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Anaerobic Power Cycling Training and Lower-Extremity Performance in Elite Female Handball Players: A Predictive Model Based on Morphological Indices

Jannatul Ferdaus Rickta[1], Fatima Tus Johora Mukta[1], Shaik Nazmus Shakib Shaim[1], Musfiqur Rahman[1], *Md. Yeasir Arafat[2]

1. Department of Physical Education & Sports Science, Jashore University of Science and Technology, Bangladesh.
2. Physical Education Office; Chittagong University of Engineering & Technology, Bangladesh.

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ABSTRACT

Objective Handball requires high levels of anaerobic power, explosive strength, and repeated sprint ability. This study aimed to evaluate the effects of power cycling training on anaerobic capacity and explosive performance in elite female handball players.

Methods Forty-three elite female handball players who had participated in the Bangladesh National Female Handball League and had at least five years of continuous handball experience were recruited. Participants were allocated to either a control group ($n = 21$) or a training group ($n = 22$). All data were recorded in Microsoft Excel and analyzed using IBM SPSS Statistics version 25.0.

Results Between-group comparisons revealed no statistically significant differences in most power cycling variables at baseline (all $p > 0.05$), confirming group homogeneity. However, significant within-group improvements in mean power and peak power relative to body weight were observed in the training group following the intervention ($p < 0.05$). Strong positive correlations were identified between peak power performance and lower-extremity skeletal muscle mass as well as thigh circumference ($r = 0.91$, $p < 0.001$). Multiple linear regression models explained 86.6% of the variance in peak power and 82.8% of the variance in mean power, indicating that lower-limb morphological indices are reliable predictors of anaerobic cycling performance.

Conclusion The training group demonstrated improvements in key Wingate performance variables despite the absence of significant between-group differences. Lower-extremity skeletal muscle mass and thigh circumference were strong predictors of anaerobic cycling performance, and the proposed regression models may offer a practical approach for monitoring anaerobic capacity in female handball players.

Corresponding Author:
Md. Yeasir Arafat
Address: Physical Education Office; Chittagong University of Engineering & Technology, Bangladesh.
E-mail: arafat4232@cuet.ac.bd

1. Introduction

Handball is an Olympic team sport played worldwide and characterized by frequent transitions between high-intensity and low-intensity activities (1). A standard match consists of two 30-minute halves, during which players repeatedly perform explosive actions such as sprinting, accelerating, jumping, throwing, and changing direction, interspersed with periods of walking or standing (2, 3). Consequently, repeated sprint ability, agility, and explosive power are essential determinants of successful performance (4). Physiological studies have shown that handball players spend a considerable proportion of match time at high exercise intensities, with approximately 47% of playing time performed at 81–90% of maximum heart rate and a further 24% above 90% of maximum heart rate (5, 6). Therefore, both anaerobic and aerobic energy systems are required to sustain performance, with anaerobic metabolism supporting high-intensity actions and aerobic metabolism facilitating recovery and prolonged activity (6).

Given the demanding nature of handball, training programs should incorporate anaerobic conditioning, explosive strength development, and sport-specific drills that replicate the rapid directional changes and repeated high-intensity efforts encountered during competition (7, 8). The frequent execution of sprinting, jumping, accelerating, decelerating, and directional changes places substantial demands on lower-extremity power and anaerobic capacity (9–13). These physical qualities are critical for achieving optimal performance during competitive matches (14). The repeated high-intensity actions performed during handball competition result in elevated blood lactate concentrations and substantial metabolic stress (15–17). Accordingly, handball players require well-developed anaerobic fitness to repeatedly perform intense efforts and recover efficiently between actions (18, 19). Previous research has demonstrated that high-intensity interval training (HIIT), plyometric exercises, explosive resistance training, and other anaerobic conditioning methods can improve performance-related physiological adaptations in handball players (20–22).

