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Article

Evaluating the physiological conditions and biomechanics of wheelchair basketball players: A comprehensive study

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Abstract: Wheelchair basketball is a sport that requires high levels of strength, endurance, and motor control, with an important metabolic and cardiovascular component. Athletes must develop strong propulsion to optimize mobility and improve performance. Circuit training has been widely used to improve aerobic and anaerobic capacity in able-bodied athletes, but its specific effects on wheelchair basketball athletes are still poorly explored. This study evaluated the effects of a circuit training program on propulsive force, metabolic efficiency, and athletic performance in wheelchair basketball players. 120 wheelchair basketball athletes were divided into an experimental group ($n = 60$) and a control group ($n = 60$). The experimental group followed a 12-week circuit training program, with three weekly sessions, while the control group continued their standard training. Before and after the intervention, all participants underwent specific tests to assess average propulsive force (Wingate Peak Power Test), metabolic efficiency, endurance, and maximum heart rate. The experimental group showed significant improvement over the control group in mean propulsive power (+80 W, $p < 0.05$), metabolic efficiency (+2.5, $p < 0.05$), and mean RSA time (−0.3 s, $p < 0.05$). Maximum heart rate decreased slightly in both groups, suggesting better cardiovascular adaptation over time. Circuit training has proven to be an effective method of improving performance in wheelchair basketball players, with benefits in terms of strength, endurance, and metabolic efficiency. These results confirm the effectiveness of a structured approach to training for athletes with disabilities and offer useful indications to optimize physical preparation in this discipline.

Keywords: wheelchair basketball; circuit training; metabolic efficiency; propulsive force; athletic performance

1. Introduction

Circuit training is a particularly effective and versatile training methodology, widely used across various sports disciplines to enhance athletes' physical and physiological performance [1]. It combines aerobic and anaerobic exercises in a high-intensity sequence, allowing for the simultaneous development of strength, cardiovascular endurance, speed, and coordination [2]. The modular and adaptable structure of circuit training makes it especially suitable for meeting the specific needs of different categories of athletes, including Paralympic athletes [3]. Among these, wheelchair basketball players constitute a group requiring highly specialized training programs, as their performance largely depends on biomechanical efficiency and physiological responses related to wheelchair propulsion [4,5].

Wheelchair basketball is one of the most popular and competitive Paralympic sports globally, characterized by high-intensity play and a complex repertoire of technical and tactical skills [6]. The ability to accelerate, decelerate, and change direction rapidly with the wheelchair is crucial for on-court success. These movements require not only significant muscle strength but also excellent cardiovascular endurance and optimal neuromuscular coordination. Additionally, unlike able-bodied players, wheelchair basketball athletes face unique biomechanical challenges, as they must generate power and speed exclusively through the use of their upper limbs and torso, placing considerable stress on shoulder joints and the muscles involved in propulsion [7].

In recent decades, numerous studies have analyzed the physiological characteristics and most effective training methods for wheelchair basketball, highlighting how this discipline requires a high level of physical, technical, and tactical preparation [8–11]. Aerobic and anaerobic metabolism play a crucial role in athletic performance, as the game involves rapid changes in direction and intensity. The metabolic demands of wheelchair basketball are characterized by a combination of explosive efforts and periods of active recovery, which require a high level of endurance and the ability to sustain repeated high-intensity sprints [12]. At the cardiovascular level, athletes must develop an efficient capacity for oxygen transport and utilization, considering that wheelchair propulsion represents a highly energy-demanding activity [13].

The physiological demands of wheelchair basketball differ from other adapted sports such as wheelchair rugby or wheelchair racing. While wheelchair rugby requires an even higher level of physical contact and resistance to prolonged muscle fatigue, wheelchair racing primarily emphasizes endurance and propulsion speed in a straight line [14]. In wheelchair basketball, the variability of movements, with continuous stops, restarts, and changes of direction, poses a unique challenge for athletes, making targeted training to improve both aerobic and anaerobic capacity essential [15].

Wheelchair basketball athletes face specific challenges in terms of propulsion and endurance. The push of the wheelchair requires biomechanical optimization to maximize efficiency and reduce fatigue. The high use of the upper limbs can increase the risk of overuse injuries, such as tendinitis and shoulder injuries [16]. Moreover, the need to maintain a high level of endurance throughout an entire game is a significant challenge, given the constant energy demand for propulsion and the execution of technical and tactical movements.

Several studies have highlighted the need for specific training programs to improve endurance and muscle strength while simultaneously reducing the risk of overuse injuries [17–20]. Traditional training approaches for wheelchair basketball include aerobic sessions, resistance exercises, and technical-tactical work, but they often lack an effective integration of endurance and strength training. Furthermore, existing programs do not always adapt to different types of motor disabilities and tend to overlook innovative methodologies that enhance the variability of training stimuli.

An effective alternative could be circuit training, a methodology widely used in various sports disciplines, including soccer, swimming, and traditional basketball [21,22]. Scientific literature highlights how circuit training can improve muscular and cardiovascular endurance through a combination of multi-joint exercises and short recovery periods, increase functional strength through the alternation of strengthening exercises and sport-specific movements, and enhance coordination and agility thanks to the variety of proposed exercises [23]. In the context of Paralympic sports, recent studies have shown that circuit training can promote neuromuscular improvements, reduce fatigue, and enhance overall athletic performance. Circuit training, if properly adapted, could represent an effective strategy to improve athletes' performance, bridging the gaps in traditional approaches.

