

Potential Therapeutic Effects of Passive Limb Movement in Patients with Spinal Cord Injuries

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Abstract

Spinal cord injuries (SCI) lead to significant changes in autonomic function, hemodynamics, and body composition. These structural and functional alterations are closely associated with the development of cardiovascular pathologies and other metabolic diseases. Recent clinical studies suggest that passive limb movement (PLM) has beneficial effects on cardiovascular function and skeletal muscle health, which has drawn a growing interest for the use of PLM as a therapeutic option for patients with SCI. However, there is a lack of mechanistic studies that examine the underlying mechanisms of how PLM may ameliorate cardiovascular and skeletal muscle function in patients with SCIs. In this review, we will discuss potential mechanisms of SCI-induced perturbations in autonomic function, hemodynamics, and body composition. Furthermore, we will highlight the therapeutic effects of PLM on autonomic function, vascular structure and function, and skeletal muscle in patients with SCIs. Additionally, we will also introduce the effects of other passive therapeutic interventions such as vibration and massage therapy with potential benefits and concerns for cardiovascular and skeletal muscle adaptations in SCI. Therefore, optimizing the application of PLM in patients with SCIs may be useful to salvage SCI-induced attenuations in vascular function and body composition.

Abbreviations

SCI = Spinal Cord Injury, PLM = Passive Limb Movement, CVD= Cardiovascular Disease, ANS = Autonomic Nervous System, WBV = Whole Body Vibration

Introduction

There are between 250,000 and 500,000 new spinal cord injuries (SCIs) reported worldwide every year¹. Unfortunately, ~80% of SCIs occur in those between the ages of 15-35 years. Given that SCIs happen relatively early in life, it has been reported that this population may have a greater propensity to develop cardiovascular diseases (CVDs) and have reduced quality of life. Additionally, according to the Center for Disease Control and Prevention, CVDs are the leading causes of death among patients^{2,3} with SCI.

SCIs are reported to have a complicated symptomology because of variation in the level of injury to the spinal cord. Generally, it has been reported that patients with SCI have sensory and motor nerve impairment and autonomic nervous system (ANS) dysfunction, which limits functional mobility, and increases the risk of developing

metabolic dysfunctions and vascular maladaptations⁴. The ANS is the major regulator for hemodynamics, heart rate, blood pressure, and respiration. Impairments of the ANS have been known to increase the prevalence of both arterial hypo- and hyper-tension, brady- and tachy-cardia, and autonomic dysreflexia,⁵ which may prevent patients with SCI from engaging in regular physical activity and may lead to significant changes in body composition and vascular health⁶.

The increased incidence of CVDs among those with SCIs may be partially attributed to decreased physical activity, prolonged periods of immobility, muscle atrophy, increases in intramuscular fat, and vascular maladaptations^{7,8}. Therefore, devising methods to target higher levels of physical activity and the subsequent changes in muscular and vascular environments may serve to provide protective effects against the development of CVDs in this population. Physical activity and exercise training programs have been shown to be clinically effective modalities to reduce CVD risk in those with SCIs⁹. Although physical activity and exercise guidelines already exist for patients with SCIs, most of these guidelines focus on only upper limb movements that are adapted from guidelines for non-SCI individuals¹⁰. Furthermore, many patients with SCIs suffer from upper limb pain and experience upper body muscle injuries¹¹. Therefore, there is a need for exercise training protocols and modalities that target the lower limbs, which may promote autonomic function, improve hemodynamics, and prevent cardiovascular and metabolic maladaptations. Recently, passive limb movement (PLM) has been used to improve hemodynamics in the lower limbs in those with SCIs and in healthy people during prolonged sitting. Therefore, we and others reported that PLM may be an effective, cost-efficient, and accessible intervention to improve vascular function^{12,13}. Therefore, in this review, we will discuss the potential beneficial effects of PLM on central and local autonomic function, hemodynamics, body composition, and potential application for patients with SCIs.

