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EFFECT OF FLYWHEEL RESISTANCE TRAINING ON UPPER LIMB MUSCLE QUALITY IN INDIVIDUALS WITH SPINAL CORD INJURY: A PRE-POST INTERVENTION STUDY

Ítalo Santiago Alves Viana[1], Lucas Vieira Santos[1], Leonardo Silveira Goulart Silva[2]
Karla Raphaela da Silva Ramos Freitas[1], Eveline Torres Pereira[1]
Claudia Eliza Patrocínio de Oliveira[1], Osvaldo Costa Moreira[1]

ABSTRACT

Spinal cord injury (SCI) poses significant challenges after hospital discharge, particularly in preserving and recovering muscle mass, which is essential for functionality, autonomy, and social participation. In the initial weeks post-injury, muscle loss can reach up to 50% compared to individuals without SCI. Flywheel resistance training (FWRT) combines eccentric and concentric actions, promoting strength and power gains with lower energy demands, making it suitable for individuals with SCI. This method recruits high-threshold motor units, favoring adaptations such as increased muscle mass, fascicle length, and tendon strength. Muscle quality (MQ), defined as the ratio between lean mass and strength/power, is crucial for functional independence and well-being. This study investigated the effects of FWRT on strength-to-lean mass and power-to-lean mass ratios in individuals with SCI. Eight participants completed an 8-week FWRT program (2 sessions/week), with progressive volume (2×8 to 4×10 repetitions; 1-minute rest). Exercises targeted muscles with preserved function, at moderate to high intensities (OMNI-RES scale). Strength was assessed using the one-repetition maximum (1RM), and power via a linear transducer and Chronojump software at 40%, 60%, and 80% of 1RM, using unilateral elbow flexion with the dominant arm. Body composition was measured by DXA. MQ was calculated based on strength (kg) and power (W) relative to lean mass (kg). Data were analyzed with SPSS 23 using the Wilcoxon test ($p<0.05$). The strength-to-lean mass ratio significantly increased ($p=0.010$). Power-to-lean mass ratio decreased at 40% 1RM, with no significant changes at 60% and 80%. FWRT proved effective in improving strength relative to lean mass in individuals with SCI.

Key words: Paraplegia. Resistance training. Quality of life. Inertial training.

1 - Department of Physical Education, Federal University of Viçosa, Viçosa Campus, Viçosa, Minas Gerais, Brazil.

RESUMO

Efeito do treino de resistência com volante de inércia na qualidade muscular dos membros superiores em indivíduos com lesão medular: um estudo pré-pós intervenção

A lesão medular (LM) impõe desafios após a alta hospitalar, especialmente na preservação e recuperação da massa muscular, essencial para a funcionalidade, autonomia e participação social. Nas primeiras semanas, pode ocorrer perda de até 50% da massa muscular em relação a indivíduos sem LM. O treinamento resistido com flywheel (FWRT) combina ações excêntricas e concêntricas, promovendo ganhos de força e potência com menor demanda energética, sendo indicado para pessoas com LM. Essa técnica recruta unidades motoras de alto limiar, favorecendo adaptações como aumento da massa muscular, comprimento dos fascículos e força tendínea. Este estudo investigou os efeitos do FWRT nas razões força/massa magra e potência/massa magra em indivíduos com LM. Oito participantes realizaram FWRT por 8 semanas (2 sessões/semana), com progressão de volume (2×8 a 4×10 repetições; 1 minuto de intervalo). Os exercícios focaram em músculos com função preservada, em intensidades moderadas a altas (escala OMNI-RES). A força foi avaliada por 1RM e a potência, com transdutor linear e software Chronojump a 40%, 60% e 80% do 1RM, por meio de flexão unilateral de cotovelo com o braço dominante. A composição corporal foi medida por DXA. A QM foi calculada com base na força (kg) e potência (W) por kg de massa magra. A razão força/massa magra aumentou significativamente ($p=0,010$). A potência/massa magra diminuiu a 40% do 1RM, sem alterações significativas nas demais cargas. O FWRT mostrou-se eficaz para melhorar a força relativa à massa magra em indivíduos com LM.

