{C} = \left(\mathbf{H}^T\mathbf{H}\right)^{-1} = \begin{bmatrix} D_{11} & D_{12} & D_{13} & D_{14} \\ D_{21} & D_{22} & D_{23} & D_{24} \\ D_{31} & D_{32} & D_{33} & D_{34} \\ D_{41} & D_{42} & D_{43} & D_{44} \end{bmatrix} \tag{2}$$

$$\text{GDOP} = \sqrt{D_{11} + D_{22} + D_{33} + D_{44}} \tag{3}$$

The positioning accuracy, σ_{pos}, can be calculated using the covariance of user measurement error, σ_{UERE}, as follow.

$$\sigma_{\text{pos}} = \text{GDOP} \cdot \sigma_{\text{UERE}} \tag{4}$$

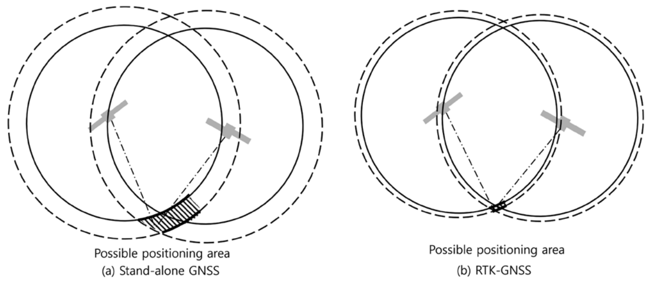

Figure 1 | The possible positioning areas: (a) stand-alone GNSS positioning, (b) RTK-GNSS positioning.

The positioning accuracy is affected by the measurement error, and RTK-GNSS has a smaller covariance of user measurement error compared to stand-alone GNSS.

RTK-GNSS is a method for improving the positioning performance of GNSS by using correction information from one or more base stations at known locations. GNSS signals consist of a PRN (pseudo-random noise) code and a carrier phase code. The carrier phase code provides more precise information than the PRN code due to its shorter wavelength. The carrier phase measurement, which is used in RTK-GNSS, can be obtained using the following Equation (5).

$$\phi = \rho - I + T + c(b_{\text{rcv}} - b_{\text{sat}}) + N\lambda + e_{\phi} \tag{5}$$

where ϕ is the carrier phase measurement, ρ is the distance between a satellite and a receiver, I is the ionosphere error, T is the troposphere error, c is the speed of light, b_{rcv} is the clock bias at a receiver, b_{sat} is the clock bias at a satellite, N is the integer ambiguity, λ is the carrier nominal wavelength, and e_{ϕ} is the measurement noise components. Then, errors can be reduced through a double-differencing method utilizing carrier phase measurements obtained from multiple receivers and satellites [13]. Consequently, we propose the implementation of RTK-GNSS in wearable EPTS to improve positioning accuracy in harsh environments in the study.

Aforementioned, GDOP is determined by the geometric information of visible GNSS satellites. It implies that the values of GDOP in a stand-alone GNSS system and a RTK-GNSS system are not significantly different. However, the error range of RTK-GNSS signals is smaller than that of stand-alone GNSS signals due to the error correction. Figure 1 shows the positioning areas of stand-alone GNSS and RTK-GNSS. The possible positioning area of RTK-GNSS is narrower than that of stand-alone GNSS, due to the smaller user measurement error of RTK-GNSS. Consequently, according to Equation (4), RTK-GNSS systems achieve better positioning accuracy than stand-alone GNSS systems.

3 | Hardware Experiment Environments

Hardware experiments were performed to validate the performance of the RTK-GNSS for a wearable EPTS for football players. The performance of the wearable EPTS applied to the proposed RTK-GNSS technique was compared with the performance of two commercial wearable EPTS systems with stand-alone GNSS

Table 1 | The specification of GNSS receivers.

	Position accuracy	Velocity accuracy	Update rate
RTK-GNSS	0.01 m	0.05 ms^{-1}	10 Hz
Stand-alone GNSS A	2.00 m	0.05 ms^{-1}	10 Hz
Stand-alone GNSS B	2.50 m	0.05 ms^{-1}	18 Hz

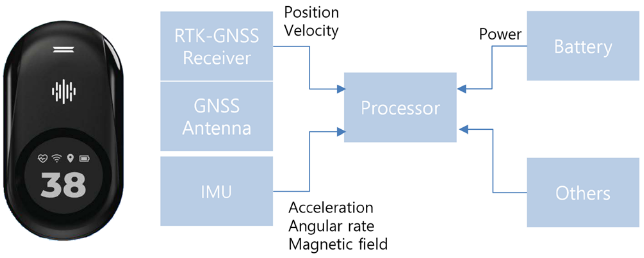

Figure 2 | A wearable EPTS of football player and the device architecture.