Autonomic Function

SCIs often results in various levels of ANS dysfunction. The degree of ANS dysfunction is highly dependent on the level of injury to the spinal cord. For example, those with cervical SCIs often exhibit greater ANS dysfunction than those with thoracic SCIs¹⁴. This dysfunction is usually characterized by an imbalance between sympathetic and parasympathetic nervous system activity. Intraspinous sympathetic fibers are anatomically or physiologically disrupted during an SCI and can lead to reduced vascular tone and hyperactivity of the parasympathetic nervous system⁷. This loss of synergy is especially common in patients with cervical or high thoracic SCIs¹⁵. For example, injuries occurring in the cervical spine (C1-C8) disrupt

supraspinous control to the heart, and injuries occurring in the upper thoracic spine (T1-T5) affects sympathetic outflow to the heart; however, injuries occurring in the lower thoracic spine (T6-T12) leave sympathetic control to the heart intact¹⁶.

The development of ANS dysfunction in patients with SCIs can be subdivided into acute and chronic phases. In the acute phase of SCI, the pre-dominance of parasympathetic nervous system activity can result in bradycardia, hypotension, poikilothermia, bradyarrhythmia, and vascular stasis. In the chronic phase, patients with SCI can maintain stable cardiac function but continue to have impaired cardiovascular reflexes and are prone to other complications. These complications manifest themselves in the form of impaired transmission of cardiogenic pain, and cardiac atrophy.

For both the acute and chronic stages, patients with SCIs demonstrate an inability to adequately regulate and maintain blood pressure through neurogenic pathways. The neurogenic pathways, through the baroreceptor reflexes (afferent nerves, vasomotor system, intraspinal sympathetic system and extra spinal postganglionic outflow), are responsible for short term regulation of blood pressure. In patients with SCIs these regulatory mechanisms are defective or nonoperative because of central interruptions of the descending intraspinal sympathetic pathways⁴ and leads to autonomic dysreflexia, which becomes a medical emergency that can cause seizures, myocardial infarction, intracranial bleeding, and even death^{17,18}.

Although the number of studies investigating the effects of PLM on blood pressure regulation and autonomic dysreflexia in those with SCIs are scarce, there are studies that have investigated this in healthy individuals. Shi et al. aimed to identify the autonomic nervous system response to PLM in healthy individuals¹⁹. Results showed that PLM leads to the suppression of sympathetic nervous system activity and vagal activity achieves dominance. Similarly, Fouladi et al. reported that PLM can decrease the sympathetic control and increase parasympathetic control of heart rate²⁰. Doherty et al. found a reduction in leg muscle sympathetic nervous activity and a reduction of sympathetic baroreceptor sensitivity after an acute bout of PLM²¹. Matsui et al. also showed that PLM can decrease vasomotor tone without the abrupt changes in heart rate and arterial blood pressure²². Combining the results of these previous studies, PLM may be a viable and useful intervention to increase leg blood flow in those with SCIs^{12,23}. Furthermore, PLM may not trigger abrupt changes in heart rate or blood pressure that could ultimately lead to episodes of autonomic dysreflexia.

Clinically relevant animal models have also been used to investigate the effects of PLM on blood pressure regulation

and autonomic dysreflexia. West et al. reported that passive cycling stabilizes resting blood pressure and prevents maladaptive cardiac remodeling in rodents with T3 SCIs²⁴. West et al. also reported that one month of passive leg cycling can reduce autonomic dysreflexia severity in rats with high-thoracic SCIs²⁵. To confirm if these results can be translated to humans, there is a need for future studies that examine the effects of lower-limb passive cycling on cardio-autonomic profiles in patients with SCIs and/or other clinical populations with autonomic dysreflexia.

