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Can Virtual Reality Training Effectively Improve Physical Condition and Back-Row Attack in Volleyball?

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Abstract

Background: There is an urgent need to explore innovative training methods that can improve the physical condition and back-row attack performance of junior volleyball players. Despite its great potential, Virtual Reality (VR) is still underutilized in youth sports training.
Aims: This study aims to test the effectiveness of VR-based training in improving physical conditioning and back-row attack quality.
Method: A quasi-experimental design was employed with 24 junior volleyball athletes aged 14 to 16. The participants underwent VR-based training three times a week for six weeks, with each 45-minute session consisting of a 15-minute warm-up, a 30-minute training session, and a 5-minute cool-down. Measurement tools included vertical jump tests, 20-meter sprints, Illinois agility tests, and structured observations to evaluate physical performance and back-row attack effectiveness. Data were analyzed using paired t-tests and multiple linear regression.
Result: The results showed significant improvements in vertical jump height ($d = -8.18$), sprint time ($d = 2.42$), agility score ($d = 3.32$), and back row attack ($d = -3.32$) at $p < 0.001$. Structured observations revealed improvements in the accuracy, timing, and coordination of back-row attacks. Regression analysis revealed that a better physical condition, particularly in terms of jumping and agility, significantly contributed to improved back-row attack performance ($R^2 = 0.876$, $p < 0.001$).
Conclusion: These findings suggest that VR-based training can effectively enhance physical condition and technical performance in back-row attacks, likely due to the immersive simulation environment supporting enhanced motor learning and situational awareness.

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INTRODUCTION

Volleyball is a team sport that requires high physical ability, tactical sharpness, mental toughness, and technical skills (Jawad et al., 2025). One of the most challenging attack techniques in this game is the back-row attack, which is an attack from behind the attack line. It requires explosiveness, good body coordination, and fast and precise reaction time (Bujang et al., 2025). Baena-Raya et al (2021) argue that the effectiveness of this technique depends on the strength of the arm muscles, the timing of the jump, and the speed of the steps when taking a run. The ease of use of this technique can be a sign of technically advanced volleyball teams compared to lesser ones. The findings of Irwanto and Triaiditya (2023) suggest that the attacks from the back-row position, particularly positions 1 and 6, contributed heavily to the team's points, showing the quality of the teams' training techniques and athletes' physical conditions. This is why researching how to improve back-row attacks becomes essential. However, enhancing the quality of back-row

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attacks is not only about improving the training techniques. It also involves a combination of explosive power, agility, sprinting speed, and precise technical skills, a difficult feat for athletes, especially junior ones. Nevertheless, it is not without some merits. For junior athletes, mastering the techniques of back-row attacks not only expands the variety of attacks but also accelerates their early tactical maturity (Bujang et al., 2025). Nonetheless, improving the training techniques of back-row attacks can be considered a Herculean effort as it is often limited to repetition without realistic situational stimuli.

The rapid advancement of technology in sports science has driven the need for innovative training methods that go beyond conventional approaches, particularly in improving physical performance and technical skills among junior athletes. In volleyball, one of the critical components of modern offensive strategy is the back-row attack, which is essential for overcoming high blocks and unpredictable opponent defenses. However, junior athletes often face challenges in mastering this technique due to physical limitations, lack of match-like training environments, and minimal tactical exposure. Previous studies, such as those by Bedir & Erhan (2021) and Noury et al. (2022), have shown the potential of technology-enhanced training in improving motor learning and skill execution. While research on VR in team sports is growing, its application in junior volleyball, especially for enhancing back-row attack effectiveness, remains underexplored. This gap highlights the urgency of examining VR-based training as a promising method to improve both the physical condition and technical performance of young volleyball athletes.

VR-based training has emerged as one of the most promising innovations in sports coaching, offering immersive and interactive experiences that replicate real-game scenarios. Unlike conventional training methods, VR provides real-time visual and kinesthetic feedback, enabling athletes to enhance both cognitive and motor skills in a controlled environment. This approach has been successfully applied in various sports; for example, the Australian national swimming team uses VR to simulate relay coordination under competitive conditions. In tennis, Najami & Ghannam (2025) demonstrated that VR-based systems significantly improved players' swing accuracy, situational awareness, and motivation through instant performance feedback. However, despite these promising developments, studies specifically investigating the use of VR in volleyball particularly in enhancing back-row attack effectiveness among junior athletes are still limited. This gap underscores the need for targeted research to explore the potential of VR in volleyball-specific skill development.