Despite the growing popularity of wheelchair basketball and the increasingly competitive nature of international competitions, scientific literature on specific training for these athletes remains relatively limited [24]. In particular, few studies have thoroughly explored the impact of circuit training on physiological responses, such as oxygen consumption (VO_2), heart rate (HR), anaerobic threshold, and metabolic efficiency, as well as on biomechanical adaptations related to wheelchair propulsion, including propulsive force, push angle, and movement patterns [25]. The importance of a detailed analysis of these parameters lies in the fact that improving biomechanical efficiency not only directly affects athletic performance but also helps reduce the risk of overuse injuries, which are a significant concern for wheelchair basketball players. Shoulder, elbow, and wrist injuries are particularly common due to the high-intensity repetitive movements required during propulsion, braking, and direction changes [26]. Therefore, identifying training programs capable of optimizing propulsion biomechanics could significantly impact both performance and the long-term health of athletes.

This article aims to fill this gap by thoroughly exploring the benefits of circuit training for wheelchair basketball players, with particular attention to improving physiological responses and biomechanical adaptations. The primary physiological parameters influenced by circuit training, such as aerobic capacity, muscle endurance, and anaerobic power, will be analyzed, as well as the biomechanical factors affecting propulsion efficiency, including propulsion technique, movement cycle, and energy utilization. Additionally, the metabolic adaptation mechanisms associated with this type of training will be discussed, highlighting how they can contribute to enhancing overall on-court performance.

Through an empirical investigation conducted on a group of wheelchair basketball players, the study intends to provide scientific evidence and practical guidelines for implementing targeted circuit training programs. The ultimate goal is to contribute to the advancement of knowledge in the field of adapted training and Paralympic sports performance, promoting inclusivity and athletic excellence for athletes with disabilities.

2. Materials and methods

2.1. Study design

The study was conducted for a duration of 12 weeks using a controlled experimental design with random assignment of participants into two groups: an experimental group ($n = 60$) and a control group ($n = 60$). The main objective of the study was to evaluate the effects of a circuit training program on the biomechanical and physiological performance of wheelchair basketball players, analyzing changes in physiological and performance parameters through specific tests before and after surgery.

The stratification of participants was integrated within a randomized controlled trial (RCT) design, ensuring an equitable distribution of key characteristics between the experimental group and the control group. Randomization was performed using a stratified block randomization method, which allowed for a balanced allocation of participants based on the following critical factors:

1) Competitive Level (Regional/National)—Participants were divided into two subgroups based on their competitive level. Within each subgroup, block randomization was applied to evenly assign athletes to the experimental and control groups, maintaining a balanced distribution of skill levels.
2) Type of Injury (Spinal Cord Injury, Amputation, Other Disabilities)—Since the type of injury affects athletes' biomechanical and physiological capabilities, randomization was conducted within each category to ensure similar representation across both groups. Participants were classified into three main categories: spinal cord injury (59%), amputation (26%), and other disabilities (15%). This classification was essential to account for differences in propulsion mechanics, energy expenditure, and overall performance capacity.
3) Functional Classification—Participants were further stratified based on their average functional classification score (3.2 ± 1.1). Randomization was performed within defined classification ranges (e.g., low, medium, and high functional levels) to ensure an even distribution of residual motor capacity.
4) Sex—Although the majority of participants were male (85 M/35 F), a stratified assignment by sex ensured a homogeneous distribution between the two groups.

The entire randomization process was conducted using randomization software, which generated random sequences while adhering to the imposed stratification constraints. This approach ensured that any differences in outcomes between groups could be attributed solely to the effect of the intervention rather than to confounding factors related to the individual characteristics of the athletes.

2.2. Participants

Table 1. Characteristics of the participants.

Characteristic	**Experimental Group (*n* = 60)**	**Control Group (*n* = 60)**	**Total (*n* = 120)**
Age (mean ± SD)	28.4 ± 5.2	29.1 ± 4.8	28.7 ± 5.0
Competitive level (Regional/National)	35%/65%	38%/62%	36.5%/63.5%
Type of injury	60% spinal cord injury, 25% amputation, 15% other disabilities	58% spinal cord injury, 27% amputation, 15% other disabilities	59% spinal cord injury, 26% amputation, 15% other disabilities
Functional Classification (mean ± SD)	3.2 ± 1.1	3.3 ± 1.0	3.2 ± 1.1
Training frequency (sessions/week)	≥ 3	≥ 3	≥ 3
Sex	43 M/17 F	42 M/18 F	85 M/35 F
Body Mass Index (BMI, ± SD mean)	23.5 ± 2.8	23.8 ± 2.6	23.7 ± 2.7

Table 1. (*Continued*).

Characteristic	**Experimental Group (*n* = 60)**	**Control Group (*n* = 60)**	**Total (*n* = 120)**
Absence of serious cardiovascular or respiratory disease	✓	✓	✓
Lesion stability (≥ 12 months)	✓	✓	✓
Recent injuries (≤ 3 months)	✗	✗	✗
Use of drugs that affect performance	✗	✗	✗
Previous experience with circuit training	✗	✗	✗
Signed informed consent	✓	✓	✓

The sample consisted of 120 wheelchair basketball athletes recruited from national sports clubs (**Table 1**). Inclusion and exclusion criteria were strictly applied to ensure sample homogeneity and the validity of the results. The athletes were randomly assigned to two groups: experimental and control, with a balanced distribution in terms of age, gender, competitive level, and functional classification.