Several field and laboratory tests have been used to evaluate anaerobic performance in handball athletes, including repeated sprint ability (RSA) tests, suicide runs, vertical jump assessments, and the Wingate anaerobic cycling test (23–25). Among these, the 30-second Wingate test is widely recognized as a valid and reliable measure of anaerobic power and capacity (8, 25, 26). Previous studies have shown that various training interventions, including circuit resistance training under hypoxic conditions, HIIT, and Swiss-ball-based core power training, can enhance anaerobic exercise capacity and power production in athletes (27–29). Nevertheless, current training approaches do not always fully replicate the intermittent, high-intensity demands of competitive handball. Body composition and lower-extremity morphology are also important determinants of anaerobic performance. Limb circumference, muscle volume, and skeletal muscle mass are commonly used indicators of muscular development in sports science and physical education research (30, 31). Previous studies have demonstrated that muscle mass, limb circumference, and muscle volume can be modified through targeted training interventions and are positively associated with muscular strength and power production (30–35). Because muscle strength is closely related to muscle cross-sectional area, limb girth measurements are frequently used as practical indicators of strength development in both athletic and clinical populations (32, 33). Furthermore, resistance training has been shown to increase lower-extremity power and thigh circumference, and positive associations have been reported between thigh girth and power-related performance measures (30, 34, 35).

Evidence further suggests that anaerobic cycling performance is closely associated with body composition characteristics. Greater fat-free mass and skeletal muscle mass are generally associated with higher peak power, mean power, and jump performance, whereas higher body fat percentages are associated with reduced performance and increased fatigue (39, 40). In addition, different resistance-training approaches may influence specific performance outcomes, with velocity-based training being particularly effective for improving explosive strength and peak power, while percentage-based training may be more beneficial for enhancing mean power and endurance-related capacities (41–43). Therefore, the present study was designed to evaluate the effectiveness of power cycling training as a targeted intervention for improving anaerobic exercise capacity in elite female handball players, a population in which explosive strength and short-duration high-intensity performance are critical determinants of success. In addition, this study sought to investigate the relationships among lower-extremity circumference, skeletal muscle mass, and anaerobic cycling performance variables. By integrating these parameters, the study aimed to develop predictive models that may provide practical, objective, and cost-effective tools for monitoring athlete development and optimizing training strategies.

2. Methods

2.1. Participants

The study recruited 43 elite female handball players who had participated in the Bangladesh National Female Handball League and had been continuously engaged in handball training for at least five years. Participants were allocated into two groups based on their baseline anaerobic cycling performance. Following baseline assessment, athletes were assigned to either a control group (n = 21) or a training group (n = 22). To ensure methodological rigor, predefined inclusion and exclusion criteria were applied. Baseline homogeneity between groups was verified using independent-samples t-tests, which revealed no significant differences in the primary anaerobic performance variables. Athletes with known cardiovascular disease or any medical condition contraindicating high-intensity anaerobic exercise were excluded from participation. All participants volunteered to participate without financial compensation and provided written informed consent prior to data collection. All procedures were conducted according to standardized testing instructions. Prior to data collection, demographic information including age, height, weight, and body mass index (BMI) was recorded. Body composition and skeletal muscle mass were assessed using a validated bioelectrical impedance analyzer (InBody 720, Biospace Co., Ltd., Seoul, South Korea) (44, 45).

2.2. Anthropometric and Lower-Extremity Morphology Measurements

Before testing, the objectives and procedures of the study were explained in detail to all participants. To ensure measurement accuracy and reliability, all lower-extremity morphological assessments were performed by a certified examiner. Participants stood in an upright position with body weight evenly distributed between both lower limbs. Thigh circumference was measured using a Lufkin W606PM anthropometric tape at the midpoint between the greater trochanter and the lateral femoral condyle and recorded in centimeters (46, 47). Calf circumference was measured at the point of greatest girth. Baseline measurements were obtained one day before the commencement of the intervention, whereas follow-up assessments were conducted one day after completion of the final training session.

