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Effects of high-speed resistance training and flywheel resistance training on the different manifestations of muscle strength, functional capacity, symptoms of anxiety and depression, and quality of life of people with spinal cord injury

Lucas Vieira Santos
Doctor Scientiae

VIÇOSA - MINAS GERAIS
2025

LUCAS VIEIRA SANTOS

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Thesis submitted to the Physical Education Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

Adviser: Osvaldo Costa Moreira

Co-advisers: Eveline Torres Pereira
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Assent:

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For those who cannot bear the
comfort of not understanding.

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“A coisa não está nem na partida nem na chegada. Está é na travessia...”.
(João Guimarães Rosa)

“Luto por uma educação que nos ensine a pensar e não por uma educação que nos ensine a obedecer”.
(Paulo Freire)

ABSTRACT

SANTOS, Lucas Vieira, D.Sc., Universidade Federal de Viçosa, December, 2025. **Effects of high-speed resistance training and flywheel resistance training on the different manifestations of muscle strength, functional capacity, symptoms of anxiety and depression, and quality of life of people with spinal cord injury**. Adviser: Osvaldo Costa Moreira. Co-advisers: Eveline Torres Pereira and Claudia Eliza Patrocinio de Oliveira.

This thesis investigated the effects of three resistance training (RT) modalities—Traditional Resistance Training (TRT), Flywheel Resistance Training (FWRT), and High-Velocity Resistance Training (HVRT)—on different manifestations of muscle strength, functional capacity, anxiety and depression symptoms, and quality of life in individuals with spinal cord injury (SCI). Thirty-two participants with chronic SCI were divided into three groups (TRT: n = 12; FWRT: n = 8; HVRT: n = 12) and trained twice weekly for eight weeks. All sessions were supervised, and no adverse events occurred during the intervention. Functional capacity, muscle strength (isometric, dynamic, and power), body composition, and mental health indicators were assessed before and after training. Statistical analyses included repeated measures ANOVA and minimal clinically important difference (MCID) calculations to determine both statistical and clinical relevance. All training modalities promoted significant improvements in at least one functional domain. FWRT produced the greatest enhancement in functional agility, reducing the completion time of agility tests beyond the MCID threshold, which highlights the efficiency of eccentric overload in improving neuromotor control and task execution speed. TRT and HVRT significantly increased maximal voluntary isometric contraction (MVIC), while HVRT demonstrated superior effects on dynamic strength (1RM) and muscle power across multiple load intensities (40–80% 1RM). These findings confirm that high-velocity training can enhance neuromuscular performance even with moderate loads, offering a feasible strategy for individuals with physical limitations. Regarding body composition, FWRT led to significant increases in lean mass and bone mineral content, whereas HVRT effectively prevented fat mass gain. Although none of the RT modalities reversed osteopenia, FWRT and TRT induced meaningful bone health improvements. Psychologically, TRT contributed to reduced anxiety symptoms and enhanced social interaction, FWRT improved perceived functionality and pain management, and HVRT promoted greater vitality and reduced emotional limitations. Collectively, these adaptations translated into improved quality of life and emotional well-being, demonstrating the multidimensional benefits of resistance

training for individuals with SCI. This study is the first to compare three resistance training modalities under similar protocols in this population, and the first to implement flywheel and high-velocity resistance training approaches in individuals with SCI. Despite methodological challenges related to participant heterogeneity and non-randomized allocation, the pragmatic design increased ecological validity, reflecting real-world rehabilitation contexts. In conclusion, TRT, FWRT, and HVRT each confer distinct but complementary benefits for people with spinal cord injury. FWRT is particularly effective for improving functional agility and lean mass, HVRT excels in enhancing dynamic strength and muscle power, and TRT supports psychological and social outcomes. Combining these modalities within individualized rehabilitation programs can maximize physical and psychological adaptations, reinforcing resistance training as a safe, accessible, and comprehensive strategy to promote autonomy, functionality, and quality of life in individuals with spinal cord injury.

Keywords: Spinal cord injury; Resistance training; Flywheel; Eccentric training; High-velocity training; Functional capacity; Mental health; Quality of life.

RESUMO

SANTOS, Lucas Vieira, D.Sc., Universidade Federal de Viçosa, dezembro de 2025. **Efeitos do treinamento resistido de alta velocidade e do treinamento resistido com volantes inerciais nas diferentes manifestações de força muscular, capacidade funcional, sintomas de ansiedade e depressão e qualidade de vida de pessoas com lesão medular**. Orientador: Osvaldo Costa Moreira. Coorientadores: Eveline Torres Pereira e Claudia Eliza Patrocinio de Oliveira.

Esta tese investigou os efeitos de três modalidades de treinamento resistido (TR) — Treinamento Resistido Tradicional (TRT), Treinamento Resistido com Roda de Inércia (Flywheel) (FWRT) e Treinamento Resistido de Alta Velocidade (HVRT) — sobre diferentes manifestações de força muscular, capacidade funcional, sintomas de ansiedade e depressão e qualidade de vida em indivíduos com lesão medular (LM). Trinta e dois participantes com LM crônica foram divididos em três grupos (TRT: n = 12; FWRT: n = 8; HVRT: n = 12) e realizaram oito semanas de treinamento supervisionado, com duas sessões semanais. Nenhum evento adverso foi relatado durante a intervenção. Foram avaliadas a capacidade funcional, a força muscular (isométrica, dinâmica e de potência), a composição corporal e indicadores de saúde mental antes e após o período de treinamento. As análises estatísticas envolveram ANOVA de medidas repetidas e o cálculo da diferença mínima clinicamente importante (MCID), a fim de identificar relevância estatística e clínica dos resultados. Todas as modalidades de treinamento promoveram melhorias significativas em pelo menos um domínio funcional. O FWRT apresentou o maior ganho de agilidade funcional, reduzindo significativamente o tempo de execução do teste — valor superior ao limiar clínico mínimo — evidenciando a eficácia da sobrecarga excêntrica em aprimorar o controle neuromotor e a eficiência nas tarefas. O TRT e o HVRT aumentaram significativamente a contração isométrica voluntária máxima (MIVC), enquanto o HVRT mostrou efeitos superiores sobre a força dinâmica (1RM) e a potência muscular em múltiplas intensidades de carga (40–80% de 1RM). Esses achados confirmam que o treinamento em alta velocidade pode melhorar o desempenho neuromuscular mesmo com cargas moderadas, sendo uma estratégia viável para pessoas com limitações físicas. Na composição corporal, o FWRT promoveu aumento significativo da massa magra e do conteúdo mineral ósseo, enquanto o HVRT preveniu o acúmulo de gordura corporal. Embora nenhuma modalidade tenha revertido a osteopenia, FWRT e TRT resultaram em melhora clinicamente relevante da saúde óssea. Do ponto de vista psicológico, o TRT reduziu sintomas de ansiedade e favoreceu a interação

social; o FWRT melhorou a percepção de funcionalidade e o manejo da dor; e o HVRT aumentou a vitalidade e reduziu limitações emocionais. Em conjunto, esses efeitos refletiram melhorias consistentes na qualidade de vida e no bem-estar emocional, reforçando os múltiplos benefícios do treinamento resistido para pessoas com LM. Este é o primeiro estudo a comparar três modalidades de TR sob protocolos similares nessa população e o primeiro a aplicar o treinamento com roda de inércia e o treinamento de alta velocidade em indivíduos com LM. Apesar de limitações metodológicas relacionadas à heterogeneidade da amostra e à ausência de randomização, o desenho pragmático conferiu maior validade ecológica, refletindo condições reais de reabilitação. Conclui-se que TRT, FWRT e HVRT produzem benefícios distintos e complementares em pessoas com lesão medular. O FWRT destaca-se pela melhora da agilidade e da massa magra; o HVRT, pelo aumento da força dinâmica e da potência muscular; e o TRT, por favorecer aspectos psicológicos e sociais. A combinação dessas modalidades em programas individualizados pode maximizar adaptações físicas e mentais, consolidando o treinamento resistido como uma estratégia segura, acessível e abrangente para promover autonomia, funcionalidade e qualidade de vida em indivíduos com lesão medular.

Palavras-chave: Lesão medular; Treinamento resistido; Flywheel; Treinamento excêntrico; Treinamento de alta velocidade; Capacidade funcional; Saúde mental; Qualidade de vida.

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LIST OF ACRONYMS AND ABBREVIATIONS

SCI: Spinal Cord Injury

QoL: Quality of Life

MH: Mental Health

ET: Eccentric Training

RT: Resistance Training

TRT: Traditional Resistance Training

FWRT: Flywheel Resistance Training

HVRT: High-Velocity Resistance Training

MCID: Minimal Clinical Important Difference

MIVC: Maximal Isometric Voluntary Contraction

PWR: Muscle Power

1 RM: One Repetition Maximum – Maximal Strength Test

P40: Power at 40% of 1RM

P60: Power at 60% of 1RM

P80: Power at 80% of 1RM

BC: Body Composition

BM: Body Mass

LM: Lean Mass

FM: Fat Mass

BMC: Bone Mineral Content

BMD: Bone Mineral Density

CRT: Circuit Resistance Training

HADS: Hospital Anxiety and Depression Scale

HADS-D: HADS Depression Score

HADS-A: HADS Anxiety Score

SUMMARY

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1. INTRODUCTION

Adapted from an article accepted to publication in
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Spinal cord injury (SCI) is a highly disabling condition with significant physiological, psychological, and social consequences for affected individuals. SCI encompasses various alterations in the spinal cord, occurring either acutely or chronically. Symptoms such as motor and sensory dysfunction, muscle dystonia, and pathological reflexes vary depending on the type, level, and severity of the injury. Additionally, SCI is associated with muscle fatigue resulting from factors such as atrophy, increased body fat, and changes in muscle fiber composition. Over time, these alterations negatively impact muscle strength, body mass index, and overall muscle mass (Fu et al., 2016; Frontera; Mollet, 2017; Parker et al., 2022).

Despite the substantial impact of SCI, life expectancy for affected individuals has been increasing. However, it is important to note that mortality rates remain higher and overall life expectancy is still shorter when compared to individuals without SCI (Alves-Rodrigues et al., 2021). This discrepancy may be attributed to the rehabilitation process, which prioritizes not only life expectancy but also improvements in functional capacity and quality of life (Donovan, 2007).

From a psychological perspective, factors such as the cause of the injury and the patient's demographic characteristics may increase the incidence of depression. Studies suggest that approximately 30% of individuals with SCI experience anxiety, while 22% suffer from depression (Frontera; Mollet, 2017; Parker et al., 2022). These issues may be further exacerbated in chronic patients due to declining functional capacity and secondary medical complications associated with aging (Frontera; Mollet, 2017).

Physical exercise is a valuable and safe approach to mitigating the negative effects of SCI, enhancing autonomy, and preventing secondary complications. Additionally, various rehabilitation strategies employ physical exercise as a tool to promote greater independence in performing daily living activities. Among the different types of exercise, resistance training (RT) has proven effective in improving muscle strength, power, functionality, and multiple aspects of quality of life (QoL) and mental health (MH) in individuals with SCI, with no reported adverse effects (Akkurt et al., 2017; Santos et al., 2022; Santos et al., 2024).

However, despite evidence supporting the feasibility of RT for individuals with SCI, there remains a gap in the exploration and in-depth analysis of specific RT types and methods applied to this population. Some researchers have recently focused on investigating these possibilities.

Within the field of RT, eccentric training (ET) has been extensively studied and is characterized by greater maximal force production, lower muscle activation, reduced metabolic cost, and higher recruitment of type IIx muscle fibers (Maroto-Izquierdo et al., 2017). Despite the acute muscle damage and soreness associated with ET, it provides long-term protective effects against muscle injuries (Lindstedt; LaStayo; Reich, 2001; Suchomel et al., 2019).

Flywheel resistance training (FWRT) is an advanced form of ET that utilizes flywheel inertia-based machines to generate constant tension throughout the movement, resulting in greater power output compared to traditional RT. Originally developed for astronauts, FWRT integrates eccentric overload with concentric actions, offering potential benefits in the prevention and rehabilitation of muscle and joint injuries (Maroto-Izquierdo et al., 2017; Suchomel et al., 2019; Yánez et al., 2020). According to Beato e Dello Iacono (2020), FWRT presents unique advantages, including lower energy expenditure, greater gains in strength and power, increased recruitment of high-threshold motor units, elongation of muscle fascicles, and enhanced tendon stiffness.

FWRT is a type of RT that has been thoroughly studied over the last twenty years. However, its application remains limited due to the low accessibility of flywheel inertia-based machines and the lack of high-quality studies with standardized protocols. Nonetheless, the current literature provides evidence suggesting that FWRT is a viable training method for individuals with SCI, provided that its fundamental characteristics are considered—most notably, prioritizing unilateral, single-joint exercises to achieve optimal results (Maroto-Izquierdo et al., 2017; Suchomel et al., 2019; Yánez et al., 2020; Beato et al., 2020).

Equally, High-velocity Resistance Training (HVRT) has shown significant improvements in functional capacity, muscle strength, and power, with these benefits achieved through low-to-moderate training loads an important advantage for individuals with spinal cord injury-related limitations (Feter et al., 2023; Lopez et al., 2023). Recently, a study conducted by Rodrigues et al. (2024) demonstrated that high-intensity resistance training with progressive volume, performed twice weekly

over 12 weeks, can improve or maintain body composition, enhance upper limb muscle power, anaerobic power, and explosive strength. These improvements positively impact functional capacity, promoting greater autonomy and reflecting improvements in the mental state and quality of life for individuals with spinal cord injury. These results highlight the potential of FWRT and HVRT as effective and accessible training methods for individuals with spinal cord injury, targeting both strength and functionality with notable efficiency. However, the impacts of resistance training modalities may vary based on the severity of spinal cord injuries and individual specific factors.

Although the benefits of FWRT and HVRT are well documented compared with traditional resistance training (TRT) or other forms of RT, a knowledge gap remains regarding their specific effects on individuals with spinal cord injury. Therefore, this thesis aims to compare the effects of TRT, FWRT, and HVRT on functional outcomes, body composition, mental health (anxiety and depression) and quality of life. We hypothesize that all three training modalities will lead to improvements in mental health and quality of life in individuals with spinal cord injury.

2. OBJECTIVES

General Objective:

To investigate the effects of High-Velocity Resistance Training and Eccentrically Enhanced Resistance Training on different manifestations of muscle strength, muscle capacity, anxiety and depression symptoms, and quality of life in individuals with SCI.

Specific Objectives:

- Critically review the literature and establish a theoretical proposition for Resistance Training in individuals with SCI.
- Determine the effects of High-Velocity Resistance Training and Eccentrically Enhanced Resistance Training on different manifestations of muscle strength in individuals with SCI.

- Assess the effects of High-Velocity Resistance Training and Eccentrically Enhanced Resistance Training on body composition and bone health in individuals with SCI.
- Establish the effects of High-Velocity Resistance Training and Eccentrically Enhanced Resistance Training on the functional capacity of individuals with SCI.
- Investigate the effects of High-Velocity Resistance Training and Eccentrically Enhanced Resistance Training on mental health and quality of life in individuals with SCI.

3. RESEARCHER'S EXPERIENCE REPORT

"Education alone does not transform society, but without it, society does not change either."

— Paulo Freire

Education is, perhaps, the greatest transformative force in society. When it is neglected, underfunded, or undervalued, individualism and barbarism become likely outcomes. This understanding has been with me since childhood, as I come from a family of teachers — my mother and aunts — and chose Physical Education as both an emotional and professional legacy. My mother, a teacher of the discipline for decades, was my greatest example of dedication and love for teaching. Any account of my professional journey would be incomplete without acknowledging that origin.

During my undergraduate studies, my main goal was to apply in practice what I learned in class. Interestingly, I realized that I became a much better student after graduation than I had been during my time in “PE.” Professional experience awakened in me a constant need to revisit theoretical foundations, understand the scientific basis of my practice, and seek deeper explanations for the phenomena observed in the field.

It is impossible to write about my doctoral thesis without recounting the path that led me to it. Before the PhD came the master’s degree — and it was certainly “an emotional ride.” Upon completing my third specialization, the opportunity arose to pursue a master’s degree under the supervision of Professor Osvaldo, whom I already knew, admired, and shared thematic interests with. In our first conversation,

he explained that the only requirement was that the study population consist of individuals with spinal cord injury (SCI), as part of a project developed in collaboration with Professor Eveline, a national reference in Physical Education and disability studies. I was honest when I said: *“Vadinho, I don’t know anything about spinal cord injury right now… but I’ll learn!”*

I wrote the proposal, took the entrance exam, and despite an administrative mix-up that nearly cost me the oral evaluation, I was accepted. I then spent two semesters studying SCI intensively, seeking to understand its physiological, psychological, and social aspects. My data collection was scheduled to begin in March 2020, when the COVID-19 pandemic abruptly halted all in-person activities. In the middle of my master’s, still adapting and learning, I faced a period of uncertainty, fear, and redirection — in both life and research. Without direct contact with participants, I had to rely on books, articles, and other sources to grasp the multiple dimensions of SCI as deeply as possible.

The resulting dissertation comprised two chapters, both published in the *Journal of Bodywork and Movement Therapies.* The first addressed the effects of resistance training on strength performance, and the second examined the effects of such training on body composition, symptoms of anxiety and depression, and quality of life in individuals with SCI. The first paper was accepted just weeks before my defense; the second, already during my PhD, one year, ten months, and twenty days after submission.

My initial project aimed to investigate the effects of high-velocity resistance training in this population — an approach that, as I demonstrate throughout this thesis, offers promising benefits, though it remains underexplored among individuals with SCI. The pandemic made that study impossible at the time, but later, during the doctorate, this line of inquiry was resumed, now including Flywheel resistance training and traditional training for comparison. Once again, I told my supervisor: *“I don’t know anything about Flywheel training, but I’ll learn!”*

I believe my journey through graduate school has been marked by adaptability, dedication, and, above all, openness to new ideas. I deeply admire researchers who devote their entire careers to a single theme, but I recognize that this is not my path. Mine has been guided by curiosity and the desire to learn, to move across topics, and to seek connections between them.