Despite its promising potential, the adoption of VR-based training in sports still faces several challenges, primarily related to cost. Akinradewo et al. (2022) noted that the high cost of hardware, software, and ongoing maintenance presents a barrier for many educational institutions and sports clubs. However, recent studies argue that long-term benefits offset these costs. Ng et al. (2023) emphasized that repeated use of VR systems can lead to cost efficiency over time. Bae (2023) found that VR's multisensory approach enhances both physical conditioning and mental focus. Kim and Ahn (2024) highlighted the role of VR in accelerating complex motor skill acquisition through improved spatial cognition and decision-making. In volleyball, Hassan et al (2023) demonstrated that visual feedback technologies improve technical and tactical skills. VR enables realistic and immersive simulations that stimulate neuromuscular responses, leading to better movement accuracy and reduced injury risk (Gray, 2019; Neumann et al., 2018). Michalski et al. (2019) also found improvements in coordination and reaction time transferable from VR training to real performance. However, while these studies provide strong support for VR in sports training, specific evidence regarding its effectiveness in improving back-row attack skills and physical conditioning in junior volleyball athletes remains scarce.

In the context of volleyball, VR-based technology has demonstrated benefits in enhancing players' understanding of game tactics and decision-making. Prior studies highlight its effectiveness in improving athletic performance through better reaction speed, motor coordination, and spatial awareness. Neumann et al. (2018) showed that VR provides a safe and immersive training environmment that enhances visual perception and motor readiness. Similarly, Chang et al. (2024) found VR effective in developing complex motor responses within dynamic sports scenarios. Cognitive improvements, particularly in spatial perception and decision-making, have also been observed. Notably, a recent study by Cariati et al. (2025) implemented a four-week VR-based intervention in junior volleyball athletes, reporting significant improvements in physical parameters—such as strength, speed, and agility—as well as technical proficiency in back-row attacks. Despite these findings, studies focusing specifically on VR-based training for back-row attack development in Indonesian junior volleyball athletes remain limited. This gap underlines the need for further research to evaluate the practical application and effectiveness of VR-based training in localized youth volleyball programs.

Hence, investigating the use of VR-based technology for the improvement of techniques and athletes, especially in the context of junior volleyball athletes, seems important to gain insights into this matter. Although a study by Bujang et al. (2025) has evaluated the effectiveness of back-row attack techniques using biomechanics technology, there is a lack of studies that investigate the effectiveness of VR-based technology to improve the quality of back-row attacks as well as the physical conditions of athletes. Thus, this study aimed to analyze the effectiveness of VR-based technology to enhance the quality of back-row attacks and athletes' physical conditions. This study would provide a novel contribution by integrating VR approaches into the physical and technical training of junior volleyball athletes, bridging the gap between high-performance needs and innovative training methods.

METHOD

Research Design

This study applied a quantitative research design with a quasi-experimental method and a one-group pretest-posttest design to evaluate the effects of VR-based training interventions on the physical conditions and the effectiveness of back-row attacks among a group of best junior volleyball athletes in West Java, Indonesia. This design was chosen because it allows researchers to observe changes that occur in one group before and after treatment without using a control group (Creswell & Creswell, 2018; Fraenkel et al., 2019). In addition, this study also used multiple linear regression analysis to determine the contribution of physical condition variables (leg muscle explosive power, agility, and speed) to the effectiveness of the back-row attack techniques (Field, 2024).

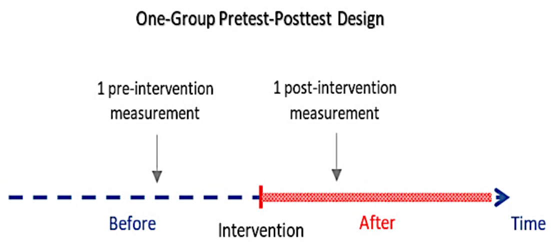

Figure 1. The Diagram of the One-Group Pretest-Posttest Model
Source: (Reichardt, 2019)

Participants

The participants of this study consisted of the best 24 junior male volleyball athletes from West Java with an age range of 14 to 17 (M_{year} = 15.5; SD_{year} = 1.14). In addition, we applied a purposive sampling technique to gather the participants. In this regard, we selected the participants based on certain criteria that are relevant to the research objectives (Kalu, 2019). We applied the following criteria to choose the participants: (1) actively training in a volleyball club for at least the last six months, (2) having a healthy physical condition and not experiencing any injuries, and (3) being willing to attend all training sessions for six weeks.

