



The Development and Educational Evaluation of a Smart IoT Relay Baton with Accelerometer Technology

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Abstract

Background. Relay performance depends on both individual speed and the efficiency of baton exchanges. However, conventional batons lack quantitative feedback to guide training.

Objectives. This study aimed to develop and evaluate a Smart IoT Relay Baton equipped with an accelerometer to provide objective, real-time performance data.

Materials and Methods. A modified R&D approach by Borg and Gall was used, involving needs analysis, system design, expert validation, small/large-scale trials, product revision, and finalization. The prototype used an accelerometer + NodeMCU ESP32, MQTT streaming, and a web dashboard. The participants were 241 sprint relay athletes (19–23 years). Baseline runs with conventional batons were followed by identical runs with the IoT baton. The outcomes included the measurement of transition time, entry speed, average acceleration, and team coordination (sync delay). The statistical analysis employed comprised using the Shapiro–Wilk test, paired t-tests, Cohen's d, and Pearson correlations ($\alpha = .05$).

Results. Significant improvements were observed across all variables: transition time -9.97% , entry speed $+9.85\%$, average acceleration $+8.98\%$, and coordination $+24.21\%$ (all $p < .05$). Effect sizes were large to very large ($d = 0.70-1.20$). Correlations highlighted strong links between entry speed and acceleration ($r = .74$), as well as between transition time and coordination ($r = .68$).

Conclusions. The IoT baton effectively supported coaches with accurate evaluations and strategic decision-making. These findings underscore the transformative role of IoT-based devices in advancing evidence-based sprint training. Further research should validate the tool in official competitions, integrate biometric and video-tracking technologies.

Keywords: IoT in sports, sprint relay performance, accelerometer evaluation.

Introduction

Individualized training is key to improving athletic performance (Yuwono, Adi S, et al., 2025) and honing talent

(Yuwono, Billiandri, et al., 2025), thereby supporting better athletic performance in the future (Kusuma et al., 2023; Yuwono et al., 2024). In line with the need for peak performance, innovations in relay baton design are necessary. Conventional batons may not be suitable for all athletes; modified batons are safer, more comfortable (Hidayatullah et al., 2020), and more precise (Shandal, 2022). In addition, conventional batons do not take into account ergonomic and measurement needs. Conventional batons are unable to pro-

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vide quantitative data on the speed, acceleration, and rhythm of runners' steps during the exchange. Coaches find it difficult to evaluate athletes due to the scarcity of reliable statistical data (Griffin et al., 2021). Objective data such as race times and movement analysis are crucial for accurate athlete selection and performance evaluation (Johnston & Baker, 2022). Time is critical in extracting insights (Komitova et al., 2022). Optimal baton-passing techniques are crucial in relay races. The lack of objective data makes it difficult for coaches to identify their team's weaknesses. To overcome the difficulties in evaluation caused by scarcity of objective data, the integration of 5G IoT technology and accelerometer sensors provides an innovative solution that supplies real-time data.

The lack of quantitative data makes it difficult for coaches to identify weaknesses in baton exchange techniques and determine the most optimal runner order. This is crucial considering that the success of a relay team is greatly influenced by the combination of individual speed and efficient baton exchange techniques. In the national context, although Indonesia won the gold medal in the men's 4x100 m event in 2023, this achievement has not been consistent across all relay events. Until now, there has been no objective evaluation that can determine with certainty which runners are the fastest or slowest in baton exchanges, so team strategies still rely on subjective estimates. This situation underscores the need for technology that can provide real-time, accurate, and practical data to support performance development.

The integration of 5G IoT technology facilitates the collection and analysis of multi-index sports data (Wang & Zhao, 2021). Wearable sensors play an important role in improving performance (Sattaburuth & Wannapiroon, 2021), measuring acceleration (Sheerin et al., 2020; Tenforde et al., 2020) and measuring acceleration patterns (Lariviere et al., 2020). In addition, accelerometers can estimate walking speed by analyzing raw data (Davis et al., 2023). By integrating accelerometers into IoT-based relay batons, coaches can obtain detailed information about acceleration, deceleration, and baton exchange effectiveness. This technology not only enables more accurate performance monitoring but also provides a systematic basis for evaluating training strategies and determining team composition.

