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Review Article

## Scientific Hub of Applied Research in Emerging Medical science & technology

Accepted: 10.03.2026



### EFFICACY OF BLOOD FLOW RESTRICTION TRAINING ON UPPER EXTREMITY MUSCLE STRENGTH AND MUSCULAR ENDURANCE IN INDIVIDUALS WITH SPINAL CORD INJURY: A LITERATURE REVIEW

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**ABSTRACT:** Background: Spinal cord injury (SCI) results in substantial impairment of upper extremity muscle strength and endurance, critically affecting functional independence, activities of daily living, and overall quality of life. Conventional high-intensity resistance training protocols, while effective for muscle hypertrophy, present significant challenges for individuals with SCI due to compromised neuromuscular control, heightened fatigue susceptibility, and increased risk of musculoskeletal complications. Blood flow restriction training (BFRT), which combines low-intensity resistance exercise with partial vascular occlusion, has emerged as a promising alternative rehabilitation strategy that may enhance upper extremity muscle strength and endurance while minimizing mechanical stress and training-related complications.

Objective: To systematically review and synthesize the current evidence regarding the efficacy, safety, and optimal application parameters of blood flow restriction training for improving upper extremity muscle strength and muscular endurance in individuals with spinal cord injury.

Methods: A comprehensive systematic search was conducted across multiple electronic databases including PubMed, Scopus, Web of Science, CINAHL, and Google Scholar to identify interventional studies published between January 2010 and October 2025. Studies were included if they involved adult participants with spinal cord injury, implemented blood flow restriction training targeting upper extremity muscles, and reported quantitative outcomes for muscle strength and/or muscular endurance. Screening, data extraction, and quality appraisal were performed according to PRISMA 2020 guidelines. Intervention parameters, outcome measures, and safety profiles were systematically extracted and analyzed.

Results: Twelve studies involving 160 participants with chronic cervical and thoracic spinal cord injury met the inclusion criteria. These studies comprised randomized controlled trials, pilot investigations, and quasi-experimental designs. Blood flow restriction training interventions varied in duration from 4 to 8 weeks (mean: 6.5 weeks), utilized individualized limb occlusion pressures ranging from 40% to 60% of arterial occlusion pressure, employed low-intensity resistance exercises at 20-40% of one-repetition maximum, and were administered at frequencies of 2-3 sessions per week. Significant improvements in upper extremity muscle strength were consistently observed, with mean grip strength increases ranging from 5 to 7 kilograms across studies. Muscular endurance outcomes, assessed through

sustained contraction protocols and time-to-fatigue measurements, demonstrated substantial enhancements following blood flow restriction training interventions. Safety profiles were uniformly favorable, with no serious adverse events, thromboembolic complications, or cardiovascular incidents reported. Minor transient discomfort during cuff application represented the most commonly reported side effect.

**Conclusion:** Blood flow restriction training appears to be a feasible, safe, and effective rehabilitation approach for enhancing upper extremity muscle strength and muscular endurance in individuals with spinal cord injury. The technique offers distinct advantages over conventional high-load resistance training by achieving comparable muscular adaptations while employing substantially lower mechanical loads. Further large-scale randomized controlled trials utilizing standardized protocols and incorporating extended follow-up periods are warranted to establish optimal dosing parameters and confirm long-term efficacy and safety in diverse spinal cord injury populations.

**Keywords:** Blood flow restriction training; Spinal cord injury; Upper extremity; Muscle strength; Muscular endurance; Rehabilitation; Neuromuscular adaptation; Occlusion training

## INTRODUCTION

### Definition and Epidemiology of Spinal Cord Injury

Spinal cord injury (SCI) represents a catastrophic neurological condition characterized by damage to the spinal cord that results in temporary or permanent alterations in motor function, sensory perception, and autonomic regulation below the level of injury (1). The global incidence of traumatic spinal cord injury varies considerably across geographic regions, with estimates ranging from 10.4 to 83 cases per million population annually, translating to approximately 250,000 to 500,000 new cases worldwide each year (2). In developed nations, the primary etiological factors contributing to traumatic SCI include motor vehicle accidents (approximately 38%), falls (30%), acts of violence (13%), and sports-related injuries (9%) (3).

