ACRM
AMERICAN CONGRESS OF
REHABILITATION MEDICINE

Archives of Physical Medicine and Rehabilitation

journal homepage: www.archives-pmr.org

Archives of Physical Medicine and Rehabilitation 2019;100:1184-90

SPECIAL COMMUNICATION

Improving Walking Ability in People With Neurologic Conditions: A Theoretical Framework for Biomechanics-Driven Exercise Prescription

Gavin Williams, PhD,[a,b] Leanne Hassett, PhD,[c,d] Ross Clark, PhD,[e] Adam Bryant, PhD,[b] John Olver, MD,[f] Meg E. Morris, PhD,[g] Louise Ada, PhD[c]

From the [a]Physiotherapy Department, Epworth Healthcare, Melbourne; [b]School of Physiotherapy, Faculty of Medicine, Dentistry and Health Sciences, The University of Melbourne, Melbourne; [c]Faculty of Health Sciences, The University of Sydney, Sydney; [d]The George Institute for Global Health, Sydney Medical School, The University of Sydney, Sydney; [e]School of Health and Sport Sciences, University of the Sunshine Coast, Sippy Downs; [f]Rehabilitation Medicine, Epworth Healthcare, Melbourne; and [g]Healthscope & School of Allied Health, La Trobe University, Melbourne, Australia.

Abstract

The purpose of this paper is to discuss how knowledge of the biomechanics of walking can be used to inform the prescription of resistance exercises for people with mobility limitations. Muscle weakness is a key physical impairment that limits walking in commonly occurring neurologic conditions such as cerebral palsy, traumatic brain injury, and stroke. Few randomized trials to date have shown conclusively that strength training improves walking in people living with these conditions. This appears to be because (1) the most important muscle groups for forward propulsion when walking have not been targeted for strengthening, and (2) strength training protocols have focused on slow and heavy resistance exercises, which do not improve the fast muscle contractions required for walking. We propose a theoretical framework to improve exercise prescription by integrating the biomechanics of walking with the principles of strength training outlined by the American College of Sports Medicine to prescribe exercises that are specific to improving the task of walking. The high angular velocities that occur in the lower limb joints during walking indicate that resistance exercises targeting power generation would be most appropriate. Therefore, we propose the prescription of plyometric and ballistic resistance exercise, applied using the American College of Sports Medicine guidelines for task specificity, once people with neurologic conditions are ambulating, to improve walking outcomes. This new theoretical framework for resistance training ensures that exercise prescription matches how the muscles work during walking.

Archives of Physical Medicine and Rehabilitation 2019;100:1184-90

Neurologic conditions cause a major personal, health, and economic burden.[1,2] The most common neurologic conditions that limit mobility across the lifespan are cerebral palsy in children, traumatic brain injury in young adults, and stroke in older adults. Cerebral palsy (CP) is defined as a group of permanent and nonprogressive disorders[3] and is the most common cause of movement disorders in children.[4] Traumatic brain injury (TBI) is the primary cause of disability in younger adults aged 15-45 years,[5] and road traffic injuries are already the third greatest cause of global morbidity and mortality with increasing prevalence as third world countries become increasingly mechanized.[6] Despite intensive rehabilitation, over 75% of survivors of moderate and severe TBI never return to full independence.[7] Stroke is the leading cause of disability in older adults.[4] As stroke mortality has fallen nearly 70% in the past 30 years, and the population ages, there are more people living with stroke in the community.[8] More than one-third of stroke survivors are disabled, and, by the end of the first year, around half still require assistance for activities of daily living.[9]

Improving walking is an important goal of movement rehabilitation.[10] In CP, TBI, stroke, and other neurologic conditions such as multiple sclerosis and Parkinson disease, muscle weakness and/or reduced power generation are the physical impairments limiting mobility.[11-14] Compelling high-quality evidence shows

---

Disclosures: none.

0003-9993/19/$36 - see front matter © 2019 by the American Congress of Rehabilitation Medicine
https://doi.org/10.1016/j.apmr.2019.01.003

that resistance training improves muscle strength in people with CP, TBI, and stroke.[15-17] As a result, resistance training has become a core component of rehabilitation programs for people with walking limitations. The Stroke Foundation guidelines and the US stroke guidelines both strongly recommend resistance training for people with muscle weakness. However, the guidelines recognize that the optimal strengthening protocol is not known, which may explain why improvements in muscle strength have not yet translated to reductions in activity limitations in people with stroke.