Another possible outcome due to ANS dysfunction is the prevalence of sleep apnea and sleep disordered breathing. Sleep apnea has been associated with an increased risk of hypertension, coronary artery disease, stroke, and heart failure²⁶. Sleep apnea is very common within the SCI population with over 80% of tetraplegics suffering from some sort of sleep disordered breathing,²⁷ however sleep apnea is underdiagnosed and therefore remains untreated in patients with SCI²⁸. Studies have shown that sleep disordered breathing could be a confounding variable for rehabilitation interventions in patients with SCI²⁹. Therefore, future studies investigating PLM or other rehabilitation modalities should screen for sleep disordered breathing to see the outcomes of their intervention more accurately.

Hemodynamics

Due to paralysis below the SCI and subsequent disuse of the lower limbs, arterial function may deteriorate in patients with SCI. Previous studies suggest there may be arterial remodeling in the paralyzed limbs that occurs within weeks after an SCI³⁰. These alterations are characterized by significant reductions in systemic blood volume,³¹ and a consequent inward remodeling of the arterial wall,³² such that the diameter of the common femoral artery is 30-50% smaller³³⁻³⁶ and resting blood flow in the leg is 30-40% lower than in individuals without an SCI^{36,37}. These structural and functional adaptations most likely reflect the reduced physical activity and metabolic demand. Even though there is relatively little change in blood flow with respect to muscle mass, improvement of lower-limb circulation is very important, since poor lower limb circulation and venous stagnation can lead to deep vein thrombosis³⁸.

Many patients with SCIs experience a loss of supraspinal sympathetic control, which may cause impaired vasoconstriction capacity of the peripheral arteries¹⁵. Although reduced leg vascular resistance has been reported in some patients with SCIs,³⁹ the majority of studies have reported an increase in leg vascular resistance. Increased vascular resistance may be due to altered vasomotor control and impaired peripheral vascular vasoconstriction function. Sympathetic hypoactivity following high thoracic or cervical SCI causes a reduction in level of epinephrine and norepinephrine at rest and during exercise,⁴⁰ which may attenuate vasoconstriction in the peripheral vasculature.

Another likely contributor to vascular dysfunction in those with SCIs is physical inactivity. The effects of physical inactivity on healthy individuals have been previously investigated using horizontal bed rest as a model of inactivity^{32,41}. They reported a reduction in femoral artery diameter, blunted endothelial function, increased shear stress, and increased peripheral resistance⁴².

Previous studies with healthy individuals report that increased muscular contraction by voluntary exercise alters the structure and vasomotor properties of the arterial system. Interestingly, in healthy individuals, non-voluntary muscular contraction such as PLM also elicits a significant transient hyperemic response in the femoral artery⁴³. The increased hyperemic response by PLM may be explained by both central and peripheral mechanisms including stimulation of group III muscle afferents,⁴⁴ increased stroke volume due to increased venous return⁴⁵, and nitric oxide-mediated vasodilation⁴⁶. However, due to SCIs, afferent feedback to the cardiorespiratory control center may be absent. Thus, hyperemic responses in SCI may be solely due to peripheral factors⁴⁷. Venturelli et al. investigated the effects of PLM induced hyperemia in patients with SCIs and healthy individuals¹³. The results show that PLM induces a greater increase in leg blood flow in healthy individuals compared to those with SCIs. However, after normalizing leg blood flow to muscle volume there was evidence of preserved vascular function. A comparison of leg blood flow in the passively moved and stationary leg showed that 35% of the hyperemic response resulted from increased cardiac output and heart rate in healthy individuals, whereas the hyperemic response in those with SCIs appeared to have a peripheral origin¹³. Soriano et al. reported an increase in the activity of the cardiorespiratory system and improved femoral endothelial function after 10 minutes of PLM in tetraplegics⁴⁸. Muraki et al. examined the cardiovascular responses at the onset of PLM in patients with SCIs who have intact cardiac sympathetic innervation compared to healthy individuals⁴⁹. The results showed a significant increase in cardiac output for both groups. Heart rate increased rapidly in healthy individuals during PLM, whereas the heart rate response was blunted in patients with SCIs. The blunted heart rate response at the onset of PLM in patients with SCIs is presumably due to the absence of skeletal muscle afferent feedback from the lower limbs. Ballaz et al. examined the acute peripheral hemodynamic response to PLM. The main finding of the study was that blood flow velocity in the femoral artery increased by 30%²³. Additionally, Burns et al. examined the hyperemic response due to PLM in paraplegics¹². Nine patients with SCI performed five sets of 1-min bouts of PLM with 1-min recoveries. There were no changes in heart rate or mean arterial pressure, however, femoral artery blood flow and skin blood flow increased. PLM may be a clinically significant modality to improve circulation and reduce the