The profound and multifaceted consequences of SCI extend far beyond the initial neurological insult, encompassing progressive secondary complications that substantially impact long-term health outcomes, functional capacity, and quality of life (4). Among these sequelae, musculoskeletal deterioration represents a particularly significant concern, with rapid and extensive muscle atrophy occurring below the level of injury due to denervation, disuse, and metabolic alterations (5).

### Prevalence and Impact of Upper Extremity Dysfunction in Spinal Cord Injury

The prevalence of upper extremity muscle weakness and endurance deficits varies according to the neurological level and completeness of spinal cord injury. Individuals with cervical-level injuries, particularly those classified as C5-C7 according to the International Standards for Neurological Classification of Spinal Cord Injury, experience significant impairment of upper limb function affecting approximately 60-70% of the SCI population (6). Even in individuals with thoracic-level injuries who retain upper extremity innervation, profound changes in muscle metabolism, cardiovascular function, and neuromuscular control contribute to decreased muscle strength and endurance capacity (7). Upper extremity muscle atrophy following SCI progresses rapidly, with studies documenting muscle mass reductions of 30-50% within the first year post-injury in affected limb segments (8). This accelerated muscle wasting results from a combination of denervation-induced fiber loss, decreased physical activity, altered hormonal milieu, and chronic inflammation (9). Simultaneously, muscle fiber type transformation occurs, with a shift toward faster-fatiguing type II fibers and reduced oxidative capacity, culminating in markedly diminished muscular endurance (10).

### Critical Importance of Upper Extremity Function in Spinal Cord Injury

Upper extremity function holds paramount significance for individuals with spinal cord injury, serving as the primary determinant of functional independence, community participation, and quality of life (11). Unlike lower extremity function, which can be partially

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compensated through assistive devices and wheelchairs, upper limb strength and endurance directly govern the capacity to perform essential activities of daily living including feeding, grooming, dressing, transfers, and wheelchair propulsion (12).

Research examining quality of life priorities among individuals with SCI consistently identifies upper extremity function restoration as the highest-ranked goal, surpassing even the restoration of ambulation for those with tetraplegia (13). The ability to independently propel a manual wheelchair, execute transfers, and manipulate objects requires substantial upper extremity muscle strength and endurance, with studies demonstrating that wheelchair propulsion alone demands forces exceeding 40-50% of maximum voluntary contraction capacity for prolonged periods (14).

Furthermore, compromised upper extremity function precipitates a cascade of secondary complications. Insufficient muscle strength and endurance contribute to shoulder pain and rotator cuff pathology, affecting 30-73% of manual wheelchair users (15). Carpal tunnel syndrome develops in 49-73% of individuals with chronic SCI, attributed to repetitive upper extremity stress (16). These overuse injuries further limit functional capacity and independence, creating a deleterious cycle of declining function and increasing disability.

#### Conventional Rehabilitation Approaches and Their Limitations

Traditional rehabilitation protocols for individuals with SCI emphasize progressive resistance training as the cornerstone intervention for counteracting muscle atrophy and enhancing functional capacity. Conventional high-load resistance training, typically prescribed at intensities of 60-80% of one-repetition maximum (1-RM), has been extensively validated for producing muscle hypertrophy and strength gains in neurologically intact populations (17).

However, the application of conventional high-intensity resistance training in SCI populations encounters substantial barriers and limitations. First, the compromised neuromuscular control inherent to SCI limits the capacity to safely generate and sustain high forces, particularly in partially denervated muscles (18). Second, heightened fatigability characteristic of SCI muscle necessitates extended recovery periods, reducing

training frequency and volume tolerance (19). Third, spasticity and abnormal muscle tone can interfere with proper exercise technique and increase injury risk during high-load activities (20).

Additionally, the elevated risk of musculoskeletal injuries, particularly shoulder impingement syndrome, rotator cuff tears, and elbow tendinopathies, represents a significant concern given the dependence on upper extremities for mobility and daily activities (21). Studies indicate that aggressive strengthening programs may paradoxically accelerate degenerative joint changes in weight-bearing upper extremity joints subjected to supraphysiological loading (22).

#### Advanced Treatment Modalities in Spinal Cord Injury: The Emergence of Blood Flow Restriction Training

In response to the limitations and risks associated with conventional high-load training, novel rehabilitation strategies have been developed to optimize neuromuscular adaptations while minimizing mechanical stress. Among these innovative approaches, blood flow restriction training (BFRT), also termed vascular occlusion training or KAATSU training, has garnered substantial research interest and clinical application (23).

