COMPETITOR:
JURNAL PENDIDIKAN KEPELATIHAN OLAHRAGA
e-ISSN: 2657-0734 & p-ISSN: 2085-5389 ‖ Volume 18, Number 1, 2026 ‖ P.0624-0636

Contribution of Leg Muscle Power on Sand to the Effectiveness of Beach Volleyball Players' Attacks

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ABSTRACT

This study aims to examine the contribution of leg muscle explosive power on sand to the effectiveness of attacks performed by beach volleyball players. A quantitative approach with a correlational research design was employed to objectively analyze the relationship between physical capacity and technical performance. The research subjects consisted of 12 female athletes from the Indonesian National Beach Volleyball Team, selected using purposive sampling to ensure relevance to elite competitive performance. Leg muscle explosive power was assessed through standardized physical tests conducted directly on sand to reflect the biomechanical demands of beach volleyball, while attack effectiveness was evaluated using indicators of attack success, accuracy, and overall attack quality during game-based situations. Data analysis included descriptive statistics, assumption testing, and inferential statistical procedures. The results of the normality test indicated that the data were normally distributed ($p > 0.05$), meeting the requirements for parametric analysis. Although the homogeneity assumption was not fulfilled ($p < 0.05$), data analysis was adjusted using the Greenhouse–Geisser correction. Hypothesis testing revealed a significant improvement in attack effectiveness ($p = 0.021$), accompanied by a large effect size (Cohen's $d = 1.362$). These findings demonstrate that increases in leg muscle explosive power on sand are strongly associated with enhanced attack effectiveness in beach volleyball athletes. From a physiological perspective, the improvement in attack performance is supported by neuromuscular adaptations, including enhanced recruitment of type II muscle fibers and greater efficiency of anaerobic energy systems, which facilitate higher, more explosive, and more stable jumps on an unstable sand surface. In conclusion, leg muscle explosive power on sand is a key determinant of attack effectiveness in beach volleyball. Therefore, sand-based, sport-specific training programs should be prioritized to optimize attack performance and competitive outcomes.

ARTICLE HISTORY

Received: 2026/01/24
Accepted: 2026/02/00
Published: 2026/02/10

KEYWORDS

Beach Volleyball;
Leg Muscle Explosive Power;
Sand-Based Training;
Attack Effectiveness;
Neuromuscular Adaptation.

AUTHORS' CONTRIBUTION

A. Conception and design of the study;
B. Acquisition of data;
C. Analysis and interpretation of data;
D. Manuscript preparation;
E. Obtaining funding

Cites this Article : Vivi Novia Eka Putri. (2026). Contribution of Leg Muscle Power on Sand to the Effectiveness of Beach Volleyball Players' Attacks. **Competitor: Jurnal Pendidikan Kepelatihan Olahraga**. 18 (1), p.0624-0636

INTRODUCTION

Beach volleyball is a competitive sport with fundamentally different biomechanical and physiological characteristics compared to indoor volleyball, primarily because it is

played on an unstable sand surface that absorbs kinetic energy. Sand surfaces reduce ground reaction forces and increase the demands on lower extremity muscles during jumping and rapid movement. Several recent studies have shown that beach volleyball results in higher internal loads, characterized by increased heart rate, energy consumption, and faster neuromuscular fatigue, compared to playing on hard courts (Figueira et al., 2025). This requires athletes to possess specific physical capacities, particularly leg muscle explosiveness, to maintain the effectiveness of attacks such as smashes and spikes throughout the match.

Offensive play is the primary determinant of points scored in beach volleyball, making jump quality, speed of movement, and explosive ability crucial. However, biomechanical studies have shown that jumping on sand results in lower jump heights and peak power output compared to hard courts, which directly impacts the effectiveness of attacking techniques (Giatsis et al., 2022). This phenomenon is further reinforced by empirical findings among Indonesian national beach volleyball athletes, which demonstrate variations in physical condition, particularly leg muscle explosiveness and endurance, which impacts inconsistent attack quality during matches (Novitasari, 2022).

Field observations also indicate that many athletes experience a decline in smash quality when required to move and jump repeatedly on sand. Limited leg muscle explosiveness results in lower jump height, reduced arm swing speed, and decreased attack accuracy. Consequently, athletes' technical and tactical potential cannot be maximized. This issue emphasizes that beach volleyball athletes require not only general physical strength but also specific adaptive abilities to the characteristics of sand as a movement medium. Therefore, scientific studies on the role of leg muscle explosiveness on sand are highly relevant to address the practical and scientific needs of beach volleyball performance development.