risk of deep vein thrombosis. Future research is needed to evaluate the potential for PLM to improve long-term cardiovascular health for patients with SCIs. The effects of PLM are summarized in Table 1.

Body Composition

Those with SCIs tend to exhibit alterations in body composition^{7,50-52}. Specifically, those with SCIs have a higher percentage of fat mass and lower percentage of fat-free mass in the lower-limbs compared to healthy individuals⁵³.

These maladaptations are typically due to paralysis, which causes the loss of volitional muscle contractions, tissue metabolic impairments, and vascular hypotrophy. Monroe et al. previously reported that patients with SCIs have reduced total energy expenditure, a lower resting metabolic rate, and a diminished thermic effect from physical activity and food intake⁵⁴. Reduced skeletal muscle mass in the face of unchanged dietary habits, in conjunction with reduced physical activity results in an unhealthy balance between caloric intake and energy expenditure⁵⁵.

Table 1 : Summary of Effects of Passive Limb Movement Therapy

Year	Author	Model	n	AIS	Severity of SCI	Level of Lesion	Age	Sex	Intervention	Outcomes
2014	West	Winstar Rats	21	A	C	T3	9 weeks	Male	Passive Hind-Cycling 2x 30 min/day, 5 days/week for 4 weeks beginning 6 days post- SCI	Maladaptive Cardiac Remodeling ↓ Blood Pressure ←→
2016	West	Winstar Rats	45	A	C	T3	NA	Male	Passive Hind-Cycling 2x 30 min/day, 5 days/week for 4 weeks beginning 6 days post- SCI	Autonomic Dysreflexia Severity ↓
2014	Venturelli	Humans	8	A	C	T6-T12	42 ± 8 years	Male & Female	2 minutes of passive knee extension at 1 Hz	Preserved Vascular Function when Normalized to Muscle Volume
2022	Soriano	Humans	11	A-C	9 C, 2 I	C3-C7	40 ± 10 years	Male & Female	10 minutes of cycling at 29 ± 1 rpm	Cardiorespiratory Activity ↑ Femoral Endothelial Function ↑
2000	Muraki	Humans	6	A-B	C	T8-L1	49.2 ± 4.5 years	Male	Passive Leg Cycling for 6 min at 40 rpm	Cardiac Output ↑ Stroke Volume ↑
2007	Ballaz	Humans	15	A-C	13 C, 2 I	T3-L1	47 ± 8 years	Male & Female	Passive Leg Cycling for 10 min at 40 rpm	Femoral Blood Flow Velocity ↑
2018	Burns	Humans	9	A	C	T3-T11	46 ± 6 years	Male & Female	5x1 min bouts of passive knee extension/flexion at 1 Hz with a 1 min recovery period between each bout	Femoral Blood Flow ↑ Skin Blood Flow ↑
2016	Shi	Humans	30	Healthy	—	—	22.5 ± 2.3 years	Male & Female	Three 8-min trials of passive cycling at 5 cycles/min, 10 cycles/min, and 15 cycles/min	Sympathetic Nervous System Activity ↓ Vagal Activity ↑
1998	Matsui	Humans	9	Healthy	—	—	22.2 ± .34	Female	10 min of passive leg cycling at 17 rpm	Vasomotor Tone ↓
2019	Fouladi	Humans	22	Healthy	—	—	Men 22.8 ± 0.9 years; Women 21.8 ± 0.5 years	Male & Female	Passive leg movement for 3 min at 0.5 Hz	Sympathetic Control of HR ↓ Parasympathetic Control of HR ↑
2018	Doherty	Humans	25	Healthy	—	—	22 ± 3 years	Male & Female	1-2 min of single-leg passive leg cycling (50 revs/min)	Leg Muscle Sympathetic Activity ↓ Sympathetic Baroreceptor Sensitivity ↓