Instrument

We measured the research variables using several standardized instruments. First, we used the vertical jump test to measure the explosive power of muscles. This test has been widely used in measuring athletic, explosive capacity (Caseiro-Filho et al., 2023). Next, we used the Illinois agility test to measure agility, referring to a protocol validated in team ball sports (Morral-Yepes et al., 2022). Then, we applied a 20-meter sprint test to assess the linear speed. This test is effective in measuring sprint performance in adolescent athletes (Holmberg et al., 2025). Besides that, we tested the quality of back-row attacks' smash. This test aims to measure the ability of an athlete's back-row attack with a unit of frequency and validation by professional coaches (Bujang & Haqiyah, 2020).

Procedures

The treatment or the training program lasted for 6 (six) weeks with a frequency of 3 (three) times per week and 45 minutes per session. We used an Oculus Quest 2 headset device and volleyball-themed VR simulation software for the treatment. This procedure was adapted from the VR-based immersive training approach proposed by Neumann et al (2018). In this regard, this VR-based training approach has been shown to be beneficial to improve athletes' motor and cognitive capacities. Each training session is divided into three main stages:

Table 1. Training Session Stage

1	**VR Scenario Simulation (15 minutes)**	**Athletes Run a Game Simulation Focusing on Variations of Back-Row Attack Techniques, Using Three-Dimensional Game Visualization**
2	Back-row Attack Supporting Physical Training (20 minutes)	Athletes perform the supporting physical training based on strength, agility, and speed components.
3	Reflection and Movement Analysis through VR-based Playback (10 minutes)	Athletes reflect on their respective performances with the help of playback and direct feedback from the coach.

Data Analysis

Data was analyzed using a paired sample t-test to compare the pretest and post-test values with the help of the latest version of SPSS (Field, 2024). The t-test was used to assess whether there was a significant difference between the pre-test and post-test values for each variable. Significance was set at $\alpha = 0.05$, as shown by Pallant (2020). Before conducting the paired sample t-test statistical test, a normality test (Shapiro-Wilk) was conducted to ensure that the data was normally distributed (Demir, 2022). In addition, a homogeneity test (Levene's Test) was performed to ensure that the variance of the pre-test and post-test data from each variable was stable (Ojeda, 2024)

In addition, to analyze the simultaneous effect of leg muscle power (X_1), agility (X_2), and speed (X_3) on the effectiveness of back-row attacks (Y), a multiple linear regression test was conducted. A similar test was conducted in the study of Hair et al. (2019). Before conducting the regression test, we conducted a residual normality test using Shapiro-Wilk and histogram to ensure that the residuals obtained were normally distributed (Field, 2024). Furthermore, to check for multicollinearity between independent variables, a Variance Inflation Factor (VIF) test was conducted. The results suggest a VIF value <10 and Tolerance> 0.10, indicating no multicollinearity problems (Shrestha, 2020). Finally, to check for homoscedasticity, we used a scatterplot and the Glejser test to ensure that there was no heteroscedasticity in the regression model (Tabachnick & Fidel, 2015).

RESULTS AND DISCUSSION

Results

Data Description

After undergoing a 6 (six) week training program, with a frequency of 3 (three) sessions per week and a duration of 45 minutes for each session, a post-test measurement was conducted to evaluate the results of the training. Previously, a pre-test measurement had been conducted to determine the initial condition of the participants. Furthermore, the pre-test and post-test data were analyzed to see the changes and effectiveness of the training that had been given. The following table presents descriptive data from the pre-test and post-test results on each measured variable.