Palavras-chave: Paraplegia. Treinamento resistido. Qualidade de vida. Treinamento inercial.

INTRODUCTION

Spinal cord injury (SCI) is a complex neurological condition that leads to profound consequences in functionality and quality of life, especially after hospital discharge. SCI compromises sensory and motor signaling at the lesion level and also impacts autonomic control (Tweedy et al., 2017; Rupp et al., 2021).

One of the greatest challenges individuals face post-injury is the preservation and recovery of muscle mass, an essential component for autonomy, mobility, and participation in social life (Nash, Gater, 2020).

Within the first weeks following SCI, muscle atrophy can be dramatic, with losses of up to 50% in muscle mass compared to able-bodied individuals, severely impairing physical capacity (Shah et al., 2006; Otzel et al., 2021; Almada et al., 2024).

In this context, implementing effective rehabilitation strategies aimed at mitigating muscle atrophy and promoting neuromuscular recovery becomes paramount. Multiple reviews and meta-analyses have demonstrated that resistance training can improve strength, endurance, and muscular power in individuals with SCI (van der Scheer et al., 2017; Chiou et al., 2022; Santos et al., 2022).

Among innovative strategies, flywheel resistance training (FWRT) has emerged as a promising method (Moreira et al., 2025).

This modality involves concentric and eccentric muscle actions under variable resistance, promoting substantial gains in muscular strength and power with relatively low metabolic costa key advantage for individuals with reduced fatigue tolerance (Nuñez Sanchez, Sáez de Villarreal, 2017).

FWRT has also been linked to greater recruitment of high-threshold motor units, increased muscle hypertrophy, elongation of fascicle length, and enhancements in musculoskeletal power.

In this context, the concept of muscle quality (MQ)-defined as the ratio between force or power output and the amount of lean muscle mass-has gained attention as a relevant indicator of functional capacity. Higher MQ is associated with improved performance in daily activities and is positively related to physical autonomy and mental well-being in individuals with SCI (Barbat-Artigas et al., 2012; Johansen et al. 2003).

However, despite growing interest in resistance-based rehabilitation, studies exploring the relationship between muscular power and lean mass in SCI are still scarce, particularly regarding relative power (i.e., power-to-lean mass ratio).

Most studies emphasize absolute force or mass gains, often overlooking how efficiently lean mass contributes to high-velocity movements, key to performing functional tasks such as transfers and reaching.

Therefore, this study aimed to investigate the effects of three resistance training modalities traditional resistance training (TRT), flywheel resistance training (FWRT), and high-velocity resistance training (HVRT) on strength-to-lean mass and power-to-lean mass ratios in the upper limbs of individuals with SCI.

We hypothesized that HVRT would improve the strength-to-lean mass ratio but would have limited effects on the power-to-lean mass ratio, particularly at lighter loads, due to neuromuscular limitations commonly observed in SCI.

By addressing this gap, the study seeks to broaden the understanding of muscle quality adaptations and inform more precise rehabilitation protocols for this population.

MATERIALS AND METHODS

Experimental Approach to the Problem

This study aimed to compare the effects of Flywheel Resistance Training (FWRT) on muscle quality (MQ) in individuals with spinal cord injury (SCI).

The approach also considered the unique challenges related to mobility and adherence commonly faced by people with SCI.

The training protocol followed principles aimed at maintaining intensity while gradually increasing training volume, optimizing the training load throughout the intervention. All participants received detailed information about the study procedures and were given opportunities to ask questions either individually or in group sessions.

Participants

The sample consisted of eight individual familiars with the university's programs for people with disabilities, as well as others recruited through a partnership with the local government. Inclusion criteria required: a clinically confirmed diagnosis of spinal cord injury; no upper-limb musculoskeletal injuries within the past year; no prior experience with resistance training; and a commitment to attend at least 80% of training sessions without starting any new exercise programs. Participants were also instructed to maintain their regular diet throughout the study. Ages ranged from 55 to 65 years (mean 60 ± 5.34), with an average time since injury of 37 ± 18.17 years and an average body weight of 58.25 ± 3.58 kg.