Although it is well established that resistance training can be effective at improving muscle strength, strength gains have not necessarily translated to improved walking outcomes.[15-17] Several theories have been proposed for the failure to translate greater muscle strength to improved mobility in people with neurologic conditions. They include (1) the training stimulus was too low,[18-20] (2) the strengthening programs were too short in overall duration,[19,20] or (3) failure to adhere to American College Sports Medicine (ACSM) guidelines for traditional resistance exercise.[18,20] However, the main problem is not that patients failed to improve their muscle strength (ie, the interventions did actually improve muscle strength), but that strength gains failed to translate to improved walking. Therefore, it is timely to consider the principles for the application of resistance training to improve muscle weakness that results in improving walking. The first aim of this paper was to align the biomechanics of walking with exercise prescription. The second aim was to use the ACSM guidelines for task-specific and ballistic resistance training and muscle function for walking, to discuss exercises that are more likely to improve walking in people with neurologic conditions.

Gait and muscle function during walking

The key biomechanical features of walking have been established for decades.[21-23] An understanding of the range and speed through which the muscles move the major lower limb joints is fundamental to inform exercise selection during movement rehabilitation. How the muscles work (ie, type of contraction)[24] and at which phase of the walking cycle they are active are important considerations when prescribing resistance exercises. Muscle architecture also influences motor performance, particularly in relation to the calf and Achilles complex[25] where the tendon plays a major role in energy storage and release. Muscle features, function, and role may inform the selection and application of resistance exercises.[26-28]

Resistance training for the purpose of improving walking appears to be most effective when it is task-specific.[29] Task-specificity is a key principle of resistance training programs[30] and means that the resistance exercises prescribed should reflect how the muscles perform during walking. The ACSM guidelines outline key aspects to consider when designing and implementing a resistance training program.[30] The ACSM guidelines state that "all training adaptations are specific to the stimulus applied," and the "most effective resistance training programs are those that are . . . . specific."[30(p.688)] This concept of specificity of resistance training considers factors such as (1) the muscle groups that are targeted, (2) the range of motion through which the movement is performed, (3) the speed of movement, and (4) the muscle actions involved.

List of abbreviations:

ACSM	**American College of Sports Medicine**
CP	**cerebral palsy**
TBI	**traumatic brain injury**

A prerequisite amount of muscle strength is required in all lower limb muscle groups to walk even if they do not directly contribute to forward propulsion. For example, the hip abductors are responsible for pelvic stability in the coronal plane during stance phase, and the ankle dorsiflexors contribute to foot clearance in swing phase.[23] However, if the goal is to improve walking speed in already ambulatory patients, then it is reasonable to assume that the main muscle groups that provide the majority of muscle power generation for forward propulsion should be targeted. Overall, there are 3 main contributors to power generation for forward propulsion during walking and 2 main contributors to power absorption.[21-23,31] They include the following (fig 1): hip extensor power generation in early stance (H1); ankle plantar flexor power generation in late stance (A2); hip flexor power generation at toe-off (H3); knee extensor power absorption in late stance (K3); knee flexor power absorption in late swing (K4).

Once people with neurologic conditions are ambulatory, weakness in these muscle groups can be disproportionately disabling because of their specific role during the gait cycle.[32] In order to optimize exercise prescription so that there will be translation into faster walking speeds, the exercises prescribed need to not only target the muscles that are most likely to contribute to forward propulsion, but also replicate the type of muscle action in the relevant phase of the walking cycle.

Ankle power generation at push-off supplies >60% of all the power generated for forward propulsion during walking.[33] Because the ankle joint and calf muscle are so important for forward propulsion and walking speed, we focus on this region to explain how the relevant biomechanics may influence exercise selection in neurologic conditions. For example, after midstance the ankle moves from 5° dorsiflexion to 20° plantar flexion for push-off, plantar flexing at >300°/s during push-off at normal walking speeds.[34] However, few people with neurologic conditions walk at normal speeds (ie, 1.3-1.4 m/s), perhaps because they cannot achieve high angular velocity at the ankle joint while under load, as occurs at push-off.[34,35] It can be argued that a training program designed to improve ankle power generation for push-off should include loaded exercises at high angular velocities to improve walking speed.