2.3. Anaerobic Cycling Training Protocol

The anaerobic cycling intervention was implemented longitudinally across four seasonal periods (winter, spring, summer, and autumn). During each seasonal period, the training group completed a progressive 3.5-week intervention block consisting of seven training sessions performed twice weekly. All training sessions were incorporated into the athletes' regular competitive-season training schedule. Each session consisted of a standardized active warm-up involving 120 seconds of light cycling, followed by a 30-second maximal Wingate-style sprint against a braking resistance equivalent to $0.075\ \mathrm{kg \cdot kg^{-1}}$ body mass. Participants then completed 300 seconds of passive recovery. This sequence was repeated four times within each training session (Fig. 1). The control group continued their regular handball training program, including technical, tactical, and conditioning activities, without additional cycling training. Outcome assessments were performed at baseline and following completion of the intervention period. The training protocol was based on established exercise physiology principles commonly used to evaluate anaerobic performance and training adaptations (8, 49).

2.4. Statistical Analysis

All data were entered into Microsoft Excel and analyzed using IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). Data entry was independently verified to ensure accuracy. Prior to inferential analysis, data normality was assessed using the Shapiro–Wilk test, and homogeneity of variance was evaluated using Levene's test. All primary outcome variables satisfied the assumptions required for parametric statistical analyses ($p > 0.05$). Descriptive statistics are presented as mean ± standard deviation (SD). Independent-samples t-tests were used to examine baseline differences between groups. Repeated-measures one-way ANOVA was used to assess within-group changes across training sessions, whereas repeated-measures two-way ANOVA was applied to evaluate group × time interaction effects. When significant effects were identified, post hoc comparisons were performed using the Least Significant Difference (LSD) test.

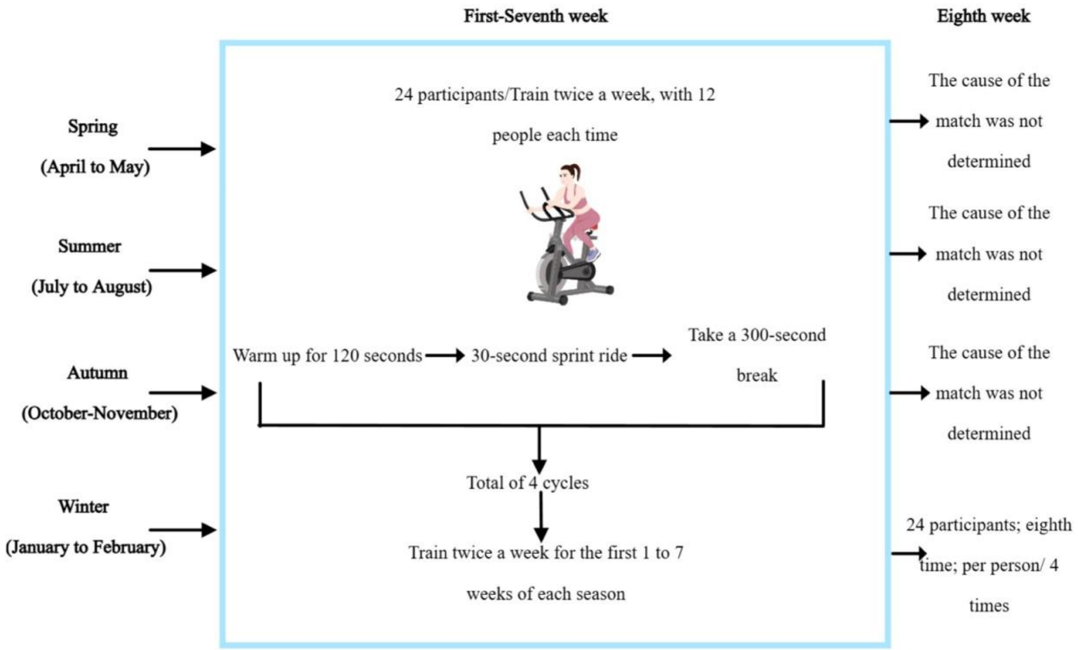

Fig. 1. Schematic representation of the anaerobic power cycling training protocol.