The statistical power analysis was performed using GPower software (GPower 3.1.9.2, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). Based on a moderate expected effect size (d = 0.6), an alpha level of 0.05, and a statistical power of 80% (1−β = 0.80), the minimum required sample size was estimated to be 8 participants. This number was deemed sufficient to detect within-group differences in a pre- and post-intervention study design.

Given the exploratory nature of the study and the specific challenges involved in recruiting individuals with spinal cord injury (SCI), the final sample consisted of eight participants.

This sample size aligns with previous pilot studies in the field (Maroto-Izquierdo et al., 2024; Rodrigues et al., 2024), which also faced recruitment constraints due to the clinical and functional limitations of the population. Therefore, the sample size decision was informed by both statistical considerations and the practical feasibility of conducting the intervention.

The inclusion and exclusion criteria and their potential impact were thoroughly discussed during the study's planning phase. It is known that individuals with SCI can develop various secondary conditions such as hypertension, anxiety, and depression. Furthermore, significant mobility challenges are common and were considered key exclusion factors. Therefore, only musculoskeletal injuries to the upper limbs were used as exclusion criteria.

Spinal cord injuries are highly unpredictable, as two similar injuries can lead to vastly different outcomes, such as muscle spasticity or flaccidity. Considering these characteristics, the researcher responsible for the initial contact with participants conducted individual interviews to understand each participant's capacities and limitations. During this interaction, participants were presented with the Informed Consent Form, and any questions regarding evaluations, the training period, and study details were addressed.

At this stage, the researcher collected documents confirming participants' spinal cord injury diagnoses and discussed individual limitations and capabilities. All participants had complete spinal cord lesions caused by either gunshot wounds or motor vehicle accidents. Additionally, the traumatic injuries were found to range between vertebral levels T4 and L1.

This study was approved by the Ethics Committee of the Federal University of Viçosa under protocol number 5.418.335 in May 2022 and was conducted during the second half of 2023.

Training Protocols

The eight participants were instructed to perform the concentric phase of each movement as quickly as possible and to decelerate during the final third of the eccentric phase to maximize the benefits of the eccentric overload provided by the flywheel device (Multi-leg Isoinertial, Physical Solutions, São Paulo, Brazil).

The training program lasted eight weeks, with two sessions per week, progressively increasing from 25 to 50 minutes per session over time. Each session began with two warm-up sets performed at a moderate execution speed. All exercises were performed on the same machine.

Training volume progressed from 2 sets of 8 repetitions to 4 sets of 12 repetitions (see figure 1), focusing on upper trunk functional muscles and tailored to the individual needs of each participant. Adaptations included researcher assistance for wheelchair positioning, use of bars with various diameters to facilitate grip, and straps to stabilize the trunk. A detailed description of the training session is provided in figure 1. All participants performed the same exercises in the same order, with minor adjustments to ensure safety and comfort.

Exercise intensity was monitored using the OMNI-RES scale (1 to 10), a validated and widely adopted tool for assessing perceived exertion during resistance training (Robertson et al., 2003), including in populations with functional limitations.

Although no formal validation of this scale has been reported specifically for individuals with spinal cord injury, its use in the present study was deemed appropriate due to

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its simplicity, practical applicability, and consistent use in research involving clinical populations and older adults. In this study, intensity was maintained between levels 7 and 9, corresponding to 'hard' to 'very hard' perceived effort, a range commonly associated with neuromuscular adaptation without compromising safety. A one-minute rest interval was adopted between sets to ensure adequate energy recovery and preserve total session volume. All training sessions and assessments were conducted at the Department of Physical Education of the Federal University of Viçosa, which is equipped with accessible infrastructure and trained personnel experienced in working with individuals with physical disabilities.