In the first months of the PhD, I focused on fulfilling course requirements and refining the project's methodology. Initially, upper-limb hypertrophy assessment would be conducted via ultrasound, but this was replaced with whole-body composition analysis using DXA. The functional testing battery proposed by Kawanishi & Greguol (2014) was also replaced by the *Texas Fitness Test* (Gorgatti & Böhme, 2003) to allow comparisons with prior studies supervised by Professor Eveline. Additionally, master's student Karla Raphaela Freitas, whose research examined functional independence in individuals with SCI, joined the data collection team. Her dual background in Physical Education and Physiotherapy was instrumental to the study's success, given her prior experience with this population.

One of the main challenges was recruiting participants. I sought collaboration with the city government of Viçosa, hoping to find potential volunteers through the municipal disability registry. I was referred to the Association of People with Disabilities, where I was warmly welcomed by its president, Marzinho. I received a list of 1,659 contacts but soon realized it was outdated. It took several days of phone calls, and most contacts went unanswered. Some expressed interest but did not meet the inclusion criteria. This experience highlighted the challenges of reaching and communicating with this population and demonstrated that a large dataset does not necessarily mean useful or applicable information.

During the development of the research design, the main objective was to structure the training sessions as similarly as possible across the three study groups. Consequently, exercise selection had to consider the participants' physical limitations, the available equipment, and well-established training principles to ensure that, throughout the eight-week intervention, the sessions would effectively provide the necessary stimulus to elicit adaptations consistent with resistance training.

Although the exercises were focused on the upper limbs and all participants had complete spinal cord injuries, the different levels of injury imposed distinct constraints that demanded careful attention and limited the range of exercises that could be safely performed. It is well known that spinal cord injuries present heterogeneous challenges even when classified at similar levels. Some volunteers experienced difficulties stabilizing the trunk during various movements, others required additional support or the use of stabilizing straps on the wheelchair, while a few were nearly capable of training independently.

After three weeks of study, experimentation, discussion, and testing, we reached the training structure described in Chapters I, II, and III of this thesis. Data collection began with the maximum number of volunteers available; however, within the first three weeks, two participants were lost—one moved to another city, and the other stopped attending sessions without justification. Training sessions were held on Mondays, Wednesdays, and Fridays, with each participant attending twice a week. Most sessions were conducted by Karla and me, with occasional assistance from master’s and undergraduate students. In some instances, however, this support created more logistical difficulties than actual help.

Because the facilities required for the different training groups were not centralized within the Department, we had to divide our time among them. This prevented greater interaction between participants from different groups and, in some cases, contributed to lower levels of motivation.

Undoubtedly, this was the most challenging stage of the entire research process. Beyond the inherent complexities of data collection, there was a constant sense that something could go wrong at any time. The rainy season in Viçosa made commuting particularly difficult for participants with spinal cord injuries, and the flywheel training—conducted individually—further limited social interaction, an important factor for motivation and adherence, especially among individuals with less previous engagement in structured exercise programs.

I often think back to a conversation I had with Professor Eveline early in my master’s, when we discussed the true role of research in Physical Education. We discussed how quantitative studies allow us to identify means, standard deviations, effect sizes, and statistical significance — yet they cannot fully capture the human transformations that occur throughout the process. A questionnaire may indicate improved quality of life, but it cannot convey the sparkle in one’s eyes, the change in tone of voice, or the smile of someone who feels part of something again. Seeing a participant arrive withdrawn and leave energized after training is an experience that transcends numbers — one that cannot be contained within a scientific article.

Thus, both the master’s and the doctorate have given me lessons that go far beyond methods and results. I have worked, studied, and dedicated myself intensely to understanding subjects I never imagined studying. And whenever I needed it, I could count on the invaluable support of my supervisor and co-supervisors.

Every graduate journey is unique. Mine has been shaped by challenges, partnerships, and collective growth. I learned that a thesis is never built alone — and, more importantly, that a researcher is never formed alone.

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CHAPTER I

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Which different resistance training types enhance functional performance in people with spinal cord injury? A comparison of traditional, flywheel, and high-velocity resistance training

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Background: Individuals with spinal cord injury (SCI) experience significant impairments in strength, mobility, and functional independence due to neuromuscular alterations. Resistance training (RT) is recognized as a safe and effective intervention to mitigate these deficits, yet the specific effects of different RT modalities such as traditional (TRT), flywheel-based (FWRT), and high-velocity training (HVRT) remain unclear in this population.
Purpose: To compare the effects of TRT, FWRT, and HVRT on functional agility, isometric strength, maximal dynamic strength, and muscle power in individuals with SCI.
Methods: Thirty-two adults with SCI (49 ± 11.78 years; 22 ± 17.32 years post-injury) were allocated into TRT (n = 12), FWRT (n = 8), and HVRT (n = 12) groups and underwent 8 weeks of twice-weekly upper-body resistance training. Functional and strength outcomes were assessed pre- and post-intervention. A two-way repeated-measures ANOVA analyzed group × time effects, with $p < 0.05$ and partial eta squared (η^2) reported.
Results: FWRT presented a significant reduction in the time required to complete the functional agility test (pre: 29.97s ±0.51, post: 26.75s ±0.83, $p = 0.001$, $\eta^2 = 0.528$). Both the TRT (pre-15.70kg ±5.75, post-16.70kg ±4.72, $p = 0.004$, $\eta^2 = 0.436$) and HVRT groups (pre-16.88kg ±4.02, post-19.63kg ±2.38, $p = 0.004$, $\eta^2 = 0.436$) demonstrated significant increases in MIVC. In the 1RM test, all groups showed statistically significant improvements TRT: (pre-23.17kg ±9.02, post-24.50kg ±8.67, *p*

< 0.001, $\eta^2 = 0.819$), FWRT: (pre-15.00kg ±3.09, post-16.50kg ±4.63, $p < 0.001$, $\eta^2 = 0.819$) and HVRT: (pre-20.50kg ±5.59, post-23.26kg ±4.28, $p < 0.001$, $\eta^2 = 0.819$). Additionally, the HVRT group exhibited a significant increase in performance in the P40 test (pre-80.37w ±36.51, post-86.50w ±34.96, $p < 0.001$, $\eta^2 = 0.995$) and the P60 test (pre-68.91w ±14.76, post-90.92w ±29.95, $p = 0.001$, $\eta^2 = 0.505$). Only the HVRT group showed statistically significant changes in P80 (pre-78.23w ±19.93, post-88.69w ±24.72, $p = 0.012$, $\eta^2 = 0.352$).

Conclusion: TRT, FWRT, and HVRT generate distinct neuromuscular and functional adaptations in individuals with SCI. FWRT is most effective for improving agility, TRT enhances isometric and maximal strength, and HVRT is optimal for increasing both strength and power. Training modality should be selected based on individual functional goals in rehabilitation programs.

Keywords: Functional Capacity; Paraplegia; Eccentric Resistance Training; Power Training; Quality of Life

INTRODUCTION

Spinal cord injury (SCI) leads to acute and chronic symptoms, encompassing motor dysfunction, sensory impairment, and muscle dystonia. Additionally, SCI induces muscle fatigue, atrophy, and alterations in muscle fiber, significantly influencing strength and long-term body composition. Upper limb imbalances detrimentally impact mobility, with a review emphasizing age-aggravated degenerative alterations in the glenohumeral joint (Frontera & Mollett 2017; Fu et al., 2016; Hou & Rabchevsky 2014). This impedes community participation, fostering psychological disorders such as anxiety and depression (Parker et al., 2022).

In this context, physical exercise emerges as a valuable and safe strategy to alleviate the adverse impacts of SCI, promoting autonomy and preventing secondary complications. When motor neurons lose their ability to transmit signals the resulting paralysis muscles lead to atrophy due the lack of use. The changes in muscle architecture impact negatively the capacity to generate strength in all your manifestations (Gordon & Mao 1994; Narici et al., 2016; Santos et al., 2024). Among exercise modalities, Resistance training (RT) stands out as an effective and secure exercise modality that enhances body composition, muscle strength, power, and upper limb functionality without causing adverse effects (Akkurt et al., 2017; Mogharnasi et al., 2019; Santos et al., 2022; Santos et al., 2024).

Among the various types of RT, two stand out for their significant benefits to other populations and may also provide significant benefits for individuals with SCI: Flywheel Resistance Training (FWRT) and High Velocity Resistance Training (HVRT). FWRT is an advanced version of eccentric resistance training that uses flywheel machines to provide constant and unlimited tension throughout the full range of motion, resulting in greater power compared to TRT.

Originally designed to address musculoskeletal deficits in astronauts during space missions, FWRT operates on a yo-yo mechanism, generating kinetic energy during the concentric phase and requiring individuals to resist the inertial force during the eccentric phase. Flywheel devices utilize inertial resistance created by the unwinding of the flywheel’s strap during a concentric muscle action, which is then followed by the rewinding of the strap, leading to eccentric muscle action. The exercise intensity is determined by the diameter and the mass of the pivot system and the speed of the concentric phase. FWRT presents a distinctive set of

advantages by combining eccentric overload and concentric actions, resulting in enhanced strength and power output with reduced energy expenditure (Maroto-Izquierdo et al., 2017; Suchomel et al., 2019). Additionally, it facilitates high-threshold motor unit recruitment and brings improvements in muscle mass, fascicle length, and tendon stiffness (Beato & Dello Iacono 2020; Suchomel et al., 2019).

High-velocity resistance training (HVRT) has shown significant benefits in improving muscle power and strength, which directly contribute to enhanced functional capacity. Muscle power is defined as the peak rate at which work is performed, highlighting the ability to generate strength rapidly rather than merely producing maximal strength. This attribute typically involves a rapid concentric contraction executed with maximal effort, followed by a slower eccentric phase (Haque et al., 2024). Importantly, such improvements can be achieved using moderate training loads, a key advantage for individuals with SCI, who often face physical and physiological limitations that restrict their ability to tolerate high-load resistance training (Feter et al., 2023; Lopez et al., 2023).

Taken together, these findings underscore the potential of FWRT and HVRT as effective and accessible training strategies for individuals with SCI, addressing both strength and functional aspects with optimal efficiency. While the advantages of FWRT and HVRT are well-established in comparison to TRT or other RT types, a notable gap in knowledge persists regarding their specific benefits for individuals with SCI. Therefore, the purpose of this study is to investigate the FWRT and HVRT in comparison with TRT and their effects in different strength manifestations and functional aspects of people with SCI.

METHODS

Experimental Approach to the Problem

This study employed a quasi-experimental design with parallel groups and an active control, comparing the effects of three resistance training modalities: Traditional Resistance Training (TRT), Flywheel Resistance Training (FWRT), and High-Velocity Resistance Training (HVRT) on functional outcomes and strength manifestations in individuals with SCI. Given that TRT has already demonstrated positive effects in this population, it was adopted as the control condition to maintain

participant engagement and facilitate attendance at pre- and post-intervention assessments. The sample consisted of individuals recruited through announcements in local programs and direct contact with the community and should be characterized as a convenience sample, reflecting the accessibility and willingness of participants to engage in the intervention.

Participants were allocated into groups through a non-randomized process, based on clinical and functional criteria, to balance injury level and physical potential across groups and minimize potential biases. This approach was deemed necessary due to the considerable variability among individuals with SCI and the practical challenges related to mobility and adherence. The training protocols followed established principles of RT, ensuring progressive overload and intensity control throughout the intervention. All participants were thoroughly informed about the study procedures, and any questions were addressed individually or collectively. The inclusion of both pre- and post-intervention assessments allowed for within-group and between-group comparisons, contributing to the internal validity of the findings, despite the absence of randomization typically expected in randomized controlled trials.

Subjects

The sample consisted of 34 individuals who were already aware of the activities offered by the University for people with disabilities, as well as those who expressed interest after direct contact via messaging, through a partnership with City Hall. All individuals had to have an SCI confirmed by a clinical diagnosis, no musculoskeletal injuries in the upper limbs in the past year, no prior experience with RT was needed, and they had to attend at least 80% of the training sessions without starting another exercise program, whether strength training or aerobic training. They were also instructed to maintain their regular eating routine. The individuals were between 28 and 65 years old (49 ± 11.78), with 22 ± 17.32 years since injury, weighing 64.62 ± 3.33 kg (Figure 1). The study received ethical approval from the Ethics Committee of the Federal University of Viçosa (approval number 5.418.335) in May 2022 and was conducted during the second half of 2023.

During the planning phase of this study, extensive discussions were held regarding the potential inclusion and exclusion criteria and their influence on the

outcomes. It is widely recognized that individuals with SCI are susceptible to various secondary conditions, including hypertension, anxiety, and depression. Additionally, significant mobility limitations are common in this population, often serving as a primary exclusion factor. Therefore, the research team determined that only upper limb musculoskeletal injuries would be considered grounds for exclusion.

Spinal cord injuries are inherently unpredictable, with two seemingly similar cases potentially resulting in vastly different outcomes, such as muscle spasticity or flaccidity. In light of these variations, the lead researcher conducted an initial interview with each prospective participant to assess their individual capacities and limitations. Upon completing all interviews, it was concluded that organizing participants based on their injury level would be sufficient to control for potential biases in the results.

During the first interaction between each volunteer and the researcher responsible for group allocation, a brief interview was conducted. At this point, the informed consent form was reviewed, and any doubts regarding the assessment procedures, training timeline, and other pertinent aspects were addressed. The researcher also collected documentation confirming the SCI diagnosis and discussed the specific capabilities and constraints of each volunteer. All participants had complete spinal cord injuries caused by either firearm incidents or motor vehicle accidents. Injuries ranged anatomically from the T4 to L1 vertebrae, indicating varying levels of trauma among the participants.

Due to the variability in physical condition among participants, random assignments were not employed. Instead, the lead researcher allocated participants into groups to ensure balanced distribution based on injury level, functional potential, and physical limitations. This strategy avoided concentrating similar injury profiles within a single group, which could have introduced bias into the study's findings. The researcher responsible for group assignment did not participate in data collection or training sessions, being involved solely in the statistical analysis and interpretation of the results.

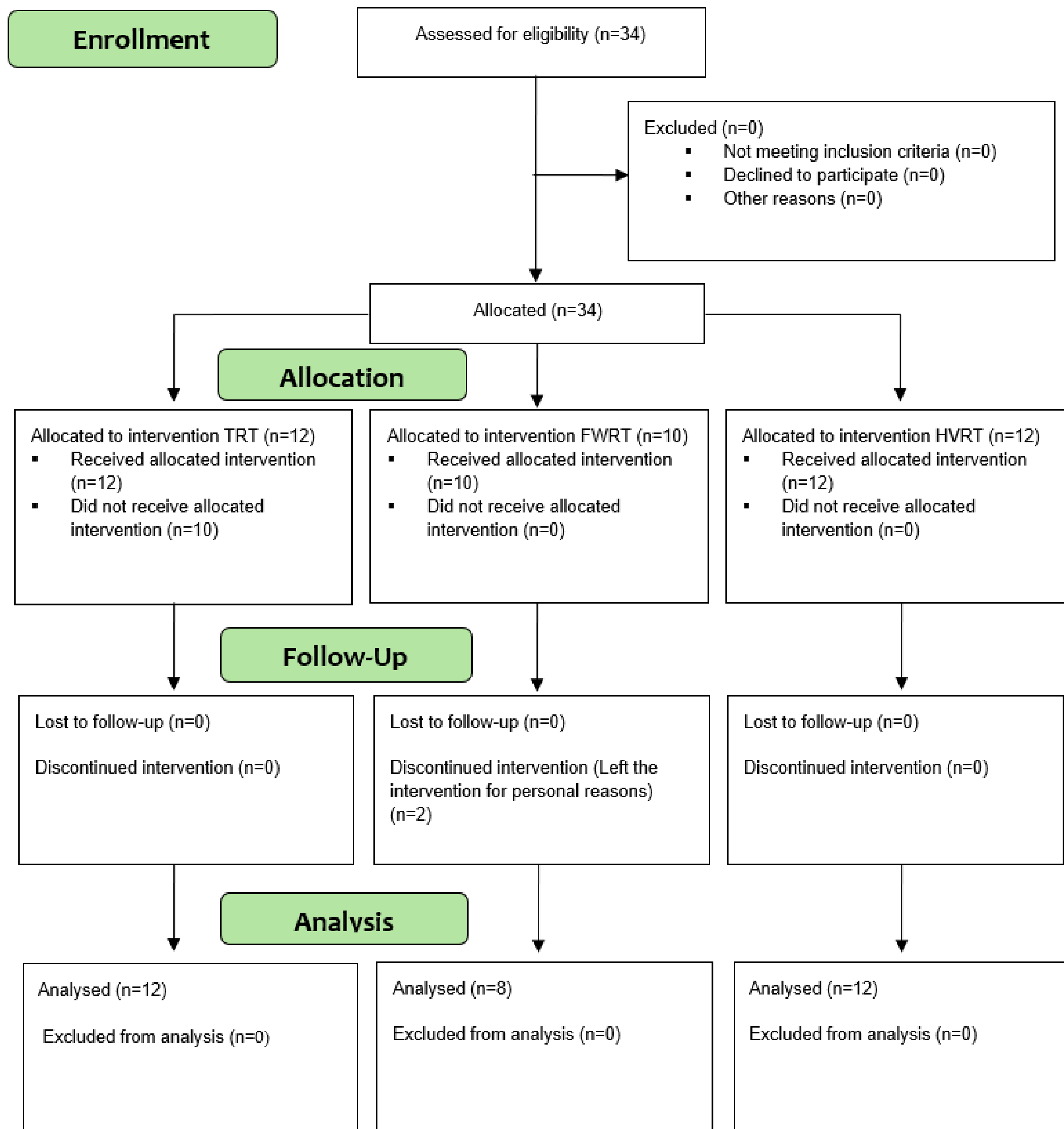

Figure 1: Study trial design. Overview of volunteer group allocation and dropout information. (TRT) Traditional resistance training; (FWRT) Flywheel resistance training; (HVRT) High-velocity resistance training.