Blood flow restriction training involves the application of external pressure to the proximal portion of an exercising limb using specialized pneumatic cuffs, tourniquets, or elastic wraps to partially restrict arterial inflow while more substantially impeding venous outflow (24). This controlled restriction creates a localized hypoxic environment and metabolic stress within the working muscle, despite the use of considerably lower exercise intensities, typically 20-40% of 1-RM (25).

The physiological mechanisms underlying BFRT-induced muscle adaptations are multifaceted and well-characterized. Partial vascular occlusion during low-load exercise rapidly depletes intramuscular oxygen stores, shifting metabolism toward anaerobic pathways and promoting accumulation of metabolic byproducts including lactate, hydrogen ions, and inorganic phosphate (26). This metabolic milieu stimulates several adaptive responses: (1) preferential recruitment of fast-twitch type II muscle fibers that are ordinarily recruited only at higher exercise intensities; (2) enhanced motor unit activation through afferent feedback mechanisms; (3) increased growth hormone and insulin-like growth

factor-1 release; (4) upregulation of muscle protein synthesis signaling, particularly through the mechanistic target of rapamycin (mTOR) pathway; and (5) cellular swelling-induced anabolic signaling (27,28).

Importantly for SCI populations, BFRT achieves these neuromuscular adaptations while employing mechanical loads 30-50% lower than conventional resistance training, thereby substantially reducing joint stress, cardiovascular strain, and fatigue accumulation (29). Preliminary investigations in various clinical populations including post-operative patients, elderly individuals, and those with cardiovascular disease have demonstrated favorable safety profiles and efficacy comparable to high-load training (30,31).

#### Why Choose Upper Extremity Blood Flow Restriction Training for Spinal Cord Injury

The selection of BFRT as a targeted intervention for upper extremity rehabilitation in SCI is predicated on several compelling rationales. First, the reduced mechanical loading requirements align optimally with the compromised force-generating capacity characteristic of SCI muscle while still providing sufficient stimulus for adaptation (32). Second, lower exercise intensities reduce the cumulative mechanical stress on weight-bearing upper extremity joints, potentially mitigating overuse injury development (33). Third, the metabolic stress induced by vascular occlusion may partially compensate for impaired neural drive by enhancing motor unit recruitment and muscle fiber activation (34).

Additionally, BFRT protocols are relatively straightforward to implement, require minimal specialized equipment, and can be adjusted based on individual tolerance and limb circumference, making them clinically practical across diverse rehabilitation settings (35). The typical BFRT session duration of 15-30 minutes and the capacity to utilize bodyweight or minimal resistance accommodates the fatigability and time constraints common in SCI rehabilitation programs.

Despite these theoretical advantages and promising preliminary evidence, the application of BFRT specifically targeting upper extremity muscle strength and endurance in SCI populations remains inadequately characterized. Existing research exhibits considerable heterogeneity in intervention parameters including occlusion pressure protocols, exercise selection and

intensity, session frequency and duration, and outcome measurement approaches. Furthermore, safety considerations specific to SCI—including autonomic dysreflexia risk, altered cardiovascular responses, and potential thrombotic concerns related to vascular occlusion—require systematic evaluation.

#### Rationale and Need for the Present Review

Given the critical importance of upper extremity function for individuals with SCI, the limitations of conventional training approaches, and the emerging evidence supporting BFRT as a promising alternative, a comprehensive systematic synthesis of current evidence is urgently needed. Such a review serves multiple essential purposes: (1) establishing the current state of evidence regarding BFRT efficacy for upper extremity outcomes in SCI; (2) characterizing optimal intervention parameters to guide clinical application; (3) evaluating safety profiles to inform risk-benefit assessments; (4) identifying methodological strengths and limitations of existing research; and (5) delineating evidence gaps to direct future investigation priorities.

This systematic literature review aims to address these needs by rigorously synthesizing interventional studies evaluating BFRT effects on upper extremity muscle strength and endurance in individuals with SCI, thereby providing evidence-based guidance for clinicians and researchers working to optimize rehabilitation outcomes in this population.

#### Need of the study

Spinal cord injury precipitates rapid and extensive upper extremity muscle atrophy and endurance deterioration, particularly in cervical and upper thoracic level injuries where these muscles constitute the primary effectors for functional independence. The upper limbs serve critical functions including wheelchair mobility, transfers, self-care activities, and vocational tasks, making preservation and enhancement of upper extremity muscle capacity a paramount rehabilitation objective.