Strength Testing

Strength assessments were conducted in a single session in the following order: maximal isometric voluntary contraction (MIVC), one-repetition maximum (1RM), and peak muscle power. All tests were performed using a unilateral elbow flexion movement on a low pulley system with the participant's dominant arm (Martins et al., 2022).

MIVC

The maximal isometric voluntary contraction (MIVC) was assessed using a load cell, with the elbow fixed at a 90° angle, measured with a goniometer. Participants were instructed to maintain a maximal isometric contraction for 3 seconds. Each participant performed two trials, with a 3-minute rest between attempts. The highest value recorded in kilograms was considered for analysis (Oliveira et al., 2018; Rodrigues et al., 2024).

1RM

To assess dynamic strength, a one-repetition maximum (1RM) test was conducted. The protocol began with four warm-up repetitions at 50% of each participant’s previously recorded MIVC value, followed by a perceived exertion assessment using the OMNI-RES (OMNI-Resistance Exercise Scale).

Although this scale has not been validated for individuals with LM, participants were already familiar with it, having taken part in a previous study where the tool was applied and trained. During the 1RM test, it was explained that an intensity rating of 10 on the OMNI-RES represents the participant’s maximum perceived effort that is, the greatest force they can exert to complete one repetition. This level corresponds to an extremely difficult effort sensation, close to muscular exhaustion, and was used to anchor the perceived exertion during the test.

The load was then progressively increased in increments of 3 or 5 kg. Participants attempted two repetitions at each load until they could only complete one. The final load successfully lifted for one full repetition was recorded as the 1RM (Oliveira et al., 2018; Rodrigues et al., 2024).

If a participant was unable to complete a full repetition, the final value was estimated as an intermediate score between the last load at which two repetitions were completed and the load at which failure occurred. A maximum of five attempts was allowed, with 3-minute rest intervals between attempts.

Peak Muscle Power

Peak muscle power (PWR) was assessed using a linear position transducer with three submaximal loads relative to the participant’s 1RM (40%, 60%, and 80%) and recorded via Chronojump software version 2.2.1 (Boscosystem, version 2.35).

For each load, participants performed three elbow flexion repetitions through the full range of motion. A 2-minute rest interval was provided between sets. Participants were instructed to perform the concentric phase “as fast as possible,” while the eccentric phase was to be executed slowly (lasting approximately 2 seconds) (Medina-Pérez et al., 2016; Rodrigues et al., 2024).

Body Composition

To assess body composition and its variables, a comprehensive Dual-Energy X-ray Absorptiometry (DXA) scan was performed using the GE Healthcare Lunar Prodigy Advance DXA System with software version 13.31, both before and after the training period. The analyzed variables included Total Body Mass (TBM), Fat Mass (FM), Lean Mass (LM), and Bone Mineral Content (BMC).

During the scan, participants lay in a supine position on the device, with the upper limbs extended parallel to the torso and hands in a pronated position.

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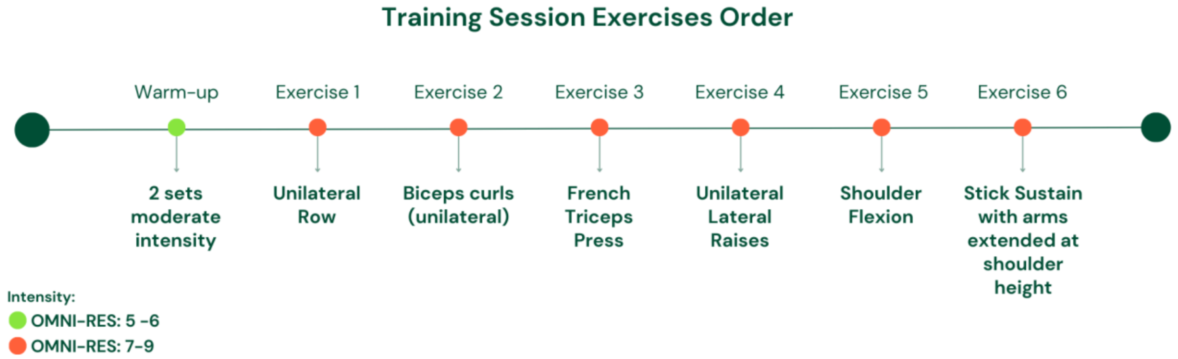
The lower limbs were kept extended and positioned hip-width apart. Participants were instructed to remain as still as possible during the assessment (Moreira et al., 2015; Hirsch et al., 2017). Each scan lasted approximately 7 minutes, during which DXA parameters were automatically calculated.