Castro et al. investigated the influence of SCIs on skeletal muscle cross-sectional area within the first 6 months of injury. Within 6-weeks after an SCI, skeletal muscle cross-sectional area was decreased by 24% and 12% in the gastrocnemius and soleus, respectively. The quadriceps femoris, hamstring muscles, and adductor muscles also showed decreases in cross-sectional area of 16%, 14%, and 16%, respectively. After 24 weeks, the average cross-sectional area of atrophied muscles in the SCI group was 45-80% lower than age- and weigh-match non-SCI controls⁵⁶. In addition to a reduction in muscle mass, a reduction in bone mineral density has also been observed in SCI⁵⁷⁻⁵⁹. In general, there was no difference in total body bone mineral density between patients with SCI and healthy individuals⁶⁰. However, there was a significant reduction in bone mineral density in the lower limbs of patients with SCI⁶⁰. Furthermore, loss of skeletal muscle mass in the upper limbs is more common in tetraplegics. However, in paraplegics this trend seems to be inverted for the upper-limbs⁶¹. Patients with paraplegia showed higher bone mineral density in the upper-limbs and this could be due to the constant reliance of their arms for daily tasks and wheelchair use⁸. Key factors for the loss of bone mineral density in patients with SCI may be attributed to the absence of gravitational load on the lower limbs, whereas the differences in fat mass could be due to changes in activity/movement⁶⁰.

Singh et al. investigated changes in body composition in patients with SCIs over the course of a year. The authors observed a decrease in bone mineral content and lean body mass with an increase in adiposity during the first year of SCI⁶². Spungen et al. explored changes in body composition between healthy males and males with SCIs. The study reported that patients with SCIs had less lean mass and more adipose tissue⁶¹. Interestingly, they also found that tetraplegics had lower lean tissue and a higher fat percentage in the upper limbs and trunk compared to those with paraplegia. This could indicate that tetraplegics are at the greatest risk for detrimental changes in body composition. Spungen et al. also examined the effect of paralysis on body composition. For this study, eight pairs of monozygotic twins, one twin in each pair with paraplegia, were recruited. Regionally, arm lean tissue mass was not different between the twin pairs, whereas trunk, leg, and total lean tissue masses were significantly lower in the paralyzed twin⁶³.

Skeletal muscle atrophy is accompanied by an increase in both the absolute and relative intramuscular fat cross-sectional area and other chronic health conditions including glucose intolerance, diabetes, and cardiovascular disease in patients with SCI⁶⁴⁻⁶⁶. Additionally, skeletal muscle oxidative capacity reflects the oxygen uptake and substrate utilization of skeletal muscle tissue, and it is

decreased after SCI or through reductions in physical activity in humans and rodents^{67,68}. Furthermore, the loss of mitochondrial density and function occur alongside muscle atrophy after the onset of paralysis⁶⁹. More research is needed to evaluate the effects of PLM on mitochondrial function and density in patients with SCI.

While the number of studies investigating the effects of PLM on body composition in SCI patients are scarce, different patient populations have been investigated. Jigjid et al. evaluated the effects of PLM on muscle oxygenation level and electromyographic activity in the lower limbs of chronic stroke patients. Results showed that PLM have the capacity to enhance oxygen metabolism and muscle activity even in the paretic lower limb⁷⁰. While this study only investigated the acute effects of PLM, the increases in muscle oxygen metabolism and muscle activity may lead to changes in body composition over time. Longitudinal studies are needed to fully evaluate the effects of PLM on body composition in patients with SCI.