Figure 3 | Three athletes, wearing three different EPTS systems, walking along the track in a stadium for field tests (right).

technique. EPTS A and EPTS B with stand-alone GNSS provide GNSS data at 10 Hz and at 18 Hz, respectively. The horizontal position and velocity accuracies of the EPTS A with stand-alone GNSS are 2.00 m and 0.05 ms^{-1}, respectively [14]. The horizontal position and velocity accuracies of the EPTS B with stand-alone GNSS are 2.50 m and 0.05 ms^{-1}, respectively [15]. Table 1 summarizes the specifications of the GNSS receivers used in the study. Figure 2 shows the designed wearable EPTS integrating an RTK-GNSS receiver, an IMU (Inertial Measurement Unit), and other components, along with the device architecture.

Field tests with athletes wearing an EPTS were performed in three different environments: an open environment (Hyochang stadium), a half-closed environment (Jeju statium), and a closed environment (Daegu stadium). Three athletes, wearing three wearable EPTS systems, walked along track simultaneously at a speed of approximately 1.4 ms^{-1} in three environments. Figure 3 shows three athletes, wearing three different EPTS systems, walking along the track in a stadium for field tests.

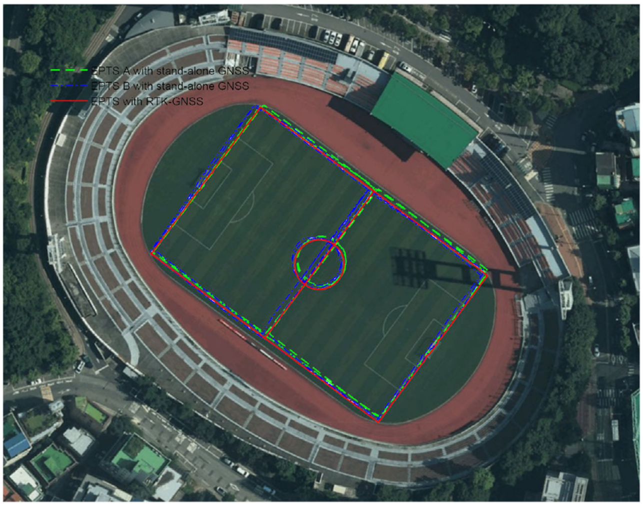

Figure 4 | Full pitch tracking result in Hyochang stadium (Open environment).

4 | Full Pitch Tracking Tests

Full pitch tracking tests were first performed in three different environments. Lines of the full pitches marked along the edges in stadiums. It implies that the experiment environments posed a challenge in receiving GNSS signals in Jeju and Daegu stadiums, due to the presence of the roofs. Figure 4 shows full pitch tracking results using three wearable devices with different GNSS technique in Hyochang stadium (open environment) located in Seoul. In Figure 4, the green dashed line denotes the result of EPTS A with stand-alone GNSS, the blue dashed-dot represents the result of EPTS B with stand-alone GNSS, and the red line is the result of EPTS with RTK-GNSS. In the open environment, three wearable devices utilizing RTK-GNSS and stand-alone GNSS demonstrate good tracking performance. Notably, the wearable device equipped with the proposed RTK-GNSS exhibits more accurate and precise compared to other wearable devices utilizing stand-alone GNSS.

Figure 5 shows full pitch tracking results using three wearable devices with different GNSS technique in Jeju stadium (half-closed environment). The wearable device equipped with the proposed RTK-GNSS shows the best performance to track the full pitch of Jeju stadium, despite the presence of stadium roofs on one side as shown in Figure 5. However, the wearable devices equipped with stand-alone GNSS perform have less accurate and precise tracking performance due to the stadium roofs.