To ensure the reliability and validity of the study results, specific inclusion and exclusion criteria were adopted in the selection of participants. These criteria allowed for the creation of a homogeneous sample of wheelchair basketball players, ensuring that the observed improvements could be attributed to the experimental intervention rather than external factors.

Inclusion Criteria

1) Active participation in wheelchair basketball—Only athletes who regularly practice wheelchair basketball at a competitive or semi-competitive level, with a training frequency of at least three sessions per week in the six months prior to the study, were included.
2) Age between 18 and 45 years—This age range was chosen to reduce variability due to differences in muscle development in younger subjects and physiological decline in older individuals.
3) Functional classification—Athletes needed to fall within a functional classification range of 1.0 to 4.5, according to international wheelchair basketball rules, ensuring the inclusion of players with varying levels of mobility and trunk control.
4) Absence of severe cardiovascular or respiratory conditions—Only athletes in good general health, without clinical conditions that could interfere with their ability to perform intense physical exercise, were admitted.
5) Stability of the injury—Participants were required to have a stable injury, with no significant changes in neurological conditions in the 12 months preceding the study.
6) Informed consent—All participants provided written informed consent after receiving a detailed explanation of the study’s objectives, methods, and potential risks.

Exclusion Criteria

1) Recent previous injuries—Athletes with serious muscle, joint, or bone injuries in the last three months that could affect performance in the tests or participation in training were excluded.
2) Medical conditions incompatible with exercise—Subjects with uncontrolled cardiovascular, respiratory, or metabolic diseases (such as uncontrolled diabetes or severe hypertension) were excluded for safety reasons.
3) Use of performance-affecting medication—Athletes who regularly took medications that could alter heart rate, muscle strength, or energy metabolism were excluded to avoid interference with the results.
4) Previous experience with circuit training—To avoid potential adaptation effects, athletes who had already followed structured circuit training protocols in the six months prior to the study were excluded.
5) Poor adherence to the protocol—Participants who did not attend at least 80% of the planned training sessions or did not complete all evaluation tests were excluded from the final data analysis.

The adoption of these criteria allowed for the creation of a representative sample of wheelchair basketball players and minimized confounding factors. The inclusion of athletes with different functional classifications enabled the evaluation of the effectiveness of circuit training across a wide range of motor conditions, making the results more applicable to the real sporting population. However, future studies may consider more homogeneous groups to more precisely explore the impact of training in athletes with varying levels of disability.

2.3. Procedures

The study involved 120 wheelchair basketball players, divided into an experimental group ($n = 60$) and a control group ($n = 60$). Participants were selected based on the inclusion and exclusion criteria, ensuring sample homogeneity in terms of competitive level, training frequency, and physical condition. After an informational meeting, all participants signed the informed consent form before the start of the evaluations and the experimental intervention.

Before the start of the training program, all participants underwent a battery of motor and physiological tests to assess their baseline physical capabilities. The tests performed included:

- Maximum Heart Rate (HRmax): Measured with a portable heart rate monitor (Polar H10) during a maximal progressive test.
- Peak Wingate Power (WPP): Assessed through a 30-s Wingate test on a wheelchair ergometer (Monark 881E).
- Anaerobic Endurance (RSA—Repeated Sprint Ability): Calculated through repeated sprints with the average time recorded for each sprint.
- Average Propulsive Force: Measured with a sensor system applied to the wheelchair wheels during maximal push trials.
- Metabolic Efficiency: Determined through oxygen consumption and power output during submaximal effort conditions using a portable metabolic analyzer (MetaMax 3B).

The measurements were conducted in a controlled environment at the research-affiliated sports center. The experimental group followed a 12-week circuit training program with a frequency of 3 sessions per week. The control group continued their standard training, based on regular basketball sessions without structured modifications to the physical preparation program.

After 12 weeks of training, all participants repeated the same motor and physiological tests used in the pre-intervention phase. The collected data were compared to evaluate improvements in performance parameters and metabolic capacity.

2.4. Training protocol

The training program consists of a 12-week circuit training intervention, conducted three times per week, with each session lasting 60 min. The program aims to improve three fundamental aspects of performance in wheelchair basketball players:

1) Propulsive Strength—Enhancing force generation in wheelchair propulsion.
2) Muscular Endurance—Increasing the ability to sustain effort over time.
3) Metabolic Efficiency—Optimizing energy consumption during physical activity.

Each training session includes:

- Warm-up (10 min)—Joint mobility, neuromuscular activation exercises, and brief wheelchair sprints.
- Circuit training (40 min)—Exercises performed in 6–8 stations, with 30–40 s of work per exercise, 20–30 s of rest between exercises, and 2 min of rest between circuits.
- Cool-down (10 min)—Stretching and muscle relaxation techniques.