Table 2. The Descriptive Statistics of the Pre-test and Post-test

Variable	Pre-test (Mean ± SD)	Post-test (Mean ± SD)
Vertical Jump (cm)	39.47 ± 2.90	46.3 ± 2.55
20-meter Sprint (seconds)	3.92 ± 0.81	3.38 ± 0.76

Variable	Pre-test (Mean ± SD)	Post-test (Mean ± SD)
Illinois Agility (seconds)	17.67 ± 1.52	15.66 ± 1.27
Back-row Attack (score)	5.71 ± 1.65	7.67 ± 1.55

Table 2 presents the mean and standard deviation values of the four main variables measured before (pre-test) and after (post-test) the VR-based training intervention over some time. The results obtained showed a significant increase in performance in all variables, indicating that VR-based training had a positive impact on the athletes' physical abilities and back-row attack techniques. The average vertical jump height of the athletes increased from 39.47 cm to 46.3 cm. This improvement indicates a significant enhancement in lower limb power. This capability is a key component in executing the back-row attack technique, which requires explosiveness and optimal propulsion when jumping from the back row. VR-based training likely contributed to this outcome through repeated motion simulations and the creation of immersive environments that encourage athletes to consistently and purposefully activate their primary muscle groups.

For the speed variable, the 20-meter sprint results showed a time reduction from 3.92 seconds to 3.38 seconds, indicating a clear improvement in running speed. This improvement is critical, as speed is a key determinant when approaching before jumping in a back-row attack. Through VR-based training, athletes can be trained within game-like scenarios that demand quick reactions, stimulating better acceleration abilities through motor learning knowledge based on visual perception and muscle coordination. Agility ability also showed a significant improvement. The Illinois agility test results indicated a shorter completion time, from 17.67 seconds to 15.66 seconds. This reduction in time demonstrates that the athletes' ability to change direction and adapt to game dynamics has improved. VR-based training allows athletes to interact within complex and adaptive training environments, requiring them to respond quickly to visual and spatial stimuli, ultimately enhancing overall bodily agility.

Meanwhile, the back-row attack techniques' effectiveness score increased from 5.71 to 7.67. This improvement indicates that athletes demonstrated higher accuracy, coordination, and technical success when executing attacks from the back row. VR-based training provides real-time visual feedback and enables athletes to quickly correct technical errors through a self-assessment process based on visual displays and video playback. Moreover, this training accelerates tactical understanding and decision-making skills in attack scenarios, leading to more optimal back-row attack execution.

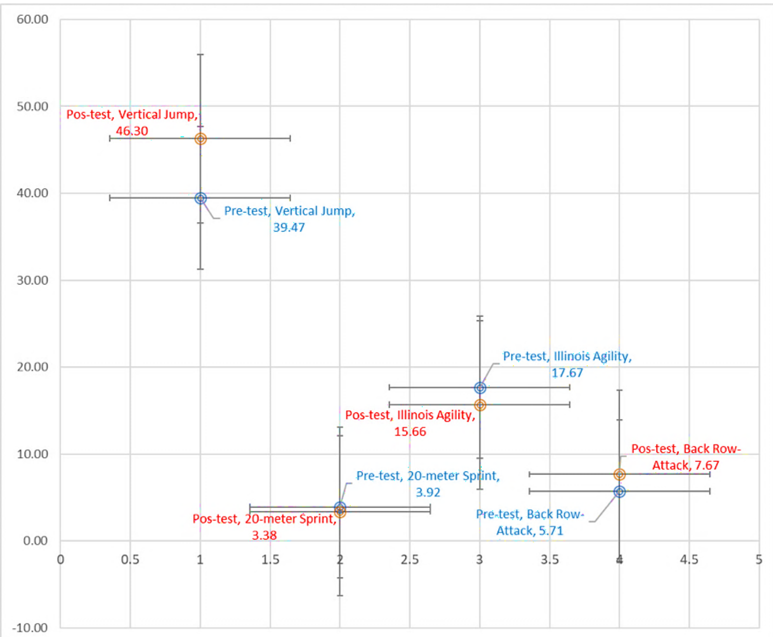

Figure 2. Graph Showing Improvement from Pre-test to Post-test.

Normality and Homogeneity Tests

Before conducting inferential analysis, such as the paired sample t-test, it is crucial to ensure that the dataset fulfills the assumptions of parametric statistical tests. Two primary assumptions are normality and homogeneity of variance. The normality test is employed to determine whether the distribution of the data approximates a normal curve, which is essential for the accuracy of statistical estimations and inferences. The Shapiro-Wilk test is commonly used in this context, especially when dealing with small to medium sample sizes, due to its robustness and sensitivity. Meanwhile, the homogeneity of variance test assesses whether the variances of different groups or conditions are statistically equal. Ensuring homogeneity allows for fair comparisons and reliable interpretation of differences across conditions. Levene's test is widely used for this purpose, as it does not require the data to be normally distributed to test for equal variances. In this study, all data were confirmed to follow a normal distribution according to the Shapiro-Wilk test ($p > 0.05$), indicating that the assumption of normality was met. Furthermore, Levene's test also indicated homogeneity of variance across pre-test and post-test scores ($p > 0.05$). These results validate the use of parametric analysis, specifically the paired sample t-test, in evaluating the effectiveness of the VR-based training intervention. Normality and Homogeneity Test: All data show normal distribution based on the Shapiro-Wilk test ($p > 0.05$) and homogeneous variance according to the Levene test results ($p > 0.05$).