In addition to the range of motion and angular velocity through which the ankle joint works, an understanding of muscle action may also influence exercise selection to improve walking. For example, at the ankle, after the brief plantar flexion following initial contact, the ankle dorsiflexes slowly during most of stance phase followed by rapid plantar flexion at push-off. Although eccentric lengthening occurs in the calf muscle-tendon unit during stance phase at the ankle joint, the muscle fascicles do not lengthen. The majority of the eccentric lengthening and elastic recoil occurs in the Achilles tendon and aponeurosis.[36-38] This allows for energy storage and release in the Achilles tendon. As such, the majority of ankle power generation for push-off (approximately 80%) comes from the lengthening and elastic recoil of the Achilles tendon.[39] Consequently, the role of the Achilles tendon during walking has been likened to a spring or catapult action[31,36-38] and suggests that exercises performed rapidly while under load may be appropriate. The key criteria to be considered when designing and implementing an exercise targeted toward strengthening the calf muscles for walking are muscle action, active range of motion, and ankle joint angular velocity (table 1).

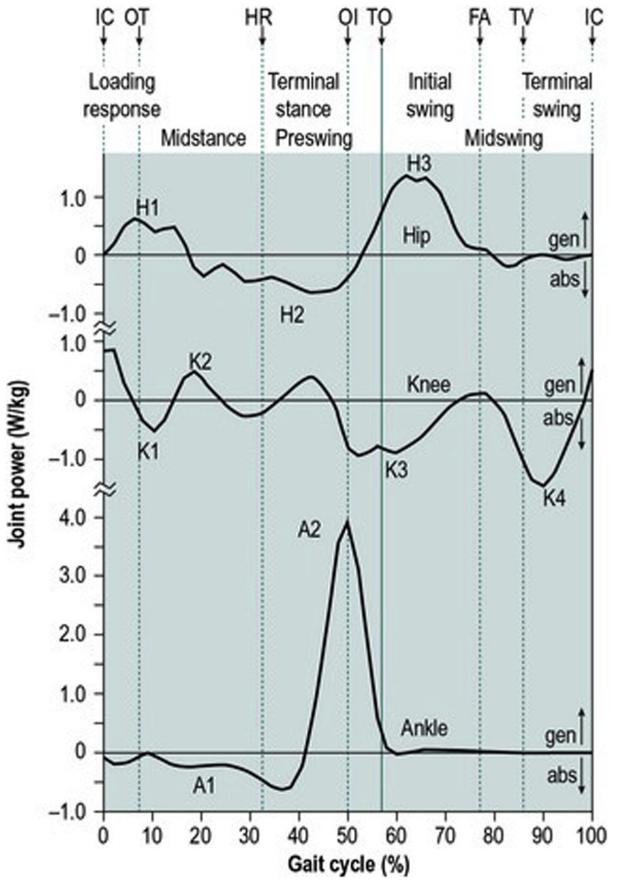

Fig 1 Lower limb muscle power generation and absorption during walking. NOTE. Figure reproduced from Whittle MW.[23(p60)] Copyright Elsevier. H1-H3, K1-K4, and A1-A2 refer to the peaks of power generation and absorption for the hip, knee, and ankle joints, respectively. Abbreviations: FA, feet adjacent; HR, heel rise; IC, initial contact; OI, opposite initial contact; OT, opposite toe-off; TO, toe-off; TV, tibia vertical.

Rationale for ballistic training to improve walking

Power generation is essential for walking. The standard definition of power is:

Power = Force × Velocity

As such, it is possible to increase power by increasing only the force, only the velocity or both the force and velocity. This is important in the context of prescribing exercises because traditional resistance training is typically relatively high load (force), with less focus on the speed of movement (velocity), which is typically slow.[30] In contrast, plyometric training typically focuses on optimizing the speed of movement (velocity) and consists of explosive movements performed as quickly as possible with a major focus on rapid reactive contacts.[41] Plyometric training is typically used in sports where fast or jumping movements are required.[41] However, the actual load used for the exercise (force) is usually less than used in traditional resistance training. To improve power generation for walking in a neurologic population with muscle paresis, exercise prescription may need to target higher velocities as well as higher force.[23] Therefore, traditional resistance and plyometric training performed in isolation may be suboptimal for translation to optimal muscle performance for walking. This may be solved by the application of ballistic training. Ballistic training focuses on optimizing the power generated during the movement by balancing the force and velocity and is a term used to describe loaded exercises (force) that are performed as rapidly as possible (velocity) with the intention to propel a load into free space.[41] This propulsion can consist of throwing the load away from the body, for example, throwing a medicine ball at a wall, or propelling the body itself, for example, jumping into the air with a barbell on the shoulders.

