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Development and preliminary evaluation of a real-time sensor-based coaching model for fencing performance

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ABSTRACT

Background: Fencing requires rapid movement execution, precise technical performance, and timely corrective feedback. Conventional coaching practices often rely on subjective observation and delayed performance evaluation. **Objectives:** This study aimed to develop and preliminarily evaluate a sensor-based fencing coaching model integrating real-time performance feedback into training. **Methods:** A research and development design based on a modified Borg and Gall model was employed, comprising needs analysis, model design, expert validation, limited testing, revision, and extensive field testing. Five nationally licensed fencing coaches participated in expert validation, while 10 athletes participated in the limited trial and 30 athletes in the extensive trial. Performance was assessed using motion sensors and technical performance measures. Pre–post changes were examined using paired-samples t-tests and Cohen's d. **Results:** The extensive trial showed significant pre–post improvements in attack execution time, punch accuracy, reaction time, and footwork efficiency ($p < .05$), with large effect sizes (Cohen's $d = 0.85–1.02$). Athletes and coaches also reported high perceived usability and satisfaction with the model. **Conclusion:** The findings provide preliminary evidence that integrating real-time sensor-based feedback into fencing training may improve selected technical performance indicators and enhance the perceived usefulness of training. However, controlled and longer-term studies are needed to determine the causal effectiveness and generalizability of the model.

Keywords: Fencing coaching; performance analysis; real-time feedback; evidence-based coaching; sports technology

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INTRODUCTION

Fencing is a competitive sport that demands high-speed decision-making, precise movement execution, and complex tactical performance, requiring systematic and evidence-based coaching approaches. The success of fencing athletes is strongly influenced by coaching that integrates technical, tactical, physical, and psychological components in a systematic manner (Supriyoko & Mahardika, 2018). However, fencing coaching still relies substantially on conventional approaches, particularly subjective visual observation and post-training or post-match evaluation. Such approaches may limit the objectivity and timeliness of feedback, potentially delaying the identification and correction of performance errors during training.

Previous research has addressed important aspects of fencing development, but these contributions remain relatively fragmented. An et al. (2023) highlighted the need to improve competitive training systems in fencing, whereas Caldwell and De Luigi (2023) emphasised technological adaptation in wheelchair fencing. Eda et al. (2022) demonstrated the relevance of real-time monitoring of athletes' physical condition, while Feddersen et al. (2020) examined challenges related to psychological training. The importance of mental preparedness has also been emphasised by Kalkan (2020), while Cynarski (2022) and Driukov (2020) highlighted contextual and cultural considerations in sport. Collectively, these studies demonstrate the multidimensional nature of fencing performance but do not provide an integrated coaching model that combines objective performance monitoring with real-time feedback during training.

A major limitation of conventional coaching is therefore the lack of an integrated mechanism for obtaining and using objective performance information during training. Retrospective analysis and qualitative observation may not capture subtle technical errors as they occur, limiting the opportunity for immediate corrective intervention. Although technological approaches have increasingly been applied to biomechanical and performance analysis, their application has often remained focused on individual performance components rather than being translated into a practical, sport-specific coaching system. Consequently, the potential of technology as a real-time decision-support tool for fencing coaches remains insufficiently developed.

Real-time feedback is particularly relevant to fencing because technical actions are executed within short time windows and require rapid coordination between perception, movement, and tactical decision-making. The increasing use of immersive and data-driven technologies in sport further supports the potential of real-time systems to enhance performance monitoring and training processes (Li et al., 2025). Nevertheless, limited research has translated these technological developments into an integrated fencing coaching model capable of providing immediate, actionable performance feedback during training. To address this gap, the present study developed a technology-based fencing coaching model that integrates motion sensors with interactive training software to enable real-time performance monitoring and feedback. The model was designed to provide coaches and athletes with objective and measurable information that can support immediate technical correction and performance-based decision-making. Rather than replacing the coach's role, the system is intended to complement coaching expertise by providing additional quantitative information during training.

The relevance of this approach is further supported by recent research on structured fencing training and technology-assisted skill development. Mahdi et al. (2024) emphasised the importance of structured training programmes for improving the physical and technical performance of fencing athletes. Reda et al. (2024) demonstrated that 3D models can support the mastery of fencing techniques such as the lunge, illustrating the potential value of visual and technology-assisted learning. Similarly, Marsan et al. (2024) highlighted the importance of objective performance criteria and innovative training strategies for athlete development in less mainstream sports such as fencing.