Procedures

Training Protocols

Thirty-four individuals with Spinal Cord Injury (SCI) were assigned to three distinct groups: Traditional Resistance Training (TRT) (n=12), Flywheel Inertial

Training (FWRT) (n=10), and High Velocity Resistance Training (HVRT)(n=12). The FWRT and HVRT groups focused on executing the concentric phase of the movement as rapidly as possible. The FWRT group was instructed to follow the movement of the machine during the eccentric phase and to break the movement in the final third of the eccentric phase to maximize the benefit of the eccentric overload generated by the inertial flywheel machine. The HVRT group was instructed to perform the eccentric phase in a controlled manner, without exceeding 2 seconds in duration. The TRT group performed the exercises with a duration of 2 seconds for both the concentric and eccentric phases. The training protocol involved a volume ranging from 2 sets of 10 repetitions to 4 sets of 12 repetitions (Figure 2A). Furthermore, two warm-up series with light loads (equivalent to 50% of the training load or an OMNI-RES rating between 5 and 7) were incorporated (Figure 2B). The exercises were specifically designed for functional muscle groups allowing each volunteer to execute them as effectively as their individual abilities permitted (Figure 3).

The training loads were calibrated to uphold high-intensity training, overseen by the OMNI-RES scale, aiming to maintain a perceived effort level between 7 and 9. The OMNI-RES scale is used to assess perceived exertion during resistance training sessions. It is easy to apply and understand. The scale ranges from 1 to 10, with 1 being extremely easy and 10 being extremely difficult. A rest period of 1 minute between sets was implemented. Throughout the 8 weeks of training, two times per week, the sessions varied in duration over the weeks, spanning from 25 minutes on the first to 50 in the last one. Training sessions and all tests were done in the Department of Physical Education of the Federal University of Viçosa.

Figure 2: 2A Training Planning: Duration of intervention, volume, rest between sets and intensity. 2B Organization of the 10 weeks of intervention showing when the assessments were performed and the weekly progression of training volume.

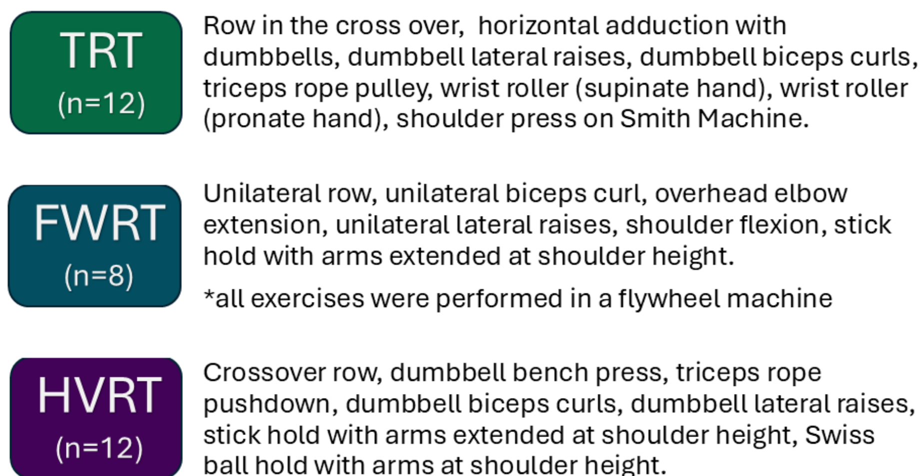

Figure 3: Exercises performed during training sessions by each of the groups.

Functional Agility

The adapted Texas Fitness Test (Gorgatti & Böhme 2003) served as a functional capacity indicator in this study. The primary objective of this test was to successfully complete the total distance of a rectangular course measuring 6 x 9 meters, involving directional changes at maximal velocity and efficiency. Each participant, utilizing their own wheelchair, navigated the track a total of five times, with a 5-minute rest period between each iteration. The initial lap served as a warm-up, followed by a second lap where participants were instructed to perform a faster warm-up than the first. The subsequent three attempts were deemed valid, and the test outcome was determined based on the fastest lap recorded during the course.

Strength Tests

The strength tests were conducted in a single session in the following order: maximal voluntary isometric contraction (MVIC), maximal strength (1RM), and muscle power. These tests were performed using the biceps curl on a low pulley with the dominant arm. The description of each test is as follows.

The assessment of maximal voluntary isometric contraction involved utilizing a load cell, maintaining the elbow at a fixed angle of 90° using a goniometer. Volunteers were required to sustain a maximal isometric contraction for 3 seconds.

Each participant underwent two attempts, with a 3-minute interval between them. The highest recorded result in kilograms was considered as the test score (Oliveira et al., 2018; Rodrigues et al., 2020).

To assess dynamic strength a 1 maximal repetition test (1RM) was conducted. The protocol included four warm-up repetitions with a 50% maximal isometric voluntary contraction (MIVC) load, followed by an OMNI-RES effort evaluation. The load was incrementally increased by 3 or 5 kg, and the volunteer performed two repetitions with each load until they could only complete one maximal repetition. The recorded test result was based on the last lifted load (Oliveira et al., 2018; Rodrigues et al., 2024). If the volunteer could not complete a full repetition, the test result was determined by considering an intermediary load between the last load lifted twice and the one associated with the incomplete repetition. The testing protocol allowed for five attempts, with a 3-minute rest interval between each attempt.

Muscular Power Peak (PWR) was assessed by a transducer of linear position over a range of 3 related 1RM submaximal loads (40%, 60%, 80%) and recorded via Chronojump software (version 2.2.1 – Boscosystem 2.35). To measure the PWR, three elbow flexions with total range of motion with each pre-established load. Volunteers could rest 2 minutes after each set of repetitions. They were also instructed to execute the concentric phase “as fast as possible” while the eccentric should be executed slowly (approximately 2 seconds) (Medina-Perez et al., 2016; Rodrigues et al., 2024).

Statistical Analysis

For the statistical analysis, descriptive statistics were initially applied to summarize the data. The Shapiro–Wilk test assessed data normality, and for variables that did not meet the normality assumption, a log transformation (base 10) was applied to normalize the data, allowing for the consistent use of parametric tests across all analyses. M Box test was used to evaluate the homogeneity of variances. Group comparisons at baseline were conducted with a one-way analysis of variance (ANOVA), followed by Bonferroni post hoc analysis. To examine intra- and intergroup differences over time, a two-way repeated measures ANOVA was used, incorporating two factors: time (pre- and post-intervention) and condition (comparing TRT, FWRT, and HVRT groups). Partial eta squared ($\eta 2$) effect size was calculated

for the two analyzed factors, when a statistically significant difference was observed, considering cutoff points to define small ($\eta2<0.01$), medium ($\eta2$ between 0.02 and 0.06), and large ($\eta2 > 0.14$) effects (Cohen 1992). A statistical significance level of $p<0.05$ was adopted for all tests. Additionally, statistical power ($1-\beta$) was also calculated, considering a value greater than or equal to 80% as acceptable. The statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS), version 21.0.

To complement the interpretation of statistical significance, the minimal clinically important difference (MCID) was estimated for key functional outcomes using a distribution-based approach. This method defines MCID as 0.2 times the baseline standard deviation (SD), representing the smallest change likely to be meaningful from a clinical perspective (Norman et al. 2003). For each outcome, the MCID was calculated using the SD of the pre-intervention values in the respective group. The observed differences were then compared to these thresholds to determine their clinical relevance. This strategy was applied to agility, maximum voluntary isometric contraction (MVIC), one-repetition maximum (1RM), and muscular power outputs (P40, P60, and P80), providing additional context regarding the practical implications of the training-induced improvements.

RESULTS

Two volunteers from the FWRT group discontinued their participation in the training program: one relocated to another city after the second week, and the other ceased attending sessions after the third week. The research team attempted to contact this volunteer to understand the reason for the dropping out but received no response to phone calls or messages. Therefore, the results presented here are based on data from thirty-two participants after statistical analysis. Consequently, the analysis was conducted considering the following groups: TRT ($n = 12$), FWRT ($n = 8$), and HVRT ($n = 12$). Throughout the interventions, there were no adverse events or injuries associated with the training protocols.

At the baseline, the functional Agility Test (Texas Fitness Test) revealed that the TRT group had significantly longer initial times compared to those observed by HVRT. In the 1RM assessments, TRT initially showed significantly higher results than FWRT, which in turn had significantly higher results than HVRT.

Figure 4 presents the results of functional agility and strength manifestations before and after intervention. In the functional agility test (Figure 4A), TRT showed a reduction in the time required to complete the circuit, although without significant intragroup changes (pre 33.08s ±7.07, post 32.55s ±4.86, p = 0.001, η^2 = 0.528). Conversely, FWRT exhibited a significant reduction in the time needed to complete the test after training (pre 29.97s ±0.51, post 26.75s ±0.83, p = 0.001, η^2 = 0.528), while HVRT did not yield any significant changes (pre 28.34s ±4.82, post 28.12s ±2.61, p = 0.001, η^2 = 0.528). It's noteworthy that FWRT proved to be more efficient in improving functional agility compared to TRT and HVRT.

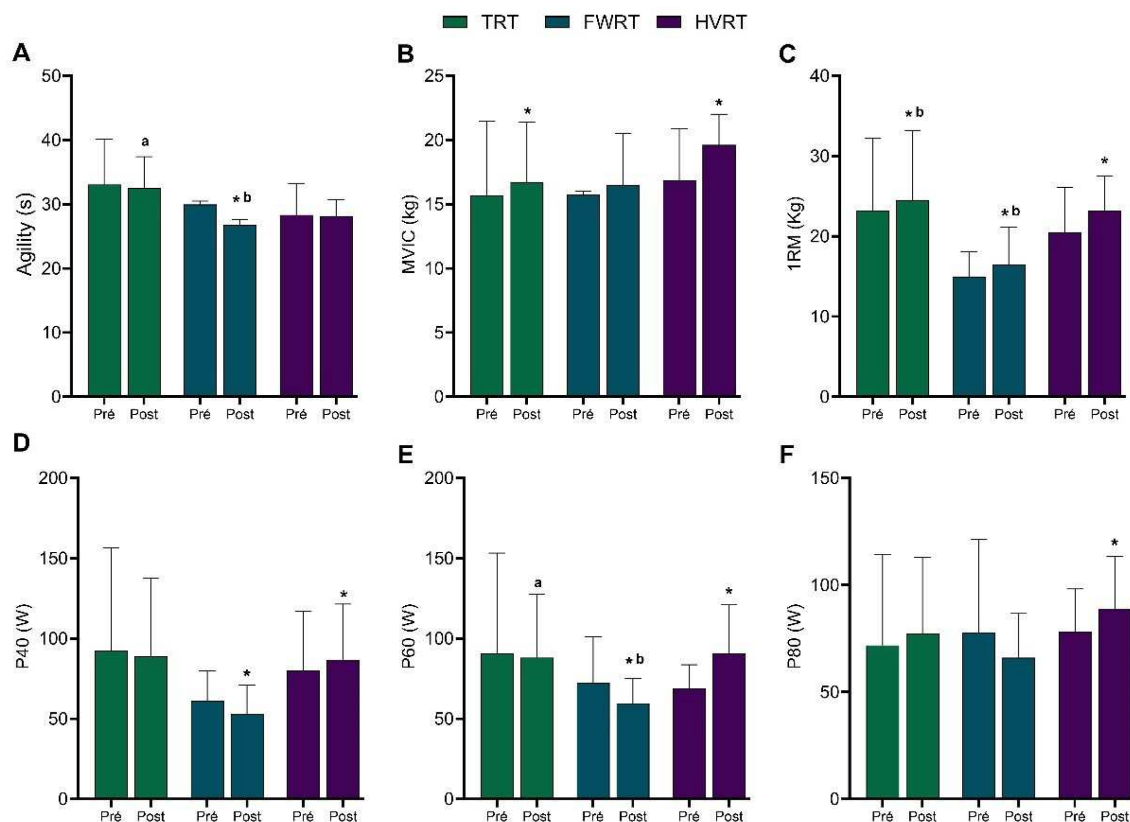

Figure 4: (A) Agility; (B) MVIC: Maximal Voluntary Isometric Contraction; (C) 1RM: 1 RM test – Maximal Strength Test; (D) P40: Power 40%; (E) P60: Power 60% 1RM; (F) - P80: Power 80% 1RM; (TRT) traditional resistance training; (FWRT) Flywheel resistance training; (HVRT) high-velocity resistance training. * $p < 0.05$ vs. post-intervention; a $p < 0.05$ vs. FWRT; b $p < 0.05$ vs. HVRT.

Both groups demonstrated significant changes in MIVC (Figure 4B) before and after the training period TRT (pre-15.70kg ±5.75, post-16.70kg ±4.72, p = 0.004, η^2 = 0.436) and HVRT (pre-16.88kg ±4.02, post-19.63kg ±2.38, p = 0.004, η^2 = 0.436), with no marked advantage in intergroup comparison. In the 1RM test (Figure 4C),

TRT (pre-23.17kg ±9.02, post-24.50kg ±8.67, $p < 0.001$, $\eta^2 = 0.819$), FWRT (pre-15.00kg ±3.09, post-16.50kg ±4.63, $p < 0.001$, $\eta^2 = 0.819$), and HVRT (pre-20.50kg ±5.59, post-23.26kg ±4.28, $p < 0.001$, $\eta^2 = 0.819$) significantly enhanced maximal strength. In intragroup comparison, TRT and FWRT were more effective than HVRT in improving 1RM results, with no significant differences between them. FWRT exhibited a decrease in P40 (pre-61.46w ±18.56, post-53.16w ±17.93, $p < 0.001$, $\eta^2 = 0.995$), whereas HVRT demonstrated a significant increase in P40 (pre-80.37w ±36.51, post-86.50w ±34.96, $p = 0.001$, $\eta^2 = 0.528$). TRT showed no significant changes before and after the training program (Figure 4D). Additionally, TRT (pre-90.93w ±62.27, post-88.12w ±39.62, $p = 0.001$, $\eta^2 = 0.505$) displayed a significant reduction in P60 (Figure 4E) compared to FWRT (pre-72.49w ±28.50, post-59.67w ±15.42, $p = 0.001$, $\eta^2 = 0.505$), which also reduced P60 and was less effective than HVRT (pre-68.91w ±14.76, post-90.92w ±29.95, $p = 0.001$, $\eta^2 = 0.505$), which demonstrated a significant increase in P60 before and after the training period in comparison with FWRT. Only HVRT (pre-78.23w ±19.93, post-88.69w ±24.72, $p = 0.012$, $\eta^2 = 0.352$) showed significant changes in P80 (Figure 4F).

To contextualize the magnitude of the changes observed, the minimal clinically important difference (MCID) was calculated for each functional variable using 0.2 times the baseline standard deviation. In the FWRT group, the improvement in agility (3.22 s) exceeded the estimated MCID (0.10 s). In the HVRT group, changes in MVIC (2.75 kg), 1RM (2.75 kg), and power at 60% and 80% of 1RM (22.01 W and 10.46 W, respectively) all surpassed their respective MCIDs (0.80 kg, 1.12 kg, 2.95 W, and 3.99 W). Conversely, the increase in power at 40% of 1RM (6.13 W) did not exceed its MCID threshold (7.30 W). These values provide additional perspective regarding the potential clinical impact of the training protocols.

DISCUSSION

The purpose of this research was to investigate the effects of FWRT and HVRT in comparison with TRT and their effects in different strength manifestations and functional aspects of people with SCI. After eight weeks of training, the following results were observed: all groups presented intragroup enhancements in different Functional Aspects. FWRT impacted significantly on Functional Agility in intragroup analysis and compared to the other groups. TRT and HVRT improved MVIC after the

training period but no significant differences were found between groups. All groups had significant increase in 1RM results, and HVRT was the most effective type of RT to raise maximal dynamic strength in comparison with other groups. When evaluating muscle power, TRT did not result in any significant changes, while FWRT lead to significant reduction and HVRT notably improved muscle power. HVRT also showed the biggest improvement in P60 compared to TRT and FWRT.

The functional results of this study revealed that different resistance training modalities induced distinct adaptations in individuals with spinal cord injury. Notably, the FWRT group demonstrated a significant and clinically meaningful improvement in agility, reducing completion time by 3.22 seconds well above the estimated MCID of 0.10 seconds. This finding underscores the potential of eccentric overload strategies in improving neuromotor efficiency and task execution speed in this population. In the HVRT group, significant gains were observed in MVIC and 1RM, with improvements of 2.75 kg in both measures, exceeding their respective MCID thresholds (0.80 kg and 1.12 kg). These findings suggest that high-velocity training may effectively enhance both isometric strength and dynamic force production, even when performed with moderate loads. Furthermore, muscular power at 60% and 80% of 1RM increased substantially in the HVRT group, with changes of 22.01 W and 10.46 W, respectively—well beyond their calculated MCIDs (2.95 W and 3.99 W). These adaptations highlight the specificity of HVRT in improving neuromuscular power output under load conditions that mimic functional tasks. However, although the increase in power at 40% of 1RM reached statistical significance, the observed change (6.13 W) did not surpass the MCID (7.30 W), suggesting that improvements at lower intensities may be less functionally impactful. Collectively, these findings support the use of FWRT and HVRT as viable strategies for improving functionally relevant outcomes in individuals with SCI, each with specific advantages depending on the targeted capacity.

In our group’s systematic review (Santos et al., 2024) we identified resistance training as an effective tool to increase functionality which has agility between its factors. Consistent with these findings, our current experimental results corroborate with those found in a recent study with progressive volume and high intensity resistance training (Rodrigues et al., 2024) as a type of RT which can improve agility as well as TRT and FWRT. Conversely, HVRT results are distinct from those found by Feter et al. (2023) and Schaun et al. (2021), in which HVRT improved the agility

and functional performance of older adults without SCI and mobility-limited older adults.

The comparison of our results with those of Feter et al. (2023) and Schaun et al. (2021) can be supported by a broader perspective, which acknowledges that SCI often imposes physiological and functional challenges similar to those observed in aging populations. Although research on resistance training in individuals with SCI remains limited, the impacts of SCI on body composition, neuromuscular decline, reduced mobility, quality of life, and mental health resemble those commonly seen in older adults. In this sense, SCI may be considered a condition of accelerated and premature aging, which justifies drawing conceptual parallels between these populations. Therefore, comparing our results, particularly regarding power and functional performance, with findings from studies on older adults is not only reasonable but, at some point, necessary to expand the evidence base for resistance training in clinical populations with reduced mobility. This perspective frames the findings reported by Feter et al. (2023) and Schaun et al. (2021) as relevant reference points when discussing the potential and limitations of HVRT in individuals with SCI.