Table 1 Ankle joint and calf muscle function for push-off during walking[21,22,38,40]

Biomechanical Feature	During Push-Off Phase
Muscle action	Eccentric* to concentric
Active range of motion	10° DF to 20° PF
Ankle joint angular velocity	≈300°/s
Load	Reducing from 100% BW

Abbreviations: BW, body weight; DF, dorsiflexion; PF, plantar flexion.
* Eccentric refers to the joint motion rather than a change in muscle fascicle length.

Ballistic exercises are commonly prescribed when the goal is to improve muscle power generation for sporting situations that are not necessarily reliant on using the stretch-shortening cycle.[41] Plyometrics, such as drop jumps, are prescribed to increase repeated rapid jumping ability (eg, during rebounding a basketball); ballistic training is prescribed to improve leg power (eg, during tackling in rugby). The theoretical advantage for prescribing ballistic resistance training over traditional resistance exercise for walking can be demonstrated when considering the role of the calf muscle during gait. When speed is introduced to a resistance exercise, such as in ballistic resistance training, more emphasis is placed on the rate of force production vs the maximum force to allow for propulsion.[41] In the context of gait, power is described in terms of generation and absorption, with generation indicating positive work being done and absorption indicating negative work during the contraction. The high angular velocities that occur during the walking cycle indicate periods of rapid power generation and absorption.[23] Therefore, it is important to consider how quickly muscles have to generate force, not just how much force they can generate.

Hakkinen and Komi[40] reported force production for traditional and ballistic resistance exercise performance. They found that traditional resistance exercise was superior to ballistic for maximum force production, whereas ballistic resistance exercises were superior for rate of force development. When considering that the push-off phase in terminal stance occurs in ∼150 milliseconds,[23] considerably more force is produced in this brief period of time with ballistic compared with traditional resistance exercise.[40] These findings indicate that the application of traditional resistance exercise to the calf muscle, even if optimally performed, may fail to translate to greater ankle power generation at push-off and, therefore, faster walking speeds, because the benefits obtained from this type of resistance training may not be realized within the 150-millisecond time frame for push-off. However, ballistic resistance training for walking in adult and pediatric neurologic conditions has received little attention compared with traditional resistance exercises. Muscle power is rarely measured in studies that have used resistance exercises to improve walking, and exercises that target power generation or absorption are uncommon in resistance training protocols.[15]

Application of ballistic strengthening to improve walking

This following section illustrates how knowledge of the biomechanics of walking and the principles of resistance training as outlined by the ACSM[30] can inform the prescription of ballistic resistance exercises specific to walking.

Load

Compared with traditional resistance exercise, ballistic exercises are usually performed with lower resistance or load.[30] There are a range of potential options for implementing ballistic exercises for people with neurologic conditions to reduce resistance or load, particularly when their own body weight may be too much for their weak muscles. Harnesses for body weight support, hydrotherapy pools, AlterG treadmills, Pilates reformers, or leg sleds may be used to *de-weight* individuals. To highlight the application of the principles of traditional and ballistic resistance training for walking, 2 calf muscle exercises are described and contrasted. Calf raises are typically performed standing with the knees extended, the feet placed comfortably apart, weight evenly distributed, and through as much plantar flexion range as the person can generate. In contrast, the leg sled hop can be performed in an inclined supported position on the affected lower limb with the knee relatively straight (ie, not fully extended) while the person lands briefly on their forefoot and pushes off again to generate a flight phase (fig 2).[42-45] Load can be varied to accommodate weak muscles by shifting body weight away from the affected leg or using a body-weight harness during calf raises, or by lowering the inclination or adjusting the springs of the sled for the leg sled hop.