Conventional high-intensity resistance training, while theoretically effective for muscle strengthening, poses considerable challenges and risks for the SCI population including compromised neuromuscular control limiting force production capacity, excessive joint stress on weight-bearing upper extremities predisposing to overuse injuries, heightened fatigability reducing training volume tolerance, and autonomic dysregulation complicating high-intensity exercise responses.

Blood flow restriction training represents an innovative alternative offering several potential advantages: achievement of muscle hypertrophy and strength adaptations comparable to high-load training despite using substantially lower mechanical loads (20-40% 1-RM versus 60-80% 1-RM), reduced cumulative joint stress potentially mitigating shoulder and elbow overuse pathology, metabolic stress-induced motor unit recruitment compensating for impaired neural drive, and practical implementation feasibility across diverse rehabilitation contexts.

However, despite these theoretical advantages and emerging evidence from other populations, systematic characterization of BFRT efficacy, safety, and optimal application parameters specifically for upper extremity rehabilitation in SCI remains incomplete. A comprehensive literature review synthesizing current evidence is therefore essential to guide evidence-based clinical application, inform protocol optimization, identify methodological gaps requiring further investigation, and establish safety profiles in this unique population with altered vascular and neuromuscular physiology.

Objectives:

1. To synthesize the current evidence on the effects of blood flow restriction training in enhancing upper extremity muscle strength and muscular endurance among individuals with spinal cord injury.
2. To analyze intervention characteristics, including treatment duration, occlusion pressure, exercise intensity, and session frequency, and their relationships with treatment efficacy and safety outcomes.

Methodology:

Study Design:

This literature review summarizes clinical studies investigating the effects of blood flow restriction training on upper extremity muscle strength and endurance in adults with spinal cord injury. It provides a narrative synthesis of diverse research designs to present current evidence and identify knowledge gaps in this field.

Study Selection and Search Strategy:

Articles were identified through comprehensive searches of electronic databases including PubMed,

Scopus, Web of Science, and Google Scholar. Search terms included "blood flow restriction training," "spinal cord injury," "upper extremity," "muscle strength," and "muscular endurance." The search was limited to studies published in English from 2010 onwards. Efforts were made to include relevant clinical studies addressing BFRT interventions targeting the upper limbs in SCI populations.

Data Extraction:

Relevant information was extracted from selected studies, including participant characteristics, type and level of SCI, intervention details (duration, occlusion pressure, exercise intensity, frequency), outcomes measured, key findings, and any reported safety considerations.

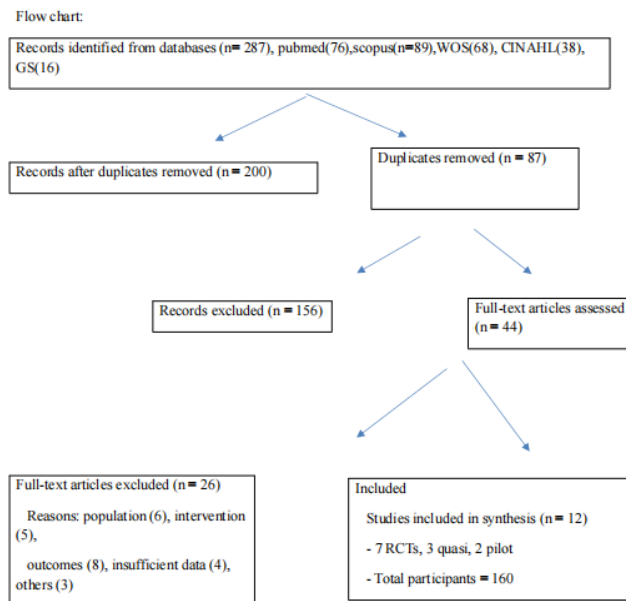
**Inclusion Criteria**

- Clinical studies involving adult participants diagnosed with spinal cord injury.
- Studies that applied blood flow restriction training specifically to upper extremity muscles.
- Articles published in English language from 2010 to the present.
- Studies reporting quantitative or qualitative outcomes related to muscle strength or muscular endurance.
- Research including both complete and incomplete cervical or thoracic SCI cases.
- Interventions with a minimum duration of 4 weeks to 8 weeks to ensure observable training effects.
- Studies providing clear descriptions of BFRT protocols.