To ensure precision and consistency, all DXA scans were conducted by a trained technician following standardized procedures.

After each scan, the data were reviewed to verify correct alignment and the absence of motion artifacts. Any discrepancies were noted, and scans were repeated if necessary.

The results were then analyzed to provide a detailed assessment of body composition variables, which were subsequently used to evaluate the effects of the training intervention.



Volume Training Planning (sets x reps)

Weeks	1	2	3	4	5	6	7	8	9	10
Sets	Tests	2	3	3	3	3	4	4	4	Tests
Reps		8	10	10	12	12	10	10	12	

Figure 1 - A training protocol was applied to participants in the FWRT group over 8 weeks, showing the progression in training volume (number of sets and repetitions) and the standardized exercises performed throughout the intervention.

Statistical Analysis

Muscle quality was determined by calculating the ratios between maximum strength (kg) and lean mass (kg), as well as between power output (W) and lean mass (kg), at both pre- and post-intervention time points. The formulas used to calculate muscle quality were:

$$Strength - Lean\ Mass\ Ratio = \frac{Maximum\ Strength\ (kg)}{Lean\ Mass\ (kg)}$$

$$Strength - Lean\ Mass\ Ratio = \frac{Power\ (w)}{Lean\ Mass\ (kg)}$$

Data were processed and analyzed using IBM SPSS Statistics software (version 23.0). Descriptive statistics were first computed, including means, standard deviations, and minimum and maximum values. The normality of the data was assessed using the Shapiro-Wilk test. As the data did not follow a normal distribution and due to the small sample size (n = 8), the non-parametric Wilcoxon signed-rank test was applied to compare pre- and post-intervention measurements. Statistical significance was set at p<0.05. In addition, effect sizes were calculated using Cohen's D to complement the p-values and estimate the magnitude of the observed effects, with the following thresholds: small (d=0.2), moderate (d=0.5), and large (d=0.8).

RESULTS

Figure 2 presents the strength-to-lean mass and power-to-lean mass ratios at pre- and post-intervention time points following FWRT in individuals with spinal cord injury. After 8 weeks of training, participants demonstrated significant increases in strength (pre: 15.00 ± 3.00, post: 16.50 ± 4.63; p<0.001, Δ = 1.50; IC95% [0.22 to 2.78]) and lean mass (pre: 33.33 ± 4.34, post: 35.98 ± 4.68; p<0.001, Δ = 2.65; IC95% [0.74 to 4.56]).

Additionally, a significant reduction was observed in muscular power at 40% of 1RM (P40LM) (pre: 61.48 ± 18.56, post: 53.16 ± 17.93; p < 0.001, Δ = −8.32; IC95% [−14.79 to −1.85]) and at 60% of 1RM (P60LM) (pre: 72.49 ± 28.50, post: 59.97 ± 15.42; p = 0.001, Δ = −12.52; IC95% [−22.14 to −2.90]) - see figure 3.

Furthermore, a statistically significant increase was found in the strength-to-lean mass ratio pre and post-intervention (pre: 0.469 ± 0.21, post: 0.547 ± 0.31; p=0.010, Δ = 0.078; IC95% [0.016-0.140]).

Similarly, a significant reduction was observed in the power-to-lean mass ratio at 40% of 1RM following the intervention (pre: 1.943 ± 1.11, post: 1.775 ± 1.13; p = 0.01; Δ = −0.168; 95% CI [−0.305 to −0.031]). In contrast, no statistically significant differences were found between time points in the power-to-lean mass ratios at 60% (p=0.251) or 80% of 1RM (p=0.251).