Figure 6 shows full pitch tracking results using three wearable devices with different GNSS technique in Daegu stadium (closed environment). In Daegu statium, stadium roofs are installed on all sides, making Daegu stadium the most harsh environment for GNSS tracking among the three stadiums. The wearable device equipped with the proposed RTK-GNSS shows the best performance to track the full pitch of Daegu stadium, despite the presence of small tracking errors near the centre line as shown in Figure 6. However, the full pitch tracking performance of the wearable devices equipped with stand-alone GNSS is degraded in Daegu stadium. In particular, it is extremely challenging for

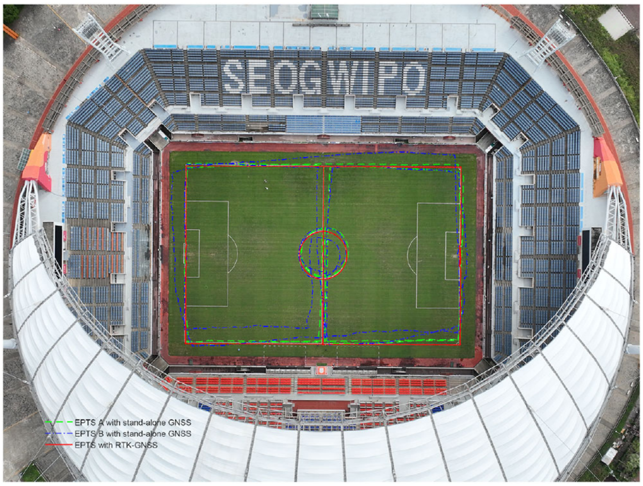

Figure 5 | Full pitch tracking result in Jeju stadium (half-closed environment).

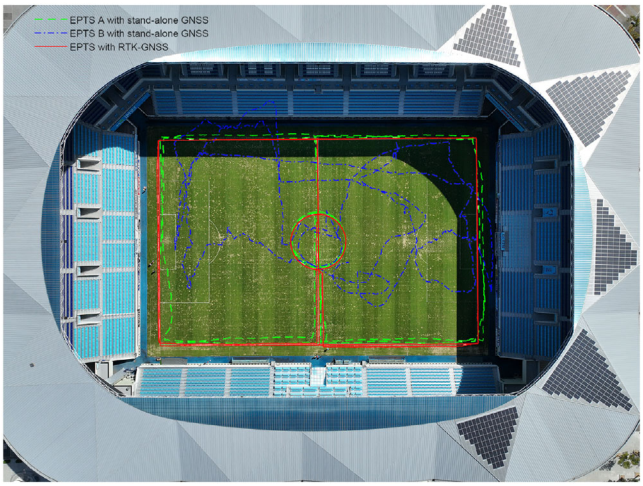

Figure 6 | Full pitch tracking result in Daegu stadium (closed environment).

the wearable EPTS B with stand-alone GNSS to achieve full pitch tracking in Daegu stadium as shown in Figure 6.

Tables 2 summarizes the full pitch tracking maximum errors using three different wearable EPTS in three different environments. The tracking errors are calculated by the difference between the true position data and the measured position data. Note that true position data are provided from National Geographic Information Institute of Korea. The full pitch tracking results of the wearable device equipped with the proposed RTK-GNSS technology validate the most accurate performance, the

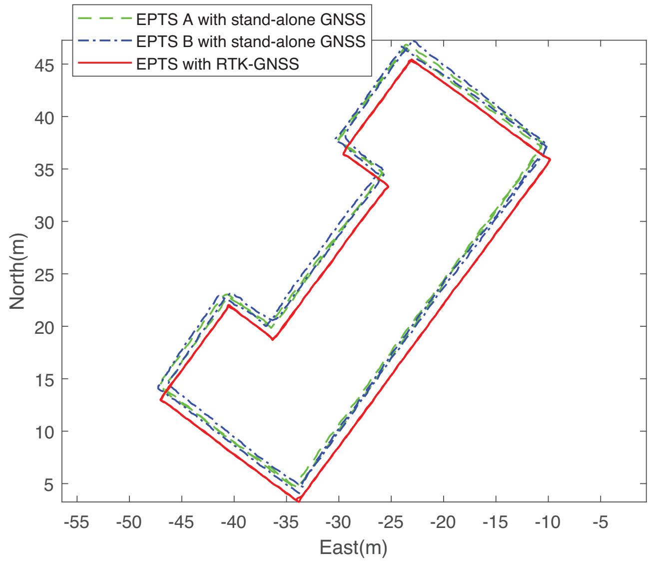

Figure 7 | Penalty area tracking results in Hyochang stadium (open environment).

maximum errors of 0.15 m, 0.24 m, and 1.56 m, compared to other wearable devices equipped with a stand-alone GNSS technology in all three environment. The RMSE (root mean square error) and STD (standard deviation) of the wearable device equipped with the proposed RTK-GNSS technology are the smallest values in all three environments as shown in Table 2. This means that the wearable device with RTK-GNSS shows more stable and accurate performance than other devices with stand-alone GNSS.