While HVRT did not improve functional agility test, it reduced perceived physical limitations in people with SCI, as assessed by the SF-36 questionnaire, significantly impacting their quality of life (Santos et al.2025). Supporting this perspective, Alves-Rodrigues et al. (2021a; 2021b) in two previous works studied the impact of functional training and circuit resistance training in functional agility of people with SCI and observed both can lead to a reduction in time needed to complete the track’s test. Comparison with these studies is particularly relevant because they used the same functional agility test applied in our study, allowing a direct comparison of the results and leading to an understanding that there are many types of RT with potential to improve agility in individuals with complete SCI.

The SCI-related limitations lead individuals to a reduced physical capacity with decreased independence and functional capacity. It is well documented that the decline in functional capacity in individuals with spinal cord injury reflects morphological changes associated with the injury (Fu et al., 2016; Hou & Rabchevsky, 2014; Santos et al., 2024). Muscle atrophy, increased body and intramuscular fat, aging with the injury, and their consequent impacts on the ability to generate strength and resist fatigue are commonly related to functional capacity

(Santos et al., 2024). Therefore, it is possible to understand the improvement in functional capacity as a reflection of positive effects in these morphophysiological aspects even when they are not statistically significant. Understanding this, along with the direct and indirect impacts of SCI, improving functional capacity becomes necessary to avoid consequences ranging from reduced community participation to psychological disorders such as anxiety and depression (Parker et al., 2023; Santos et al., 2024).

Despite the known benefits of RT to several populations, few studies have analyzed its effects in strength manifestations in people with SCI. Additionally, the low methodological quality of many of them compromises further interpretation and comparison of the results. Bye et al (2014) and Serra-Año et al (2012) used isometric contractions and TRT respectively in trainings for people with SCI. Their results for MIVC corroborate with those found in this study to TRT and HVRT. It leads to an understanding that MIVC in people with SCI can be improved by training isometric contractions or with movements which concentric and eccentric phase are performed. The increased MIVC holds significant benefits for individuals with SCI due to their varied needs, such as changes in body position while in a wheelchair or sitting or lying on a bed. Additionally, it aids in preventing bedsores and other complications. Moreover, isometric strength plays a crucial role in activities of daily living facilitating transfers between the bed and wheelchair, enabling individuals to perform self-care tasks and enhancing mobility, all of which contribute to greater independence. However, despite the insights gleaned from this study and related research (Bye et al., 2017; Serra-Año et al., 2012), drawing robust conclusions about a direct correlation between functional capacity and increased MIVC remains challenging due to the complexities involved in conceptualizing and assessing functional capacity comprehensively across its various aspects and applications (Gaspar et al., 2019; Freitas et al., 2024).

The maximal dynamic strength evaluated by 1RM test seems to be the most sensitive strength manifestation of all three types of RT, presenting significant improvements for all groups with some advantage to HVRT. One reason to it may be that in 1RM tests, individuals must apply a great effort to complete the concentric phase, and the increased muscle power can be a factor of success in the test. Tørhaug et al (2016) trained 9 SCI individuals with high intensity (85%-95% 1RM) in a randomized controlled trial and observed gains in maximal strength after 6 weeks.

In a well-designed study, Turbanski et al (2010) compared wheelchair athletes and active physical education students as the control group and observed similar improvements in 1RM test for both groups. The authors highlight that these results are important to answer those who speculated SCI individuals have their adaptation capacities reduced after injury. Additionally, our results show the capacity of these individuals to adapt to 3 types of RT in a short period of training. Ours and Turbanski et al (2010) studies had the same duration and number of training sessions meanwhile Tørhaug et al (2016) training period lasted 2 weeks less. According to Gaspar et al., (2019) sedentarism and inactivity are the main risk factors to the development of metabolic and cardiovascular disorders and there is an association between it and loses in muscles strength and reduced aerobic capacity. On the other hand, strength is considered an independent predictor of mortality (Oliveira et al., 2018). Therefore, in addition to the health benefits, both isometric strength and dynamic maximum strength are important physical attributes that directly or indirectly impact on the aforementioned activities of daily living and the quality of life of individuals with spinal cord injury (Rodrigues et al., 2020; Santos et al., 2024).

In our results HVRT was the most effective type of RT to promote improvements in maximal dynamic strength (1RM). To try to explain our findings, it is important to know about the nature of the 1RM test and some power training specific adaptations. In the 1RM test, the objective is to lift the maximum load possible for a single repetition in a specific exercise. In this investigation the 1RM test was performed using the elbow flexion. Therefore, the movement's first phase was the concentric instead of the eccentric one like in squats or bench press which are usually choices in studies with individuals with no physical disabilities. It is well known that neural adaptations resulting from power training (HVRT), have been characterized by the preferential recruitment of high-threshold motor units to produce maximum strength in short periods, and it could play a crucial role in enhancing performance in this test (Kraemer & Fleck, 1996). But, besides this, Tillin & Folland (2014) compared maximal strength training and explosive (power) training (HVRT), and their findings indicated improvements in strength in both groups with greater gains observed in the maximal strength training. However, only power training group showed improvements in the early phase of explosive strength and, they affirmed this based on greater levels of neuromuscular activation followed by training period. Thus, the nature of the test and the exercise performed in 1RM test, the power

adaptations already known in the literature and Tillin & Folland (2014) findings, may, together, help to draw an explanation to the observed advantage to HRVT group in our maximal dynamic strength results.

Evidence shows that muscle power is correlated with functional capacity and the implementation of exercises to improve this strength manifestation is recommended for many populations in current literature (ACSM 2009; Fragala et al., 2019; Lopez et al., 2023; Sklivas et al., 2022). Our results showed that HVRT was effective in increasing muscle power over the range of loads tested. Alternatively, TRT and FWRT showed reductions in this strength manifestation.

Previous studies (Tørhaug et al 2016; Turbanski et al., 2010) used moderate to high intensity but without the instructions to perform concentric phase at maximum velocity. Meanwhile, our training protocols were focused on performing the concentric phase of movement as fast as possible, and the loads were adjusted to guarantee high effort perception. It is important to note that types of RT can generate effect in more than one strength manifestation. In other words, it means that training protocols designed to improve a specific strength manifestation can generate residual effects in others, as it is possible to see in our review (Santos et al., 2022) and in the studies with circuit training and functional training carried out by Alves-Rodrigues et al. (2021a, 2021b) and Yildirim et al. (2016). Our results demonstrate the capacity of individuals with SCI to adapt to HVRT but also provide data which show that the principle of training specificity must also be observed in this population. If evidence points out that it is important to keep and to increase power, training protocols should then be designed to reach this objective.

Ginis et al. (2003) suggested that exercise is associated with improvements in physical self-concept, using psychological well-being and quality of life as indicators of perceived well-being. In a recent study (Santos et al. 2025), it was observed that TRT, FWRT, and HVRT positively influenced both physical and psychological well-being indicators in individuals with SCI. These findings highlight two important contributions to resistance training research for this population. First, investigating the effects of RT on strength manifestations may be a valuable approach to complement results obtained through self-reported questionnaires, as it enables the quantification of objective variables that potentially influence perceived outcomes. Second, the functional improvements resulting from RT may help modulate mental health responses and overall quality of life in people with SCI. This dual perspective

strengthens the rationale for incorporating targeted RT protocols into rehabilitation and long-term care strategies, aiming not only at physical enhancement but also at the psychological well-being of this population.

This study presents some limitations primarily related to the inherent heterogeneity of the population with SCI, which made it challenging to form homogeneous groups. Participants varied in trunk stability, upper limb function, and time since injury, reflecting the diverse clinical profiles commonly encountered in real-world settings. Due to these factors, participants were not randomly allocated to intervention groups; instead, group assignment was based on functional potential and injury level. Although this approach helped minimize group imbalances, the absence of randomization introduces a potential risk of selection bias, which may have influenced the results.

The lack of randomization in participant allocation represents a methodological limitation of this study, as it may introduce bias related to baseline group characteristics. This decision was driven by practical and ethical considerations inherent to the population with spinal cord injury, such as mobility constraints, program adherence, and clinical heterogeneity. Despite efforts to balance groups in terms of injury level and functional capacity, the sample still exhibited considerable variability in factors such as time since injury, trunk stability, and upper limb mobility, which may have influenced the outcomes. These limitations should be considered when interpreting the results and highlighting the need for future studies with larger, randomized samples to further strengthen the evidence regarding resistance training effects in individuals with spinal cord injury.

Conversely, this pragmatic allocation strategy enhances the external validity of the study, as it closely replicates how individualized interventions are typically prescribed in community-based rehabilitation settings. Practical limitations also affected intervention logistics, for example, the availability of only one flywheel machine limited opportunities for participant interaction during FWRT sessions, possibly affecting motivation and adherence. Additionally, although the functional agility test used in this study offered useful insights, future research should include adapted functional assessments involving directional changes, obstacle negotiation, and other task-specific elements that better reflect the functional demands of daily living for wheelchair users. Where feasible, future studies could also benefit from

using stratified allocation methods or statistical controls for baseline differences to further strengthen internal validity without compromising ecological relevance.

However, we must observe that this is the first study which applied three different types of RT with similar training protocols in people with SCI, providing a comparison between them. We also make a thorough evaluation of strength manifestations, basing our discussion in the dialogue with well-designed studies. A strong point of this study is having investigated not only physiological outcomes such as changes in strength but also, in conjunction with this, through agility testing, we sought to understand how different types of resistance training would influence important functional outcomes for individuals with spinal cord injury. Our research also seems to be the first to use a flywheel overload machine and the HVRT with this population, which we hope can motivate other researchers to further explore this method and improve the range of training methods available to individuals with SCI.

CONCLUSION

This study demonstrated that different resistance training modalities confer specific benefits depending on the physical attribute targeted. It is essential for professionals to consider the heterogeneity of spinal cord injury (SCI) including injury classification and environmental context — when designing training programs, as these factors influence functional limitations and rehabilitation needs.

Our findings highlight that flywheel resistance training (FWRT) significantly improves functional agility, a critical aspect of mobility and quality of life for individuals with SCI. Traditional resistance training (TRT) and high-velocity resistance training (HVRT) both enhanced isometric strength; however, HVRT was superior in increasing dynamic strength and muscle power, key components for functional independence and everyday activities.

These results underscore the clinical importance of a tailored approach to resistance training. Combining FWRT and HVRT could provide complementary neuromuscular adaptations, enhancing wheelchair maneuverability and rapid force generation—thus optimizing rehabilitation outcomes. Implementing individualized, evidence-based resistance training strategies can support greater autonomy and improve overall quality of life for people with SCI.

PRACTICAL APPLICATIONS

In line with these findings, it is important for professionals to understand the practical implications of each strength manifestation targeted by resistance training. Maximal voluntary isometric contraction (MVIC) plays a key role in daily activities such as repositioning the body, performing transfers, and preventing pressure injuries, making it highly relevant for individuals with limited trunk and upper limb control. Maximal dynamic strength (1RM) emerged as the most sensitive outcome across all training modalities and is considered a determinant of functional autonomy and an independent predictor of longevity. Meanwhile, muscle power (PWR) is the strength manifestation most strongly associated with functional capacity in both clinical and general populations. Improvements in PWR directly support actions like reaching, propelling a wheelchair quickly, or initiating transfers with speed and efficiency. Understanding these specific contributions allows rehabilitation professionals to tailor interventions not only to the injury profile but also to the physical demands and goals of each individual, ultimately enhancing functional outcomes and independence.

The results of this study provide valuable guidance for professionals involved in the rehabilitation and physical training of individuals with spinal cord injury (SCI), emphasizing the need for tailored exercise interventions based on specific functional goals.

Flywheel Resistance Training (FWRT) demonstrated significant improvements in functional agility, making it a promising tool for enhancing wheelchair maneuverability, change-of-direction ability, and general mobility in confined or obstacle-rich environments. This modality can be especially beneficial in rehabilitation settings aiming to promote community reintegration, where agility is essential for navigating public spaces, home layouts, or work environments. Professionals should consider incorporating FWRT when the focus is on improving dynamic motor control, deceleration ability, and eccentric strength, particularly in upper limb movements related to propulsion and balance correction.

High-Velocity Resistance Training (HVRT), by contrast, elicited the most robust gains in muscle power and dynamic strength, which are strongly associated with performance in essential daily activities such as transfers, reaching, and stabilization tasks. Its emphasis on rapid concentric actions supports neuromuscular

adaptations that improve the speed and efficiency of movement—crucial for increasing independence. HVRT is especially indicated when the clinical goal is to maximize explosive strength output, optimize reaction time, or support high-demand upper body tasks like lifting or positioning during bed-to-chair transfers. Professionals should prioritize HVRT protocols when aiming to enhance peak force production within short time frames, even when using moderate loads—an important feature for individuals with SCI who may have limited tolerance for high-intensity loading.

The integration of both FWRT and HVRT into rehabilitation programs allows for a complementary approach, where one modality targets agility and the other enhances power and rapid strength expression. The strategic use of each training type based on individual assessment can lead to more efficient progress, greater independence, and improved quality of life for people with SCI. Rehabilitation professionals are encouraged to move beyond general resistance training and adopt evidence-based, goal-specific methods aligned with the patient's injury profile, capabilities, and daily functional demands.

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CHAPTER II

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Flywheel Resistance Training Enhances Lean Mass and High-Velocity Training Prevents Fat Gain in Spinal Cord Injury: An Experimental Comparative Trial

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Study Design: Nonrandomized controlled trial

Objective: To compare the effects of Traditional Resistance Training (TRT), Flywheel Resistance Training (FWRT), and High-velocity Resistance Training (HVRT) on body composition and bone health in individuals with Spinal Cord Injury over an 8-week period.

Setting: Department of Physical Education, Federal University of Viçosa, Campus Viçosa, Viçosa, Minas Gerais, Brazil

Methods: Thirty-two adults were assigned to TRT, FWRT, or HVRT groups and trained twice weekly. Body composition was evaluated via DXA pre- and post-intervention. ANOVA was applied for intra- and inter-group comparisons ($p < 0.05$).

Results: FWRT led to significant Lean Mass gains (pre-33.33 kg ± 4.34, post-35.98kg ± 4.68, $p < 0.001$, $\eta^2 = 0.693$). TRT (pre- 2.25 ± 0.56, post- 2.28kg ± 0.56, $p < 0.001$, $\eta^2 = 0.879$) and FWRT (pre-1.90 kg ± 0.26, post- 1.97 ± 0.26, $p < 0.001$, $\eta^2 = 0.879$) showed Bone Mineral Content increases, but no reversal of osteopenia was observed. Fat Mass increased significantly in TRT (pre-22.84kg ± 5.68, post- 23.77kg ± 5.26, $p < 0.001$, $\eta^2 = 0.790$) and FWRT (pre-27.10kg ± 0.30, post- 28.98kg ± 1.45, $p < 0.001$, $\eta^2 = 0.790$), with TRT showing higher Fat Mass compared to HVRT post-training.

Conclusion: Only FWRT significantly increased lean mass, while both FWRT and TRT improved bone mineral content.

Keywords: resistance training; muscle power; paraplegia; strength training; rehabilitation; eccentric training, body composition

INTRODUCTION

Spinal cord injury (SCI) leads to persistent impairments in motor, sensory, and muscle function, accompanied by fatigue, muscle atrophy, and changes in fiber composition that compromise strength and body composition (BC). Upper limb asymmetries and age-related shoulder degeneration further restrict mobility, often contributing to anxiety and depression [1-3].

Hormonal and metabolic disturbances after SCI increase the risk of osteoporosis, obesity, cardiovascular disease, and type II diabetes. Early bone and muscle loss, combined with fat gain, frequently result in sarcopenic obesity. These alterations, compounded by inflammation, elevate cardiometabolic risk even in mild overweight. Exercise emerges as a safe and effective strategy to mitigate these complications and preserve independence [4].

SCI induces rapid and lasting BC changes, modulated by injury type and severity. Gorgey et al. [5] highlighted the early onset of these alterations and their association with metabolic disorders, while Singh et al. [6] demonstrated differences between paraplegic and tetraplegic individuals. The ASIA Impairment Scale also plays a key role in predicting and monitoring such outcomes [5-7].

Resistance training (RT) is a safe and effective strategy to improve body composition, strength, power, and upper limb function in individuals with SCI [8-10]. Among its modalities, flywheel (FWRT) and high-velocity resistance training (HVRT) have shown health benefits in other populations and may offer similar advantages for SCI. FWRT offers unique advantages through its combination of eccentric overload and concentric actions, leading to improved strength and power output with reduced energy expenditure. FWRT operates like a yo-yo mechanism, generating kinetic energy during the concentric phase and requiring individuals to resist the inertial force during the eccentric phase. Flywheel devices create inertial resistance through the unwinding of the flywheel’s strap during a concentric muscle action, followed by the rewinding of the strap, leading to an eccentric muscle action. Moreover, it facilitates the recruitment of high-threshold motor units and contributes to enhancements in muscle volume, cross section area, fascicle length, and tendon stiffness [11,12].

In addition, HVRT has been shown to enhance functional capacity, muscle thickness, power, and strength, with the notable advantage of achieving these

benefits through low to moderate training loads — a particularly relevant feature for individuals with SCI-related impairments [13-15]. Together with FWRT, which leverages eccentric overload, these modalities emerge as effective and accessible strategies that address both strength and functional outcomes in this population.

Despite the well-established role of TRT in SCI [4,10], FWRT and HVRT remain largely underexplored, even though their mechanistic advantages, such as eccentric overload and power development, are well documented. The scarcity of direct comparisons between RT modalities reinforces this gap, particularly concerning the effects of FWRT and HVRT on BC in individuals with SCI.

This gap in literature underscores the need to explore the potential of these modalities. To address it, the present study is the first to directly compare three types of RT — TRT, FWRT, and HVRT — in individuals with SCI. By examining their effects on BC, this research aims to advance understanding of the most effective strategies to improve physical health outcomes in this population.

METHODS

Experimental Approach to the Problem

This quasi-experimental study compared the effects of traditional resistance training (TRT), flywheel resistance training (FWRT), and high-velocity resistance training (HVRT) on body composition and bone health in individuals with SCI. TRT served as the active control due to its well-documented benefits and support for participant engagement.

Participants were recruited via community outreach and public agencies, forming a convenience sample. Group allocation was non-randomized but purposeful, balancing injury level and functional potential to address heterogeneity in SCI and logistical constraints (Fig 1). All training protocols followed established resistance training principles, ensuring progressive overload and intensity control.