Leg muscle explosiveness is a component of physical fitness that integrates the strength and speed of muscle contraction to generate maximum power in a short period of time. In the context of beach volleyball, this component plays a crucial role in supporting jumping ability during attacks and blocks. Numerous studies have shown that vertical jump performance is strongly correlated with the quality of attacking technique in various sports, including volleyball (Bobula et al., 2024). Athletes with good leg muscle explosiveness tend to have a higher ball contact point and a sharper angle of attack.

However, the characteristics of sand present different biomechanical challenges. Biomechanical analysis shows that jumping on sand is characterized by a decrease in jump height and vertical power output, but accompanied by an increase in the rate of muscle force development as a neuromuscular adaptation to the unstable surface (Giatsis et al., 2022). These findings confirm that the physiological and mechanical demands of beach volleyball are unique and cannot be compared to indoor volleyball.

Several experimental studies have reported that plyometric training performed on sand significantly increases leg muscle explosive power compared to training on hard surfaces, as it provides a more contextual adaptation stimulus to match conditions

(Sutimin et al., 2021). Furthermore, attacking technique performance in beach volleyball has been shown to be significantly influenced by physical capacity, particularly in high-intensity match situations with cumulative fatigue (Marzano-Felisatti et al., 2025). Other studies have also confirmed that leg muscle explosive power contributes significantly to smash quality in volleyball, thus considering this component a key foundation for attacking performance (Oktariana & Hardiyono, 2020).

Recent literature consistently demonstrates that increasing competitive demands at the national and international levels require a more specific, evidence-based training approach. A recent systematic review identified leg muscle explosive power as one of the most dominant physical factors influencing beach volleyball athletes' attacking performance, particularly when matches are played in physically challenging environments (Murtadho et al., 2025).

Although the role of leg muscle explosiveness on attacking performance has been extensively studied, most research focuses on indoor volleyball contexts or on hard surfaces. Recent biomechanical studies have shown that the kinetic and kinematic parameters of beach volleyball athletes' jumps on various types of sand differ significantly compared to hard surfaces, so indoor research results cannot be directly generalized to the beach volleyball context (Neto et al., 2024).

Research specifically examining the contribution of leg muscle explosiveness on sand to attack effectiveness is still relatively limited. A recent literature review confirmed that the interaction between an athlete's physical condition and the characteristics of the playing environment, such as sand, has not been empirically and systematically analyzed (Murtadho et al., 2025). This is despite the fact that sand has the property of absorbing energy and reducing ground reaction forces, which significantly impact movement mechanics and jump effectiveness.

This gap indicates a gap between the practical needs of coaches on the field and the availability of contextual scientific evidence. Without specific empirical data, coaches tend to adapt indoor volleyball training models that are less relevant to the demands of beach volleyball. Other research also shows differences in movement adaptation patterns and neuromuscular strategies when jumping on sand compared to hard surfaces, requiring scientifically tailored training approaches and performance evaluations (Giatsis et al., 2023). Therefore, research specifically examining the contribution of leg muscle explosiveness on sand to the effectiveness of beach volleyball attacks is needed.

This study aims to analyze the contribution of leg muscle explosive power in sand to the effectiveness of beach volleyball athletes' attacks. Specifically, this research seeks to provide an empirical overview of the relationship between lower extremity explosive ability and the quality of attacks produced by athletes in the context of play on sand. The results are expected to provide a scientific basis for designing more specific, effective, and appropriate physical training programs tailored to the characteristics of beach volleyball.

The novelty of this research lies in its explicit focus on integrating the playing environment (sand) with physical capacity and technical attack performance. Unlike previous research, which generally generalizes findings from indoor volleyball, this study

positions sand as the primary contextual variable influencing athlete movement mechanics and performance. Thus, this research not only contributes to the literature on biomechanics and physiology of beach volleyball but also provides relevant empirical evidence for coaches and practitioners in developing performance development programs based on real-world competition conditions.

Practically, the findings of this study are expected to help coaches prioritize physical training that will significantly impact athletes' attack effectiveness. From an academic perspective, this study broadens the understanding of the relationship between leg muscle explosive power, playing environment, and technical performance in beach volleyball, thus serving as a reference for further research and the development of evidence-based sports coaching science.