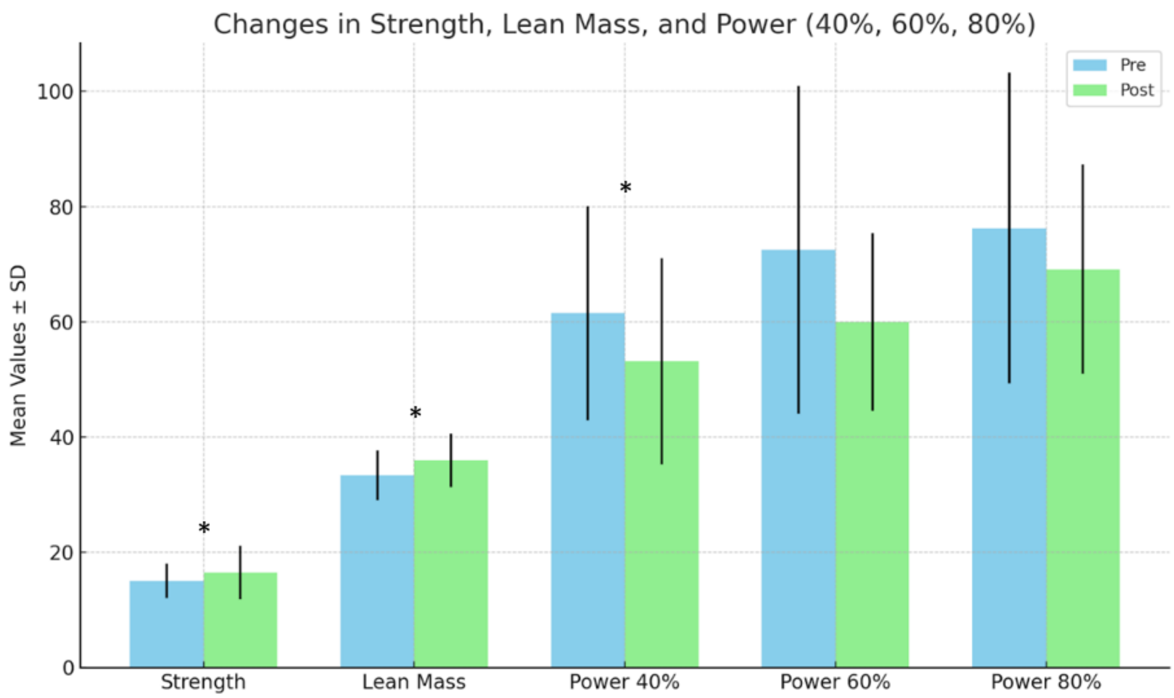


Figure 2 - Progression of mean strength, lean mass, and muscle power values before and after the FWRT intervention in individuals with spinal cord injury. The asterisk indicates a significant difference between pre- and post-intervention (p<0.05).