Vascular Adaptations

A shortcoming of the studies that have investigated the effects of SCIs on muscle mass is that alterations in the vasculature were not studied in relation to these changes. Several other studies have reported that vascular atrophy occurs in this population. For example, femoral artery diameter size is 50% smaller than healthy individuals in both paraplegics^{33,71} and tetraplegics³⁴. Olive et al. compared femoral artery diameter size and reactive hyperemia with Doppler ultrasound in patients with SCIs and healthy individuals. They found that patients with SCIs had smaller muscle cross-sectional areas and volumes compared to healthy people. Femoral artery diameter and femoral artery maximal blood flow were also lower in patients with SCIs compared to healthy individuals⁶. However, when femoral artery diameter and blood flow were normalized by muscle volume, no differences were found between healthy individuals and patients with SCI. De Groot et al. assessed the time course of vascular adaptations to inactivity and paralyzes in humans. The authors concluded that vascular adaptations such as reduced common femoral artery diameter and blood flow are largely completed within 6 weeks of injury³⁶. De Groot et al. also assessed endothelial function in paralyzed limbs (legs) and chronically active limbs (arms) in patients with SCIs. The flow-mediated dilation technique was used to assesses endothelial function in the superficial femoral artery and the brachial artery. Results showed that patients with SCIs had reduced endothelial function in the inactive legs and preserved endothelial function in the active arms compared to healthy controls⁷². While some studies have investigated the changes in body composition of patients with SCIs both acutely and over time, little is known about the vascular structural and functional adaptations by PLM.

The effects of PLM on vascular structural adaptations such as artery size and angiogenic capacity have not been examined, nor have the effects of a reduced artery diameter and blood flow on muscular function during exercise. The SCI-mediated changes in body composition, such as the combination of increased fat mass, reduced skeletal muscle mass, and attenuated bone mineral density puts the SCI population at risk for the development of CVDs, diabetes⁷³, obesity⁵³, and inflammation⁷⁴. Creating modalities that can improve health in this population should be of upmost importance. Future research is needed to investigate the chronic effects of PLM on vascular structure and function in the lower limbs and body composition in patients with SCIs.

Other Potential Exercise Modalities

The SCI population has limited options for exercise training. Paraplegics are limited to upper-limb exercises and require help to perform lower-limb movements, whereas tetraplegics require assistance with any type

of movement. A limited selection of exercise protocols coupled with a sedentary lifestyle puts this population at the forefront for the development of cardiovascular and metabolic diseases. Potentially, passively inducible therapies including massage and vibration therapies may be beneficial for patients with SCIs.

Massage and vibration modalities involve the stimulation of soft tissues such as muscles, tendons, and ligaments. These therapies may be used to improve range of motion and attenuate muscle spasticity in patients with SCIs. Lovas et al. showed that a 30-minute muscle massage once a week for 5 weeks is enough to effectively reduce pain scores in patients with SCI⁷⁵. Diego et al. investigated the effect of massage therapy and further compared with exercise training, the results of this study suggested that massage therapy showed greater improvements in muscle strength and fine motor (wrist) range of motion than the exercise group in patients with tetraplegia⁷⁶. Massage therapy has been shown to reduce pain and fatigue in patients with SCI^{75,76} but the effects on vascular function and