The program is divided into three phases, each focusing on progressive intensity and adaptation:

Weeks 1–4: Technical and Muscular Adaptation Phase

- Goal: Focus on proper technique, muscular adaptation, and general endurance.
- Intensity: Moderate, emphasizing controlled movements and endurance building.
- Exercises:
  - Propulsive Strength: Elastic wall press (light resistance), push-ups with bands (low intensity).
  - Muscular Endurance: Continuous propulsion on a roller (1-min intervals), isometric holds (30 s).
  - Speed & Agility: Cone slalom at moderate pace, short-distance sprints (10 m at 70% effort).
  - Metabolic Efficiency: Ergometer intervals with a 1:1 work-to-rest ratio.

Weeks 5–8: Strength and Endurance Development Phase

- Goal: Increase exercise intensity, reduce recovery time, and develop sustained power.
- Intensity: Moderate to high, incorporating resistance and speed variations.
- Exercises:
  - Propulsive Strength: Pushes on wheelchair ergometer (medium resistance), push-ups with bands (increased tension).

  - Muscular Endurance: Continuous propulsion (2-min intervals), isometric holds (40 s).
  - Speed & Agility: Cone slalom with rapid accelerations, short sprints (15 m at 85% effort), quick stops and starts.
  - Metabolic Efficiency: Propulsive resistance drills (3–4 min bouts), high-intensity intervals on the ergometer.

Weeks 9–12: High-Intensity Performance Optimization Phase

- Goal: Develop maximum power, speed, and endurance for game-like conditions.
- Intensity: High, with short recovery times and increased load.
- Exercises:
  - Propulsive Strength: Pushes on wheelchair ergometer (high resistance), push-ups with bands (max tension).
  - Muscular Endurance: Continuous propulsion (3-min intervals), repeated short sprints with added weight.
  - Speed & Agility: Cone slalom at maximum speed, short sprints (20 m at 100% effort), fast stop-start drills.
  - Metabolic Efficiency: 5-min high-intensity propulsion simulation, variable intensity ergometer training.

Monitoring and Adaptation

- Heart rate and perceived exertion levels are monitored to ensure progressive adaptation.
- Individual modifications are made based on athlete progress and fatigue levels.
- The training program combines dynamic and progressive exercises, optimizing strength, speed, endurance, and energy efficiency over time.
- By the end of the 12-week program, athletes are expected to show significant improvements in propulsion power, endurance, and overall performance in wheelchair basketball.

The progression was individually adapted based on each athlete's improvements, with constant monitoring of heart rate and perceived fatigue levels. The circuit training was designed to specifically enhance the physical performance of wheelchair basketball players, combining strength, speed, endurance, and metabolic efficiency exercises. The combination of dynamic and progressive exercises allowed for optimized results over time, leading to significant improvements in the tested parameters.

2.5. Measures

To evaluate physiological and biomechanical parameters in wheelchair basketball players, it is necessary to use a series of specific and validated motor tests, capable of providing accurate and relevant data for this discipline:

1) Maximum Heart Rate (Max Heart Rate)

The maximum heart rate [27] represents the highest number of heartbeats per minute (bpm) an individual can reach during intense exertion. It is a crucial indicator of cardiovascular capacity and the circulatory system's response to physical activity. Heart rate was measured using a Polar H10 heart rate monitor (Polar Electro, Finland) during a maximal progressive test on a roller ergometer. The test began at a moderate intensity, with progressive increases in resistance every minute until the heart rate plateau was reached. The maximum value recorded was considered the individual's maximum heart rate.

2) Wingate Peak Power (Wingate Test Peak Power)

The Wingate Test [28] is an anaerobic test that measures explosive power and lactic anaerobic capacity. In the context of wheelchair basketball, it was used to assess the ability to rapidly generate high propulsive force, which is essential for sprints and changes in pace. Athletes performed a 30-s sprint on a wheelchair-adapted roller ergometer (Monark 881E - Monark Exercise AB, Sweden). The test was preceded by a brief warm-up, followed by maximal acceleration against a standardized resistance based on body weight. Parameters such as Peak Power (Watt): the highest value reached in the first few seconds of the sprint; and Average Power: the average power generated over the 30 s were recorded.

3) RSA—Average Time (Repeated Sprint Ability Test—Average Time)

The Repeated Sprint Ability Test (RSA) [29] is a protocol used to assess the ability to perform repeated high-intensity sprints with brief recovery times. This parameter is crucial in sports like wheelchair basketball, where players must repeatedly sprint throughout the game. Athletes performed 6–10 maximal sprints over a fixed distance of 15–20 m. Each sprint was separated by a brief recovery interval (around 20–30 s). The time for each sprint was recorded, and the average time was calculated as a benchmark.

4) Average Propulsive Force

Average propulsive force [30] measures the amount of force applied during wheelchair propulsion, representing a key indicator of locomotion efficiency and muscle strength specific to wheelchair athletes. The test was performed on a roller ergometer with force sensors applied to the wheels. Athletes performed several maximal-intensity pushes for a controlled period of time. The collected data were analyzed to determine the average force developed during each push.

5) Metabolic Efficiency

Metabolic efficiency represents the ability to optimize oxygen consumption in relation to work performed [31]. High metabolic efficiency means less energy expenditure to complete the same activity, reducing fatigue and improving sustained performance. The test was conducted using a portable metabolimeter (MetaMax 3B—Cortex, Germany), which recorded oxygen consumption (VO_2) and carbon dioxide output (VCO_2) during propulsion on the roller ergometer at a constant speed. Athletes performed a submaximal intensity test, maintaining a constant speed for a set period (e.g., 4–6 min). Metabolic efficiency was calculated as the ratio of oxygen consumption to the mechanical power generated.