Previous studies have explored running support technologies, such as the use of drones, smart shoes, and video analysis systems (Balasubramaniam et al., 2023; Cardenas Hernandez et al., 2024; Hébert-Losier & Pamment,

2023). However, these approaches still have limitations, including high costs, complex personalization requirements, limited coverage of straight sprints, and a lack of ability to provide direct quantitative feedback (Mohamed Zaki et al., 2024). This emphasizes the urgency of innovating devices that are more practical, Real-time, and adaptive to the actual conditions of the relay track.

Based on this background, this study aims to develop and evaluate a Smart IoT Relay Baton with an accelerometer sensor as an innovative solution for monitoring the performance of relay runners. The resulting prototype not only functions as a handover tool but also as a data-based evaluation instrument that supports coaches in identifying athletes' strengths and weaknesses, developing team strategies, and comprehensively optimizing sprint performance.

Materials and Methods

Research Design

This study employed a Research and Development (R&D) design based on a modified Borg and Gall model. The process included needs analysis, system design, expert validation, small- and large-scale field testing, product revision, and finalization.

Participants

A total of 241 sprint relay athletes from PASI (Indonesian Athletics Federation) Central Java participated. Purposive sampling was applied with inclusion criteria: age 19–23 years, provincial-level competition experience, and regular training (≥ 3 sessions per week). Athletes with acute injuries or medical contraindications were excluded. Participant characteristics are summarized in Table 1.

Instruments

The primary instrument was the Smart IoT Relay Baton, integrating an accelerometer with a NodeMCU ESP32 microcontroller. A web-based monitoring application visualized real-time data via MQTT protocol, with PHP backend and MySQL database. Additional tools included observation sheets, expert validation questionnaires, and a digital stopwatch as backup.

Table 1. Participant Characteristics (n = 241)

Variable	Total (n=241) Mean \pm SD	Male (n=121) Mean \pm SD	Female (n=120) Mean \pm SD
Age (years)	19.3 \pm 2.4	19.5 \pm 2.5	19.1 \pm 2.3
Height (cm)	170.6 \pm 8.1	174.8 \pm 6.9	166.2 \pm 6.7
Weight (kg)	62.9 \pm 9.8	68.1 \pm 8.2	57.7 \pm 7.5
Training experience (years)	3.8 \pm 1.9	4.0 \pm 1.8	3.6 \pm 2.0
Event specialization, n (%)			
– 4x100 m	181 (75%)	92 (76%)	89 (74%)
– 4x400 m	60 (25%)	29 (24%)	31 (26%)
Preferred handover hand (R/L), n (%)	197 / 44	104 / 17	93 / 27
Recent injury (last 6 months), n (%)	38 (15.8%)	20 (16.5%)	18 (15.0%)



Fig. 1. Smart IoT Relay Baton Prototype

Procedure

Baseline trials were conducted using conventional batons, followed by trials with the IoT baton under identical conditions. Each athlete performed multiple runs, with performance metrics recorded: (1) transition time, (2) sprint speed entering the exchange zone, (3) average acceleration, and (4) team coordination (sync delay). Expert validation involved sport technology specialists and PASI coaches, ensuring both technical reliability and practical usability.

Ethical Considerations

This study was conducted following ethical standards for research involving human participants. Ethical approval was obtained from the Ethics Committee under Approval No: 0419/KEPK/UNNES/IX/2025. All participants were informed about the study objectives, procedures, potential risks, and benefits, and provided written informed consent prior to participation. To minimize risks, athletes were screened for acute injuries or medical contraindications before data collection, and only those deemed safe to participate continued with the trials. Participation was voluntary, and athletes were allowed to withdraw at any time without penalty.

Data Analysis

Data normality was tested using Shapiro–Wilk. Pre–post comparisons were analyzed with paired sample t-tests, and Cohen’s d quantified effect sizes. Pearson’s correlation assessed relationships between key variables. Descriptive statistics (mean, SD, percentage improvement) complemented inferential results. Significance was set at $p < 0.05$.

Results

Prior to hypothesis testing, a normality check was conducted using the Shapiro–Wilk test. The results showed

that the distribution of all four performance variables met the assumption of normality, with significance values greater than 0.05. This finding indicates that the dataset was suitable for further analysis using parametric statistical tests, specifically paired sample t-tests. The details are presented in Table 2.