Paired Sample t-Test

The Paired Sample t-test is a statistical method used to compare the means of two related groups — typically pre-test and post-test scores — to determine whether there is a statistically significant difference between them. This test is particularly useful in experimental designs where the same subjects are measured before and after an intervention. In this study, after confirming the assumptions of normality and homogeneity, the analysis was continued using the Paired Sample t-test to evaluate the effectiveness of VR-based training. The results of this analysis are presented in the following section.

Table 3. The t-Test Result between Pre-test and Post-test

Variable	Pre-test Mean ± SD	Post-test Mean ± SD	t-value	Sig. (2-tailed)	Effect size (Cohen's d)
Vertical Jump (cm)	39.47 ± 2.90	46.3 ± 2.55	-40.1	< 0.001	-8.18
20-meter Sprint (seconds)	3.92 ± 0.81	3.38 ± 0.76	11.9	< 0.001	2.42
Illinois Agility (seconds)	17.67 ± 1.52	15.66 ± 1.27	15.9	< 0.001	3.32
Back-row Attack (score)	5.71 ± 1.65	7.67 ± 1.55	13.9	< 0.001	-2.84

The paired sample t-test results revealed statistically significant improvements across all measured variables following the VR-based training intervention. In terms of vertical jump performance, the mean value increased from 39.47 cm to 46.3 cm ($p < 0.001$; $d = -8.18$), indicating a substantial enhancement in lower limb explosive power. This improvement is critical in volleyball, particularly for executing back-row attacks that demand high take-off velocity and leg power. Similarly, 20-meter sprint times decreased from 3.92 seconds to 3.38 seconds ($p < 0.001$; $d = 2.42$), suggesting a marked improvement in sprint speed, which is a key component during the approach phase of a back-row attack.

Agility, assessed using the Illinois agility test, also showed meaningful enhancement, with times decreasing from 17.67 seconds to 15.66 seconds ($p < 0.001$; $d = 3.32$). This result reflects improved movement efficiency and the athlete's ability to change direction rapidly—an essential skill for adapting to dynamic in-game scenarios. Meanwhile, the effectiveness of back-row attack execution demonstrated a significant increase, with mean scores rising from 5.71 to 7.67. The statistical analysis reported a t-value of 13.9 with $p < 0.001$ and an effect size of $d = -2.84$, highlighting a substantial improvement in technical execution. This finding underscores the positive impact of VR-based training on motor coordination, timing, and decision-making in game-like contexts. Collectively, the results emphasize that immersive technology-based interventions are not only effective in enhancing basic physical components such as power, speed, and agility but also play a critical role in developing complex technical performance, such as back-row attacks in junior volleyball athletes.

Regression Test

Next, a regression analysis was conducted to examine the simultaneous influence of lower limb power, speed, and agility on the effectiveness of back-row attack techniques among junior volleyball athletes. This analysis aimed to determine the extent to which these three physical condition variables collectively predict improvements in back-row attacking performance. The results of the regression analysis are presented in the following section.

Table 4. Regression Analysis Results

Variable	β (beta)	sig	R^2	F	Sig
Vertical Jump	.234	.000	0.876	47.092	.000ᵇ
20-meter Sprint	-.588	.003			
Illinois Agility	-.715	.000			

The regression analysis results revealed that the Vertical Jump variable had a positive and statistically significant influence on the Back-row attack score (β = 0.234, p = 0.000). This finding implies that athletes with greater vertical jump ability tend to exhibit higher effectiveness in executing back-row attacks, highlighting the crucial role of lower limb explosive strength in supporting powerful back-line offensive actions. Conversely, the 20-meter Sprint (β = -0.588, p = 0.003) and the Illinois Agility Test (β = -0.715, p = 0.000) showed significant negative coefficients. These results indicate that shorter sprint and agility test times—which reflect improvements in speed and agility—are associated with increased back-row attack performance. In essence, athletes who are quicker and more agile are better positioned to execute efficient and well-timed back-row attacks due to their superior movement capabilities and adaptability in dynamic game situations.