Pre- and post-intervention assessments enabled within- and between-group analyses. Volunteers provided informed consent and received detailed explanations of procedures. Training protocols followed established resistance training principles, ensuring progressive overload and intensity control. Although randomization was not feasible, careful group allocation and monitoring were employed to enhance internal validity.

Subjects

Thirty-four individuals with clinically confirmed SCI (T4–L1) were enrolled (ages 28–65 years, mean 49 ± 11.8; body weight 64.6 ± 3.3 kg; time since injury 22 ± 17.3 years). Exclusion criteria included upper-limb musculoskeletal injuries in the previous year; other secondary conditions (e.g., hypertension, anxiety, depression) were not exclusionary. Participants were instructed to maintain their usual diet and avoid new exercise programs. Initial interviews assessed functional abilities, clarified study procedures, and confirmed SCI diagnosis. Group allocation was conducted by a researcher not involved in training or data collection to prevent bias. Ethical approval was obtained from the Federal University of Viçosa (approval 5.418.335).

During the planning phase, the research team extensively discussed inclusion and exclusion criteria, deciding that only upper-limb musculoskeletal injuries would be exclusionary, despite the frequent presence of secondary conditions in SCI such as hypertension, anxiety, depression, and mobility challenges. Given the variability of outcomes among individuals with similar SCI (e.g., spasticity or flaccidity), the lead researcher conducted initial interviews to assess each volunteer’s abilities and limitations, review informed consent, clarify study procedures and schedules, and collect documentation confirming the SCI diagnosis.

All volunteers had complete injuries between T4 and L1, resulting from firearm incidents or motor vehicle accidents. Due to the heterogeneity of their physical condition, random group allocation was not applied; instead, volunteers were distributed across groups to balance injury level, functional potential, and limitations, preventing overrepresentation of specific profiles. The researcher responsible for group allocation did not take part in data collection or training sessions and contributed solely to statistical analysis and interpretation of the results.

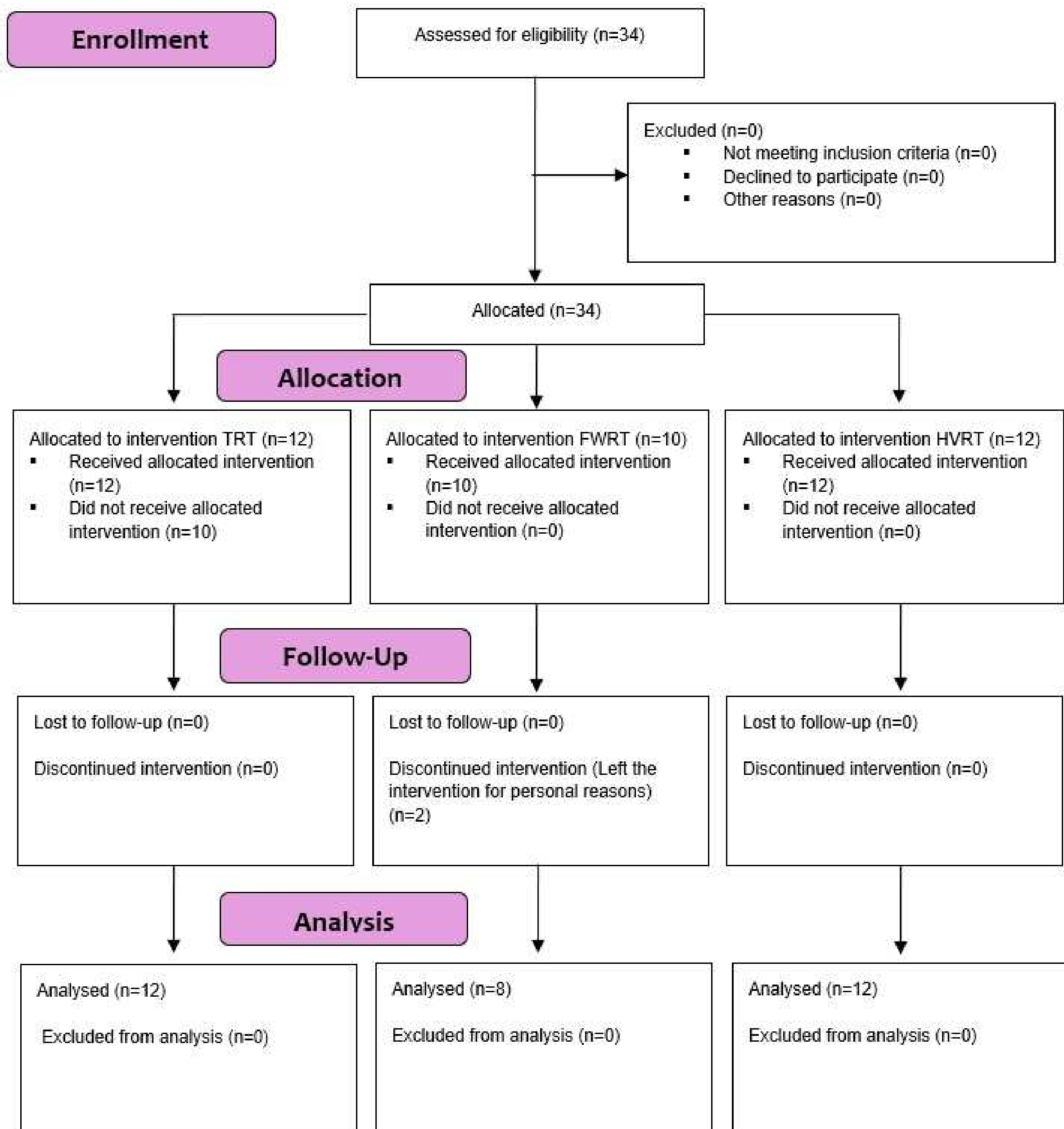

Figure 1: CONSORT flow diagram showing the progression of participants through the study phases: enrollment, allocation to Traditional Resistance Training (TRT), Flywheel Resistance Training (FWRT), and High-Velocity Resistance Training (HVRT), follow-up, and analysis.

Procedures

Training Protocols

Initially, thirty-four individuals with SCI were allocated into three intervention groups: TRT (n = 12), FWRT (n = 10), and HVRT; (n = 12). Both the FWRT and

HVRT groups were instructed to perform the concentric phase of each movement as rapidly as possible. In the FWRT group, participants were guided to follow the motion of the flywheel during the eccentric phase and to apply a braking force during the final third of that phase to maximize the eccentric overload generated by the inertia of the device. In contrast, the HVRT group performed the eccentric phase in a controlled manner, ensuring it did not exceed 2 seconds in duration. The TRT group executed both concentric and eccentric phases with a consistent 2-second tempo.

Training sessions were held twice weekly at the Department of Physical Education of the Federal University of Viçosa, under professional supervision. Session duration increased from 25 to 50 minutes over the 8 weeks. Training volume progressed from 2×10 to 4×12 repetitions (Fig 2), with high intensity confirmed by OMNI-RES scores between 7 and 9 and 1 minute rest between sets. Two warm-up sets were performed at 50% load. Exercises targeted upper-body functional muscles, adapted to individual capacities, and are detailed in Figure 3.

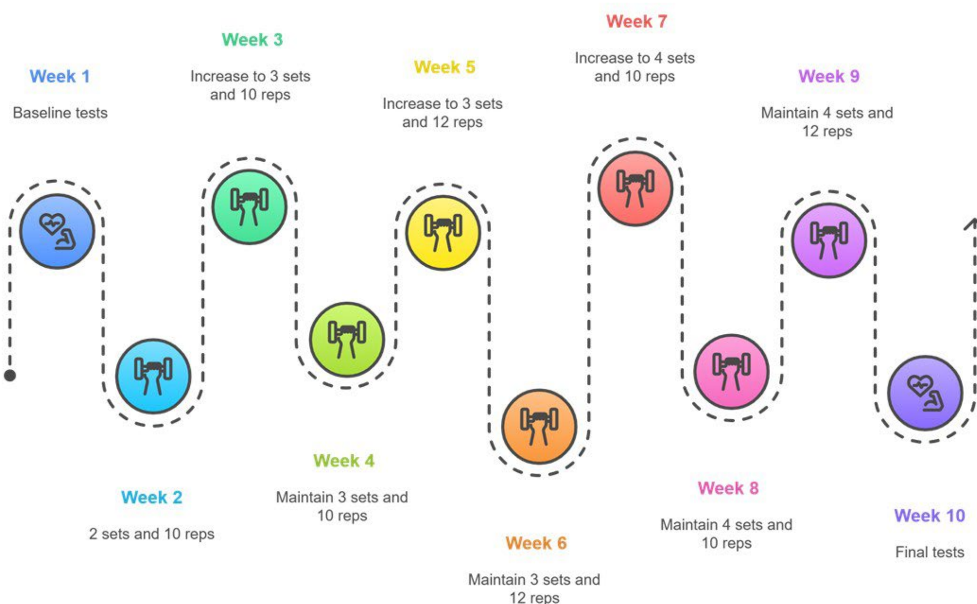

Figure 2: Schematic representation of the 10-week resistance training progression. The intervention included baseline and final assessments, with gradual increases in training volume (sets and repetitions) over time.

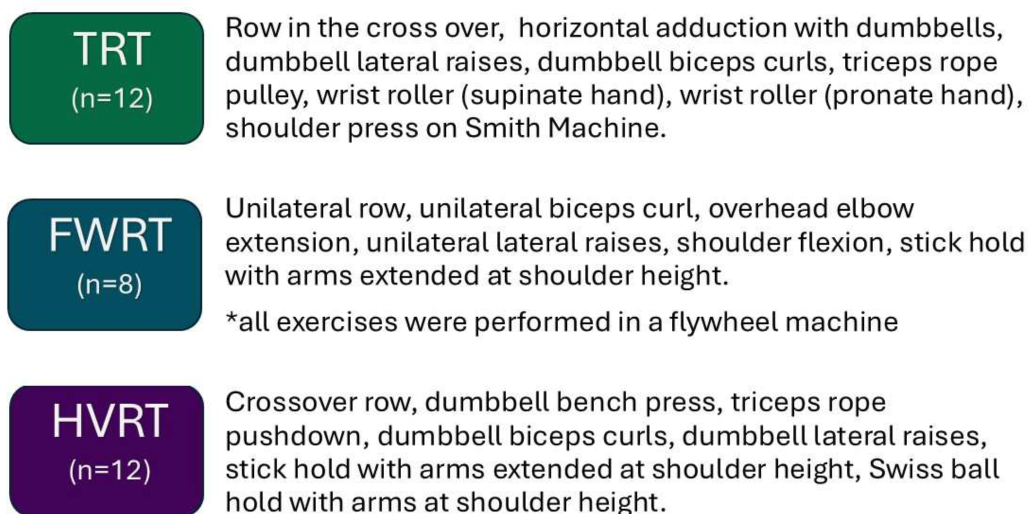

Figure 3: Exercises performed by participants in each experimental group: Traditional Resistance Training (TRT), Flywheel Resistance Training (FWRT), and High-Velocity Resistance Training (HVRT). The FWRT protocol was performed entirely using a flywheel device*.*

Body Composition

Body composition (BC) was assessed using a full-body GE Healthcare Lunar Prodigy Advance DXA System (software v13.31, Chicago, IL, USA) before and after the training periods. Variables included total body mass (BM), fat mass (FM), lean mass (LM), and bone mineral content (BMC). Individuals were positioned prone on the table, with upper limbs extended alongside the torso, hands pronated, and lower limbs stretched hip-width apart. They were instructed to remain as still as possible throughout the approximately 7-minute scan [16,17].

All scans were conducted by a trained technician following standardized procedures. After each scan, images were checked for correct alignment and absence of movement artifacts; any deviations were noted, and the scan was repeated if necessary. The resulting data provided a detailed assessment of BC variables, which were then used to evaluate the effects of the training interventions.

Statistical Analysis

Descriptive statistics summarized the dataset, and normality was assessed using the Shapiro–Wilk test. Logarithmic (base 10) transformations were applied when normality was violated. Homogeneity of variances was verified with Box's M test. Baseline group comparisons used one-way ANOVA with Bonferroni post hoc tests. Intervention effects over time were analyzed via two-way repeated measures ANOVA ("time" × "group"), with partial eta squared (η^2) calculated for effect sizes (small <0.01, medium 0.02–0.06, large >0.14) [18]. Significance was set at $p < 0.05$, and statistical power ≥80% was considered acceptable. Analyses were conducted in SPSS v21.0.

Clinical relevance of lean mass changes was estimated using the minimal clinically important difference (MCID), calculated as 0.2 × baseline standard deviation, following Cohen's approach [19]. For the FWRT group, this corresponded to 0.87 kg (0.2 × 4.34 kg), serving as a reference to interpret meaningful improvements alongside statistical significance.

RESULTS

In the pre-intervention data analysis of BC, the TRT group showed a significant difference in FM compared to HVRT and in BMC compared to FWRT. In the Z-score assessment, TRT was significantly lower than FWRT, while FWRT was significantly higher compared to HVRT. During the interventions, there were no adverse events or injuries related to the training protocols. It should be noted that two volunteers from the FWRT group discontinued their participation during the intervention period, one in the second week and the other in the third week. One individual moved to another city and was therefore unable to continue the training. The second volunteer did not respond to repeated contact attempts by the research team, and the reason for withdrawal could not be determined. All remaining participants met the research´s criterion of ≥80% session attendance for inclusion in the data analysis. Therefore, the analysis was performed based on the following groups: TRT (n = 12), FWRT (n = 8), and HVRT (n = 12).

Figure 1 provides the results of BC and bone health before and after the 8-week training period. BM remained unchanged, while other parameters showed significant modifications.

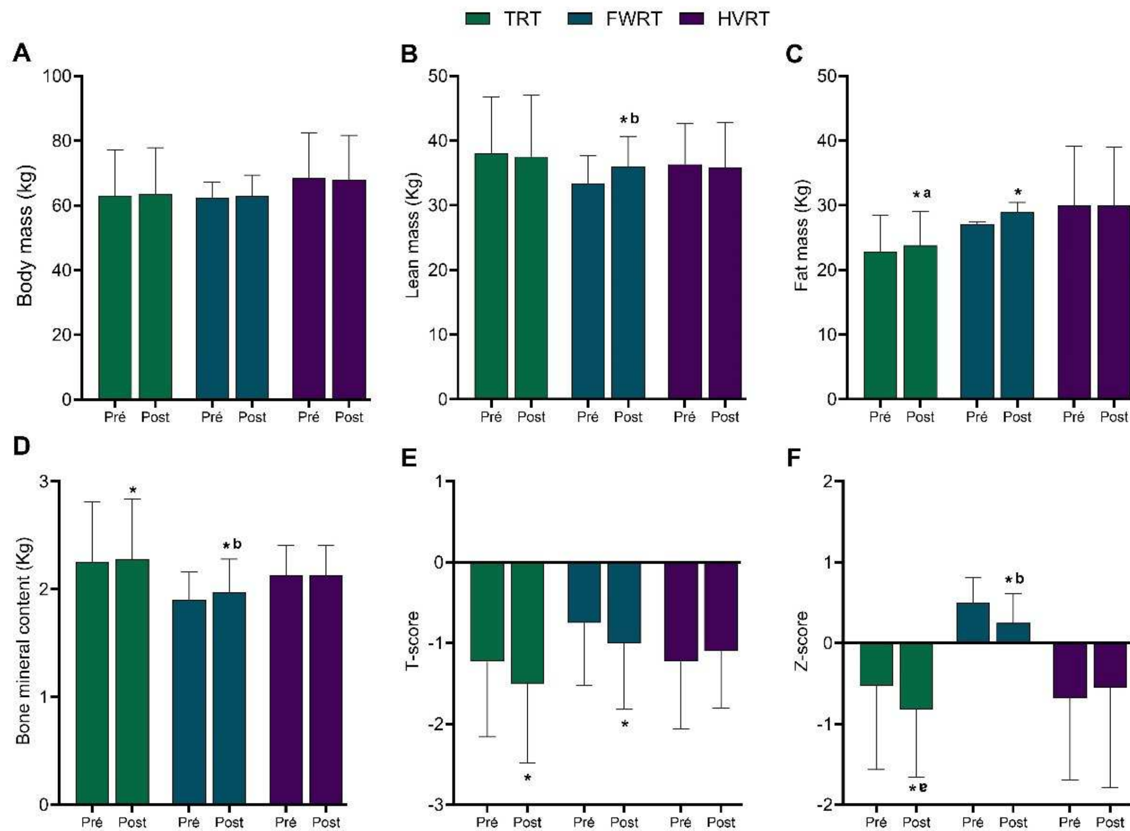

Figure 4: (**A**) Body Mass; (**B**) LM: Lean Mass; (**C**) FM: Fat Mass; (**D)** BMC: Bone Mineral Content; (**E**) T-Score; (**F**) Z-Score; (**TRT**) traditional resistance training; (**FWRT**) Flywheel resistance training; (**HVRT**) high-velocity resistance training. ***** $p < 0.05$ vs. post-intervention; **a** $p < 0.05$ vs. FWRT; **b** $p < 0.05$ vs. HVRT.

Within-group changes (pre vs. post):

LM increased significantly in the FWRT group from baseline to post-intervention (pre 33.33 ± 4.34 kg; post 35.98 ± 4.68 kg, $p < 0.001$, $\eta^2 = 0.693$). FM increased significantly in both TRT (pre 22.84 ± 5.68 kg; post 23.77 ± 5.26 kg, $p < 0.001$, $\eta^2 = 0.790$) and FWRT (pre 27.10 ± 0.30 kg; post 28.98 ± 1.45 kg, $p < 0.001$, $\eta^2 = 0.790$). BMC also improved significantly in TRT (pre 2.25 ± 0.56 kg; post 2.28 ± 0.56 kg, $p < 0.001$, $\eta^2 = 0.879$) and FWRT (pre 1.90 ± 0.26 kg; post 1.97 ± 0.31 kg, $p < 0.001$, $\eta^2 = 0.879$). For bone density indices, both TRT (pre -1.23 ± 0.93; post -1.50 ± 0.98, $p = 0.001$, $\eta^2 = 0.503$) and FWRT (pre -0.75 ± 0.77; post -1.00 ± 0.82, p =

0.001, $\eta^2 = 0.503$) showed reductions in T-score, while significant reductions in Z-score were observed in TRT (pre -0.53 ± 1.03; post -0.82 ± 0.84, $p = 0.003$, $\eta^2 = 0.452$) and FWRT (pre 0.50 ± 0.31; post 0.25 ± 0.36, $p = 0.003$, $\eta^2 = 0.452$).