Active range of motion

Similarly, the active range of motion through which a person performs the exercise can also be varied, for example by using a wedge for calf raises, in order to target the active range of the ankle (10° dorsiflexion to 20° plantar flexion) for push-off.[23]

Muscle action

During the stance phase of walking, the calf muscle fascicles themselves barely lengthen, which allows for elastic energy storage and release in the Achilles tendon.[36,37] The leg sled hop exercise aims to replicate this action by maintaining forefoot contact so that the Achilles tendon can quickly store energy when landing and release it when pushing off. Use of the normal energy storage and release mechanism is time dependent, in other words, it will only occur if the contact time between the loading and push-off phase is very brief, replicating the 0.6 second for stance phase in normal walking. In contrast, muscle action during a calf raise is concentric during the heel raise, followed by eccentric when the heel is lowered. Although both resistance exercises target the calf muscle, the muscle actions during a calf raise and a leg sled hop differ.

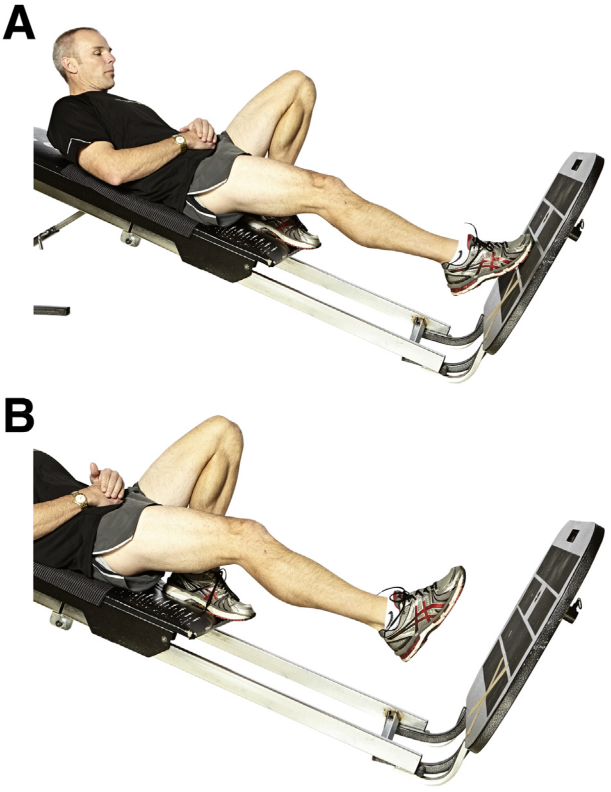

Fig 2 Hopping exercise performed on the leg sled.

Ankle joint angular velocity

Angular velocities ~300°/s plantar flexion occur during push-off at normal walking speeds and approximate 200°/s at slower walking speeds.[34] Calf raises are typically performed at slower angular velocities.[46] In contrast, higher angular velocities can be achieved when performing a leg sled hop, particularly if the natural energy storage and release mechanism of the Achilles tendon is incorporated as described before.[44] It is important to reduce the load when performing ballistic resistance exercises in order to provide the necessary conditions for energy storage and release in the Achilles tendon, which may then be used to replicate and train the rate of force production,[45] and subsequent power generation, required for walking. The leg sled can be adjusted and the proportion of body weight supported modified for the hopping task to replicate the high ankle joint angular velocities required for faster walking.

Progression

Another important aspect of resistance exercise implementation is how the exercises may be progressed as the person improves. The ACSM guidelines outline the principles of progression.[30] For example, if the goal is to improve maximum force, then the number of repetitions and sets remains similar, but the load or resistance is progressively increased as improvement occurs. Alternatively, if the goal is to improve the rate of force production or muscle power, then ballistic exercises are recommended to replicate the high angular velocities attained during walking. Initially, load is lowered to achieve higher angular velocities during training. Once higher angular velocities are achieved, the load is then increased.

Evidence for ballistic resistance training in neurologic conditions

The application of ballistic exercise for ambulatory people with neurologic conditions to improve walking speed is relatively novel and is not yet supported by Level I evidence. In comparison with studies using traditional resistance training, there have only been a handful of studies that have used ballistic training exercises in adult and pediatric cohorts.[45,47-51] Mehrholz et al[47] used jump training in the subacute phase following stroke in 6 people who required assistance to walk in the first attempt to use ballistic exercise in adults with a neurologic condition. They reported jump training was safe and feasible with severely disabled people with stroke. Walking speed and endurance improved, but there was no comparison group to evaluate whether the improvements reported were greater than those which may be expected in the rehabilitation phase after stroke.