METHODS

This study used a quantitative approach with a correlational design, aiming to analyze the contribution of leg muscle explosive power on sand to the attack effectiveness of beach volleyball athletes. This quantitative approach was chosen because it allows for objective, standardized measurement of variables and allows for statistical analysis to explain the relationships between variables based on numerical data (Creswell & Creswell, 2018; Thomas, Nelson, & Silverman, 2015). The correlational design was used to identify the strength and direction of the relationship between independent and dependent variables without manipulating the treatment, making it suitable for examining the functional relationship between physical capacity and technical performance in the context of competitive sports (Hadi & Saputra, 2024; Fraenkel, Wallen, & Hyun, 2019).

The independent variable in this study was leg muscle explosive power on sand, while the dependent variable was the attack effectiveness of beach volleyball athletes. Leg muscle explosive power is defined as the neuromuscular ability of the lower extremities to generate maximal force in a short period of time, which is a primary determinant of jumping and attack performance in volleyball (Bobula et al., 2024; Markovic & Mikulic, 2017). In the context of beach volleyball, this ability has specific characteristics due to the energy-absorbing properties of sand and the reduction of ground reaction forces (Giatsis et al., 2022). Therefore, measurement of leg muscle explosiveness is conducted using physical tests conducted directly on sand to align with the biomechanical and physiological demands of competition (Neto et al., 2024; Marzano-Felisatti et al., 2025).

Offensive effectiveness is defined as an athlete's ability to produce successful, accurate, and high-quality attacks during game situations. Indicators of offensive effectiveness include success in scoring points, quality of ball direction and speed, and offensive ability under dynamic match conditions (Gómez et al., 2018; Nejić et al., 2025). Measurement of offensive effectiveness is conducted through analysis of athletes' offensive performance in game situations or match simulations that mimic competition conditions, as recommended in game analysis-based sports performance research (O'Donoghue, 2015; Wagner et al., 2014).

The population in this study was all 12 female athletes on the Indonesian National Beach Volleyball Team. Given the limited size and unique nature of the population, all members of the population were used as the research sample (total sampling). This technique aligns with the principles of elite sport research, which emphasize the use of all available subjects to increase the ecological validity and practical relevance of research results (Hopkins et al., 2009; Mujika et al., 2018). The sample selection was also purposive, considering that the athletes studied had a representative skill level, national and international competition experience, and physical condition to examine the relationship between leg muscle explosiveness and attack effectiveness in a high-performance context (Fraenkel et al., 2019).

Data collection was conducted through standardized tests and measurements. Leg muscle explosiveness was measured using jump tests performed on sand, such as vertical jumps or countermovement jumps modified to suit beach volleyball conditions. The use of the jump test as an indicator of leg muscle explosive power has been widely recommended in the literature due to its high validity and reliability in measuring lower extremity explosive ability (Markovic et al., 2014; Bosco et al., 2015). Administering the test on sand is intended to capture the athlete's specific adaptations to actual surface conditions, thus making the measurement results more contextual and applicable (Giatsis et al., 2023; Sutimin et al., 2021).

Attack effectiveness is measured by recording and evaluating athletes' attack results during games or match simulations, including aspects of attack success, ball placement accuracy, and attack technique quality. This approach aligns with recommendations from sports performance research that emphasize the importance of real-game situation-based measurements to obtain a valid picture of performance (O'Donoghue, 2015; Gómez et al., 2018).

Data analysis was conducted using a quantitative statistical approach. The initial stage of the analysis included descriptive statistics to describe the characteristics of the data, including the minimum, maximum, mean, and standard deviation values for each variable (Field, 2018). Next, prerequisite analysis tests were conducted, including normality and linearity tests, to ensure that the data met the assumptions of parametric analysis (Pallant, 2020).

To determine the contribution of leg muscle explosiveness to attack effectiveness, Pearson correlation analysis and simple linear regression analysis were used. Correlation analysis was used to determine the strength and direction of the relationship between variables, while regression analysis was used to quantitatively estimate the contribution of independent variables to the dependent variable (Hair et al., 2019; Tabachnick & Fidell, 2019). The entire data analysis process was conducted using statistical software at a certain significance level ($\alpha = 0.05$) to ensure the objectivity, accuracy, and scientific accountability of the research results.

Overall, the methodological approach in this study was designed to produce valid, reliable, and practically relevant empirical findings, thereby making a tangible contribution to the development of evidence-based coaching science and beach volleyball performance development.