Pearson correlation analysis was used to examine relationships between lower-extremity morphological characteristics and anaerobic cycling performance variables. Multiple linear regression analyses were subsequently conducted to develop predictive models for key anaerobic performance outcomes using lower-extremity anthropometric and skeletal muscle variables as predictors. Statistical significance was established at $p < 0.05$ for all analyses.

3. Results

Descriptive characteristics of the participants are presented in Table 1. No significant differences were observed in the baseline anthropometric characteristics of the participants across the study periods. Table 2 presents the baseline Wingate test results for the control and training groups before the intervention. No significant between-group differences were observed in mean power, mean power relative to body weight, peak power, peak power relative to body weight, fatigue index, or total work (all $p > 0.05$), confirming baseline homogeneity between groups.

Changes in Wingate performance variables following the intervention are presented in Table 3. Significant between-group differences were observed for mean power ($p = 0.029$) and peak power relative to body weight ($p = 0.022$). Although improvements were observed in several performance variables in the training group, no significant differences were found between groups for peak power, fatigue index, or total work ($p > 0.05$). The effects of the power cycling training program across the seven training sessions are summarized in Table 4. Significant improvements were observed in mean power ($p = 0.004$), mean power relative to body weight ($p < 0.001$), minimum power ($p = 0.017$), and total work ($p = 0.037$). Post hoc analyses indicated that performance during sessions 5–7 was significantly greater than during the earlier sessions. In contrast, peak power, peak power relative to body weight, and fatigue index did not change significantly across the training period ($p > 0.05$).

Table 1. Descriptive Characteristics of the Participants Across the Study Periods

Variable	Winter	Spring	Summer	Autumn
Age (years)	21.16 ± 1.73	21.16 ± 1.73	21.16 ± 1.73	21.16 ± 1.73
Weight (kg)	60.23 ± 0.47	62.15 ± 12.39	61.94 ± 11.67	62.63 ± 12.28
Height (cm)	166.12 ± 6.19	166.12 ± 6.19	166.22 ± 6.27	166.12 ± 6.19
BMI (kg/m²)	22.23 ± 1.97	22.36 ± 1.81	22.36 ± 1.81	22.27 ± 1.74
Training Experience (years)	6.23 ± 2.54	6.33 ± 2.54	6.54 ± 2.57	6.63 ± 2.63

BMI = Body Mass Index.

Fig. 2 illustrates the correlations between lower-extremity morphological characteristics and anaerobic cycling performance variables. Significant positive associations were observed between anaerobic performance measures and skeletal muscle mass, thigh circumference, and calf circumference. In addition, body weight was positively associated with lower-extremity skeletal muscle mass and selected circumference measures. Multiple linear regression analyses were performed to determine the predictive value of lower-extremity morphological characteristics for anaerobic cycling performance (Table 5). The regression models explained 86.6% of the variance in peak power, 82.8% of the variance in mean power, 61.8% of the variance in peak power relative to body weight, and 70.1% of the variance in fatigue index. These findings indicate that lower-extremity skeletal muscle mass and limb circumferences are significant predictors of anaerobic cycling performance in elite female handball players.

4. Discussion

The present study examined the effects of anaerobic power cycling training on anaerobic performance and explored the relationships between lower-extremity morphological characteristics and anaerobic cycling performance in elite female handball players. The findings demonstrated that power cycling training improved several Wingate performance variables, particularly mean power, mean power relative to body weight, minimum power, and total work. In addition, lower-extremity skeletal muscle mass and thigh circumference were strongly associated with anaerobic cycling performance and emerged as significant predictors in the regression models. Anaerobic capacity is a critical component of performance in handball because the sport requires repeated bouts of sprinting, jumping, accelerating, decelerating, and rapid changes of direction throughout a match (4, 9–13). Consequently, training methods capable of enhancing lower-extremity power and short-duration high-intensity performance are of considerable practical importance.