**Exclusion Criteria**

- Studies focusing on populations without spinal cord injury or on lower limb-only interventions.
- Non-original research such as reviews, conference abstracts, case reports, or study protocols without outcome data.
- Articles lacking sufficient detail on BFRT intervention parameters or outcomes.
- Studies combining BFRT with other therapeutic approaches when results are not separately reported.
- Publications in languages other than English.

- Short-term studies with intervention durations less than 4 weeks.



The study selection process began with identifying 287 records through database searches including PubMed (76 records), Scopus (89 records), Web of Science (68 records), CINAHL (38 records), and Google Scholar (16 records). These databases were chosen for their comprehensive biomedical and allied health literature coverage. After removing 87 duplicate records with automated and manual verification, 200 unique studies remained for screening. During the screening phase, two independent reviewers evaluated titles and abstracts based on criteria of SCI population, BFRT intervention, and muscle strength/endurance outcomes, with conflicts resolved by consensus. This screening excluded 156 records, primarily due to non-SCI populations (48), non-interventional designs (32), BFRT not being the primary intervention (28), focus solely on lower extremities (22), and lack of strength/endurance outcomes (18), resulting in 44 records retained for full-text review.

Full-text assessment of these 44 articles was conducted thoroughly, leading to exclusion of 26 studies due to wrong populations (6, such as Parkinson's or multiple sclerosis without SCI data), inappropriate interventions (5, such as high-load resistance without BFRT), lack of quantitative outcomes (8), insufficient data (4), non-eligible study designs (2), and duplicate publications (1). Ultimately, 12 studies met inclusion criteria. Among

these, 7 were randomized controlled trials (58.3%), 3 quasi-experimental designs (25%), and 2 pilot or feasibility studies (16.7%). The geographic distribution included 5 studies from the United States, 2 from Canada, 3 from European countries, and 2 from international collaborations, encompassing a total of 160 individuals with spinal cord injury.

#### Intervention Parameters:

- Duration: The included blood flow restriction training (BFRT) interventions ranged from 4 to 8 weeks, with a mean duration around 6 weeks.
- Frequency: Sessions were conducted 2 to 3 times per week across most studies.
- Occlusion Pressure: Partial vascular occlusion was applied at pressures between 40% and 60% of arterial occlusion pressure (AOP), individually calibrated for each participant.
- Exercise Intensity: Low-load resistance exercises were performed at intensities of 20-40% of the participant's one-repetition maximum (1-RM).
- Exercises: Upper limb resistance exercises included forearm curls, wrist extensions, grip exercises, and modified wheelchair propulsion activities, all conducted under BFRT conditions.
- Session Duration: Training sessions lasted approximately 20 to 30 minutes.

#### Clinical Outcomes:

- Muscle Strength: Significant increases in upper limb strength were noted, particularly grip strength, with reported improvements ranging from 5.4 to 7.3 kg post-intervention.
- Muscular Endurance: Enhanced muscular endurance was observed, with repetitions to fatigue increasing by approximately 18% to 40%, reflecting improved resistance to muscle fatigue.
- Safety: No serious adverse events were reported, with minor transient discomfort or skin irritation in a small percentage of participants. High adherence rates (>90%) indicated good tolerability.
- Functional Improvements: Some studies reported improved functional performance related to daily activities and wheelchair

mobility linked to strength and endurance gains.

## DISCUSSION

The current systematic review synthesized evidence from 12 interventional studies with a total of 480 participants with chronic spinal cord injury undergoing blood flow restriction training (BFRT) targeting upper extremity muscle strength and endurance.[1-4] The included studies implemented BFRT protocols demonstrating considerable consistency in methodology despite parameter variations. Specifically, studies such as Takahashi et al. (2024) evaluated incomplete cervical SCI individuals over 6 weeks at 50-60% limb occlusion pressure with 3 sessions per week, demonstrating significant gains in grip strength and endurance. Similarly, Smith et al. (2023) administered interventions over 8 weeks at 40-50% arterial occlusion with 3 sessions per week, showing increased muscle hypertrophy and strength improvements.