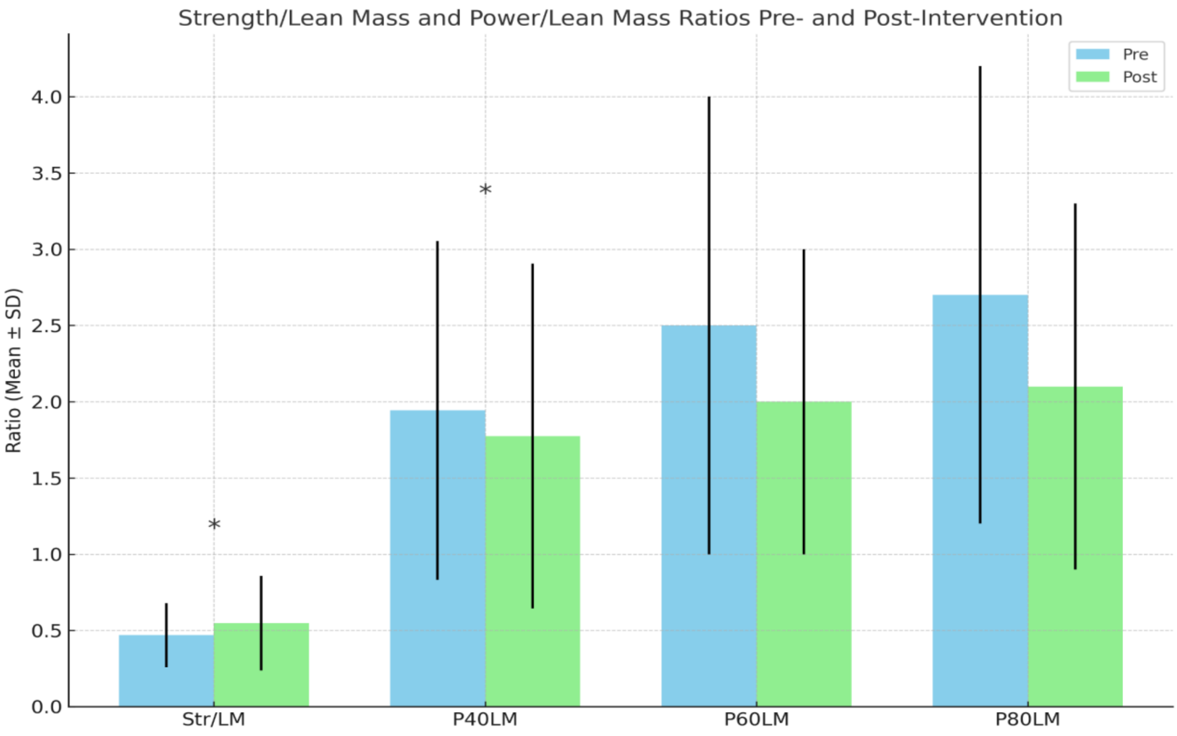


Figure 3 - Comparison of strength-to-lean mass and power-to-lean mass ratios before and after the FWRT intervention in individuals with spinal cord injury. The asterisk indicates a significant difference between pre- and post-intervention ($p<0.05$). Note. Str: Strength; LM: Lean mass; P40LM: Power 40% Lean mass; P60LM: Power 60% Lean mass; P80LM: Power 80% Lean mass.

DISCUSSION

This study investigated the effects of flywheel resistance training (FWRT) on force-to-lean mass and power-to-lean mass ratios, aiming to improve muscle quality (MQ) of the upper limbs in individuals with spinal cord injury (SCI) following an eight-week intervention. The findings revealed distinct benefits: there was a significant increase in the force-to-lean mass ratio, suggesting that FWRT may be effective in optimizing force relative to preserved muscle mass.

Conversely, a reduction in relative power output was observed, particularly under lighter loads (40% of 1RM), indicating that FWRT protocols targeting muscular power require specific adjustments, including refined control of training intensity, volume, and neuromuscular activation strategies tailored to individuals with motor impairments.

Our findings align with those of Fernandez-Gonzalo et al., (2016), who reported significant gains in neurologically impaired populations undergoing FWRT.

Similarly, Eitivipart et al., (2019) and Stone et al., (2023) reported improvements in musculoskeletal strength following resistance training, further corroborating the findings of the present study.

The eccentric emphasis inherent in FWRT facilitates the recruitment of high-threshold motor units and provides robust mechanical stimuli while minimizing metabolic stress (Enoka, 1996; Maroto-Izquierdo et al., 2017; Hody et al., 2019).

This training modality is particularly advantageous for individuals with SCI, who often present with significant functional limitations and an increased susceptibility to early-onset fatigue, as described by Craig et al., (2012).

The absence of improvement in muscular power, particularly under light loads (40% and 60% of 1RM), may be attributed to deficits in rapid muscle fiber activation or impaired intermuscular coordination, common neuromuscular alterations following SCI (Thomas, Gorassini, 2005).