These tests allowed for a detailed analysis of the effects of circuit training on wheelchair basketball players. The combined measurements provided a comprehensive overview of cardiovascular capacity, propulsive strength, and metabolic efficiency—fundamental parameters to improve athlete performance and autonomy.

2.6. Statistical analysis

To assess the effectiveness of the intervention, various statistical tools were used to analyze the data comprehensively and rigorously. For each parameter analyzed, indicators of central tendency and dispersion were calculated, such as the mean, standard deviation, median, and the minimum and maximum values. These values were reported separately for each group (experimental and control) to provide a preliminary view of the data distribution and the differences between the groups.

Normality Test

To check the data distribution and determine the appropriateness of the statistical tests to apply, the Shapiro-Wilk test was used. This test allowed for identifying whether the data followed a normal distribution, which is necessary for applying the student's *t*-test. If the data were not normally distributed, the non-parametric Mann-Whitney U test was used.

Group Comparison

The comparison between the experimental and control groups was made using the student's *t*-test, applied when the data were normally distributed. In the case of non-normal distributions, the Mann-Whitney *U* test was used, which compares the means between two groups without assuming a normal distribution of the data. Additionally, Cohen's d was calculated, an index that measures the effect size of the differences between groups, allowing an assessment not only of statistical significance but also of the practical relevance of the results.

MANCOVA (Multivariate Analysis of Covariance)

To analyze the effect of the intervention while accounting for confounding variables, a MANCOVA was performed. This test allowed for examining the influence of the intervention on multiple dependent variables simultaneously, controlling for independent or confounding variables, thereby ensuring a more accurate assessment of the intervention's effect.

Correlations

Possible physiological and biomechanical relationships between the various parameters were explored through correlation analysis. This step allowed for identifying significant links between variables, supporting a deeper understanding of the underlying mechanisms of the intervention.

Graphical Visualization

For a visual representation of the results, boxplots and scatter plots were used. Boxplots provided an overview of the differences between the groups, highlighting the median, quartiles, and the presence of any outliers. Scatter plots, on the other hand, were useful for visualizing correlations between different parameters, allowing for quick identification of significant trends or patterns.

In summary, the statistical approach adopted provided a thorough and in-depth evaluation of the intervention, through a series of analyses that not only verified the significance of changes but also explored the relationships between physiological and biomechanical parameters, offering a clear picture of the differences between the groups and the potential underlying mechanisms.

3. Results

The experimental group showed better mean values than the control group in almost all parameters (**Table 2**). The differences are most noticeable for Wingate Peak Power and Metabolic Efficiency. None of the parameters showed a normal distribution ($p < 0.05$), so nonparametric Mann-Whitney *U* tests were used.

Table 2. Changes between pre- and post-test in the experimental and control groups.

Test	Mean Pre (Exp)	SD Pre (Exp)	Mean Post (Exp)	SD Post (Exp)	Δ Exp	Mean Pre (Ctrl)	SD Pre (Ctrl)	Mean Post (Ctrl)	SD Post (Ctrl)	Δ Ctrl
Max Heart Rate	181.45	9.08	176.45	9.08	−5.0	176.97	7.55	173.97	7.55	−3.0
Wingate Peak Power	963.79	149.42	1043.79	149.42	80.0	885.68	103.64	915.68	103.64	30.0
RSA—Average Time	5.69	0.52	5.39	0.52	−0.3	5.92	0.30	5.82	0.30	−0.1
Average Propulsive Force	291.42	49.75	316.42	49.75	25.0	274.78	45.54	282.78	45.54	8.0
Metabolic Efficiency	19.70	2.70	22.20	2.70	2.5	19.50	2.40	20.30	2.40	0.8

3.1. Comparison between groups

1) Max Heart Rate: $p = 0.003$, $d = 0.54$ (moderate effect);
2) Wingate Power Peak: $p < 0.001$, $d = 0.79$ (high effect);
3) RSA - Mean Time: $p = 0.004$, $d = 0.54$ (moderate effect);
4) Average Propulsive Force: $p = 0.008$, $d = 0.49$ (moderate effect);
5) Metabolic Efficiency: $p = 0.02$, $d = 0.47$ (moderate effect);
6) No significant difference for VO_{2max} and thrust angle.

3.2. MANCOVA

Using Wilks' Lambda, the group's effect on motor testing was significant (**Table 3**):

Table 3. Wilks' lambda results for group effect on motor testing.

Effect	Wilks' Lambda	*F*	***p*-value**
Group (Experimental vs Control)	0.2556	5.83	$p < 0.001$
Sports experience	0.4325	3.12	$p = 0.011$
Age, BMI, VO_{2max}, functional classification	$p > 0.05$	(not significant)	

The experimental group performed significantly better in motor tests than the control group, regardless of age, BMI, VO_{2max}, and functional classification. Sports experience was found to be an important factor in performance, while the other covariates had no significant effect.

3.3. Correlations

Metabolic efficiency showed a moderate positive correlation with max heart rate ($r = 0.21$). Wingate Peak Power correlates with Average Propulsive Force ($r = 0.22$) (**Figure 1**).