5 | Distance Tests

Distance tests were performed to measure the perimeter of penalty areas in three different environments. One essential performance metrics in football is the distance covered by a professional player. In modern football tactics, midfielders are expected to cover greater distances or wider areas during matches. Accordingly, it is important to provide accurate information of distance covered by football players. The overall dimensions of full pitches can vary, but the dimensions of penalty areas should comply with FIFA standards, since fouls within the penalty area can significantly impact match results. According to FIFA standards, the perimeter of the penalty areas should be 124.60 m [16]. The penalty area tracking results are illustrated in ENU (East-North-Up) coordinates, and the origin of ENU coordinates is the given reference point of each stadium.

Figure 7 shows penalty area tracking results using three wearable devices with different GNSS technique in Hyochang stadium

Table 2 | The full pitch tracking evaluation metrics: maximum errors (RMSE, STD).

	Hyochang	Jeju	Daegu
EPTS (RTK-GNSS)	0.15 m (0.14 m, 0.01 m)	0.24 m (0.21 m, 0.02 m)	1.56 m (0.51 m, 0.21 m)
EPTS A (stand-alone GNSS)	1.76 m (1.70 m, 0.17 m)	1.77 m (0.80 m, 0.29 m)	4.05 m (2.46 m, 0.61 m)
EPTS B (stand-alone GNSS)	2.21 m (2.14 m, 0.24 m)	6.58 m (4.77 m, 0.43 m)	37.17 m (22.06 m, 6.23 m)

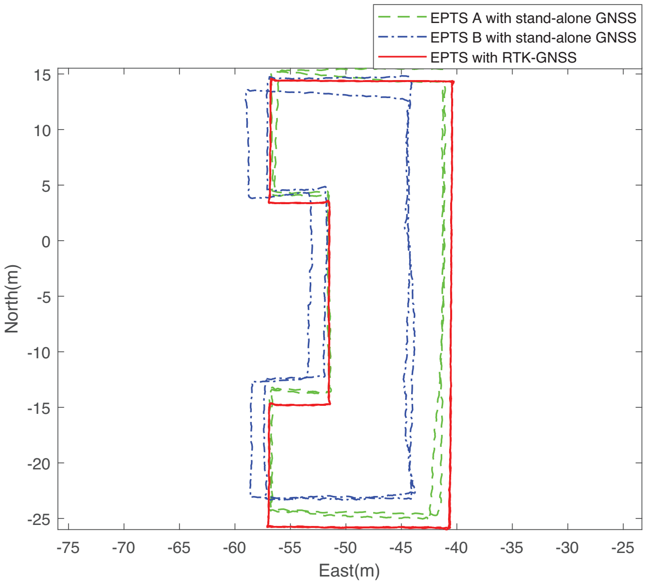

Figure 8 | Penalty area tracking results in Jeju stadium (half-closed environment).

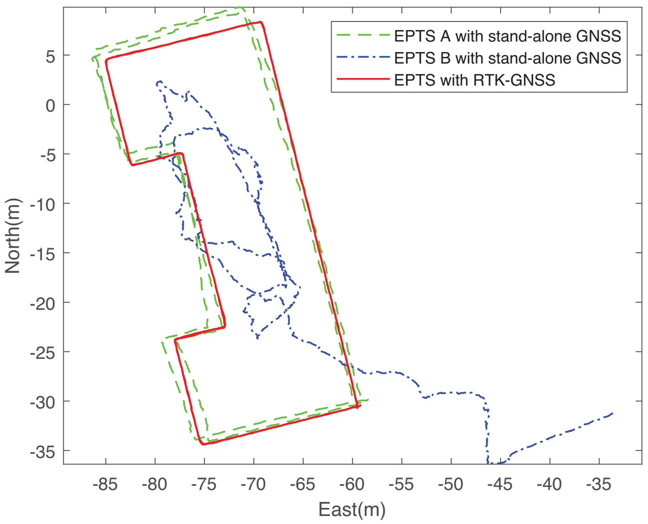

Figure 9 | Penalty area tracking results in Daegu stadium (closed environment).