Table 2. Baseline Comparison of Wingate Performance Variables Between the Control and Training Groups

Variable	Group	Mean ± SD	F	p-value
Mean Power (MP, W)	Control (n = 21)	425.27 ± 72.84	1.513	0.218
	Training (n = 22)	407.39 ± 88.21		
Mean Power/Body Weight (MP/BW, W·kg^{-1})	Control (n = 21)	5.94 ± 0.87	2.372	0.113
	Training (n = 22)	5.87 ± 0.71		
Peak Power (PP, W)	Control (n = 21)	757.37 ± 227.19	0.516	0.453
	Training (n = 22)	726.48 ± 211.21		
Peak Power/Body Weight (PP/BW, W·kg^{-1})	Control (n = 21)	11.82 ± 1.97	3.732	0.051
	Training (n = 22)	11.19 ± 1.23		
Fatigue Index (FI, W·s^{-1})	Control (n = 21)	17.88 ± 8.12	0.041	0.860
	Training (n = 22)	17.92 ± 6.21		
Total Work (TW, W)	Control (n = 21)	13013.79 ± 2401.14	1.501	0.218
	Training (n = 22)	12267.47 ± 2687.88		

Values are presented as mean ± SD.

Table 3. Changes in Wingate Performance Variables Following the Training Intervention

Variable	Group	Mean Change (Post − Pre) ± SD	F	p-value
Mean Power (MP, W)	Control (n = 21)	-9.12 ± 96.24	4.690	0.029
	Training (n = 22)	25.23 ± 48.33		
Mean Power/Body Weight (MP/BW, W·kg^{-1})	Control (n = 21)	0.18 ± 0.77	2.194	0.141
	Training (n = 22)	0.52 ± 0.91		
Peak Power (PP, W)	Control (n = 21)	-27.24 ± 201.13	1.625	0.182
	Training (n = 22)	16.66 ± 111.84		
Peak Power/Body Weight (PP/BW, W·kg^{-1})	Control (n = 21)	-0.71 ± 2.22	5.449	0.022
	Training (n = 22)	0.41 ± 1.93		
Fatigue Index (FI, W·s^{-1})	Control (n = 21)	1.07 ± 5.41	1.102	0.314
	Training (n = 22)	0.01 ± 3.81		
Total Work (TW, W)	Control (n = 21)	139.88 ± 2501.27	1.675	0.189
	Training (n = 22)	746.19 ± 1711.01		

Values are presented as mean change ± SD.

Table 4. Effects of Power Cycling Training on Wingate Performance Variables Across Seven Training Sessions

Session	MP (W)	MP/BW (W·kg^{-1})	PP (W)	PP/BW (W·kg^{-1})	MinP (W)	FI (W·s^{-1})	TW (W)
1	406.23 ± 63.58	6.11 ± 0.22	722.36 ± 203.21	11.16 ± 1.41	247.14 ± 78.13	18.71 ± 5.57	12521.17 ± 2777.92
2	410.39 ± 67.54	6.11 ± 0.19	726.41 ± 220.21	11.18 ± 1.46	241.66 ± 64.00	19.28 ± 6.95	12573.18 ± 2732.41
3	416.86 ± 71.02	6.30 ± 0.39	729.41 ± 221.10	11.19 ± 1.42	248.27 ± 71.47	18.77 ± 6.79	12609.32 ± 2699.00
4	421.88 ± 78.21	6.39 ± 0.44	731.12 ± 212.53	11.21 ± 1.56	258.25 ± 68.66	18.41 ± 6.52	12770.14 ± 2715.75
5	427.02 ± 81.29	6.47 ± 0.52	731.55 ± 210.23	11.23 ± 1.68	263.23 ± 74.31	18.09 ± 6.41	12859.07 ± 2715.11
6	429.47 ± 83.58	6.58 ± 0.56	736.64 ± 234.81	11.23 ± 1.70	264.01 ± 69.12	18.06 ± 6.01	12859.07 ± 2715.11
7	431.37 ± 84.19	6.72 ± 0.77	740.32 ± 231.01	11.27 ± 1.63	271.36 ± 63.12	18.71 ± 6.11	13078.86 ± 2553.19

ANOVA Results: MP (F = 3.158, p = 0.004), MP/BW (F = 5.337, p < 0.001), PP (F = 0.367, p = 0.849), PP/BW (F = 0.819, p = 0.547), MinP (F = 2.676, p = 0.017), FI (F = 1.359, p = 0.231), TW (F = 2.275, p = 0.037). Post hoc comparisons: MP: 5, 6, 7 > 1, 3; MP/BW: 5, 6, 7 > 1, 2, 3; MinP: 5, 6, 7 > 2; TW: 7 > 1 and 5, 6, 7 > 3.