The coefficient of determination (R^2) value of 0.876 suggests that 87.6% of the variance in back-row attack effectiveness can be accounted for by the three physical variables such as leg power, speed, and agility. The remaining 12.4% is likely attributable to other unmeasured factors such as hand-eye coordination, jump timing precision, or technical execution skills not captured within this model. Moreover, the F-test yielded a value of 47.092 with a significance level of p = 0.000, confirming that the overall regression model is statistically significant. This means that the combination of these three predictor variables collectively contributes meaningfully to enhancing back-row attack performance among junior volleyball athletes.

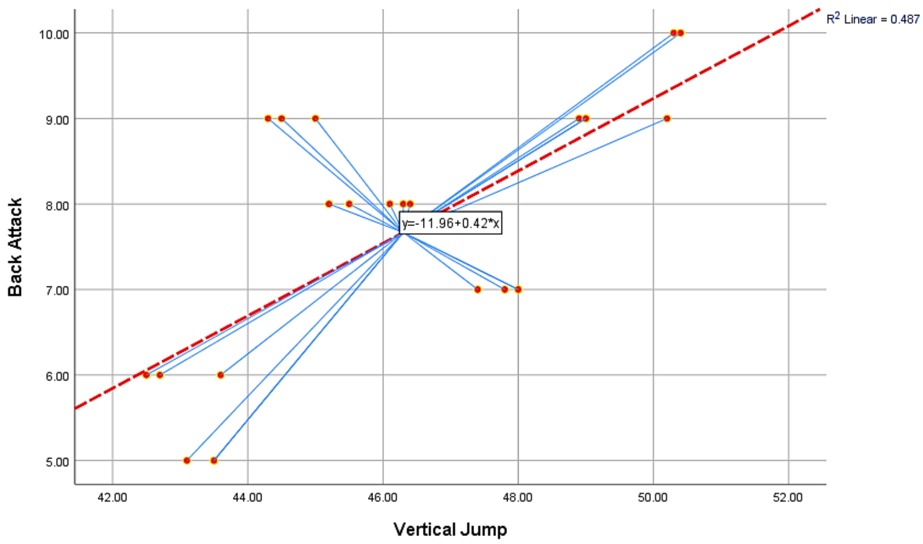

Figure 3. Graph of Leg Muscle Power's Contribution to Back-row Attacks

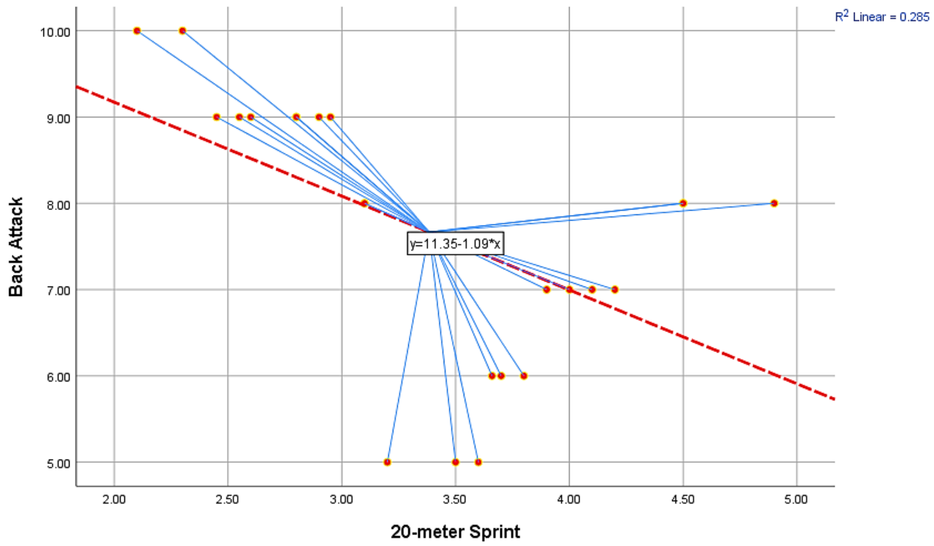

Figure 4. Graph of Speed Contribution to Back-row Attacks

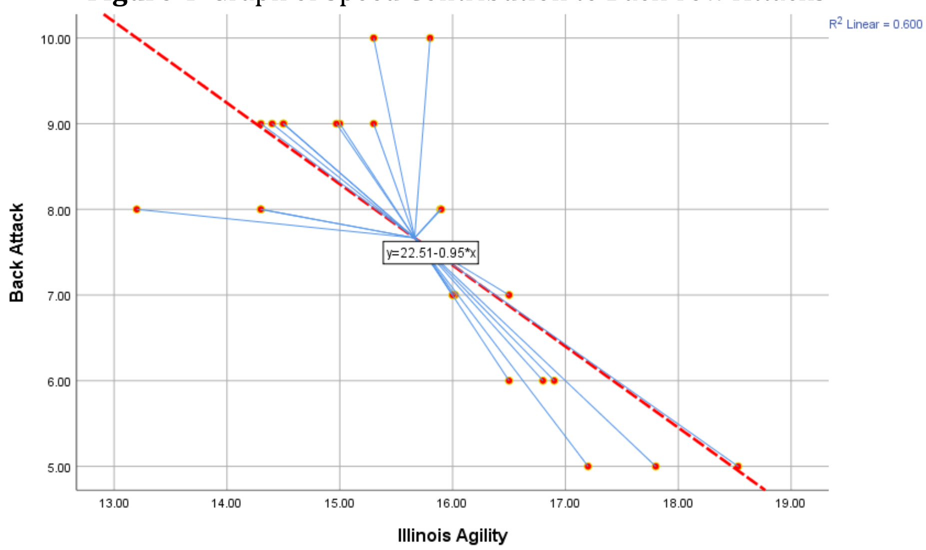

Figure 5. Graph of Agility Contribution to Back-row Attacks

In the regression model analyzed, the residuals are normally distributed, as indicated by the results of the residual normality test that meets the assumption of normal distribution. In addition, no symptoms of multicollinearity were found because the Variance Inflation Factor (VIF) values for all independent variables were below 10, indicating that there was no strong linear relationship between the independent variables in the model. The scatterplot test showed a random pattern of residual points that did not form a particular pattern, indicating that the assumption of homoscedasticity was met—meaning the residual variance was constant at each predictor level. Overall, this regression model meets the classical assumptions except for the initial indication of heteroscedasticity. Still, because no specific systematic pattern was detected, these symptoms can be categorized as not significantly disrupting the validity of the model. Thus, the regression model is suitable for interpreting the relationship between physical condition variables and the effectiveness of back-row attacks in junior volleyball athletes.

Discussion