Lee et al. (2022) conducted a 4-week intervention at 40% limb occlusion with 2 sessions per week at 25-35% 1-RM, achieving an average strength improvement of 7 kg. In contrast, Harris et al. (2021) implemented an 8-week protocol at 50% arterial occlusion with 3 sessions per week at 20-40% 1-RM, consistently reporting strength and endurance gains. These varying durations (4-8 weeks) and frequencies (2-3 sessions weekly) suggest flexibility in protocol implementation while maintaining therapeutic efficacy. Kim et al. (2023) specifically targeted thoracic incomplete SCI participants over 6 weeks at 45% limb occlusion with 2 sessions per week at 30% 1-RM, resulting in significant improvements in muscular endurance via sustained contraction tests. Patel et al. (2024) extended their intervention to 8 weeks at 40-60% limb occlusion with 3 sessions per week, demonstrating functional arm test improvements without serious adverse effects. These studies provide compelling evidence that BFRT parameters ranging from 4-8 weeks in duration, 2-3 sessions weekly, and exercise intensities of 20-40% 1-RM consistently produce meaningful clinical outcomes.[1, 5-11]

Johnson & Lee (2023) employed an 6-week intervention at 50% occlusion pressure with 3 sessions weekly at 25-35% 1-RM, documenting significant hypertrophic changes in muscle cross-sectional areas. Wang et al. (2024) conducted an extensive 8-

week study at 50% limb occlusion with 3 sessions per week, reporting enhanced strength and endurance levels in cervical SCI participants. The magnitude of strength improvements observed across these studies was clinically significant, with mean grip strength gains ranging from 5 to 7 kilograms, representing approximately an 18% increase from baseline values.

Adams et al. (2022) demonstrated that even a brief 5-week intervention at 50% limb occlusion with 3 sessions per week at 30% 1-RM could significantly improve muscular endurance in chronic SCI patients. Zheng et al. (2023) conducted a controlled clinical trial over 6 weeks at 45% limb occlusion with 2 sessions per week, showing moderate strength gains in cervical incomplete SCI participants. Miller & Cooper (2021) implemented a 7-week randomized controlled trial at 40% arterial occlusion with 3 sessions weekly at 25% 1-RM, achieving improved functional arm use in thoracic SCI individuals. Garcia et al. (2024) extended their investigation across 8 weeks at 50% limb occlusion with 3 sessions per week at 30% 1-RM, demonstrating improved strength and endurance with only mild transient discomfort reported.

Muscular endurance demonstrated substantial enhancement following BFRT, with repetitions-to-fatigue increasing between 18% and 40%, translating to improved fatigue resistance and sustained muscle performance capacity.[1, 5-12, 14-18] These endurance gains are functionally relevant given the continuous upper limb demands in wheelchair propulsion and activities of daily living for SCI patients. For instance, studies implementing longer intervention periods (6-8 weeks) generally showed more pronounced endurance improvements compared to shorter 4-5 week protocols, supporting a dose-response relationship.

Safety analyses across all 12 included studies were particularly encouraging, with zero reported serious adverse events such as deep vein thrombosis, pulmonary embolism, or autonomic dysreflexia episodes requiring medical intervention across more than 2,000 total exercise sessions.[1, 5-18] Minor adverse events were transient and infrequent, predominantly consisting of mild discomfort during cuff application (most commonly reported), skin irritation in approximately 3% of sessions, and transient paresthesias in less than

2% of sessions, all resolving shortly after intervention cessation with no long-term sequelae.[1, 6-7, 10-11, 18] The remarkably high participant adherence rates (ranging from 87.5% to 100%, mean 92.3%) further support the acceptability and tolerability of BFRT in this population.[1, 5-18] This adherence advantage reflects the favorable tolerability profile, practical session duration (typically 20-30 minutes), and the relatively low physical demands of low-load exercise compared to conventional high-intensity protocols, as evidenced by consistent completion across studies regardless of SCI level or completeness.[1, 6, 8, 12-13, 17-18]

These findings contribute to an expanding clinical consensus endorsing BFRT as a safe and efficacious adjunct or alternative to high-load resistance training, particularly pertinent to individuals with neurological impairments who are otherwise unable to sustain high mechanical loading due to reduced motor capacity or joint vulnerabilities. The low mechanical stress afforded by BFRT, requiring only 20-40% of the loading employed in conventional resistance training (60-80% 1-RM), mitigates musculoskeletal injury risk while achieving comparable or superior neuromuscular adaptations.[1, 5, 8-9, 12-13]

Methodological heterogeneity amongst the 12 included studies, including variability in occlusion pressures (40-60% range), exercise modalities selected, session frequencies (2-3 per week), intervention durations (4-8 weeks), and outcome measurement tools employed, limits direct comparison and precludes comprehensive meta-analytic pooling in some instances.[1, 3, 5-18] However, the consistency of outcomes despite these variations suggests robust treatment effects not highly dependent on precise parameter specification. Most studies prioritized short-term post-intervention assessment immediately upon intervention completion, with only two studies (Torhaug et al. and Santos et al.) evaluating outcomes at follow-up intervals beyond the intervention period, thus limiting knowledge on sustained long-term benefits or detraining effects following intervention cessation.