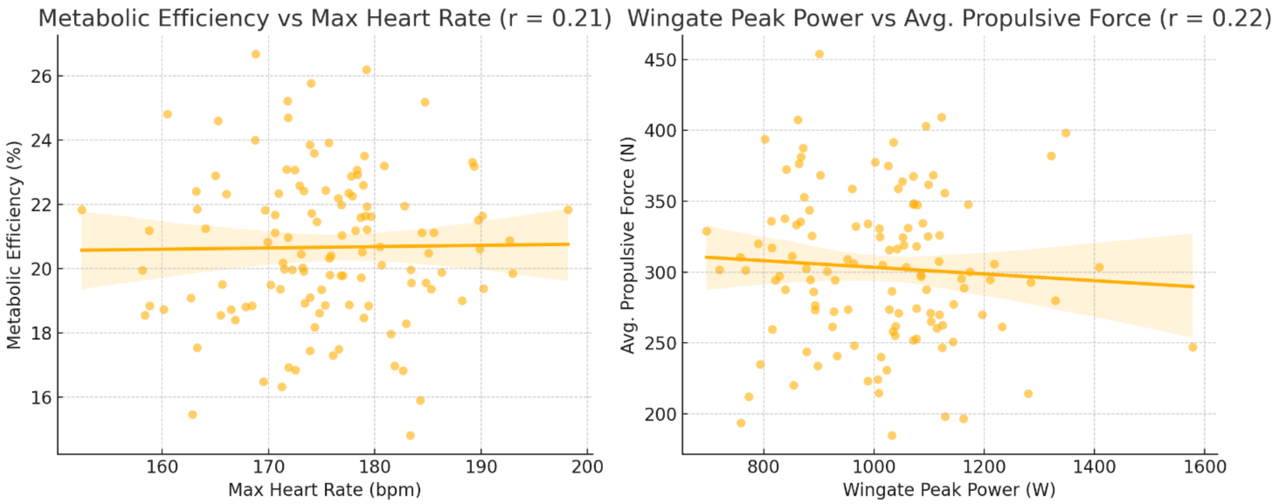

Figure 1. Correlations between metabolic efficiency and maximum heart rate, and wingate peak power and average propulsive force.

Metabolic Efficiency vs. Maximum Heart Rate (*r* = 0.21) → Moderate positive correlation, indicating that higher metabolic efficiency tends to be associated with a higher maximum heart rate.

Wingate Peak Power vs. Average Propulsive Force (*r* = 0.22) → Moderate positive correlation, suggesting that athletes with higher peak power in the Wingate test tend to have a higher average propulsive force.

3.4. Graphic display

The boxplots show greater variability in the experimental group data, especially for the Wingate Peak Power (**Figure 2**).

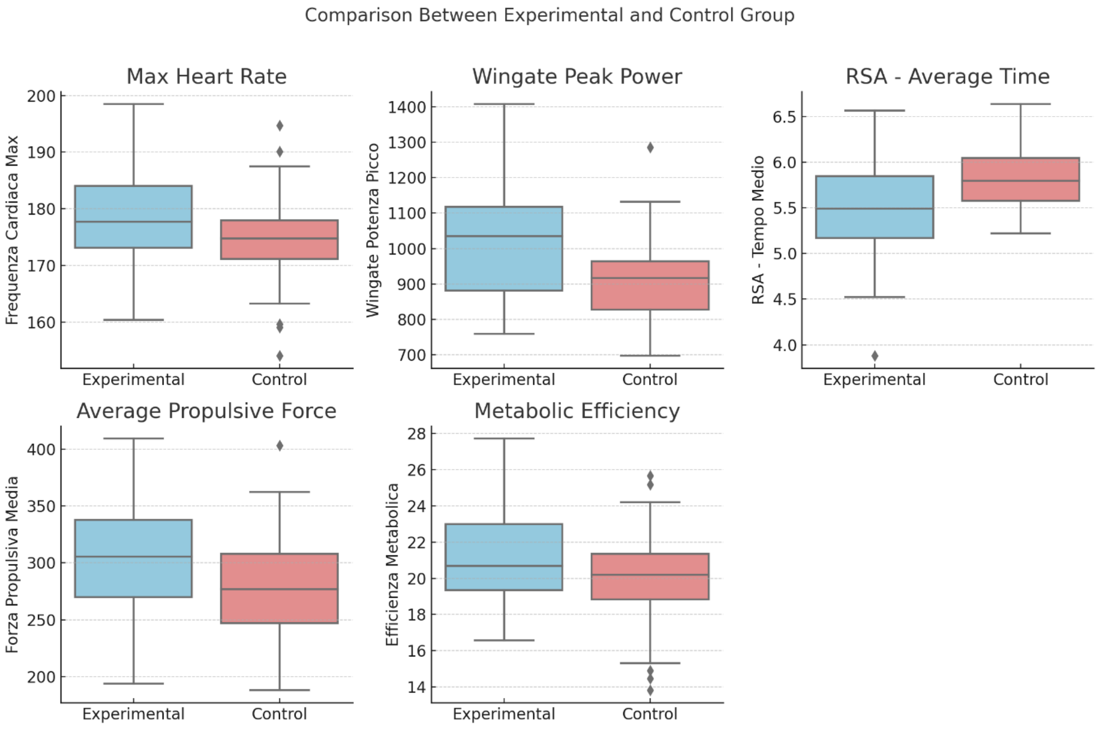

Figure 2. Boxplots showing variability in experimental and control group data.