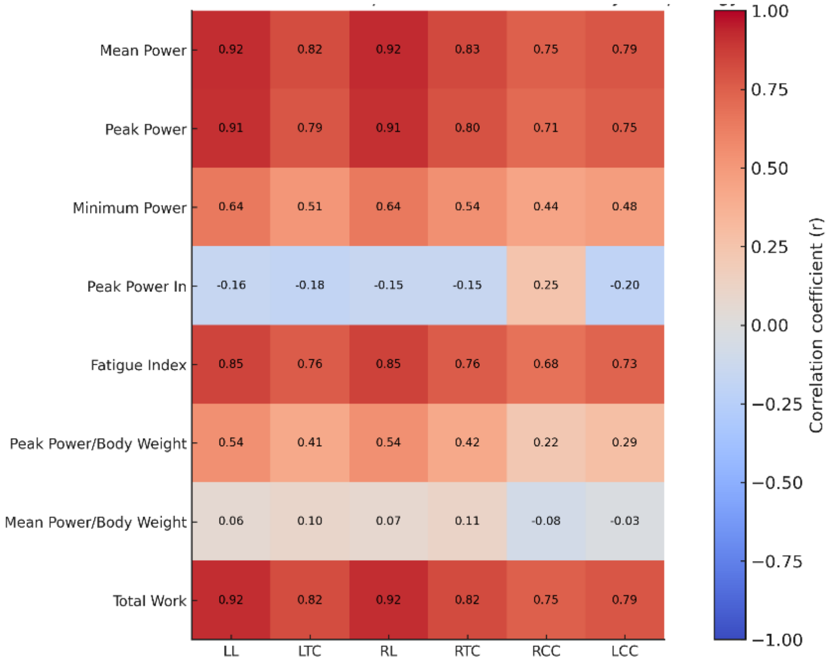

Fig. 2. Correlation Heatmap Between Lower-Extremity Morphological Indices and Anaerobic Power Metrics

Table 5. Multiple Linear Regression Models Predicting Anaerobic Cycling Performance Metrics from Lower-Extremity Morphological Indices

Dependent Variable	Predictor	B	SE	Beta	t	p-value	R²
Peak Power (PP)	Constant	-32.482	187.393	—	-0.165	0.772	0.866
	LL	132.810	15.387	0.989	9.145	<0.001	
	RCC	-44.314	11.814	-0.631	-4.283	<0.001	
	LTC	22.680	6.764	0.532	3.642	0.001	
Mean Power (MP)	Constant	17.327	27.395	—	0.424	0.578	0.828
	RL	50.734	3.388	0.921	13.865	<0.001	
Peak Power/Body Weight (PP/BW)	Constant	14.397	2.601	—	5.841	<0.001	0.618
	LL	1.210	0.189	1.101	5.671	<0.001	
	RCC	-0.876	0.138	-1.512	-6.112	<0.001	
	LTC	0.339	0.089	1.124	3.677	0.001	
Fatigue Index (FI)	Constant	-8.767	2.587	—	-3.341	0.002	0.701
	LL	3.272	0.315	0.851	10.251	<0.001	

Abbreviations: LL = Left Leg Skeletal Muscle Mass; RL = Right Leg Skeletal Muscle Mass; LTC = Left Thigh Circumference; RCC = Right Calf Circumference; B = Unstandardized Regression Coefficient; SE = Standard Error; Beta = Standardized Regression Coefficient; R² = Coefficient of Determination.