Despite these developments, evidence remains limited regarding the development and preliminary evaluation of a fencing-specific coaching model that integrates real-time sensor-based performance feedback into routine training. Therefore, this study addressed two questions: (i) how can a real-time performance analysis system be integrated into a fencing coaching model, and (ii) what preliminary changes in selected performance indicators are observed following its implementation? Accordingly, this study aimed to develop and preliminarily evaluate a real-time sensor-based coaching model for fencing performance. The study focused on the model's development, expert validation, usability, and preliminary changes in selected technical performance indicators.

METHODS

Type of Research

This study conducted an R&D approach based on a modified Borg & Gall model (Kamal, 2019). From the original ten stages proposed by Borg & Gall, this study applied six key stages relevant to model development in sports coaching, namely: (i) preliminary research and needs analysis, (ii) planning and model design, (iii) expert validation, (iv) limited field testing, (v) product revision, and (vi) extensive field testing followed by final refinement. The selection of these stages was intended to ensure systematic development, feasibility, and effectiveness testing of a fencing coaching model based on performance analysis and real time feedback.

Participants

The study involved 30 fencing athletes from Surakarta, Central Java, Indonesia, consisting of 60% male and 40% female athletes, with 70% classified as junior and 30% as senior athletes. Participants were selected using purposive sampling, based on their training experience and active participation in fencing training programmes. Although the number of participants in the extensive trial was limited, this sample size is considered appropriate for R&D based effectiveness testing, which prioritizes model feasibility, practicality, and initial effectiveness rather than population-level generalisation. In addition, five nationally licensed fencing coaches participated in the expert validation and evaluation stages of the model.

Instrument

Data were collected using validated instruments, including perception and satisfaction questionnaires, technical performance observation sheets, motion sensors integrated with a real-time analysis application, structured interviews, and expert judgement sheets. Inertial measurement units (IMUs; Xsens MTw Awinda, sampling rate 100 Hz) were attached to the dominant arm and lower limb to measure velocity, acceleration, and joint angles with accuracies of ±1.5° and ±0.1 m/s. Sensor data were transmitted wirelessly and processed in real time through an in-house application using a custom performance analysis algorithm to generate visual feedback for fencing-specific movements (attack speed, stroke accuracy, footwork pattern, reaction time). The sensor system was validated through expert review, pilot testing, and intraclass correlation coefficient (ICC) analysis, yielding ICC values of 0.87-0.94, indicating good-to-excellent inter-rater reliability. Content validity of instruments was established via expert judgement (Content Validity Index > 0.80), and questionnaire reliability was confirmed using Cronbach's alpha ($\alpha > 0.80$). This study received ethical approval from the institutional research ethics committee prior to data collection, and all participants provided written informed consent.

Table 1. Coach & Athlete Satisfaction Questionnaire and Perception of Training Model

No.	Statement	Linkert Scale				
		1	2	3	4	5
1	This training model is easy to understand and apply in training sessions.					
2	Real-time feedback helps me / us improve movement techniques faster.					
3	This model makes the exercise more purposeful and focused on technical goals.					
4	This training model increases my motivation to train consistently.					
5	The performance data displayed during practice is helpful in evaluating performance progress.					
6	I feel more aware of engineering errors when using this model.					
7	This model can be applied to different levels of athlete ability.					
8	Training becomes more efficient in terms of time and results.					
9	I was satisfied with the results of the exercises after using this model.					
10	I am willing to continue to use this model in the next exercise programme.					

Research Procedures

The research procedure comprised a preliminary study and needs analysis, followed by model design and expert validation involving five nationally licensed fencing coaches. Limited field trials were conducted with 10 athletes and followed by product revision based on expert and user feedback, after which extensive field trials were implemented with 30 athletes leading to final evaluation and refinement. The training intervention was carried out over eight sessions of 90 minutes each, consisting of a warm-up (15 minutes), technical drills supported by real-time feedback (50 minutes), tactical application exercises (15 minutes), and cool down (10 minutes), focusing on fundamental fencing techniques such as lunges, attacks, and footwork integrated with real-time feedback mechanisms.