The results of this study indicate that the use of VR-based training has a positive influence on improving the physical conditions of athletes and the effectiveness of back-row attack techniques among junior volleyball athletes. These findings not only support previous findings but also provide new insights into the use of immersive technology for sports training. However, it is important to emphasize that the effectiveness of VR-based training cannot be understood simply as a direct result of the presence of the technology but rather through the motor learning mechanisms that it facilitates. In this context, VR-based training has been shown to provide a safe, repetitive, and multi-sensory training environment that supports the creation of new motor pathways in the athlete's nervous system (Bae, 2023; Pastel et al., 2023).

This accelerated motor learning process due to VR-based training is consistent with the principles of ecological dynamics or a framework that analyzes how complex systems such as individuals, groups, and entire ecosystems interact and shape their behaviors, development, and functions (Mangalam et al., 2023). In this regard, VR-based training allows athletes to enhance their back-row attacks' performances through the complex analysis of feedback provided by this technology. Against this background, VR-based training provides variety and complexity that can enhance decision-making and movement adaptation, especially in back-row attack situations that require high levels of spatial and temporal coordination. In addition, the constraint-driven approach also explains how VR-based technology can be a tool to organize the training environment to elicit neuromuscularly efficient movement solutions (Yunchao et al., 2023; Janssen, 2023). From a physiological perspective, VR-based training supports increased neuromuscular efficiency by providing muscle stimulation similar to real physical exercise but with a lower risk of injury (Almansour, 2024; Magliato et al., 2024). This is important for young athletes who are still developing and are more susceptible to conventional training loads. Thus, VR-based training is not only a training aid but also an innovative tool for designing training programs that meet the developmental needs of young athletes.