Power cycling training represents a form of high-intensity anaerobic exercise that places substantial demands on the ATP–phosphocreatine and glycolytic energy systems, thereby stimulating adaptations related to power production and fatigue resistance. Previous studies have similarly reported improvements in anaerobic performance following high-intensity interval training (HIIT) and sprint interval training (SIT) interventions in team-sport athletes (51–57). The present findings showed that the training group experienced greater improvements in Wingate performance variables than the control group. Significant improvements were particularly evident in mean power and peak power relative to body weight following the intervention. These results are consistent with previous research demonstrating that HIIT-based training programs can improve anaerobic power, repeated-sprint ability, and high-intensity exercise performance in handball players and other athletes (21, 51–54). The progressive increases observed across training sessions suggest that repeated exposure to high-intensity cycling stimuli may enhance the ability to sustain power output during short-duration maximal efforts.

A second important finding of this study was the strong relationship between lower-extremity morphology and anaerobic performance. Thigh circumference and lower-limb skeletal muscle mass demonstrated significant positive correlations with several Wingate performance variables. These findings are consistent with previous research showing that muscle size and cross-sectional area are important determinants of force production and power output (60–62). Because larger muscle mass provides greater potential for force generation, athletes with greater lower-extremity muscle development are generally capable of producing higher peak and mean power values during anaerobic exercise. The observed relationships may also reflect the physiological adaptations associated with high-intensity and resistance-based training. Initial improvements in performance are typically attributed to neural adaptations, including improved motor-unit recruitment and coordination, whereas longer-term gains are associated with muscle hypertrophy and increases in contractile protein content (65–67). Previous studies have reported that resistance and high-intensity training can increase thigh circumference and skeletal muscle mass within several weeks of training, contributing to improvements in strength and power performance (63, 66–68). The present findings support these observations by demonstrating significant associations between lower-extremity morphology and anaerobic power measures in female handball players.

Environmental conditions, nutritional status, and training-load characteristics may also influence anaerobic performance and training adaptations (46, 68, 69). Nevertheless, the strong associations observed in this study between lower-extremity skeletal muscle mass, limb circumferences, and anaerobic cycling performance are consistent with established physiological principles indicating that muscle force production is closely related to muscle size and physiological cross-sectional area (68–70). These findings support the use of lower-extremity anthropometric measurements as practical indicators of anaerobic performance capacity. The regression models developed in the present study explained a substantial proportion of the variance in anaerobic cycling performance variables. From a practical perspective, these models may provide coaches and practitioners with a simple and cost-effective method for estimating anaerobic performance when laboratory-based testing equipment is unavailable. Such an approach may be particularly useful in applied sport settings where access to specialized performance assessment tools is limited.

Several limitations should be acknowledged. First, the study included only female handball players; therefore, the findings may not be generalizable to male athletes or other sporting populations. Second, the sample size was relatively modest, which may limit the external validity of the predictive models. Future studies should examine the applicability of these models in larger and more diverse athletic populations and investigate whether similar relationships exist across different sports and competitive levels.

5. Conclusion

This study demonstrated that a targeted anaerobic power cycling training program improved mean power and relative peak power performance in elite female handball players. Although the groups were comparable at baseline, the training group showed progressive improvements across the intervention period and superior post-intervention performance in selected Wingate variables. Furthermore, lower-extremity morphological characteristics, particularly skeletal muscle mass and thigh circumference, were significant predictors of anaerobic cycling performance. The multiple linear regression models developed in this study may provide a practical, cost-effective, and field-based approach for evaluating lower-limb conditioning and monitoring anaerobic performance, particularly in training environments where access to advanced laboratory equipment is limited.

Ethical Considerations

Compliance with ethical guidelines

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Prior to data collection, all participants received detailed information regarding the study procedures, potential risks, and data confidentiality. Written informed consent was obtained from all participants before participation.

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Authors' contributions

All authors contributed equally to the conception, design, data collection, analysis, interpretation of the results, and preparation of the manuscript. All authors reviewed and approved the final version of the manuscript.

Conflicts of interest

The authors declare that they have no conflict of interest related to this study.

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