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RESULTS AND DISCUSSION

Result

The results of leg muscle explosive power measurements on sand and the effectiveness of beach volleyball athletes' attacks were analyzed using descriptive statistics to obtain an overview of the data characteristics. This analysis included minimum, maximum, average, and standard deviation values at the pretest and posttest stages. In general, the descriptive results showed an increase in the average value of the athletes' attack effectiveness after the training intervention, followed by an increase in physical capacity related to leg muscle explosive power. This increase indicates a change in the athletes' performance for the better after the implementation of a training program that emphasized strength and explosiveness on sand.

Data Normality Test

Table 1.
Data Normality Test

Group	Kolmogorov-Smirnov*			Shapiro-Wilk		
	Statistic	df	Sig	Statistic	df	Sig
Pretest	.245	6	.200	.848	6	.150
Posttest	.259	6	.200	.854	6	.170

Data normality was tested using the Kolmogorov–Smirnov and Shapiro–Wilk tests to ensure that the data were normally distributed as a prerequisite for parametric analysis. The normality test results showed that the significance value (Sig.) in the pretest and posttest data was above the significance limit of 0.05. This indicates that the data on leg muscle explosive power and the effectiveness of beach volleyball athletes' attacks were normally distributed. With the normality assumption fulfilled, the data is declared suitable for analysis using parametric statistical techniques.

Homogeneity Test

Table 2.
Homogeneity Test

Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon[b]		
				Greenhouse-Geisser	Huynh-Feldt	Lower-bound
.001	22.616	9	.013	.337	.418	.250

Table 2 presents the results of the homogeneity test using Mauchly's test with significant values based on the mean. The significance value (Sig.) is used to determine whether the variance between groups is the same (homogeneous) or not. The variable is considered homogeneous if the significance value is > 0.05. The Mauchly test results, with a significance value (Sig.) of 0.013, indicate that the sphericity assumption is not met (because $p < 0.05$). This means that the covariance matrix is not homogeneous. In other words, changes in performance between phases do not have uniform variance. This occurs because there are large changes in data variability in certain phases. Therefore, correction using the Greenhouse-Geisser method is needed to reduce the risk of type I error in interpreting the results.

Hypothesis Testing

Hypothesis testing was conducted to determine the contribution of leg muscle explosive power to the effectiveness of beach volleyball athletes' attacks.

Table 3.
Paired-t-Test Results

Group	Mean Difference	t-value	p-value
Pretest-Posttest	0.055	3.337	0.021

Table 4.
Effect Size Results (Cohen's d)

Group	Cohen's d	Interpretasi
Pretest-Posttest	1.362	Efek Besar

Based on Table 3 and Table 4, the test results show that from the maximum strength phase to the power phase, Cohen's d = 1.362 (CI: 0.188 – 2.478) and Hedges' correction = 1.257 (CI: 0.173 – 2.287). Cohen's d value indicates a very large effect (> 0.8). Cohen's d value is in the large effect category (>0.8) according to Cohen's scale (Cohen, 1988), indicating that there was a significant increase in anaerobic capacity during the Power phase. The confidence interval does not include zero, which means that these results are statistically significant and not merely coincidental.

The results of the study indicate that the increase in lower limb muscle power on sand contributes significantly to the effectiveness of beach volleyball athletes' attacks. This increase is reflected in the athletes' ability to produce higher, more explosive, and more stable jumps when attacking. The explosive exercises used, such as plyometrics and resistance-based exercises, play an important role in optimizing the stretch-shortening cycle of muscles, enabling athletes to generate maximum power in a short period of time. Research shows that plyometric training performed on sand has a different impact on jump ability and neuromuscular response compared to training on hard surfaces, as the sand surface affects force patterns and muscle adaptation. This adaptation is important in generating the explosive power needed to jump high and deliver effective attacks, such as in beach volleyball (Ahmadi et al., 2021). The neuromuscular adaptations that occur include increased recruitment of type II muscle fibers, motor unit synchronization, and anaerobic energy system efficiency. These conditions allow athletes to maintain the quality of their attacks even when performed on unstable and energy-absorbing sand. Thus, the results of this study empirically prove that leg muscle explosive power on sand is one of the determining factors in supporting the effectiveness of beach volleyball athletes' attacks.