(open environment) located in Seoul. Like the full pitch tracking tests, three wearable devices utilizing RTK-GNSS and stand-alone GNSS demonstrate good penalty area tracking performance in the open environment. Notably, the wearable device equipped with the proposed RTK-GNSS exhibits more accurate distance measurement compared to other wearable devices utilizing stand-alone GNSS.

Figure 8 shows penalty area tracking results using three wearable devices with different GNSS technique in Jeju stadium (half-closed environment). Like Hyochang stadium experiments, the wearable device equipped with the proposed RTK-GNSS exhibits more accurate distance measurement compared to other wearable devices utilizing stand-alone GNSS.

Figure 9 shows penalty area tracking results using three wearable devices with different GNSS technique in Daegu stadium (closed environment). Like Hyochang stadium and Jeju stadium cases, the wearable device equipped with the proposed RTK-GNSS exhibits more accurate distance measurement compared to other wearable devices utilizing stand-alone GNSS. In particular, it is extremely challenging for the wearable EPTS B with stand-alone GNSS to achieve tracking and measuring the perimeter of the penalty area in Daegu stadium as shown in Figure 9.

Table 3 summarizes the comparison of perimeter measurement of the penalty areas using three different wearable EPTS in three different environments. The perimeter measurement results of penalty area in Jeju and Daegu stadium, both of which have roofs, yielded smaller values compared to the true perimeter of the penalty area in all EPTS experiments. It can be inferred that the roofs of stadiums cause lower GNSS positioning accuracy. However, the perimeter measurement results of the considered wearable device equipped with the proposed RTK-GNSS technology validate the most accurate performance, 98.97% on average, compared to the true perimeter, 124.60 m, among three wearable devices. Note that the accuracy is calculated using the absolute error values as follow;

$$\mathrm{Accu}_D = \frac{D_{\mathrm{true}} - Er_{\mathrm{D}}}{D_{\mathrm{true}}} \tag{6}$$

where $\mathrm{Accu}_{\mathrm{D}}$ is the distance accuracy, D_{true} is the true perimeter, Er_{D} is the absolute distance error calculated by $Er_{\mathrm{D}} = |D_{\mathrm{true}} - D_{\mathrm{measured}}|$, and D_{measured} is the measured perimeter.

6 | Conclusion

This study presented the RTK-GNSS for a wearable EPTS for football players. Hardware experiments were performed to validate the performance of a wearable EPTS equipped with the proposed RTK-GNSS technique for football players in three different environments: an open environment, a half-closed environment, and a closed environment which is the harshest environment. The maximum tracking errors of the wearable device equipped with RTK-GNSS are 0.15 m, 0.24 m, and 1.56 m in open, half-closed, and closed environments, respectively. Compared to the maximum tracking errors of other wearable devices equipped with stand-alone GNSS, those of the wearable devices equipped with RTK-GNSS are much smaller. The penalty area perimeter measurement results of the considered wearable device equipped with RTK-GNSS validate the most accurate performance, 98.97%, compared to those of the wearable devices equipped with stand-alone GNSS in open, half-closed, and closed environments. The results demonstrate that the utilization of RTK-GNSS can significantly improve positioning accuracy in various stadium environments, which is crucial for evaluating player performance.

It is important to consider the real conditions of sports because the fast movement of players may affect lower tracking performance. Therefore, further research is required to conduct hardware experiments under actual football match or training conditions. Moreover, additional research is considered to integrate RTK-GNSS and IMU (inertial measurement unit), and provide the advanced performance data (e.g. athletes' steps) obtained from the RTK-GNSS/IMU integration.

Table 3 | The comparison of perimeter measurement of the penalty areas.

	Hyochang	Jeju	Daegu	Accuracy
EPTS (RTK-GNSS)	124.85 m	122.73 m	122.36 m	98.97%
EPTS A (stand-alone GNSS)	123.60 m	121.86 m	122.23 m	98.37%
EPTS B (stand-alone GNSS)	123.35 m	116.63 m	92.95 m	89.07%

Author Contributions

Mingu Kim: methodology, formal analysis, software, writing – original draft, writing – review and editing. **Bit Kim:** data curation, resources, writing – review and editing. **Chulwoo Park:** data curation, resources, writing – review and editing. **Jinsung Yoon:** resources, investigation, funding acquisition.

Acknowledgements

This research was financially supported by Fitogether Inc. This is part of Fitogether's ongoing work as a "FIFA Preferred Provider for Live Player Tracking." This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Institutional Review Board of Hansung University.