Table 2. Normality Test of Performance Variables (Shapiro–Wilk)

Variable	Significance (p)
Relay Transition Time (s)	0.091
Sprint Speed Entering Zone (m/s)	0.087
Average Acceleration (m/s ²)	0.094
Team Coordination (Sync Delay) (s)	0.066

Note. All p values exceeded 0.05, confirming that the data were normally distributed

After confirming the assumption of normality, paired sample t-tests were conducted to examine differences in athletes’ performance before and after using the IoT-based relay baton. The results demonstrated statistically significant improvements across all four measured variables. Relay transition time decreased by 0.32 seconds (9.97%), sprint speed entering the exchange zone increased by 0.80 m/s (9.85%), average acceleration improved by 0.22 m/s² (8.98%), and team coordination, measured by sync delay, improved by 0.23 seconds (24.21%). These findings indicate that the use of the IoT relay baton substantially enhanced both technical and coordinative aspects of sprint relay performance. Figure 1. Pre–post comparison of relay performance variables before and after the implementation of the IoT-based relay baton. Bars represent mean ± standard deviation (SD). Gray bars = pre-test; teal bars = post-test. Percentage values above the post-test bars indicate the relative improvement compared to baseline.

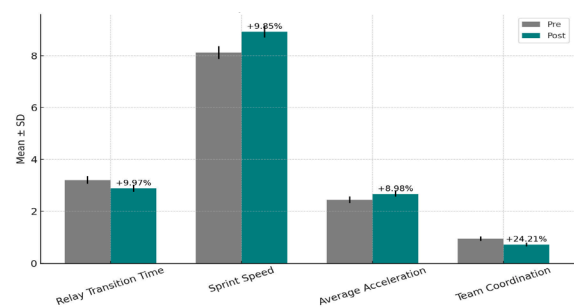


Fig. 2. Pre-Post Comparison of Performance Variables

Table 3. Paired Sample T-Test Results

Variable	Mean (Pre–Post)	t Count	Difference	Sig. (p)	% Improvement
Relay Transition Time (s)	3.21 → 2.89	4.212	–0.32	0.0011	9.97% (Time Decrease)
Sprint Speed Entering Zone (m/s)	8.12 → 8.92	3.654	+0.80	0.002	9.85% (Speed Increase)
Average Acceleration (m/s ²)	2.45 → 2.67	2.918	+0.22	0.011	8.98% (Increase)
Team Coordination (Sync Delay) (s)	0.95 → 0.72	3.101	–0.23	0.006	24.21% (Synchronization)

Beyond statistical significance, effect size analysis was conducted to determine the practical magnitude of improvements across the four performance variables. The results confirmed that the intervention had meaningful impacts on relay performance. Transition time ($d = 0.90$) and sprint speed entering the exchange zone ($d = 0.85$) demonstrated large effects, while average acceleration ($d = 0.70$) showed a medium-to-large effect. Notably, team coordination ($d = 1.20$) exhibited a very large effect, indicating that the IoT-based baton was particularly effective in enhancing synchronization among runners. These findings highlight that the improvements were not only statistically significant but also practically relevant for training and performance optimization.

Table 4. Effect Size (Cohen's d) for Performance Variables

Variable	Cohen's d	Effect Category
Relay Transition Time	0.90	Large
Sprint Speed Entering Zone	0.85	Large
Average Acceleration	0.70	Medium-Large
Team Coordination (Sync Delay)	1.20	Very Large

Note. Interpretation of effect sizes follows Cohen's (1998) guidelines, where 0.2 = small, 0.5 = medium, and 0.8 = large

To further explore the relationships between performance indicators, Pearson's correlation analysis was performed. The results revealed several meaningful associations. Transition time was strongly and positively correlated with team coordination ($r = 0.68, p = 0.003$), suggesting that shorter transition times were achieved when baton exchanges were more synchronized. Sprint speed and average acceleration showed a very strong positive correlation ($r = 0.74, p = 0.001$), indicating that higher sprinting speed entering the exchange zone was strongly supported by greater initial

acceleration. Conversely, sprint speed and team coordination were moderately and negatively correlated ($r = -0.58, p = 0.010$), implying that increases in speed without sufficient synchronization could disrupt baton exchanges. Figure 2. Correlation analysis of relay performance variables (a) relay transition time and team coordination; (b) Sprint speed entering the exchange zone and average acceleration; (c) Sprint speed and coordination.