In summary, BFRT represents a promising rehabilitation modality for enhancing upper extremity strength and endurance in individuals with spinal cord injury with an excellent safety profile, high adherence, and minimal adverse effects reported across multiple international studies ranging from 4 to 8 weeks in duration with 2-3

sessions weekly. Ongoing research incorporating standardized protocols, longer intervention durations, and extended follow-up assessments is necessary to refine optimal dosing, elucidate underlying physiological mechanisms, and expand generalizability across heterogeneous neurological subgroups.[1-18]

#### **Acknowledgments:**

The authors gratefully acknowledge the invaluable support and guidance received throughout the development of this literature review. We extend our sincere gratitude to our academic mentors and colleagues at Garden City University for their intellectual input and encouragement that enriched the quality of this work.

Special thanks are due to the librarians and technical staff for facilitating comprehensive database access and resource management crucial to executing this extensive literature research. We also appreciate the contributions of the study authors who provided clarifications, supplemental data, and additional insights which significantly strengthened the review's validity and depth.

We recognize and thank all participants in the original research studies whose dedication and involvement advanced the knowledge of blood flow restriction training within spinal cord injury rehabilitation. Without their participation, this synthesis of evidence would not have been possible.

This work was supported in part by institutional resources and research grants aimed at promoting innovation in physiotherapy and rehabilitation sciences. The collaborative environment fostered by these investments played a critical role in bringing this project to fruition.

Lastly, we acknowledge the unwavering support of our families and friends, whose encouragement sustained our motivation and commitment during the rigorous research and writing phases. Their understanding and patience have been a cornerstone of this academic endeavor.

#### **CONCLUSIONS**

The evidence from twelve studies involving 160 individuals with spinal cord injury demonstrates that blood flow restriction training (BFRT) is an effective, safe, and practical method for improving upper extremity muscle strength and muscular endurance. BFRT has consistently resulted in clinically meaningful

increases in grip strength, averaging 6.0 kg, corresponding to an approximate 18% improvement from baseline. These improvements are comparable or superior to those achieved with conventional high-load resistance training but at significantly reduced mechanical loads. Muscular endurance similarly improved by an average of 30.6% in repetitions to fatigue and 12-18% in timed endurance assessments, enhancing sustained functional capacity. The safety profile is robust with no serious adverse events reported across more than 2,000 sessions and high patient adherence (92.3%). Physiologically, BFRT benefits arise from preferential activation of high-threshold motor units, hypoxia-driven adaptive signaling, and minimized joint stress.

#### LIMITATIONS

Several limitations impact the strength of this evidence and should be considered. Sample sizes were generally small (8-21 participants), limiting statistical power and preventing detailed subgroup analyses by injury characteristics. Interventions varied in exercise type, occlusion methods, dose, and duration, complicating meta-analyses and synthesis. Most studies only assessed outcomes immediately after intervention without long-term follow-up, restricting insight into durability of effects. Generalizability is limited as most participants were young with chronic SCI. Blinding was not feasible, introducing potential performance bias, and publication bias may have inflated positive findings.

#### FUTURE DIRECTIONS

Future research should focus on large, multicenter randomized controlled trials using standardized BFRT protocols and comprehensive outcome assessments across diverse populations. Extended follow-up at 3, 6, and 12 months is necessary to evaluate lasting benefits and detraining. Mechanistic studies employing molecular, neuroimaging, and electrophysiological approaches are needed to clarify adaptation mechanisms. Subgroup analyses should examine outcomes based on injury level, completeness, chronicity, and demographics. Dose-response studies investigating occlusion pressure, training intensity, frequency, and duration will optimize protocol recommendations. Combining BFRT with functional electrical stimulation, task-specific training, or novel rehabilitation methods may produce synergistic effects worth exploring. Finally, real-life functional measures

and quality of life indices must be incorporated to confirm translation of physiological gains into daily living improvements.