Data Analysis

Data analysis employed quantitative and qualitative approaches. Descriptive statistics were used to analyse perception, satisfaction, and practicality, while expert validity for each model component was assessed using percentage agreement. Model effectiveness was evaluated through paired t-tests to examine pre–post performance differences, complemented by effect size analysis using Cohen's d and N-gain scores in accordance with R&D effectiveness evaluation standards (Achen, 2023; Sidiq et al., 2024). Qualitative interview data were analysed thematically to identify the strengths and limitations of the developed model, and inter-rater reliability for technical performance assessment was determined using the intraclass correlation coefficient (ICC) to ensure consistency among expert evaluators.

Ethical Considerations

Ethical approval for this study was obtained from the Institutional Research Ethics Committee, as evidenced by the Research Ethical Clearance Certificate No. 006/SKet/LPPM-UTP/I/2026.

RESULTS AND DISCUSSION

Results

The results are presented according to the stages of the model evaluation. The development process included a limited trial involving 10 athletes and an extensive field trial involving 30 athletes. The evaluation included quantitative performance measures, qualitative feedback from athletes and coaches, and assessments of the model's perceived usability and satisfaction. Four performance indicators were examined: attack execution time, punch accuracy, footwork efficiency, and reaction time. The results of the limited trial are presented first, followed by the qualitative findings and usability assessment, and subsequently the statistical evaluation of performance changes in the extensive field trial.

Limited Trial

The limited trial was conducted with 10 athletes to obtain preliminary evidence regarding the feasibility of implementing the sensor-based fencing coaching model and to examine initial changes in selected performance indicators. Performance was assessed before and after implementation of the model using attack execution time, punch accuracy, footwork efficiency, and reaction time.

Table 2. Mean Performance of Athletes Before and After Model Implementation in the Limited Trial (n = 10)

No.	Performance Indicators	Pretest	Posttest	Changes (%)
1	Attack Execution Time (ms)	420	375	-10.7
2	Punch Accuracy (%)	65	81	+24.6
3	Footwork Efficiency (%)	72	85	+18.1
4	Reaction Time (ms)	360	310	-13.9

Note. Negative changes in attack execution time and reaction time indicate reductions in the time required to execute the movement or response.

As shown in **Table 2**, the limited trial showed improvements across all four performance indicators following implementation of the model. Attack execution time decreased from 420 to 375 ms, while punch accuracy increased from 65% to 81%. Footwork efficiency increased from 72% to 85%, and reaction time decreased from 360 to 310 ms. These preliminary changes supported progression to the extensive field trial and indicated the feasibility of implementing the sensor-based coaching model in fencing training.

Qualitative Findings from the Limited Trial

Structured interviews with coaches and athletes were analysed thematically to identify their experiences with the sensor-based coaching model. Three dominant themes emerged: (i) real-time feedback for immediate technical correction, (ii) objective performance data for training evaluation, and (iii) increased motivation and training engagement.

Participants commonly reported that real-time feedback helped them identify and correct technical errors during training. One athlete stated, *"I can instantly correct my foot errors on the spot."* This perception was particularly relevant to footwork and movement execution, as immediate visual feedback allowed athletes to recognise and address errors during rather than after the training activity. Coaches similarly reported that real-time information facilitated more timely and specific instructional feedback.

Coaches and athletes also perceived the sensor-derived data as providing a more objective basis for performance evaluation than visual observation alone. One coach stated, *"The graphs and data from the sensors really help me make my next training decision."* This finding indicates that quantitative performance information may support coaches in identifying specific performance characteristics and adjusting subsequent training activities.

Participants further described positive experiences related to motivation and engagement. The integration of data visualisation and digital interaction made training more interesting and enjoyable for some athletes. As one athlete stated, *"Training feels like a game; I get more excited."* These responses suggest that technology-supported feedback may contribute not only to technical learning but also to athletes' engagement with training.

Perceived Usability and Satisfaction

The perceived usability and satisfaction of the coaching model were evaluated by both athletes and coaches. The results are presented in **Table 3**.