Table 2: Summary of Effects of Massage/Vibration Therapy

2017	Lovas	Humans	39	NA	20 C, 19 I	NA	46 ± 11.6 years	Male & Female	Group 1: 30 min of Massage therapy Once/week for 5 weeks Group 2: 30 min of Guided Imagery once/week for 5 weeks	Pain Scores ↓
2002	Diego	Humans	20	NA	NA	C5-C7	39 ± 12.2 years	Male & Female	Group 1: Massage Therapy 2 times/week for 5 weeks. Group 2: Exercise Routine 2 times/week for 5 weeks	Muscle Strength ↑ Wrist Range of Motion ↑
2005	Bleeker	Humans	16	Healthy	—	—	34 ± 2 years	Male & Female	Group 1: Bed Rest Control Group 2: Bed Rest with resistive vibration therapy	Superficial Femoral Artery Diameter ↑ compared to control
2016	Menendez	Humans	17	A-B	C	C4-L1	49.9 ± 12.5 years	Male & Female	Group 1: WBV + FES for 12 weeks Group 2: Control	Blood Flow ↑ Popliteal Artery Resting Diameter ↑ Muscle Thickness ↑
2011	Herrero	Humans	8	A	C	C5-L1	36.1 ± 5 years	Male & Female	WBV at 3 different frequencies (10z, 20z, 30z) and protocol (continuous, fragmented)	Peak Blood Flow Velocity ↑
2009	Cotey	Humans	11	A-C	2 C, 9 I	C2-T4	32.4 ± 14.1 years	Male & Female	BWSTT + Vibration, 4 different vibration settings each 20 sec long	Muscle EMG Activity ↑
2022	Wong	Humans	16	C-D	I	C2-C7	55 ± 8 years	Male & Female	Group1: Moderate dose of WBV Group 2: High dose of WBV	Neuropathic Pain ↓ In Moderate Dose Group

Table 1: Summary of Effects of Passive Limb Movement Therapy, Functional Electrical Stimulation Therapy, and Massage/Vibration Therapy
 Abbreviations: AIS = American Spinal Injury Association Impairment Scale; C = Complete; I = Incomplete; NA = Not Available; FES = Functional Electrical Stimulation; HR = Heart Rate; EMG = Electromyography

BWSTT = Body Weight Supported Treadmill Training; CSA= Cross Sectional Area; WBV = Whole Body Vibration

body composition have not been thoroughly investigated, further research is needed to see the full potential of this intervention.

Wong et al. showed that whole body vibration (WBV) in moderate doses appears to decrease neuropathic pain symptoms and improve reflex modulation⁷⁷. In the Berlin Bed Rest Study, conducted by Bleeker et al., the effects of bed rest deconditioning on vascular function and structure of the lower limb conduit arteries were assessed in healthy men. Results showed that the 16% decrease in superficial femoral artery diameter in the control group was reduced to 5% when combined with vibration and resistance training.⁴² Menendez et al. showed that WBV coupled with electro-stimulation can increase blood flow and resting diameter of the popliteal artery as well as increase muscle thickness⁷⁸. Herrero et al. showed that WBV is an effective method to increase leg blood flow and muscle mass in patients with SCI⁷⁹. Cotey et al. showed that WBV coupled with body weight supported treadmill training is an effective modality to increase muscle activation of the paralyzed legs⁸⁰. Vibration therapy has been shown to increase vascular function and muscle mass,⁷⁹ but only when in conjunction with another modality⁸⁰. More research is needed to see the full efficacy of WBV on its own. The effects of massage and vibration therapies have been summarized in Table 2.

Conclusion

The ramifications of SCIs lead to significant changes in autonomic function, hemodynamics, and body composition that are closely associated with risks of CVDs. While many interventions have been introduced and applied to help ameliorate the negative repercussions of SCIs, some of these interventions are not accessible or appropriate for all patients with SCI. The majority of exercise training interventions consist of upper-limb voluntary muscular contractions and only limited types of passive limb exercise have been used to improve autonomic function, hemodynamics, and body composition. PLM such as passive leg cycle ergometry is shown to improve clinical outcomes such as improve vascular function and help increase circulation for patients with SCIs. PLM is easily reproducible, accessible, and cost-effective. Therefore, we suggested that PLM may be a clinically beneficial therapeutic modality for patients with SCIs.

Disclosures

No conflicts of interest, financial or otherwise, are declared by the authors.

Author Contribution

A.B.-A., S.K., Y.-H.A., and S.-S.P. prepared figures; A.B.-A., S.-Y.P., S.K., Y.-H.A., and S.-S.P. drafted manuscript; A.B.-A., C.P.A., S.-Y.P., S.K., Y.-H.A., and S.-S.P. edited and revised

manuscript; A.B.-A., C.P.A., S.-Y.P., S.K., Y.-H.A., and S.-S.P. approved final version of manuscript.

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