Discussion

The use of IoT-based baton relay sticks significantly improves team coordination. This is evident from the significant reduction in sync delay (the interval between runners) by 24.21% reflecting improved synergy and harmony in baton exchanges. This improvement in coordination also has the greatest impact compared to other variables. The implementation of IoT-based relay batons significantly improves team coordination during relay transitions by facilitating real-time communication and feedback among team members. This interactive technology enables synchronous interaction, which is crucial in high-tempo environments where quick decision-making is essential (Georganta et al., 2024; Soenyoto et al., 2025). By providing adaptive feedback mechanisms, IoT systems can monitor team dynamics and dynamically adjust coordination strategies, thereby improving overall performance (Irawan et al., 2025; Wiltshire et al., 2024). Furthermore, the use of lean communication tools, such as gestural signals in competitive settings, demonstrates how effective communication can be optimized even under constraints, further supporting team coordination (Nova et al., 2023; Zheng et al., 2023). Overall, the integration of IoT technology in relay transitions not only streamlines the process but also fosters a more cohesive team environment, ultimately leading to improved performance outcomes (Alfariski et al., 2022; Narvios et al., 2022).

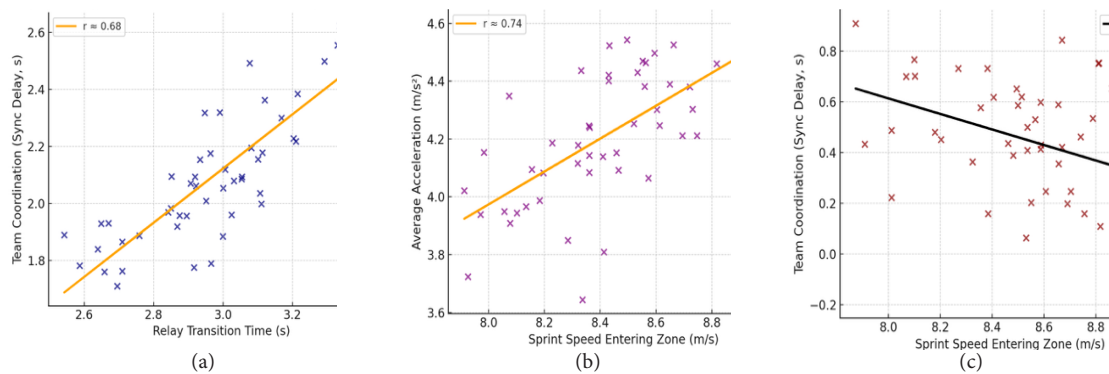


Fig. 3. Correlation analysis of relay performance variables

Table 5. Correlations Between Performance Variables

Variable Correlation	r Value	Sig. (p)	Interpretation
Transition Time vs. Team Coordination	0.68	0.003	Strong positive correlation
Sprint Speed vs. Average Acceleration	0.74	0.001	Very strong correlation
Sprint Speed vs. Team Coordination	-0.58	0.010	Moderate negative correlation

Note. Positive correlations indicate that improvements in one variable are associated with improvements in another, while negative correlations suggest a trade-off relationship

The relay transition time decreased from 3.21 seconds to 2.89 seconds, demonstrating improved technical efficiency due to the real-time information provided by the tool. This quantitative data helps coaches evaluate athletes' timing and responses objectively, which was previously based solely on manual observation. The transition time variable shows a significant improvement in performance after technological intervention due to increased efficiency in detecting and managing transitions in various contexts. For example, in healthcare, technology facilitates better integrated care coordination, addressing gaps in information exchange and communication among providers, which is particularly important for patients with chronic conditions such as CKD (Feldner & Davey, 2023). Similarly, advances in assistive devices, such as exoskeletons, leverage machine learning to optimize real-time transition detection, significantly improving processing time and user experience (Orhan et al., 2023). In product development, the use of virtual reality (VR) during transition activities has been shown to improve team performance by encouraging more effective discussion and decision-making processes (Horvat et al., 2023). Furthermore, in an organizational context, acquiring alliance partners can streamline knowledge absorption, thereby increasing inventive output and improving technological performance (McCarthy & Aalbers, 2022). Finally, innovations in adaptive optics have drastically reduced response times, demonstrating the impact of technological advances on performance metrics (Boudjema et al., 2025). Collectively, these interventions show that technology not only streamlines processes but also improves overall performance in various fields.