Between group comparisons:

Post-intervention, FWRT showed significantly greater LM compared with HVRT ($p = 0.016$, $\eta^2 = 0.446$). FM increased more in FWRT than in TRT ($p = 0.013$, $\eta^2 = 0.464$). FWRT also presented greater improvements in BMC when compared with HVRT ($p = 0.018$, $\eta^2 = 0.439$). Regarding bone density, TRT showed a larger reduction in Z-score than FWRT ($p = 0.019$, $\eta^2 = 0.432$), while FWRT exhibited a greater Z-score reduction compared with HVRT ($p = 0.019$, $\eta^2 = 0.432$).

DISCUSSION

The purpose of this research is to investigate the effects of FWRT and HVRT on BC and bone content of people with SCI in comparison with TRT´s effects on these aspects. After 8 weeks of RT was possible to observe that: no changes in BM were detected, although significant modifications occurred in other BC variables. FWRT induced significant increases in LM both pre-to-post and compared with HVRT. FM increased in TRT and HVRT groups over baseline, with TRT showing a greater increase than FWRT. BMC improved significantly in TRT and FWRT, with FWRT also exceeding HVRT. Both TRT and FWRT showed significant pre-to-post reductions in T-score and Z-score. In intergroup comparisons, TRT exhibited a larger Z-score reduction than FWRT, which in turn showed a greater reduction compared with HVRT.

FWRT induced a significant increase in lean mass ($\Delta = 2.65$ kg; $p < 0.001$, $\eta^2 = 0.693$). Considering the minimal clinically important difference (MCID), this gain was not only statistically significant but also clinically meaningful, highlighting the potential of FWRT to effectively increase muscle mass in individuals with SCI.

As current evidence suggests, individuals with SCI tend to experience muscle atrophy and bone mass loss over the years [4] . The literature on the effects of RT in people with SCI is scarce, and well-designed studies on this topic are difficult to find. Few studies have evaluated the effects of RT on LM in individuals with SCI in recent

years. Two randomized controlled trials demonstrated benefits in BC following RT interventions. Serra-Año et al. [20] observed significant improvements in arm fat-free mass and reductions in arm fat mass using DXA evaluation after a RT program that combined isometric and concentric contractions. Mogharnasi et al. [9] found significant reductions in body mass index, body fat percentage, and waist-hip ratio after an 8-week progressive RT program in terms of volume and intensity. In this case, body fat percentage was predicted with a 4-site skinfold protocol. However, methodological differences in BC assessments limit direct comparisons between studies. Still, the findings highlight the potential of resistance training to improve BC and underscore its relevance in addressing muscle atrophy and fat accumulation in individuals with SCI.

SCI is commonly associated with a marked reduction in LM, and its recovery plays a crucial role in both physical and mental health due to its direct impact on functional capacity. Our findings indicate that FWRT was the only resistance training modality capable of eliciting significant increases in LM. Therefore, it should be considered as an effective strategy for improving BC and promoting lean mass gains in individuals with SCI, while also expanding the range of training stimuli available to this population.

Although TRT and HVRT did not lead to measurable increases, both were also effective in maintaining lean mass throughout the intervention period. In two recent studies, Rodrigues et al. [21,22] also found using DXA assessments that both high-intensity resistance training and circuit resistance training (CRT) were able to maintain BC after the training period in individuals with SCI. Given the muscle atrophy commonly experienced by individuals with SCI, the preservation of lean mass can, and should, be understood as a prominent outcome, even in the absence of statistical significance. This is important because frail populations need to improve their training methods and protocols, and a wider variety of RT types can be useful in maintaining an active lifestyle.

Regarding FM, our results indicate that only HVRT was effective in preventing significant increases after the training period. When comparing these results with previous studies [9,20,21,22], it was observed that neither TRT nor FWRT were able to control the deterioration in this BC variable. An uncontrolled diet represents a study limitation, and future research should monitor volunteer´s caloric intake.

SCI causes paralysis and a specific form of neurogenic disuse osteoporosis, significantly increasing the risk of fractures in the distal femur and proximal tibia. This bone loss occurs due to increased bone resorption and almost absent bone formation during the acute post-injury recovery phase. In more chronic phases, high-turnover osteopenia emerges, influenced by continuous neural impairment and musculoskeletal unloading [23].

Bone health was assessed by measuring bone mineral content (BMC, kg) and bone mineral density (BMD), utilizing T-scores and Z-scores for evaluation. T-scores are calculated by taking the difference between a patient's measured BMD and the average BMD of healthy young adults, matched by gender and ethnic group, and expressing the difference relative to the standard deviation of the young adult population. Z-scores are similar to T scores, except that instead of comparing the patient's BMD with the average BMD of young adults, it is compared with the expected average BMD for the patient's peers (e.g., for a healthy subject matched by age, gender, and ethnic group) [24]. The participants in this study were classified as having osteopenia (T-Score); however, this condition is expected since spinal cord injury causes an unfavorable balance between bone formation and resorption [25].

In evaluating the effects of three types of RT on the bone health of people with SCI, we observed that despite the increase in BMC in the TRT and FWRT groups and the maintenance of this variable in HVRT, none of the groups showed a reversal of the osteopenia (T-score) observed pre-intervention. Our results are consistent with a recent study [22] where people with spinal cord injuries and osteopenia underwent high-intensity resistance training, and the training period was not able to reverse the bone mineral density loss. Alternatively, unlike our results, it was able to maintain bone mineral density without significant losses. In a previous study, Rodrigues et al. [21] observed that CRT was not able to reverse osteopenia but, alternatively, also prevented significant BMD losses, unlike our results for TRT and FWRT but similar to HVRT.

An important question is why the observed increases in BMC did not lead to a reversal of osteopenia. One possible explanation is that the three RT modalities applied in this study induced only localized adaptations in bone, limited to the trunk and upper limbs, without generating systemic effects. Another factor is that DXA-based assessments of T- and Z-scores are not specifically validated for individuals with SCI, which may compromise the accuracy of bone health interpretation.

Previous evidence shows that BMD and BMC loss is more pronounced in regions below the level of injury, with severity depending on the type and level of SCI [23,26].

In this context, FWRT's eccentric overload may enhance mechanotransduction pathways, such as mTOR activation and osteocyte signaling, potentially explaining its superior improvements in LM and BMC. However, the lack of lower limb loading likely limit systemic bone adaptation. Taken together, these findings underscore the need for interventions and assessment criteria tailored to individuals with SCI, as well as strategies specifically designed to stimulate bone formation below the injury level.

This study has several limitations due to the challenges of assembling a homogeneous group of individuals with SCI. Variability in time since injury, trunk stability, upper limb function, and medication use complicated group comparisons. Participants were allocated based on injury level and functional potential rather than randomized, which may introduce selection bias. While this approach helped balance the groups, substantial residual variability remained, potentially obscuring intervention effects. Additionally, the small sample size and the loss of two volunteers reduced the statistical power of the study. These limitations reflect the ethical and practical challenges of conducting research in the SCI population, including mobility restrictions, diverse clinical presentations, and adherence issues. Future trials should consider stratifying participants according to these factors to minimize heterogeneity and enhance interpretability of the results.

This pragmatic allocation strategy enhances the study's external validity by reflecting the individualized nature of interventions in real-world, community-based rehabilitation. However, a logistical limitation arose as FWRT sessions used a single flywheel device, restricting participant interaction and potentially affecting motivation. While this approach preserves ecological relevance, it underscores the challenge of balancing internal and external validity. Future studies should consider stratified allocation or statistical adjustments to control baseline differences, and use larger, randomized samples to strengthen evidence on resistance training effects in individuals with SCI.

A key strength of this study is the use of DXA, a gold-standard method for BC assessment, with all evaluations conducted by an experienced examiner to ensure accuracy. This is the first study to implement both FWRT and HVRT in individuals with SCI, providing preliminary evidence to inform future research. Given the novelty

of these interventions, further studies are needed to confirm these findings and support evidence-based training recommendations for this population.

In conclusion, after 8 weeks, FWRT was the most effective modality for increasing lean mass and bone mineral content in individuals with SCI, while HVRT helped prevent fat mass gain. Although no resistance training reversed osteopenia, FWRT produced clinically meaningful improvements, and the preservation of lean mass with TRT and HVRT remains relevant. These findings support FWRT and HVRT as viable complements to TRT in SCI rehabilitation. Future studies with larger samples and dietary control are needed to confirm and expand these results.

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CHAPTER III

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Comparative Effects of Resistance Training Modalities on Mental Health and Quality of Life in Individuals with Spinal Cord Injury

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Abstract: Background: Anxiety and depression are prevalent after spinal cord injury, impairing social participation and quality of life. Objective: This study aimed to investigate the effects of traditional resistance training (TRT), flywheel resistance training (FWRT), and high-velocity resistance training (HVRT) on the mental health and quality of life in individuals with spinal cord injury. Methods: Thirty-two participants were divided into TRT (n=12), FWRT (n=8), and HVRT (n=12) groups, undergoing 8 weeks of upper-limb training twice weekly under super-vision. Training intensity and volume were progressively increased. The Hospital Anxiety and Depression Scale and SF-36 Questionnaire were used to assess outcomes. Results: Both the TRT and FWRT groups showed a reduction in HADS-D scores post-intervention ($p < 0.001$). The TRT group also presented a significant reduction in HADS-A scores post-intervention ($p = 0.003$). Concerning quality of life, after training, TRT showed improvements in social functioning ($p = 0.013$), FWRT improved scores in physical functioning ($p = 0.002$), bodily pain ($p = 0.002$), vitality ($p = 0.046$), and role emotional ($p < 0.001$), while HVRT enhanced role physical ($p < 0.001$), social functioning ($p = 0.013$), and role emotional ($p < 0.001$). Conclusion: Overall, TRT was the most effective in reducing anxiety and depression and enhancing quality of life, while FWRT showed notable gains in physical and functional capacity. HVRT demonstrated improvements primarily in role physical but was less effective in other domains.

Keywords: functional capacity; paraplegia; eccentric resistance training; power training; quality of life

1. Introduction

Spinal cord injury profoundly affects multiple aspects of health, directly impacting the quality of life of those affected [1–3]. Spinal cord injury is associated with a range of acute and chronic impairments, including pain, motor dysfunction, sensory deficits, muscle dystonia, fatigue, atrophy, and alterations in muscle fiber composition. These physical changes often lead to reduced strength, deteriorated body composition, and gradual declines in both functionality and independence, highlighting the extensive long-term challenges faced by individuals with spinal cord injury [4–6]. In a recent study, Lee et al. [7] found that functionality losses were associated with psychological issues like anxiety, depression, sleep disorders, and suicide risk. Functional deficits also influence community participation and employment, which also might lead to mental health disorders [8–10].

Evidence suggests that, compared with able-bodied individuals, people with spinal cord injury are more likely to experience anxiety and depression. Approximately 22% of people with spinal cord injury are estimated to experience anxiety, while depression affects around 30% of this population [10]. Furthermore, the research shows that anxiety and depression can affect both paraplegic and tetraplegic individuals similarly, with injury severity or physical limitations not being the primary factors in the development of psychological disorders after spinal cord injury [11,12].

Physical exercise plays a valuable role in recovery strategies and treatments aimed at improving functionality and independence in daily activities, fostering autonomy, and preventing secondary complications. Resistance training stands out as an effective and reliable approach that not only enhances body composition and strength but also has positive effects on the mental health of individuals with spinal cord injury [4,13–15]. Additionally, active exercise induces both peripheral and central effects, promoting neuroplasticity, the release of brain-derived neurotrophic factors, pain modulation, and the normalization of GABA–glutamate neurotransmission, which are mechanisms associated with improvements in physical and mental health [16,17]. These effects highlight the potential of exercise to address both functional and psychological challenges in individuals with spinal cord injury.

Among resistance training methods, two are particularly beneficial for individuals with spinal cord injury: flywheel resistance training (FWRT) and high-

velocity resistance training (HVRT). FWRT offers unique advantages by combining eccentric overload with concentric actions, leading to improved strength and power output with lower energy demands. This method also supports high-threshold motor unit recruitment and contributes to increases in muscle mass, fascicle length, and tendon strength [18–20]. This aligns with the findings of Stone et al. [21], who demonstrated that eccentric resistance training in individuals with incomplete spinal cord injuries, performed twice weekly over 12 weeks, was effective in improving both eccentric and isometric strength.

Equally, HVRT has shown significant improvements in functional capacity, muscle strength, and power, with these benefits achieved through low-to-moderate training loads—an important advantage for individuals with spinal cord injury-related limitations [22,23]. Recently, a study conducted by Rodrigues et al. [14] demonstrated that high-intensity resistance training with progressive volume, performed twice weekly over 12 weeks, can improve or maintain body composition, enhance upper limb muscle power, anaerobic power, and explosive strength. These improvements positively impact functional capacity, promoting greater autonomy and reflecting improvements in the mental state and quality of life for individuals with spinal cord injury. These results highlight the potential of FWRT and HVRT as effective and accessible training methods for individuals with spinal cord injury, targeting both strength and functionality with notable efficiency. However, the impacts of resistance training modalities may vary based on the severity of spinal cord injuries and individual specific factors.

Although the benefits of FWRT and HVRT are well documented compared with traditional resistance training (TRT) or other forms of RT, a knowledge gap remains regarding their specific effects on individuals with spinal cord injury. Therefore, this study aims to compare the effects of TRT, FWRT, and HVRT on mental health (anxiety and depression) and quality of life. We hypothesize that all three training modalities will lead to improvements in mental health and quality of life in individuals with spinal cord injury.

2. Materials and Methods

2.1. Experimental Approach to the Problem

This experiment aimed to compare the effects of TRT, FWRT, and HVRT on mental health and quality of life outcomes in people with spinal cord injury. Given TRT's established effectiveness in this population, it was used as a control group to encourage participant engagement and facilitate attendance during initial and final evaluations. This approach also addressed the unique mobility and adherence challenges faced by the spinal cord injury population. Training protocols followed principles designed to sustain intensity and gradually increase training volume, optimizing the training load throughout this study. Participants were fully briefed on this study's procedures, with opportunities provided to address questions individually or in group settings.

2.2. Subjects

The sample consisted of 34 individuals familiar with the university's programs for people with disabilities, alongside additional participants recruited through a partnership with the city hall. Inclusion criteria required a clinically confirmed spinal cord injury, no upper limb musculoskeletal injuries within the past year, no prior RT experience, and a commitment to attend at least 80% of sessions without beginning other exercise programs. Participants were also asked to maintain their regular diets. Participants' ages ranged from 28 to 65 years (49 ± 11.78), with time since injury averaging 22 ± 17.32 years, and an average weight of 64.62 ± 3.33 kg (Figure 1).

Throughout this study's conception, potential inclusion and exclusion criteria and their possible impacts on the results were widely discussed. However, it is well known that individuals with spinal cord injury may develop various secondary effects, such as hypertension, anxiety, and depression. Additionally, these individuals face significant mobility challenges, which represent a major exclusion factor. For this reason, it was decided that only musculoskeletal injuries in the upper limbs would constitute grounds for volunteer exclusion.

Spinal cord injuries are highly unpredictable, as two similar injuries can lead to distinct sequelae, such as muscle rigidity or flaccidity. Considering these characteristics, the lead researcher responsible for the initial contact with the volunteers conducted an interview to better understand each individual's potential and limitations. After all interviews were completed, it was determined that grouping participants based on injury level would be sufficient to minimize biases in the results.

During the initial contact between the volunteers and the researcher responsible for group allocation, a brief interview was conducted, during which the informed consent form was presented, and any questions regarding the assessments, training period, and other relevant details were clarified.

At this stage, the researcher collected documents confirming the spinal cord injury and discussed each volunteer's limitations and potential abilities. All participants had complete injuries resulting from firearm wounds or automobile accidents. Furthermore, the researcher observed that the volunteers had traumatic spinal cord injuries at different levels, with lesion sites ranging from T4 to L1 vertebrae.

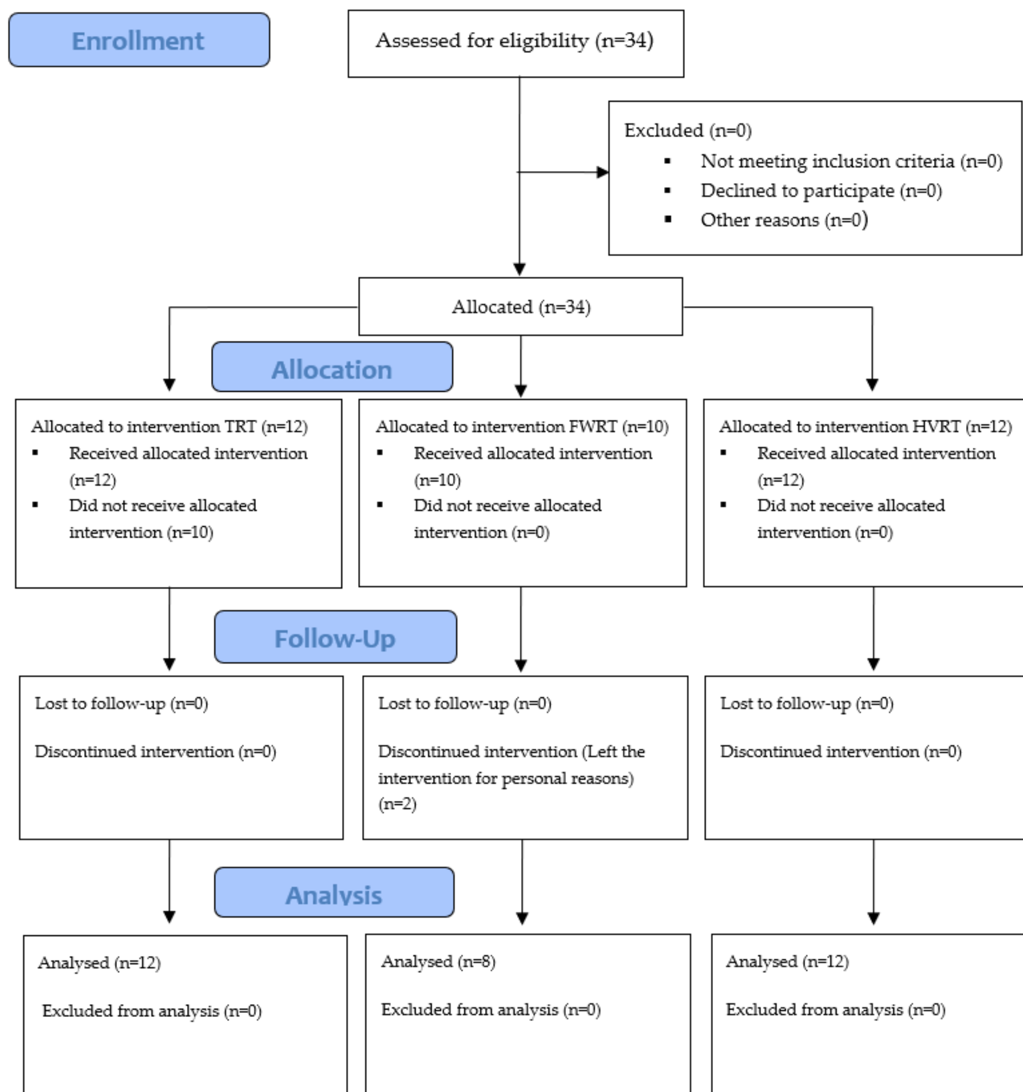


Figure 1. Study trial design. Overview of volunteer group allocation and dropout information. Flywheel resistance training (FWRT), high-velocity resistance training (HVRT), traditional resistance training (TRT).