Conflicts of Interest

Bit Kim, Chulwoo Park, and Jinsung Yoon are affiliated in Fitogether Inc. Bit Kim, Chulwoo Park, and Jinsung Yoon contributed to the data curation and resources, but they were not involved in the methodology, data analysis, and the decision to publish the results.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

References

1. S. Mohiuddin and M. L. Psiaki, "Carrier-Phase Differential Global Positioning System Navigation Filter for High-Altitude Spacecraft," *Journal of Guidance, Control, and Dynamics* 31, no. 4 (2008): 801–814.

2. I. Um, S. Park, H. T. Kim, and H. Kim, "Configuring RTK-GPS Architecture for System Redundancy in Multi-Drone Operations," *IEEE Access* 8 (2020): 76228–76242.

3. M. Huang, "Analysis of Rocket Modelling Accuracy and Capsule Landing Safety," *International Journal of Aeronautical and Space Sciences* 23 (2022): 392–405.

4. A. Rekow, T. Bell, D. Bevly, and B. Parkinson, eds., "System Identification and Adaptive Steering of Tractors Utilizing Differential Global Positioning System," *Journal of Guidance, Control, and Dynamics* 22, no. 5 (1999): 671–674.

5. M. Meron, A. Chen, O. Rabinovitz, E. Traub, V. Levine-Orlov, and U. Marchaim, "Water Distribution Analysis of a Linear Move Irrigator by Aerial Survey and RTK-GNSS Monitors," *Precision Agriculture* 23 (2022): 894–911.

6. C. Xiong and Y. Niu, "Investigation of the Dynamic Behavior of a Super High-Rise Structure Using RTK-GNSS Technique," *KSCE Journal of Civil Engineering* 23, no. 2, (2019): 654–665.

7. H. F. Ng and L. T. Hsu, "3D Mapping Database-Aided GNSS RTK and its Assessments in Urban Canyons," *IEEE Transactions on Aerospace and Electronic Systems* 57, no. 5 (2021): 3150–3166.

8. X. Ye, C. Ma, W. Liu, and F. Wang, "Robust Real-Time Kinematic Positioning Method Based on NLOS Detection and Multipath Elimination in GNSS Challenged Environments," *Electronics Letters* 56, no. 24 (2020): 1332–1335.

9. E. Andersson, M. Supej, Ø. Sandbakk, B. Sperlich, T. Stöggl, and H.-C. Holmberg, "Analysis of Sprint Cross-Country Skiing Using a Differential Global Navigation Satellite System," *European Journal of Applied Physiology* 110 (2010): 585–595.

10. M. Gilgien, J. Spörri, J. Chardonnens, J. Kröll, P. Limpach, and E. Müller, "Determination of the Ccentre of Mass Kinematics in Alpine Skiing Using Differential Global Navigation Satellite Systems," *Journal of Sports Sciences* 33, no. 9 (2015): 960–969.

11. J. C. Mertens, A. Boschmann, M. Schmidt, and C. Plessl, "Sprint Diagnostic With GPS and Inertial Sensor Fusion," *Journal Sports Engineering* 21 (2018): 441–4511.

12. B. Pellegrini, Ø. Sandbakk, T. Stöggl, et al., "Methodological Guidelines Designed to Improve the Quality of Research on Cross-Country Skiing," *Journal of Science in Sport and Exercise* 3 (2021): 207–223.

13. W. Zhao, G. Liu, M. Gao, B. Zhang, S. Hu, and M. Lyu, "A New Inter-System Double-Difference RTK Model Applicable to Both Overlapping and Non-Overlapping Signal Frequencies," *Satellite Navigation* 4 (2023): 22.

14. NEO-M9N-00B Datasheet, (10 May 2024), https://content.u-blox.com/sites/default/files/NEO-M9N-00B-DataSheet-UBX-19014285/.

15. MAX-M8 Series Datasheet, (10 May 2024), https://content.u-blox.com/sites/default/files/documents/MAX-M8-FW3-DataSheet-UBX-15031506/.

16. Pitch Dimensions and Surrounding Areas, (10 May 2024), https://publications.fifa.com/en/football-stadiums-guidelines/technical-guideline/stadium-guidelines/pitch-dimensions-and-surrounding-areas/.

17. ZED-F9P-04B Datasheet, (10 May 2024), https://content.u-blox.com/sites/default/files/ZED-F9P-04B-DataSheet-UBX-21044850/.