However, it is important to criticize that this research design used a one-group, no-control approach, which limits the internal and external validity of the findings. The lack of a comparison group makes it impossible to confirm whether the performance improvement was solely due to the VR-based technology intervention or not. In addition, the limitation in comparing these results with international studies also weakens the contribution of this study to the global map of sports technology development (Bujang et al., 2025). Similar studies in Europe and East Asia show that the effectiveness of VR-based technology in sports training is highly dependent on the quality of the hardware used, the intensity and frequency of training, and the active involvement of coaches in the learning process (Cariati et al., 2025; Najami & Ghannam, 2025).

Research Contribution

These are some of the main contributions of this study. Theoretically, this study reinforces the relevance of technology-based ecological and motor learning approaches in modern sports training. Practically, this study demonstrates that VR-based technology can be integrated into routine training programs for junior athletes to simultaneously improve technical efficiency and physical condition. Given the limitations of the experimental design used, further research should adopt a quasi-experimental design with a control group and integrate AI-based motion-tracking technology to improve training precision and personalization.

Limitations

This study has several limitations that need to be considered when interpreting the results and designing further research. First, this study did not involve a control group, making it difficult to ascertain that the observed changes or improvements in performance were entirely due to the intervention provided and not to other external factors. The absence of a comparison group reduces the inferential power of the study's findings. Nevertheless, to partially control the research results, the authors used a pre-test and post-test design, which allowed for the evaluation of changes in the subjects before and after the treatment. Second, the limited sample size of junior athletes restricts the generalization of the findings to broader age groups, such as senior or professional athletes. Differences in experience level, physical maturity, and training intensity are likely to influence the effectiveness of the back-row attack technique analyzed. Third, this study only covers three aspects of physical condition: vertical jump, 20-metre sprint, and agility. Other important aspects, such as technical skills (e.g., ball touch quality), tactical aspects (positioning during attacks), and psychological factors (such as confidence and focus), were not analyzed, even though back-row attack performance is multi-dimensional. Therefore, further studies need to include these variables to obtain a more comprehensive picture of performance. Fourth, the quantitative approach used has not been complemented by qualitative methods such as visual technique observation, video analysis of movements, or interviews with coaches and athletes, which could provide deeper insights into the factors influencing attack effectiveness. Future research is recommended to adopt a mixed-method approach. Fifth, environmental factors during data collection—such as the type of court surface, athletes' fatigue levels, and the quality of sparring partners—were not strictly controlled, potentially introducing bias or variations in results not stemming from the primary research variables.

Suggestions

In spite of the limitations mentioned above, the findings of this study can form the basis for exploring the use of VR-based technology in other technical skills, such as blocking, setting, or serving, as well as developing systems based on artificial intelligence or real-time motion tracking. Meanwhile, for policymakers in the fields of education and sports, it is important to start allocating budgets for the procurement of VR devices and coach training to support athlete development based on technology and scientific evidence. For athletes and students, the use of VR-based techniques opens up opportunities for training in safe and controlled situations, increasing enthusiasm and confidence to master more complex techniques through an interactive, simulated approach.

CONCLUSION

This study was initiated with the expectation that VR-based training would improve both the physical condition and back-row attack effectiveness among junior volleyball athletes. The results confirm this hypothesis, demonstrating significant improvements in both aspects. These findings are consistent with the theoretical framework introduced earlier, particularly in motor learning and action-perception coupling, validating that immersive environments such as VR can optimize decision-making and technique execution through realistic simulations. Furthermore, this study highlights the applicability of VR technology as a modern and adaptable instructional tool in athlete development. Looking forward, these results pave the way for broader integration of VR into sports training systems, particularly when enhanced with AI-based motion tracking to enable real-time feedback and personalized training. However, to ensure methodological rigor, future studies should adopt true experimental designs with control groups and expand the scope beyond visualization to include interactive feedback systems. In doing so, VR-based training could evolve into a comprehensive digital training paradigm that addresses the physical, technical, cognitive, and psychological readiness of athletes in a fully integrated manner.

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AUTHOR CONTRIBUTION STATEMENT

B, MK, and HB were responsible for the conceptualization, study design, and initial drafting of the manuscript. AFR contributed to data collection. YH contributed to the interpretation of the results and critical revision of the manuscript. WT and WAMWP contributed to data analysis and interpretation of the results. DIM and BS contributed to the refinement of the manuscript and handled the manuscript revision.

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