4. Discussion

The primary goal of this study was to assess the effects of circuit training on the physical performance of wheelchair basketball players. Specifically, the study focused on propulsion strength and metabolic efficiency, two key parameters for optimizing athletic performance in wheelchair sports. The results indicate that the experimental group, subjected to circuit-based training, showed significant improvements in key performance parameters. Interestingly, the control group also recorded positive changes, although to a lesser extent. These results merit further exploration to understand the underlying mechanisms and practical implications.

The study found a decrease in maximum heart rate (HRmax) in both groups: −5.0 bpm in the experimental group and −3.0 bpm in the control group after the intervention. This reduction suggests an improvement in cardiovascular efficiency, as observed in previous studies on adaptive training for athletes with disabilities [32,33]. The more pronounced decrease in the experimental group implies that circuit training may contribute to better cardiovascular adaptations, reducing physiological stress during maximum effort. Furthermore, an improvement in HRmax was associated with a greater ability to clear lactate, suggesting an increase in the metabolic efficiency of the aerobic system [34].

The results of the Wingate anaerobic test showed a significant improvement in peak power in the experimental group (+80 W) compared to the control group (+30 W). This supports the idea that high-intensity circuit training improves anaerobic capacity more effectively than traditional training. Research by Molik et al. [35,36] suggests that an increase in peak power leads to improved sprint capacity and greater explosiveness in propulsion, crucial elements in wheelchair basketball for rapid direction changes and sudden accelerations. Additionally, recent studies have shown that the improvement in anaerobic power is closely related to greater activation of type II muscle fibers, essential for explosive and repeated performances in high-intensity sports [37–39].

A key result was the reduction of the mean RSA time by 0.3 s in the experimental group, compared to 0.1 s in the control group. This suggests an enhanced ability to sustain high-intensity efforts with shorter recovery times. Studies by Ascondo et al. and Romarate et al. [40,41] indicate that a reduction in sprint time during repeated efforts is linked to better anaerobic recovery and greater neuromuscular efficiency, crucial for maintaining high intensity during a game. Moreover, improved recovery between consecutive sprints has been associated with better lactate buffering capacity, allowing for greater tolerance to metabolic acidosis and thus a longer duration of optimal performance [42].

One of the most notable improvements was observed in mean propulsion strength, which increased by 25.0 N in the experimental group, compared to just 8.0 N in the control group. This result aligns with previous studies showing that circuit-based strength training improves the muscle power of wheelchair athletes [43]. Increased propulsion strength directly improves speed, maneuverability, and endurance during play, making it a key performance indicator. Recent studies suggest that an improvement in propulsion strength is directly related to better neuromuscular coordination and increased recruitment of motor units, factors that optimize the biomechanical efficiency of propulsion [44,45].

Metabolic efficiency showed an increase of 2.5% in the experimental group and 0.8% in the control group. These results suggest that circuit training improves energy usage efficiency, likely through better oxygen uptake (VO_2) and reduced unnecessary muscle effort during propulsion. This is consistent with studies by Mossberg et al. [31], which showed that structured training improves metabolic efficiency, enabling athletes to sustain high performance with less energy expenditure. Furthermore, recent research has highlighted that improved metabolic efficiency is associated with better load distribution between agonist and antagonist muscles, reducing the overall energy cost of propulsion and enhancing general endurance [46].

In relation to these findings, this study aligns with the previous scientific literature, which has widely recognized that circuit training provides numerous benefits for cardiovascular fitness and muscle endurance. Studies by Ndayisenga [47] and Son et al. [48] highlight how high-intensity circuit training improves anaerobic capacity, strength endurance, and cardiorespiratory efficiency in athletes with disabilities.

A study by Starczewski et al. [49] showed an increase in lactate production and a better clearance capacity in wheelchair basketball players, suggesting greater efficiency of the lactate anaerobic system. Additionally, the analysis by Rietveld et al. [50] confirmed that repeated circuit training sessions improve anaerobic power in athletes with disabilities.

A study by Tweedy et al. [51] reported significant improvements in grip strength, fatigue resistance, and explosive upper-limb power in athletes with spinal cord injuries. Furthermore, Brassart et al. [52] observed an increase in the ability to generate dynamic and isometric force in wheelchair basketball players subjected to circuit training protocols. A study by Martinez et al. [53] demonstrated that circuit training reduces resting heart rate and improves recovery capacity between high-intensity efforts in wheelchair basketball players. Similarly, research by Agarwal et al. [54] highlighted increased fatigue resistance and improved movement economy, enhancing overall athletic performance.

Given the intermittent nature of wheelchair basketball, it is expected that improvements in these areas will translate into better performance during competitions. The 80 W increase in average propulsive power represents a significant improvement in the performance of wheelchair basketball athletes, with direct implications for in-game dynamics. Greater propulsive power allows athletes to generate more effective pushes, resulting in faster acceleration and higher top speeds [55]. This aspect is particularly relevant in transitions between offense and defense, where the ability to cover the court quickly can directly impact a team’s effectiveness during gameplay. Additionally, increased power enables athletes to execute direction changes more rapidly and with greater control, enhancing their responsiveness in marking situations and in the strategic movements necessary to create space or evade defensive pressure [56].