Table 3. Perceived Usability and Satisfaction with the Coaching Model

Assessment Aspects	Athlete Mean	Coach Mean
The model is easy to understand and implement.	4.6	4.8
Real-time feedback helps with motion correction.	4.7	4.6
Exercises become more purposeful and effective.	4.5	4.7
The model increases motivation to practise.	4.4	4.5
Performance data facilitates evaluation.	4.6	4.9

As shown in **Table 3**, both athletes and coaches provided favourable assessments across all aspects of the model. Athlete scores ranged from 4.4 to 4.7, whereas coach scores ranged from 4.5 to 4.9. Among coaches, the highest rating was observed for the usefulness of performance data in facilitating evaluation (4.9), followed by the ease of understanding and implementing the model (4.8). Among athletes, the highest rating was given to the usefulness of real-time feedback for movement correction (4.7). Overall, these findings indicate high perceived usability and satisfaction with the developed coaching model.

Tests of Statistical Assumptions

Before the parametric analysis was conducted, the normality of attack execution time was examined using the Kolmogorov–Smirnov test. The results are presented in **Table 4**.

Table 4. Normality Test (Kolmogorov–Smirnov)

Performance Indicator	*p*-value (Sig.)	Description
Attack Execution Time (Pre)	.193	Normally distributed
Attack Execution Time (Post)	.275	Normally distributed
Conclusion	**$p > .05$**	**Normality assumption satisfied**

Note. Statistical significance was set at $p < .05$.

Table 4 presents the results of the Kolmogorov–Smirnov normality test. The significance value for attack execution time was .193 at pretest and .275 at posttest. Both values were greater than .05, indicating that the pretest and posttest attack execution time data were normally distributed. Therefore, the normality assumption was considered satisfied for the subsequent parametric analysis.

Extensive Field Trial

Following the preliminary evaluation, an extensive field trial was conducted with 30 athletes to further examine changes in fencing performance following implementation of the sensor-based coaching model. Four performance indicators were evaluated: attack execution time, punch accuracy, reaction time, and footwork efficiency. The pretest and posttest results, together with statistical significance and effect sizes, are presented in **Table 5**.

Table 5. Results of the Athlete Performance Paired-Samples *t*-Test (n = 30)

Performance Indicators	Mean (Pre)	Mean (Post)	p-value	Cohen's d
Attack Execution Time (ms)	418	368	< .001	0.89 (Large)
Punch Accuracy (%)	67	83	< .001	1.02 (Large)
Reaction Time (ms)	350	295	.002	0.85 (Large)
Footwork Efficiency (%)	74	86	.003	0.91 (Large)

Note. Cohen's *d* represents the effect size. Statistical significance was set at $p < .05$.

As shown in **Table 5**, all four performance indicators demonstrated significant pre–post changes following implementation of the coaching model. Attack execution time decreased from 418 to 368 ms ($p < .001$, Cohen's $d = 0.89$), indicating faster attack execution. Punch accuracy increased from 67% to 83% ($p < .001$, $d = 1.02$). Reaction time decreased from 350 to 295 ms ($p = .002$, $d = 0.85$), while footwork efficiency increased from 74% to 86% ($p = .003$, $d = 0.91$).

All four indicators showed large effect sizes, ranging from 0.85 to 1.02. The largest effect was observed for punch accuracy ($d = 1.02$), followed by footwork efficiency ($d = 0.91$), attack execution time ($d = 0.89$), and reaction time ($d = 0.85$). These findings provide preliminary evidence of substantial pre–post changes in selected fencing performance indicators following implementation of the sensor-based coaching model.

Discussion

The present study provides preliminary evidence that a fencing coaching model integrating motion-sensor technology and real-time feedback can support improvements in selected performance indicators and provide a favourable training experience for athletes and coaches. Across the extensive field trial, attack execution time and reaction time decreased, whereas punch accuracy and footwork efficiency increased, with large effect sizes across all four indicators. These quantitative findings were complemented by qualitative evidence indicating that athletes perceived real-time feedback as useful for identifying and correcting technical errors, while coaches valued the objective performance information for making training decisions. Taken together, the findings suggest that the value of the developed model lies not simply in the use of technology, but in its integration into the coach–athlete learning process.

Real-Time Feedback and Technical Performance

The improvements observed in attack execution time, punch accuracy, footwork efficiency, and reaction time suggest that immediate performance information may facilitate more efficient technical learning. In fencing, where movement execution occurs within a very short time window, delayed feedback may limit an athlete's ability to associate a specific movement with the resulting performance outcome. The sensor-based system used in this study provided information during training, allowing athletes to recognise movement errors and make immediate adjustments. This interpretation is consistent with the qualitative finding that athletes perceived real-time feedback as particularly useful for correcting footwork and movement errors.