There is a very strong correlation ($r = 0.74$) between sprint speed and average acceleration. This indicates that the increase in a runner's speed when entering the transition zone is greatly influenced by their initial acceleration ability. Thus, training that combines sprinting and acceleration techniques will be more effective. The relationship between sprint speed entering the zone and the runner's average acceleration is significant, as evidenced by various studies. Research shows that the ability to generate a high force ratio during initial acceleration is crucial for sprint performance, with kinematic characteristics such as foot placement and ankle dorsiflexion playing an important role in improving acceleration ability (Bhakti et al., 2024). Additionally, hip torque has been identified as a mechanistic link between acceleration and maximum speed, suggesting that increased thigh angle acceleration can benefit both phases of sprinting (Adi et al., 2023). Research shows that the ability to generate a high force ratio during initial acceleration is crucial for sprint performance, with kinematic characteristics such as foot placement and ankle dorsiflexion playing an important role in improving acceleration ability (King et al., 2022; Rumini et al., 2024b). Additionally, hip torque has been identified as a mechanistic link between acceleration and maximum speed, suggesting that increased thigh angle acceleration can benefit both phases of sprinting (Clark & Ryan, 2022; Rumini et al., 2024a). Finally, innovations in adaptive optics have drastically reduced response times, demonstrating the impact of technological advances on performance metrics (Annas et al., 2024; Boudjema et al., 2025). Collectively, these interventions show that technology not only streamlines processes but also improves overall performance in various fields.

Furthermore, metrics such as sprint distance and acceleration at varying speeds have been shown to correlate with player workload, indicating that these factors are important for understanding the dynamics of sprinting in a competitive context (Aliriad et al., 2024; Prudholme et al., 2022). Overall, these findings underscore the interplay between acceleration and sprint speed, highlighting the importance of targeted training to optimize performance (Irawan et al., 2023; Silva et al., 2024).

Real-time data from the tool enables coaches to identify the most efficient runners and those who need improvement, as well as to sequence runners based on quantitative data such as reaction time, zone entry speed, and transition time. This provides a strategic advantage previously unavailable through subjective methods. The effectiveness of real-time data in helping coaches strategize and sequence relay runners is significantly enhanced through the use of objective measurement protocols and advanced analytics.

Wearable devices, such as inertial measurement units (IMUs), provide coaches with measurable performance metrics, enabling accurate evaluation of athletes' coordination abilities and fatigue levels, which are crucial for optimizing relay strategies (Carissimo et al., 2023; Hamidi Rad et al., 2022; Permana et al., 2024). Additionally, the integration of real-time data into training dashboards facilitates informed decision-making by providing comprehensive performance reports that track progress over time.

The integration of IoT relay batons in sports education and athlete training curriculum development holds significant implications, as evidenced by the advancements in IoT technologies across various sports contexts. The broader application of IoT in physical education, as highlighted by the use of wearable devices, underscores the potential for these technologies to facilitate more effective teaching and learning processes in sports education, thereby supporting sustainable higher education in physical education and sports (PES) (Cojocar et al., 2022). Furthermore, the integration of advanced technologies like virtual reality, augmented reality, and wearable tech in professional sports training has been shown to enhance performance metrics, reduce injury risks, and improve cognitive skills, which could be mirrored in the use of IoT relay batons to optimize training outcomes (Huang & Tang, 2024). The acceptance of wearable IoT devices, such as smart bracelets, has been shown to significantly enhance physical performance metrics among college students, suggesting that similar acceptance and integration of IoT relay batons could lead to improved training results and curriculum development in sports education (Xu et al., 2024). Additionally, the use of IoT devices in sports, such as the rowing propulsion monitoring system, demonstrates the potential for real-time data analysis and performance optimization, which could be adapted for relay baton use to provide athletes and coaches with valuable insights for performance improvement (Castro et al., 2022). The continuous advancements in wearable technology and ubiquitous computing further support the development of personalized training programs and data-driven decision-making, which are crucial for modernizing sports education curricula and enhancing athlete training programs (Setyawati et al., 2024). Overall, the integration of IoT relay batons in sports education and training curricula can lead to more personalized, data-driven, and effective

training methodologies, ultimately enhancing athletic performance and educational outcomes.