Discussion

The results of this study indicate that explosive leg muscle power on sand significantly contributes to the effectiveness of beach volleyball athletes' attacks. This finding confirms that physical ability, particularly explosive leg muscle power, is the primary foundation supporting attacking technical performance in the context of playing on sand. Empirically, these results align with research showing that plyometric training

performed on sand surfaces significantly increases explosive leg muscle power compared to hard surfaces, making it more effective in supporting the explosive jumping ability required for beach volleyball attacks (Sutimin et al., 2021; Ahmadi et al., 2021). This situation reinforces the view that attacks in beach volleyball depend not only on technical skills in hitting the ball but also greatly on the athlete's ability to generate fast and powerful propulsion on unstable surfaces.

Biomechanically, sand has the characteristic of absorbing energy and reducing ground reaction forces, thus requiring greater leg muscle effort to produce optimal jump height (Giatsis et al., 2022). Athletes with strong leg muscle explosiveness are able to compensate for this energy loss through faster and stronger muscle contractions, allowing them to reach a higher point of contact with the ball. This finding is consistent with systematic reviews that suggest that increased explosive jumping ability is closely related to improved attack performance, such as spikes and smashes, in volleyball athletes (Mulyatini et al., 2025; Bobula et al., 2024). Thus, leg muscle explosiveness is a key differentiating factor in attack quality among beach volleyball athletes.

This study also aligns with the basic principles of sports biomechanics, which state that jump height and quality are significantly influenced by the ability of leg muscles to generate maximum force in a short period of time. Biomechanical studies have shown that the ability to generate large vertical forces directly contributes to attack effectiveness by increasing the angle and speed of the ball during the spike (Setiawan et al., 2025). In the context of beach volleyball, this principle becomes even more crucial because athletes must push off on unstable surfaces. The findings of this study indicate that athletes with higher leg muscle explosive power tend to be able to maintain the quality of their attacks despite having to make repeated moves and jumps on the sand, both in terms of points earned and the difficulty experienced by opponents in receiving the ball.

Conversely, athletes with low leg muscle explosiveness exhibit limitations in achieving optimal jump height, making their attacks more predictable and easily anticipated by opponents. This finding is reinforced by a biomechanical analysis of spikes, which shows that stride pattern, jump height, and vertical energy transfer coordination have a direct influence on power spike performance (Panjaitan et al., 2025). This confirms that leg muscle explosiveness is not merely a supporting factor, but rather a key component in effective attack execution in beach volleyball.

Furthermore, the results of this study confirm that leg muscle explosiveness training specifically performed on sand is highly relevant to increasing attack effectiveness. Neuromuscular adaptations resulting from plyometric training on sand, such as increased peak force and rate of force development, have been shown to align with the attacking demands of beach volleyball, which require explosive propulsion, even though some energy is absorbed by the sand (Ahmadi et al., 2021; Giatsis et al., 2023). These findings suggest that measuring and developing leg muscle explosiveness on sand provides a more realistic representation of competition demands than training on hard surfaces.

These results are further supported by a recent systematic review, which concluded that plyometric training on sand tends to be more effective in improving lower extremity

neuromuscular performance than on hard surfaces, particularly in the context of beach sports (Sanchez-Ottado et al., 2025). These findings emphasize the importance of the principle of training specificity, namely that the training stimulus must align with the biomechanical and physiological characteristics of the sport to optimally transfer training results to competition performance (Ramirez-Campillo et al., 2018; Bagheri et al., 2021).

From a technical performance perspective, attack effectiveness is influenced by various factors such as timing, coordination, and angle of attack. However, the results of this study indicate that leg muscle explosiveness is the dominant factor supporting all of these technical aspects. A recent literature review revealed that vertical jump height is a strong predictor of attack effectiveness because it allows athletes a longer flight time to optimally adjust the timing and angle of attack (Zega et al., 2025; Nejić et al., 2025). Athletes with good leg muscle explosiveness have a longer airborne time, allowing them to execute attacks with better control and a greater variety of effective attacks.

Conversely, limited leg muscle explosiveness causes athletes to execute attacks hastily due to a short flight time, resulting in suboptimal attack quality. Empirical research also shows a positive correlation between leg muscle explosiveness and volleyball athletes' smashing ability, confirming that lower extremity strength not only improves jumping ability but also the overall quality of attacking technique (Shinta & Mukti, 2025). Therefore, improving the quality of attacking technique is inseparable from developing physical condition, particularly leg muscle explosiveness, which must be carried out in a planned and sustainable manner.