The findings reinforce an evidence-based coaching approach in which objective and systematic information is incorporated into training decisions (Carvalho & Gonçalves, 2020). Rather than relying exclusively on coaches' visual observations, the developed model provides measurable information that can complement professional judgement. This is particularly relevant to technical sports, where small variations in movement timing, accuracy, and coordination may not always be readily identified through visual observation alone.

The large effect sizes observed in the extensive field trial further indicate that the changes were not only statistically significant but also potentially meaningful from a practical perspective. However, because the study used a pre–post design without a control group, these findings should be interpreted as preliminary evidence of performance change rather than definitive evidence of causal effectiveness. Improvements may also have been influenced by normal training adaptation, repeated testing, or other aspects of the athletes' training environment.

Technology as a Coaching and Learning Tool

An important finding was that the technology was perceived not merely as an assessment instrument but as part of the coaching process. Coaches reported that sensor-derived graphs and performance data helped them make subsequent training decisions, while athletes reported that the immediate information helped them recognise and correct technical errors. This finding supports the view that coaching effectiveness increasingly depends on the coach's ability to integrate appropriate tools and strategies into the learning environment (Gomes, 2020).

The combination of quantitative performance changes and qualitative experiences also reflects a more adaptive coaching process. Rather than delivering feedback solely after an exercise has been completed, coaches can use performance information to modify instructions and training tasks according to the athlete's current needs. This interpretation is consistent with the concept of transformational coaching, in which coaches facilitate adaptive learning and athlete development rather than simply transmitting technical instructions (Turnnidge & Côté, 2020).

From this perspective, the principal contribution of the model is not the sensor itself but the integration of sensing, interpretation, feedback, and coaching action into a continuous training cycle. The technology provides data, but coaches remain responsible for interpreting those data and determining whether and how an athlete should modify a movement. This distinction is important because technology should support rather than replace expert coaching judgement.

Performance Development and Long-Term Coaching

The findings can also be interpreted within a broader athlete-development perspective. The model provides immediate information about performance while simultaneously creating opportunities for athletes to develop greater awareness of their own movement execution. This combination is consistent with approaches to coaching for development that emphasise both immediate performance and longer-term athlete learning (Allen & Muir, 2020); Jones et al., 2020).

The role of real-time monitoring may be particularly relevant in fencing because performance requires the integration of physical, cognitive, and psychological processes. Rapid movement execution, decision-making, and technical precision must occur simultaneously, meaning that technical development cannot be considered independently from the athlete's broader performance capacity (Vella & Liddle, 2020). The present model potentially contributes to this integration by providing continuous information about movement performance within the training environment.

The findings are also compatible with the principle that athlete development should be flexible and responsive to context. The use of continuous performance information allows coaches to adjust training according to observed needs rather than applying identical interventions to all athletes. This perspective is consistent with the application of CIPP-based approaches to sport development, where systematic evaluation and contextual information are incorporated into programme improvement (Hafidz, 2024).

Coach–Athlete Interaction and Contextualised Learning

The qualitative findings provide an additional explanation for the quantitative improvements. Athletes described the training as more engaging when performance information was presented through interactive digital feedback, while coaches reported that the information supported their subsequent decisions. Thus, technology appears to have influenced not only the measurement of performance but also the interaction through which learning occurred.

This interpretation is consistent with the kinesio-cultural perspective proposed by Barker et al. (2021), which emphasises that skill development is shaped by the broader social and cultural context in which movement is learned. In the present study, the sensor system became part of the training environment and consequently part of the interaction between athlete, coach, and performance information. Technology therefore functioned as a mediating component of the coaching process rather than as an independent intervention.

The findings also support the distinction between performance coaching and development coaching described by Barry et al. (2025). The developed model provides information that can be used to address immediate performance outcomes while also encouraging athletes to understand and monitor their own movement. In this sense, the model has potential to connect short-term performance correction with longer-term learning.

Similarly, Jurbala (2023) emphasises athlete development through constraints-led and lifelong learning approaches. The real-time feedback environment may contribute to this process by encouraging athletes to become more actively involved in identifying movement problems and adjusting their performance. Rather than receiving all corrections passively from the coach, athletes can increasingly engage with objective information about their own performance.