This study has several limitations that should be considered when interpreting the results. First, there is a potential for a sequence effect because all participants performed a baseline trial with a conventional cane followed by a trial using an IoT-based cane. Although the same warm-up and rest intervals were applied, fatigue or adaptation effects may have influenced the performance differences. Future studies should consider a randomized or balanced crossover design to minimize this effect. Second, the performance metrics (transition time, sprint speed, acceleration, and synchronization delay) were primarily obtained from accelerometers and a web-based dashboard developed for this study. Although these devices have been validated by experts, some level of measurement error (e.g., sensor calibration drift, data transmission latency) may have affected the accuracy of the collected data. The integration of high-speed video analysis or force plates could further strengthen the accuracy of performance measurements. Finally, participants were limited to provincial-level athletes aged 19–23 years. Therefore, generalizing the results to elite or younger athletes should be done with caution.

Conclusion

The development and evaluation of the Smart IoT Relay Baton with an integrated accelerometer proved to be effective in enhancing sprint relay performance by providing objective and real-time data. Significant improvements were observed across all measured variables, including reduced transition time (−9.97%), increased entry speed (+9.85%), enhanced average acceleration (+8.98%), and notably improved team coordination (+24.21%). Effect sizes ranging from large to very large confirm that the intervention was not only statistically significant but also practically relevant. These findings highlight the potential of IoT-based devices to replace subjective observational methods, allowing coaches to make more accurate evaluations and strategic decisions in athlete training and team composition. Future research is recommended to validate the system in official competition settings, integrate biometric and video-tracking technologies to broaden analytical capabilities, and develop predictive models for optimizing relay runner order, as well as to extend the application to other relay events and youth athletes to strengthen data-driven athletic development.

Conflict of Interest and Funding

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Author Contributions

All authors contributed substantially to the conception and design of the study, data acquisition, analysis, and interpretation, as well as drafting and revising the manuscript.

All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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Розроблення та оцінка освітньої ефективності використання смарт-естафетної палички на основі Інтернету речей (IoT) з технологією акселерометра

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 9 с., 5 табл., 3 рис., 52 джерела.

Історія питання. Результативність естафети залежить як від індивідуальної швидкості, так і від ефективності передачі естафетної палички. Однак традиційні естафетні палички не дають кількісної інформації, необхідної для планування тренувань.

Мета дослідження. Мета цього дослідження полягала у розробленні та оцінці смарт-естафетної палички з інтеграцією Інтернету речей (IoT), оснащеної акселерометром, для надання об'єктивних даних щодо продуктивності в режимі реального часу.

Матеріали та методи. Застосовано метод науково-дослідних та дослідно-конструкторських робіт за моделлю Борга і Галла, що включав аналіз потреб, дизайн системи, експертну валідацію, невеликі/великомасштабні випробування, доопрацювання продукту та фіналізацію. У прототипі використовувалися акселерометр + NodeMCU ESP32, MQTT-стрімінг та веб-дашборд. У дослідженні взяли участь 241 спортсмен зі спринтерської естафети віком 19–23 роки. Після базових забігів із звичайними естафетними паличками були проведені ідентичні забіги з паличками IoT. Результати включали вимірювання показників часу переходу, швидкості на старті, середнього прискорення та координат команди (затримка синхронізації). Статистичний аналіз охоплював використання критерію Шапіро-Вілка, t-критерії для парних вибірок, коефіцієнт d Коена та кореляції Пірсона ($\alpha = .05$).

Результати. За всіма показниками спостерігалися значні поліпшення: час переходу -9.97% , швидкість на старті $+9.85\%$, середнє прискорення $+8.98\%$ і координат $+24.21\%$ (всі $p < .05$). Розміри ефекту становили від великих до дуже великих показників ($d = 0.70-1.20$). Кореляції підкреслили міцні зв'язки між стартовою швидкістю та прискоренням ($r = .74$), а також між часом переходу та координатією ($r = .68$).

Висновки. Використання естафетної палички з інтеграцією Інтернету речей (IoT) сприяло ефективній підтримці тренерів у проведенні точних оцінок та ухваленні стратегічних рішень. Отримані результати підкреслюють трансформаційну роль пристроїв на основі Інтернету речей (IoT) у розвитку науково обґрунтованого тренування спринту. Подальші дослідження мають валідувати зазначений інструмент в офіційних змаганнях, а також інтегрувати біометричні та відео-трекінгові технології.

Ключові слова: Інтернет речей (IoT) у спорті, результативність спринтерської естафети, оцінювання даних за допомогою акселерометра.

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