Additionally, shifts in muscle fiber phenotype, such as the transition from type I to type IIx fibers-characterized by faster, yet less sustainable contractions-may compromise the efficient generation of power (Biering-Sørensen et al., 2009).

However, recent findings (Rodrigues et al., 2024) suggest that such fiber-type transitions may not occur uniformly across all individuals with SCI, challenging this assumption in specific contexts.

Another relevant factor is impaired thoracolumbar stability in individuals with SCI, which may have influenced performance during high-velocity tasks demanded by FWRT. Core stability is essential for the efficient transfer of force from the upper limbs to the inertial device, representing a key biomechanical component in explosive movement execution.

As demonstrated by Behm and Sale (1993), the intended movement velocity, more than the actual velocity, is the primary determinant of adaptive responses in velocity-specific training. Nonetheless, insufficient neural drive-in individuals with SCI may limit the translation of intended effort into effective power output, thereby constraining muscular power adaptations even under adequate training stimuli.

From a clinical standpoint, the results underscore the potential of FWRT in the rehabilitation of individuals with SCI, promoting gains in functional strength and greater independence in activities of daily living (Hicks et al., 2011; Abou, Rice, 2024; Tsoy et al., 2025).

The ability of FWRT to elicit high levels of muscular tension with minimal metabolic cost (Maroto-Izquierdo et al., 2017; Tesch et al., 2004) is particularly beneficial for this population, who are often susceptible to early fatigue.

As noted by Shields (2002), individuals with SCI frequently exhibit low-frequency fatigue due to impairments in excitation-contraction coupling, which reduces force output during low-frequency stimulation while maintaining responsiveness at higher frequencies. This phenomenon may contribute to the difficulty in enhancing muscular power through FWRT.

Given the limitations of FWRT in improving power output under low loads and high velocities, adaptations to training protocols are warranted. Strategies may include velocity variations exercises specifically targeting explosive strength or combining FWRT with methods that prioritize speed and power development (Santos et al., 2025).

Furthermore, the findings reinforce the importance of individualized resistance training protocols in individuals with SCI, considering both the extent of preserved muscle mass and the heterogeneity in neuromuscular activation patterns (Oliveira et al., 2019).

Lastly, one of the main limitations of this study was the small sample size, which may have reduced the statistical power to detect subtle differences, particularly those related to muscular power.

Future research with larger cohorts is needed to enable more robust analyses and improve the generalizability of findings. Another important limitation was the lack of velocity monitoring during the concentric phase of movement, a critical factor for neuromuscular and hypertrophic adaptations, especially in inertia-based training.

As highlighted by Wang et al., (2025), real-time monitoring technologies are strongly recommended to ensure greater precision in evaluating muscular adaptations and exercise execution.

Flywheel resistance training (FWRT) has proven to be a promising tool in the muscular rehabilitation of individuals with spinal cord injury, particularly in terms of improving muscle quality and inducing rapid and effective adaptations.

The practical implications of this study are significant, as they suggest that FWRT may be a viable and low-cost alternative for clinical rehabilitation, considering the need for efficient protocols that respect the physical limitations of patients with SCI.

The use of eccentric overloads, as demonstrated in this study, can be particularly effective, as it provides a safe approach to inducing changes in muscle tissue without requiring excessive metabolic effort, promoting strength gains and improving the overall functionality of these individuals.

CONCLUSION

It is concluded that FWRT appears to be an effective strategy for improving the strength-to-lean mass ratio in individuals with SCI.

However, it did not show a significant impact on the power-to-lean mass ratio within the sample analyzed.

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2 - Institute of Biological and Health Sciences, Federal University of Viçosa, Florestal Campus, Florestal, Minas Gerais, Brazil.

E-mail dos autores
italo.viana@ufv.br
lucas.vieira@ufv.br
leonardo.goulart@ufv.br
karla.r.freitas@ufv.br
etorres@ufv.br
osvaldo.moreira@ufv.br

Corresponding Author:
Ítalo Santiago Alves Viana
italo.viana@ufv.br

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