The Coach as an Orchestrator of Technology-Supported Training

The present findings also reinforce the continuing importance of the coach despite increased technological involvement in training. As proposed by Bjørndal and Ronglan (2017), coaches act as orchestrators who structure learning environments and manage athletes' experiences. In the current model, sensor data provide additional information, but the coach remains responsible for determining which performance errors require attention and how feedback should be delivered.

This is particularly important because not every observed technical deviation necessarily requires immediate correction. Ferguson et al. (2023) argue that errors should be interpreted in relation to the athlete's developmental context rather than automatically corrected. Accordingly, the developed system should be viewed as a decision-support mechanism, not an autonomous coaching system. Its effectiveness depends on the coach's ability to interpret the information appropriately and translate it into meaningful training interventions.

Practical Implications

The findings have several practical implications for fencing coaching. First, coaches may use real-time sensor information to supplement conventional observation, particularly when evaluating movement timing, reaction, footwork, and technical accuracy. Second, the system may help coaches identify performance changes more systematically across training sessions. Third, the high usability ratings from both athletes and coaches suggest that the model can potentially be incorporated into routine training without substantially disrupting the training process.

The model may also support more individualised training. Because performance data can provide immediate information about an athlete's execution, coaches may be able to adjust training tasks according to individual technical needs. This is particularly relevant for national-level athletes, whose performance differences may be relatively small and difficult to distinguish through general observation alone.

Implications for Coach Education and Future Research

From a coach-education perspective, the findings support the need for coaches to develop not only technical and pedagogical expertise but also the ability to interpret and apply performance data. The importance of contextualised, non-linear, and experience-based approaches to coach education has been highlighted by Wu et al. (2021) and Leeder (2024). The integration of technology into coaching should therefore be accompanied by education on data interpretation, feedback delivery, and appropriate decision-making rather than focusing solely on technical operation of the devices.

The findings are also compatible with Gale (2017), who emphasises that effective coaching requires the integration of analytical frameworks with practical knowledge and professional judgement. The present model illustrates this principle by combining quantitative sensor information with coach interpretation and athlete experience.

Limitations and Future Research

Several limitations should be considered when interpreting the findings. First, the study used a pre–post design without a control or comparison group; therefore, the observed improvements cannot be attributed exclusively to the developed coaching model. Second, the extensive field trial involved a relatively limited sample of 30 athletes, which restricts the generalisability of the findings. Third, the evaluation focused on selected technical and movement-related indicators and did not directly examine competitive performance, tactical decision-making, or long-term retention of technical improvements. Finally, the qualitative findings were based on participants' perceptions and therefore should not be interpreted as direct evidence of psychological or motivational changes.

Future research should employ controlled or randomised designs with larger and more diverse samples to establish the causal effectiveness of the model. Longer follow-up periods are also needed to determine whether the observed improvements are retained over time and transferred to competitive performance. Future studies could additionally examine how different types, frequencies, and timing of real-time feedback influence learning, and whether the effectiveness of sensor-based feedback differs according to athlete expertise or technical characteristics.

Overall, the findings suggest that a sensor-based coaching model can provide a promising framework for integrating objective performance measurement, real-time feedback, and coach-guided learning in fencing. Its greatest potential may lie not in replacing conventional coaching, but in strengthening coaches' capacity to make evidence-informed decisions while enabling athletes to participate more actively in their own technical development.

CONCLUSION

This study developed and preliminarily evaluated an adaptive, data-driven fencing coaching model integrating motion sensors and performance visualisation to provide real-time feedback for technical correction and evidence-informed coaching. The model demonstrated favourable pre–post changes in attack execution time, punch accuracy, reaction time, and footwork efficiency, with large effect sizes, while athletes and coaches reported favourable usability and satisfaction. These findings provide preliminary evidence that real-time sensor-based feedback may support technical performance and more objective coaching decisions. However, the absence of a control group, relatively small and region-specific sample, short evaluation period, and focus on selected technical indicators limit the generalisability of the findings. Future research should use controlled and longitudinal designs with larger and more diverse samples and examine the transfer of training effects to competitive performance, including tactical and psychological outcomes.

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CONFLICT OF INTEREST

No conflicts of interest related to the reported research.

AI DISCLOSURE STATEMENT

The authors used QuillBot solely for language editing, grammar checking, and improving manuscript readability. No generative AI tools were used to generate, analyse, interpret, summarise, or write the scientific content. All scientific content, study design, data analysis, interpretation, and conclusions were developed exclusively by the authors, who take full responsibility for the work.

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