2.3. Procedures

2.3.1. Training Protocols

Thirty-four participants were divided into three groups: TRT (n = 12), FWRT (n = 10), and HVRT (n = 12). In the FWRT and HVRT groups, the focus was on executing the concentric phase of each movement as quickly as possible. FWRT participants followed the machine's motion during the eccentric phase and braked in the last third to maximize eccentric overload benefits from the inertial flywheel machine (multi-leg isoinertial, Physical Solutions, São Paulo, Brazil). HVRT participants performed the eccentric phase in a controlled manner, not exceeding 2 s. TRT participants maintained a 2 s duration for both concentric and eccentric phases. The training period lasted eight weeks, with two sessions per week, progressively increasing in duration from 25 to 50 min from the first to the last week. Each session included two warm-up sets with a light load (50% of the training load). The training volume ranged from 2 sets of 8 repetitions to 4 sets of 12 (see Figure 2), and the training sessions focused on exercises for the functional upper body muscles and specific individual needs. Individual adjustments varied from researcher assistance in securing the wheelchair in the appropriate position to the use of bars with different diameters to facilitate grip during exercise execution and straps to stabilize the participant's torso against the wheelchair backrest. Accordingly, all three groups performed exercises targeting the back, pectoralis major, deltoids, biceps, triceps, forearms, and core muscles. All participants performed the same exercises in the same sequence, with minor adjustments to enhance their safety and comfort. Training intensity was monitored using the OMNI-RES scale (1 to 10), with perceived exertion maintained between 7 and 9, and a 1 min rest was allowed between sets. All sessions and evaluations took place in the Department of Physical Education at the Federal University of Viçosa.

Weekly Schedule and Volume Training Progression

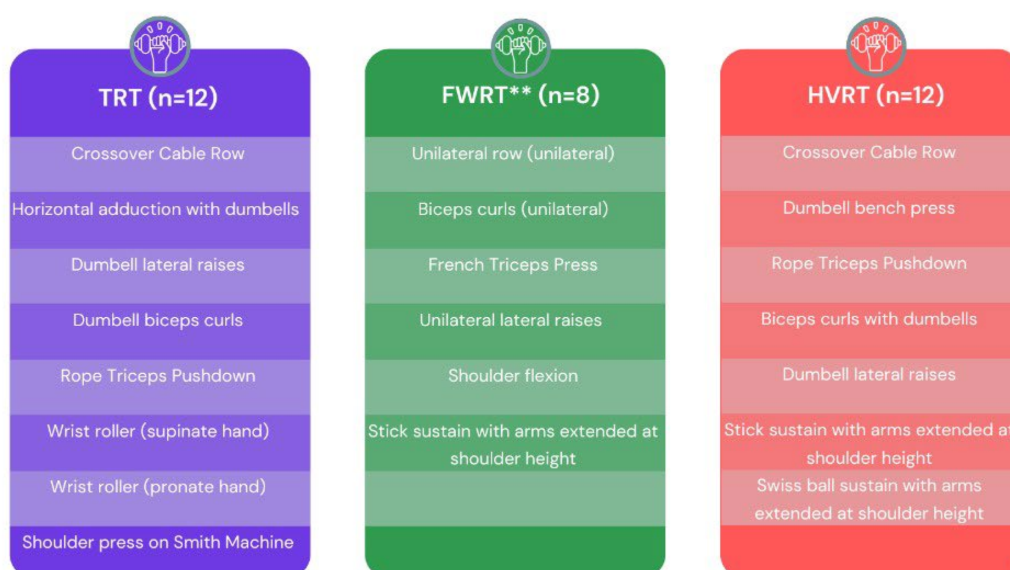
	WEEKS									
	1	2	3	4	5	6	7	8	9	10
Sets	Tests	2	3	3	3	3	4	4	4	Tests
Reps		10	10	10	12	12	10	10	12	

Training Protocols

The volunteers in each group performed the same sequence of exercises with minor individual adjustments* to ensure their safety and comfort.

The specific warm-up for each training session consisted of 2 sets of the first exercise with a light load (50% 1RM).

Training Sessions Exercises



* Individual adjustments varied from researcher assistance in securing the wheelchair in the appropriate position to the use of bars with different diameters to facilitate grip during exercise execution and straps to stabilize the participants' torso against the wheelchair backrest

** All exercises were performed on a Flywheel machine.

Figure 2. Description of the exercises performed by each group and weekly training volume throughout the intervention**.**

2.3.2. Mental Health and Quality of Life Assessment

For the assessment of mental health and quality of life, two questionnaires were administered. The Hospital Anxiety and Depression Scale (HADS) was used specifically to measure symptoms of anxiety and depression, in its Brazilian validated version [24]. This scale includes 14 multiple-choice items divided into 2 subscales, 1 for anxiety and 1 for depression, each containing 7 items scored from 0 to 3. The

total score for each subscale ranges from 0 to 21, with a cutoff score of ≥8 indicating possible anxiety or depression. Designed for use in non-psychiatric settings, HADS is a brief user-friendly tool, allowing patients to respond based on their experiences over the previous week. In addition to HADS, the SF-36 questionnaire was administered to evaluate quality of life across eight domains. This instrument is based on a thorough review of previous tools and is designed to capture changes in health, functional limitations, and social factors. Scores on SF-36 range from 0 to 100, with higher scores indicating a better quality of life [25]. Together, HADS and SF-36 provide a comprehensive assessment of mental health and quality of life, reflecting both emotional well-being and functional status.

2.4. Statistics

For the statistical analysis, descriptive statistics were initially applied to summarize the data. The Shapiro–Wilk test assessed data normality, and for variables that did not meet the normality assumption, a log transformation (base 10) was applied to normalize the data, allowing for the consistent use of parametric tests across all analyses. Box's M test was used to evaluate the homogeneity of variances. Group comparisons at baseline were conducted with a one-way analysis of variance (ANOVA), followed by Bonferroni post hoc analysis. To examine intra- and intergroup differences over time, a two-way repeated measures ANOVA was used, incorporating two factors: time (pre- and post-intervention) and condition (comparing TRT, FWRT, and HVRT groups). A significance level of $p < 0.05$ was established for all tests. Analyses were performed using SPSS software, version 21.0.

3. Results

3.1. Mental Health

The TRT and FWRT groups showed a reduction in HADS-D (Figure 3A) values at the post-intervention time point compared with the pre-intervention time point ($p < 0.001$; $\eta^2 = 0.776$; $\beta = 1.00$). Specifically, the TRT group also exhibited a reduction in HADS-A (Figure 3B) values at the post-intervention time point compared with the pre-intervention time point ($p = 0.003$; $\eta^2 = 0.517$; $\beta = 0.931$). Furthermore, in the comparison between groups at the post-intervention time point, it was observed

that the TRT group had lower HADS-A values compared with the FWRT and HVRT groups ($p < 0.001$; $\eta^2 = 0.720$; $\beta = 0.995$), indicating a moderate to large effect.

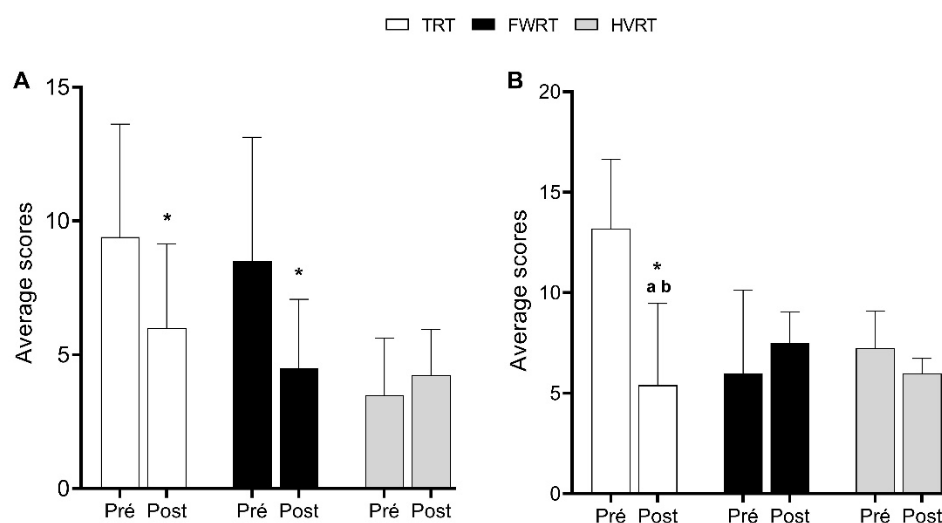


Figure 3. Hospital Anxiety and Depression Scale (HADS). (**A**) Depression (HADS-D). (**B**) Anxiety (HADS-A). Data are presented as means ± standard deviation. * $p < 0.05$ vs. post intervention; ^{a} $p < 0.05$ vs. FWRT; ^{b} $p < 0.05$ vs. HVRT. Two-way repeated measures ANOVA followed by Bonferroni post hoc analysis.

3.2. Quality of Life

Figure 2 presents quality of life data, with results indicating changes across various assessed domains. In the domain of physical functioning (Figure 4A), the FWRT group showed higher values after the intervention compared with the pre-intervention time point ($p = 0.002$; $\eta^2 = 0.500$; $\beta = 0.951$), although no differences were observed between groups at the post-intervention time point ($p = 0.306$; $\eta^2 = 0.155$; $\beta = 0.234$). For role physical (Figure 4B), the FWRT group showed higher values after the intervention ($p < 0.001$; $\eta^2 = 0.721$; $\beta = 1.00$) and also compared with the TRT and FWRT groups ($p < 0.001$; $\eta^2 = 0.893$; $\beta = 1.00$). In the bodily pain domain (Figure 4C), the FWRT group showed higher values, while the HVRT group showed lower values after the intervention ($p = 0.002$; $\eta^2 = 0.500$; $\beta = 0.951$). Additionally, the FWRT group presented higher values at the post-intervention time point compared with the HVRT group ($p = 0.001$; $\eta^2 = 0.622$; $\beta = 0.977$).

For general health (Figure 4D), no changes were observed over time or between groups ($p = 0.958$; $\eta^2 = 0.000$; $\beta = 0.050$ and $p = 0.248$; $\eta^2 = 0.180$; $\beta = 0.273$, respectively). In the vitality domain (Figure 4E), the FWRT group showed

higher values after the intervention compared with the pre-intervention time point (p = 0.046; η^2 = 0.240; β = 0.530) and lower values compared with the HVRT group (p = 0.047; η^2 = 0.355; β = 0.598). For social functioning (Figure 4F), the TRT and HVRT groups showed higher values after the intervention (p = 0.013; η^2 = 0.347; β = 0.752). Between groups, the FWRT group showed lower values compared with the TRT and HVRT groups (p = 0.008; η^2 = 0.501; β = 0.861).

In the role emotional domain (Figure 4G), the FWRT and HVRT groups showed higher values after the intervention (p < 0.001; η^2 = 0.582; β = 0.989). Additionally, the TRT group showed lower values at the post-intervention time point compared with the FWRT and HVRT groups (p = 0.004; η^2 = 0.427; β = 0.877). Finally, in the mental health domain (Figure 4H), no changes were observed over time or between groups (p = 0.979; η^2 = 0.000; β = 0.050 and p = 0.138; η^2 = 0.124; β = 0.400, respectively).

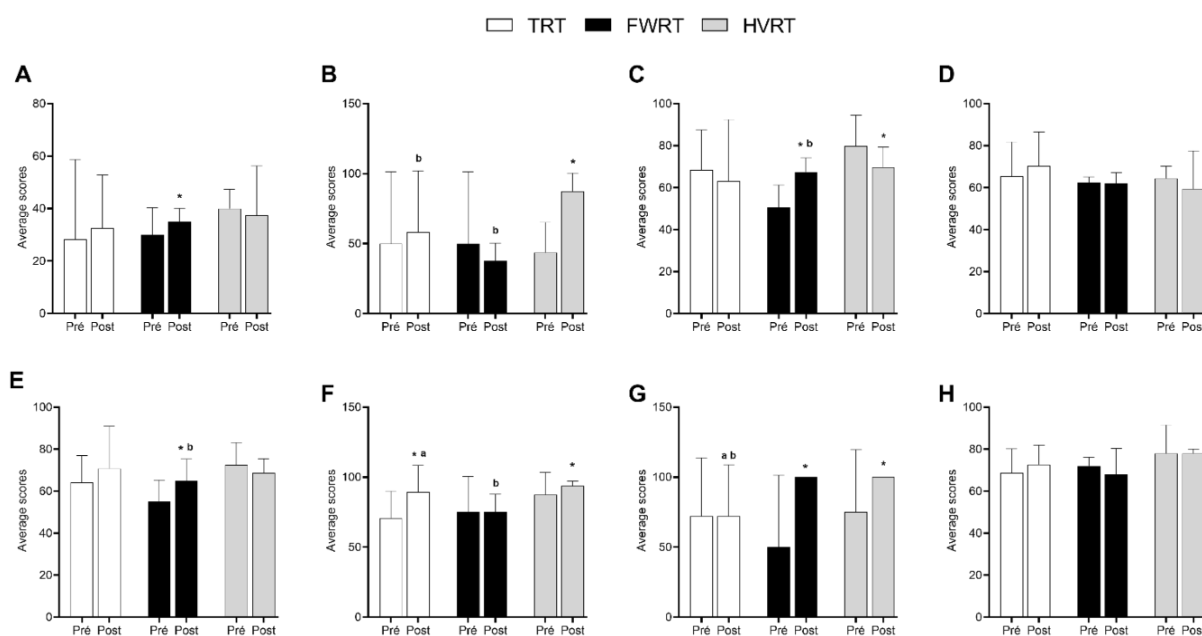


Figure 4. SF-36 health questionnaire. (**A**) Physical functioning; (**B**) role physical; (**C**) bodily pain; (**D**) general health; (**E**) vitality; (**F**) social functioning; (**G**) role emotional; (**H**) mental health. Data are presented as means ± standard deviation. * $p < 0.05$ vs. post-intervention; a $p < 0.05$ vs. FWRT; [b] $p < 0.05$ vs. HVRT. Two-way repeated measures ANOVA followed by Bonferroni post hoc analysis.

No adverse effects related to the training were reported by the volunteers, regardless of the training group. This supports evidence indicating the safety and feasibility of the resistance training methods used in this study.

4. Discussion

This study investigated the effects of three RT protocols—TRT, FWRT, and HVRT—on the mental health and quality of life in people with spinal cord injury. The results demonstrated distinct benefits among the groups, indicating that different approaches may offer specific advantages in managing these outcomes, depending on the characteristics and needs of the individuals.

4.1. Mental Health

Initially, the TRT and FWRT groups showed a reduction in HADS-D values after the intervention, corroborating the literature that highlights the ability of RT interventions to mitigate symptoms of depression in populations with adverse health conditions [26–28]. Specifically, TRT also demonstrated a significant reduction in HADS-A values, results that are particularly relevant since depression and anxiety are often associated with a decreased quality of life and limitations in the social reintegration of people with spinal cord injury [29–31].

The intergroup analysis revealed that TRT was more effective in reducing HADS-A compared with the FWRT and HVRT groups, indicating a relevant effect. This advantage may be related to the simplicity and predictability of the TRT protocol, which creates a more comfortable and safer environment for practice, reducing stress levels associated with exercise. These findings reinforce the relevance of interventions that combine regular physical stimuli adjusted to individual capacities, especially in populations facing emotional and physical challenges due to the complexity of their conditions [32,33].

4.2. Quality of Life

Regarding quality of life, the results demonstrated specific benefits for each training protocol. TRT showed a significant increase in social functioning, highlighting its contribution to improving the social interaction of people with spinal cord injury. This type of training is recognized for fostering social interaction due to its structured environment and the encouragement of participation in group activities [34–36]. These same mechanisms may have contributed to the observed results in this population, promoting greater social engagement and support during the sessions.

Additionally, the FWRT group showed improvements in physical functioning, bodily pain, vitality, and role emotional, demonstrating its ability to promote

enhancements in physical functionality, energy levels, and confidence in managing emotional limitations. Previous studies have already reported significant improvements in physical functionality and pain perception using this training method [14,37,38]. Therefore, this improvement in functional capacity may have contributed to the observed advancements in other domains by providing greater autonomy and facilitating the execution of daily tasks.

Furthermore, the HVRT group demonstrated improvements after the training period in the domains of role physical, role emotional, and social functioning, highlighting its positive impact on these aspects. These improvements may be related to the intense stimulus of the protocol, known for promoting gains in muscle functionality and quality of life by reducing perceived limitations in social and emotional interactions [39,40]. However, the significant increase in bodily pain may reflect the high physical effort required, emphasizing the importance of adjustments in intensity and progression to minimize discomfort and maximize benefits.