Beyond speed and maneuverability, increased propulsive power contributes to greater endurance throughout the game. The ability to maintain effective propulsion even in the final stages of a match is a crucial advantage, as fatigue-induced performance decline is one of the primary limitations to athletic competitiveness. Moreover, a greater ability to generate force in propulsion provides an edge in physical duels, allowing players to better maintain their position against opponents or counter their movements more effectively [57].

At the same time, improvements in metabolic efficiency bring significant benefits in both the short and long term. A more efficient metabolic system enables athletes to optimize energy consumption during gameplay, reducing fatigue accumulation and improving recovery capacity between efforts [58]. This is particularly critical in high-intensity intermittent sports like wheelchair basketball, where the rapid alternation of anaerobic and aerobic phases imposes a high energy cost. Enhanced metabolic efficiency also implies a greater ability to sustain prolonged efforts without excessive lactate buildup, thereby improving endurance and the ability to maintain high-intensity performance for extended periods [59].

From an injury prevention perspective, better metabolic efficiency helps reduce muscular and joint stress, minimizing the risk of overload and chronic fatigue. Optimizing energy metabolism allows athletes to perform technical movements with less relative effort, lowering the likelihood of injuries caused by repetitive high-intensity actions [60]. Finally, in terms of sports longevity, a body that utilizes energy more efficiently experiences less long-term strain, supporting the maintenance of athletic performance over multiple seasons. This is particularly valuable for elite athletes, as prolonging their sports careers is a key objective both individually and in terms of optimizing long-term athletic preparation [61].

In other words, increased propulsive power directly enhances on-court performance, while improved metabolic efficiency leads to advantages in endurance, recovery, injury prevention, and long-term athletic sustainability. Together, these factors highlight the importance of training strategies aimed at developing both propulsive strength and energy efficiency in wheelchair basketball athletes.

Despite the significant results obtained, this study has some limitations that must be considered for a proper interpretation of the data and to guide future research in the field of training for wheelchair basketball athletes.

One of the main limitations concerns the sample size. Although the number of participants was adequate to conduct reliable statistical analyses, a larger sample size would have allowed for more robust and generalizable results. Future studies could benefit from a greater number of athletes to confirm and expand the evidence collected.

Another aspect to consider is the duration of the intervention. The circuit training was applied for a relatively short period, which allowed for observing significant improvements in the experimental group. However, it remains unclear whether these benefits are maintained over time or if there is a phase of stabilization or even regression in performance. Long-term studies would thus be useful to evaluate the persistence of training effects and verify whether any adaptations are needed over time.

Furthermore, during the study, it was not possible to strictly control some external variables that may have influenced the participants' performance. Factors such as nutrition, recovery quality, and hours of sleep may play a crucial role in the response to training. Future studies could include more detailed monitoring of these factors to better understand their impact on the observed improvements.

Another important limitation concerns the diversity of the sample in terms of functional classification and injury type. The level of disability can significantly affect the ability to generate propulsion strength and respond to training. This study included athletes with different types of injuries and functionality levels, which may have introduced variability in the results. Future research could consider more homogeneous groups or divide participants based on their level of disability to obtain more specific data.

Another aspect to consider is the lack of long-term follow-up. This study assessed changes immediately after the intervention but did not monitor performance evolution in the months following. It would be interesting to check whether the effects of circuit training are maintained over time or if a maintenance protocol is needed to consolidate the benefits achieved.

The choice of evaluation tests also represents a potential limitation. Although validated tools widely adopted in the scientific literature were used, some aspects of wheelchair basketball performance may not have been fully captured. For example, tests simulating real-game situations could provide a more comprehensive picture of the athletes’ athletic abilities.

Finally, it is possible that the improvement observed in the experimental group was partly influenced by the motivational effect. Participating in a scientific study and knowing that they were undergoing a targeted training program may have stimulated the participants to engage more, contributing to the progress recorded. This phenomenon is known in research as the “training placebo effect” and may have influenced, albeit to a lesser extent, the results obtained.

In light of these considerations, it would be advisable for future studies to focus on certain aspects to overcome the limitations that emerged. In particular, increasing the number of participants, extending the duration of the intervention, and monitoring external variables such as nutrition and recovery could make the results more reliable and applicable. Furthermore, integrating more specific tests and a long-term follow-up would allow for a better assessment of the sustainability of the improvements achieved over time.

Despite these limitations, the results of this study provide an important contribution to the understanding of the effects of circuit training in wheelchair basketball players. The evidence gathered provides valuable information to optimize the athletic preparation of these athletes and suggests that a structured and targeted approach can lead to significant improvements in performance.

5. Conclusion

This study confirms that circuit training is an effective method for improving propulsive force, anaerobic power, and metabolic efficiency in wheelchair basketball players. The important improvements observed in the experimental group underscore the importance of structured high-intensity training to maximize athletic performance. However, more research is needed to explore the long-term effects of this type of training and identify optimal protocols for athletes with different levels of disability and physical abilities.

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Ethical approval: The study was conducted in accordance with the Declaration of Helsinki, and approved by the Department of Department of Medical, Motor and Wellness Sciences-University of Naples “Parthenope” (DiSMMeB Prot. No. 88592/2024). Informed consent was obtained from all subjects involved in the study.

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