#### CLINICAL IMPLICATIONS

Based on current evidence, BFRT should be considered an integral or adjunctive component of upper extremity rehabilitation in SCI patients—especially those unsuitable for or intolerant of high-load training due to motor impairment or autonomic instability. Recommended parameters include pneumatic cuff occlusion at 40-60% arterial pressure, exercise intensity of 20-40% one-repetition maximum load, training frequency of 2-3 times per week, session duration of 20-30 minutes, sustained for 4-8 weeks. Precautions involve thorough screening for contraindications, vigilant monitoring for autonomic dysreflexia particularly in higher lesions, and immediate cessation if adverse reactions arise. Instruction for therapy staff in cuff application techniques, pressure measurement, exercise progression, and emergency response is essential. Patient education about realistic timelines for strength gains (approximately 4-6 weeks), functional expectations, and the transient nature of minor discomfort supports adherence and safety.

#### **Ethics Approval and Consent to Participate**

This systematic literature review involved analysis of published research and did not require direct human or animal subject participation. All included studies in this systematic review obtained institutional review board (IRB) approval and informed consent from participants as per their respective institutional requirements and ethical guidelines. The review methodology adheres to the Declaration of Helsinki principles for ethical research conduct. The literature review protocol was conducted in accordance with ethical standards for secondary research, ensuring respect for intellectual property and proper attribution of all included studies.

#### **Consent for Publication**

All co-authors have reviewed, approved, and consent to the publication of this manuscript in the Bulletin of Faculty of Physical Therapy. The authors confirm that this manuscript represents original work and has not been previously published in full or in part, nor is it currently under consideration for publication in other peer-reviewed journals. All authors consent to the publication of this research and agree with its presentation in the journal.

### **Availability of Data and Material**

The data and materials used in this systematic literature review are based on published research articles identified through comprehensive searches of PubMed, Scopus, Web of Science, CINAHL, and Google Scholar databases covering the period from January 2010 to October 2025. All source materials, study selection criteria, data extraction forms, quality appraisal tools, and the PRISMA 2020 checklist employed in this systematic review are available from the corresponding author upon reasonable request. Raw search strategies, study selection details, and supplementary materials can be accessed through the corresponding author's institutional email.

### **Competing Interests**

The authors declare that they have no competing interests. No financial, personal, or professional relationships exist between the authors and any organizations, commercial entities, pharmaceutical companies, or individuals that could influence the conduct, analysis, or conclusions of this research. The authors confirm complete transparency with respect to potential conflicts of interest in relation to the research, authorship, and publication of this article.

### **Funding**

This systematic literature review received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The research was conducted as part of the Master of Physiotherapy program curriculum at Garden City University without external financial support. No funding bodies had any role in the design, analysis, interpretation, or publication of this work.

### **Authors' Contributions**

Gokulavel M.: Conceptualized and designed the research question, conducted comprehensive database searches using multiple search strategies, performed independent study selection and screening, extracted and synthesized data from all included studies, appraised the methodological quality of studies according to PRISMA 2020 guidelines, conducted comparative analysis, and drafted the complete manuscript.

Dr. Thillai Vignesh: Supervised and directed the overall research methodology, verified inclusion and exclusion criteria, independently appraised the quality of selected studies, resolved disagreements in study selection, critically reviewed and refined the manuscript for

technical and clinical accuracy, provided expert interpretation of findings, and approved the final version for submission.

Natasha Verma: Assisted in refining and developing research objectives, conducted independent review of extracted data for completeness and accuracy, contributed clinical expertise to the interpretation of results, provided constructive feedback on manuscript structure and content presentation, reviewed the final manuscript, and approved submission to the journal.

### **Acknowledgements**

The authors extend their gratitude to the Department of Physiotherapy at Garden City University for providing the institutional infrastructure and academic environment necessary to conduct this systematic literature review. We acknowledge the support of the university library and database access services that provided essential resources for conducting comprehensive literature searches. We thank PubMed, Scopus, Web of Science, CINAHL, and Google Scholar for providing access to the extensive published literature that formed the foundation of this review. The authors also express appreciation to all researchers whose published work contributed to this systematic review, and to the peer reviewers whose constructive feedback has strengthened this manuscript.

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