Building on these findings, although certain domains, such as general health, did not show significant changes, maintaining these aspects is already a positive outcome, considering the challenges faced by people with spinal cord injury. The varied impact of the protocols underscores the need for individualized interventions, integrating different training modalities to maximize benefits across multiple domains of quality of life.

Rivers et al. [41] identified a positive association between higher motor function (assessed by the functional independence measure (FIM)) and quality of life in the physical domain of SF-36V2, whereas a negative association was observed in the mental domain. While a lower FIM motor score reflects greater injury severity and poorer physical health, its correlation with higher self-reported mental health is less intuitive. Furthermore, Ditor et al. [42] demonstrated that adherence to exercise enhances quality of life, with significant benefits observed following a 9-month training intervention and an additional 3-month follow-up, including reductions in stress and pain, along with the promotion of an active lifestyle in individuals with spinal cord injury.

In the comparison between the groups, specific differences emerged in the evaluated domains. For instance, the HVRT group showed the best results in role physical and vitality, demonstrating its effectiveness in promoting functional and energetic gains. The FWRT group performed better in bodily pain, suggesting its

potential for managing physical discomfort. In the domain of social functioning, TRT and HVRT outperformed FWRT, highlighting their ability to foster social interactions. In role emotional, FWRT and HVRT showed higher values compared with TRT, reinforcing their applicability in reducing emotional limitations. These findings suggest that each protocol can be tailored to specific needs, enabling personalized approaches.

4.3. Limitations and Strengths of This Study

This study presents some limitations stemming from the challenges of assembling a homogeneous group of people with spinal cord injury and related conditions, including factors such as varying times since injury, differences in trunk stability, and upper limb mobility levels. For this reason, participants were allocated to groups based on the assessment of an experienced researcher, aiming to balance the limitations and strengths present in a heterogeneous group. There was only one flywheel machine available in the laboratory where the FWRT was conducted, which limited interaction among volunteers during training sessions. This may have affected participants' motivation throughout the training program.

Furthermore, the findings related to FWRT should not be associated with other types of eccentric training, as they represent distinct stimuli and should only be compared under equivalent conditions. It is also important to highlight the limitation in comparing TRT and FWRT, as there is no direct equivalence in execution speed and repetition duration. Therefore, being mindful of this, volunteers in the FWRT and HVRT groups were instructed and encouraged to perform the concentric phases at the highest possible speed, ensuring that all repetitions were executed at maximum or near-maximum intensity.

On the other hand, several strengths should be highlighted. Validated and widely recognized tools were chosen to assess mental health and quality of life. Furthermore, it is noteworthy that this is the first study to apply three different types of RT with similar training protocols in people with spinal cord injury, enabling a comparison between them. The present study also appears to be the first to use a flywheel machine and HVRT with this population. We hope this will encourage other researchers to further explore these methods and expand the range of training modalities available for individuals with spinal cord injury. Long-term studies spanning several months or years, along with follow-ups after training cessation,

could be highly valuable for a deeper understanding of the findings presented in this study.

Despite its limitations, this study's strengths help mitigate its impact and underscore its contributions. The heterogeneity in participant characteristics was addressed through careful group allocation, ensuring a balanced distribution of strengths and limitations. While limited flywheel equipment may have restricted interaction, this study's pioneering use of flywheel resistance training in individuals with spinal cord injury paves the way for future research. Differences in execution speed and repetition duration between traditional resistance training and flywheel resistance training were managed by standardizing volume.

4.4. Practical Applications

The results of this study highlight the importance of integrating different resistance training modalities (TRT, FWRT, and HVRT) into rehabilitation programs for individuals with spinal cord injury, considering the rapid and effective potential of these interventions. Each modality demonstrated specific benefits that can be explored according to individual needs. TRT proved effective in reducing symptoms of anxiety and improving social interaction, making it an ideal option to promote greater social engagement in controlled environments. On the other hand, FWRT stood out for improving physical functionality and reducing pain perception, offering an efficient alternative for muscle recovery and the performance of daily activities. Meanwhile, HVRT presented significant benefits in vitality and overcoming emotional limitations, contributing to greater autonomy and confidence.

Furthermore, one of the main practical applications is the rapid positive impact provided by these modalities. Even with a short intervention period of just eight weeks, with two weekly sessions, significant improvements were observed. This effect can be enhanced with increased training frequency or prolonged practice periods, highlighting resistance training as an effective and accessible approach for this population. Thus, a personalized strategy, combining modalities and adapting the frequency and duration of training, can maximize the physical and psychological benefits for people with spinal cord injuries, promoting their rehabilitation and quality of life.

Beyond the physical improvements, the observed benefits extend to important psychopathological outcomes, such as reduced anxiety, enhanced vitality, and

improvements in emotional resilience. These results demonstrate how resistance training contributes to better mood regulation, reduced emotional distress, and increased self-efficacy, creating a feedback loop where physical gains reinforce psychological well-being. The enhanced sense of control and competence may help individuals manage stress more effectively, supporting long-term adherence to rehabilitation programs. Improved social interaction, facilitated by reduced anxiety and increased physical functionality, can further promote reintegration into daily life and community activities, improving overall quality of life. This highlights resistance training as a multidimensional therapeutic tool that addresses both physical recovery and psychopathological well-being.

5. Conclusions

In our findings, we observed that not only TRT has positive effects but also FWRT and HVRT are training modalities that can be applied to people with spinal cord injury to improve their mental health and quality of life. As demonstrated in the results, each training type led to specific outcomes, which may indicate that varying training modalities could significantly benefit this population. This leads us to understand that individuals with spinal cord injury should engage in resistance training regardless of the specific type employed.

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4. GENERAL CONCLUSION

This doctoral thesis investigated the effects of three distinct resistance training modalities - Traditional Resistance Training (TRT), Flywheel Resistance Training (FWRT), and High-Velocity Resistance Training (HVRT) - on different manifestations of muscle strength, functional capacity, body composition, mental health, and quality of life in individuals with chronic spinal cord injury (SCI). Through three complementary studies, it sought to advance the understanding of how different mechanical and neuromuscular stimuli may elicit specific and clinically meaningful adaptations in this population, contributing to evidence-based exercise prescription for rehabilitation and long-term health maintenance.

Across all studies, resistance training emerged as a safe and effective non-pharmacological strategy capable of promoting both physical and psychological benefits in individuals with SCI. Collectively, the findings revealed that while each training modality produced distinct physiological and functional adaptations, all were effective in improving at least one dimension of health and performance.

From a neuromuscular perspective, TRT and HVRT demonstrated substantial improvements in maximal voluntary isometric contraction and dynamic strength, while HVRT uniquely enhanced muscle power across a wide range of loads. These findings confirm that training at high movement velocities, even under moderate external loads, can optimize power output and dynamic strength in individuals with physical limitations—a critical aspect for daily activities requiring rapid force generation. FWRT, on the other hand, was particularly effective in improving functional agility and lean mass, highlighting the value of eccentric overload for enhancing neuromotor efficiency and movement control.

In parallel, body composition analyses demonstrated favorable adaptations following both FWRT and HVRT, including increases in lean mass and bone mineral content, and the prevention of fat mass accumulation. These structural adaptations are especially relevant given the high prevalence of musculoskeletal and metabolic complications in individuals with chronic SCI. Moreover, improvements in muscle function were accompanied by significant gains in perceived functionality, vitality, and emotional well-being, as well as reductions in anxiety symptoms. These results reinforce the biopsychosocial impact of resistance training, supporting its role as an integrative approach to rehabilitation.

Methodologically, this thesis also contributes to literature by employing a pragmatic design that mirrors real-world rehabilitation settings, emphasizing ecological validity. The combination of statistical analyses and clinical significance measures, such as the minimal clinically important difference (MCID), allowed a nuanced interpretation of results, distinguishing between statistically significant and functionally meaningful improvements. Despite the inherent limitations related to sample heterogeneity and non-randomized allocation, this approach captured the complexity of training responses in a diverse SCI population and provided applicable insights for clinical and community-based interventions.

In conclusion, this thesis establishes that resistance training—whether traditional, eccentric-enhanced, or velocity-focused—offers complementary pathways to enhance strength, functionality, and psychological health in individuals with spinal cord injury. Integrating these modalities within individualized, goal-oriented rehabilitation programs can maximize neuromuscular and psychosocial adaptations, fostering autonomy and quality of life. Future research should expand upon these findings by exploring long-term interventions, hybrid training models combining eccentric and power components, and broader assessments of daily functional performance and mental health outcomes in community-dwelling individuals with SCI.

ANEXO I

Part of the results presented in this report have been published in:

I. SANTOS, L. V.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS; PEREIRA, E. T.; LEITE L. B.; FORTE P.; PATROCÍNIO DE OLIVEIRA, CLÁUDIA ELIZA; MOREIRA, OSVALDO COSTA. Comparative Effects of Resistance Training Modalities on Mental Health and Quality of Life in Individuals with Spinal Cord Injury. SPORTS, v. 13(2), p. 13020060, 2025.

ANEXO II

Part of the results presented in this report have been accepted for publication in:

I. VIANA, I. S. A. ; SANTOS, L. V. ; Silva L. S. G ; FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; PEREIRA, EVELINE TORRES ; OLIVEIRA, CLAUDIA ELIZA PATROCÍNIO DE ; MOREIRA, O. C. . Effect of Flywheel Resistance Training on Upper Limb Muscle Quality in Individuals with Spinal Cord Injury: A Pre-Post Intervention Study. REVISTA BRASILEIRA DE PRESCRIÇÃO E FISIOLOGIA DO EXERCÍCIO, 2025.

II. SANTOS, L. V.; SILVA, L. S. G.; VIANA, I. S. A.; FERREIRA, R. F.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS.; PEREIRA, E. T.; OLIVEIRA, CLAUDIA ELIZA PATROCÍNIO DE; MOREIRA, O. C. . CONTEMPORARY PERSPECTIVES ON RESISTANCE TRAINING FOR INDIVIDUALS WITH SPINAL CORD INJURY - A NARRATIVE REVIEW. REVISTA BRASILEIRA DE PRESCRIÇÃO E FISIOLOGIA DO EXERCÍCIO, 2025.

ANEXO III

Part of the results presented in this report have been sent for publication in:

I. SANTOS, L. V.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS; PEREIRA, E. T.; REGUERA-GARCÍA, MARÍA MERCEDES; OLIVEIRA, CLÁUDIA ELIZA PATROCÍNIO DE; MOREIRA, O. C. FLYWHEEL RESISTANCE TRAINING ENHANCES LEAN MASS AND HIGH-VELOCITY TRAINING PREVENTS FAT GAIN IN SPINAL CORD INJURY: AN EXPERIMENTAL COMPARATIVE TRIAL. SPINAL CORD SERIES AND CASES, submitted, 2025.

II. SANTOS, L. V.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS; LEITE, L. B.; PEREIRA, E. T.; REGUERA-GARCÍA, MARÍA MERCEDES; OLIVEIRA, CLÁUDIA ELIZA PATROCÍNIO DE; MOREIRA, O. C.. WHICH DIFFERENT RESISTANCE TRAINING TYPES ENHANCE FUNCTIONAL PERFORMANCE IN PEOPLE WITH SPINAL CORD INJURY: A COMPARISON OF TRADITIONAL, FLYWHEEL AND HIGH-VELOCITY RESISTANCE TRAINING. JOURNAL OF BODYWORK AND MOVEMENT THERAPIES, submitted, 2025.

ANEXO IV

Part of the results presented in this report have been the subject of the following communications at National and International Congresses:

I. SANTOS, L. V.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; PEREIRA, EVELINE TORRES ; CHAVES, S. F. N. ; OLIVEIRA, CLÁUDIA ELIZA PATROCÍNIO DE ; MOREIRA, O. C. . The influence of three different resistance training methods on the muscle power-to-lean mass ratio in individuals with spinal cord injury. In: II Congresso Mineiro de Fisiologia do Exercício, 2025, Ouro Preto. Anais do II Congresso Mineiro de Fisiologia do Exercício, 2025. v. 1. p. 113-113.

II. CHAVES, S. F. N. ; SANTOS, L. V. ; P. A. G. Agostinho ; ARAUJO, D. P. S. ; OLIVEIRA, CLÁUDIA ELIZA PATROCÍNIO DE ; FERREIRA JUNIOR, J. B. ; MOREIRA, O. C. . Influence of different inertial loads on power output during the flywheel squat exercise. In: II Congresso Mineiro de Fisiologia do Exercício, 2025, Ouro Preto. Anais do II Congresso Mineiro de Fisiologia do Exercício, 2025. v. 1. p. 95-95.

III. MORAES, A. A. ; SANTOS, L. V. ; FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; PEREIRA, EVELINE TORRES ; FORTE, P. ; OLIVEIRA, CLÁUDIA ELIZA PATROCÍNIO DE ; MOREIRA, O. C. . The Effect of Three Types of Resistance Training on Muscle Power/Lean Mass Ratio of People with Spinal Cord Injury. In: Sprint International Congress - 1st edition, 2025, Rio Maior. Shaping the Future of Sports - Sprint International Congress - 1st edition, 2025. v. 1. p. 161-163.

IV. MORAES, A. A. ; SANTOS, L. V. ; FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; PEREIRA, EVELINE TORRES ; FORTE, P. ; OLIVEIRA, CLAUDIA ELIZA PATROCÍNIO DE ; MOREIRA, O. C. . Eccentric-Enhanced Resistance Training and Upper Limb Muscle Quality in People with Spinal Cord Injury: a case series. In: Shaping the Future of Sports - SPRINT Congress, 2025, Rio Maior. Shaping the Future of Sports - SPRINT International Congress, 2025. v. 1. p. 164-166.

V. SANTOS, L. V.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; PEREIRA, E. T. ; OLIVEIRA, CLAUDIA ELIZA PATROCÍNIO DE ; MOREIRA, O. C. . Efeitos de diferentes métodos de treinamento resistido sobre a força de pessoas com lesão medular. In: II Simpósio Internacional de Fisiologia do Exercício e Saúde, 2024, Florestal. II Simpósio Internacional de Fisiologia do Exercício e Saúde, 2023. v. 23. p. 24-25.

VI. FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; SANTOS, L. V. ; CUPERTINO, J. C. ; PEREIRA, E. T. ; MOREIRA, O. C. . Influências de três modelos de treinamento resistido na agilidade funcional de pessoas com lesão medular. In: II Simpósio Internacional de Fisiologia do Exercício e Saúde, 2024, Florestal - MG. II Simpósio Internacional de Fisiologia do Exercício e Saúde, 2023. v. 23. p. 39-40.

VII. SANTOS, L. V.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; PEREIRA, E. T. ; OLIVEIRA, CLAUDIA ELIZA PATROCÍNIO DE ; MOREIRA, O. C. . A influência de 8 semanas de treinamento resistido de alta velocidade nas variáveis bioquímicas em pessoas com lesão medular espinhal - um estudo piloto. In: III Simpósio Internacional de Fisiologia do Exercício e Saúde, 2024, Viçosa - MG. III Simpósio Internacional de Fisiologia do Exercício e Saúde, 2024. v. 23. p. 235601.

VIII. SANTOS, L. V.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; PEREIRA, E. T. ; OLIVEIRA, CLAUDIA ELIZA PATROCÍNIO DE ; MOREIRA, O. C. . A INFLUÊNCIADE 3 TIPOS DE TREINAMENTO RESISTIDO NOS SINTOMAS DE ANSIEDADE E DEPRESSÃO DEPESSOAS COM LESÃO MEDULAR ESPINHAL. In: II Congresso de Saúde Mental da UFV, 2024, Viçosa. Anais II Congresso de Saúde Mental da UFV, 2024. p. 787-78.

IX. SANTOS, L. V.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; PEREIRA, EVELINE TORRES ; OLIVEIRA, CLAUDIA ELIZA PATROCÍNIO DE ; MOREIRA, O. C. . A influência de 3 tipos de Treinamento Resistido nos Sintomas de Ansiedade e Depressão de pessoas com Lesão Medular Espinhal. In: II Congresso de Saúde Mental da UFV, 2024, Viçosa. Anais do II Congresso de Saúde Mental da UFV. Viçosa, 2024. v. 1. p. 78-78.

X. PEREIRA, E. T. ; SANTOS, L. V. ; FREITAS, KARLA RAPHAELA DA SILVA RAMOS ; OLIVEIRA, CLÁUDIA ELIZA PATROCÍNIO DE ; MOREIRA, O. C. . O treinamento resistido e seus efeitos na qualidade de vida de pessoas com lesão medular. In: II Simpósio Internacional de Fisiologia do Exercício e Saúde, 2024, Florestal - MG. III Simpósio Internacional de Fisiologia do Exercício e Saúde, 2023. v. 23. p. 20-21.

XI. MOREIRA, O. C. ; SANTOS, L. V.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS; PEREIRA, E. T.; OLIVEIRA, CLAUDIA ELIZA PATROCÍNIO DE. Alterações na composição corporal de pessoas com lesão medular após três configurações distintas de treinamento resistido. In: II Simpósio Internacional de Fisiologia do Exercício e Saúde, 2023, Florestal - MG. II Simpósio Internacional de Fisiologia do Exercício e Saúde, 2023. v. 23. p. 53-54.

ANEXO V

Secondary data analyses are ongoing, and the following manuscripts are currently being prepared for submission.

I. SANTOS, L. V.; GOULART-SILVA, L. S.; VIANA, I. S. A.; FREITAS, KARLA RAPHAELA DA SILVA RAMOS; PEREIRA, E. T.; OLIVEIRA, CLÁUDIA ELIZA DO PATROCÍNIO DE; MOREIRA, O. C. THE INFLUENCE OF THREE TYPES OF RESISTANCE TRAINING ON MUSCLE POWER AND LEAN MASS IN INDIVIDUALS WITH SPINAL CORD INJURY. *IN PREPARATION*, 2025.

II. VIANA, Í. S. A.; SANTOS, L. V.; GOULART-SILVA, L. S.; OLIVEIRA, CLÁUDIA ELIZA DO PATROCÍNIO DE; MOREIRA, O. C. EFFECT OF FLYWHEEL RESISTANCE TRAINING ON UPPER LIMB MUSCLE QUALITY IN INDIVIDUALS WITH SPINAL CORD INJURY. *IN PREPARATION*, 2025.