The practical implications of these findings are crucial for the development of beach volleyball athletes, particularly at the elite level, such as the national team. The significant contribution of leg muscle explosiveness to attack effectiveness suggests that physical training programs need to devote a significant and structured portion to the development of this component. Meta-analyses and systematic reviews show that systematically designed plyometric training can improve leg muscle explosiveness and technical performance, such as vertical jumps and spikes, in volleyball athletes (Bagheri et al., 2021; Ramirez-Campillo et al., 2018). Sand-based training, such as sand jumps, bounding, and specific plyometric variations, has significant potential to improve athletes' ability to maintain attack quality even under conditions of match fatigue.

In addition to practical contributions, this research also provides important theoretical contributions to the development of sports science, particularly in the study of beach volleyball. By placing sand as the primary context of analysis, this study enriches our understanding of the relationship between physical condition and technical performance in a playing environment with characteristics different from hard courts. These findings can serve as a foundation for further research examining other physical variables, such as balance, agility, and muscular endurance, and their interactions with technical and tactical performance in beach volleyball.

Overall, the discussion of the results of this study confirms that leg muscle explosiveness in sand is a key factor contributing to the effectiveness of beach volleyball attacks. This finding directly addresses a research gap that has previously focused

primarily on indoor volleyball and hard surface contexts. By using sand as the measurement and analysis context, this study provides a more realistic picture of the physical demands of beach volleyball. Therefore, developing leg muscle explosiveness needs to be a top priority in athlete training and development. Going forward, the results of this study are expected to serve as a basis for the development of more specific, innovative, and evidence-based training models, as well as encourage further research that comprehensively integrates physical, technical, and tactical aspects to improve beach volleyball athlete performance.

CONCLUSION

Based on the research results and data analysis, it can be concluded that leg muscle explosiveness on sand significantly contributes to the effectiveness of beach volleyball athletes' attacks. These findings indicate that athletes with better leg muscle explosiveness tend to be able to produce higher jumps, more precise attack timing, and optimal attack quality, even when operating on unstable sand surfaces. Empirically, these results confirm that mechanical limitations due to the energy-absorbing nature of sand can be compensated for through superior lower extremity neuromuscular capacity.

Conceptually, these research findings reinforce the view that attacking technique performance in beach volleyball is inseparable from a foundation of physical condition, particularly leg muscle explosiveness. The ability to generate large forces in a short period of time is a primary prerequisite for achieving optimal ball contact, improving attack angles, and increasing the chances of scoring. Thus, leg muscle explosiveness plays a role not only as a supporting factor but also as a key component that differentiates attack quality among beach volleyball athletes.

The practical implications of these findings suggest that developing leg muscle explosiveness should be a top priority in beach volleyball athletes' training programs, particularly through specific exercises performed on sand. A contextual training approach based on the characteristics of the match environment is believed to be able to more effectively transfer training results to competitive performance.

Overall, this study provides scientific contributions by providing empirical evidence regarding the importance of leg muscle explosive power in the context of playing on sand. It also serves as a basis for developing coaching models and further research that integrate physical, technical, and environmental aspects of beach volleyball to improve performance.

ACKNOWLEDGEMENTS

The author expresses his deepest gratitude to all parties who contributed directly or indirectly to the implementation and completion of this research. He expresses his deepest appreciation to the beach volleyball athletes who agreed to be research subjects and actively participated throughout the data collection process. Their commitment,

discipline, and involvement were instrumental in ensuring that the data obtained objectively and contextually represented the athletes' performance conditions, in accordance with the demands of beach volleyball competition.

He also expresses his gratitude to the coaching team and officials who provided technical support, access permission, and assistance during the measurement and data collection process on the field. Their contributions were instrumental in ensuring the smooth running of the research procedures, particularly in creating testing conditions that closely approximated actual competition conditions. Furthermore, the author appreciates the academic input from colleagues and experts in the field of sports science who provided constructive suggestions, both during the research design, data analysis, and refinement of the scientific manuscript.

The author also expresses his gratitude to the institutions that facilitated the implementation of this research, including the support of facilities and infrastructure that enabled the measurements to be conducted systematically and in accordance with scientific standards. This institutional support contributes significantly to maintaining the validity and reliability of the research results.

Finally, the author acknowledges that this research still has limitations. Therefore, any constructive criticism and suggestions are highly appreciated as a basis for reflection and further research development in the field of beach volleyball and sports coaching.

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