Williams et al[45] compared the seated leg press and leg extension on a leg sled performed ballistically and nonballistically. When these exercises were conducted ballistically, the peak jump velocity and peak jump height were significantly greater, indicating higher rate of force production. Although only a small study ($n=11$) in a mixed adult neurologic cohort, this was the first report quantifying the rate of force generation in adults with neurologic conditions.

In 2 similar studies, Morgan et al[52] and Hunnicutt et al[53] used a slide shuttle for jump training, in 12 and 16 chronic stroke patients, respectively, for 24 sessions over 8 weeks. Both studies reported significant improvements in affected knee power generation using isokinetic dynamometry set at 40% of 1-repetition maximum as well as walking speed. Ankle power generation was not reported, and there was no control or comparison group. However, these 2 cohort studies were the first to report outcomes for muscle power generation following power training in an adult neurologic population.

Recently, Hendrey et al[48] reported the feasibility of a 6-week program of ballistic resistance exercises compared with usual care in a pilot randomized trial for 30 people after stroke. They reported that ballistic resistance training, using equipment that included a leg sled, was safe and feasible. Further, they reported greater peak jump height and peak propulsive velocity (indicating greater rate of force production) and significantly faster walking speed in the ballistic group.

In children, Johnson et al[49,50] investigated plyometric training in 2 small studies of 3 participants each. The 4 lower limb exercises included hopping and jumping tasks, but only the mildly disabled would be able to perform these exercises because they require people to jump or hop with full body weight. Although walking was not an outcome in these studies, both studies reported ballistic exercises to be safe and feasible. More recently, van Vulpen et al[51] implemented functional power training in 22 children with spastic cerebral palsy using 6 exercises that could best be described as task practice (eg, running, walking, stair climbing) in a multiple case series design. Exercises were performed quickly at 50%-70% of maximum performance, but these types of resistance exercises are only likely to be performed by mildly disabled people with neurologic conditions and are unlikely to be applicable to the majority of people with mobility limitations. The authors reported the exercises to be safe and feasible, and significant improvements were obtained in leg muscle strength, walking distance, and running speed. Muscle power generation was not recorded.

Future directions

There are several avenues requiring further development. Preliminary evidence suggests that ballistic resistance training may be safe and feasible, but future investigations need to determine whether ballistic resistance training is more effective than traditional resistance training and translates to superior mobility outcomes. Optimal loads and training protocols are currently unknown, and the clinician burden and time to administer ballistic resistance training is yet to be established. Finally, an understanding of the mechanism underlying changes associated with resistance training is vital for the development of this field. Further investigations are required to determine whether prioritizing higher rates of force development during resistance training leads to greater power generation and, therefore, faster walking speed. Although we have used the ankle joint and calf muscle to convey the theoretical framework within this paper, we believe these principles are equally applicable to the other muscle groups in the lower limb responsible for forward propulsion.

Summary

Despite decades of research showing its benefit in healthy and athletic populations, ballistic resistance training in order to improve walking in neurologic conditions is an emerging field. There is a sound rationale for why ballistic training may prove beneficial for improving walking. The evidence for ballistic resistance training for people with neurologic conditions is based on small cohort studies, and, although the exercises prescribed may be ballistic in nature, they have not necessarily been targeted toward the main contributors to power generation during forward propulsion. The theoretical framework for the selection and implementation of ballistic resistance exercises outlined in this paper has been developed by integrating the biomechanics of walking with the principles of strength training. This framework should facilitate the translation of increases in muscle strength into improved walking. However, in the absence of evidence that traditional resistance training has been effective at improving mobility in adult or pediatric neurologic populations, the application of resistance exercises needs to be reconsidered and alternatives explored. It may be that the best outcomes are achieved using a combination of traditional and ballistic resistance training,[54,55] and the greatest improvements will be observed when strengthening programs are prescribed that are specific to walking.

Keywords

Exercise; Gait; Neurology; Paresis; Physical and rehabilitation medicine; Rehabilitation

Corresponding author

Gavin Williams, PhD, Physiotherapy Department, Epworth Hospital, 89 Bridge Rd, Richmond, 3121, Victoria, Australia. *E-mail address:* gavin.williams@epworth.org.au.

References

1. Ma VY, Chan L, Carruthers KJ. Incidence, prevalence, costs, and impact on disability of common conditions requiring rehabilitation in the United States: stroke, spinal cord injury, traumatic brain injury, multiple sclerosis, osteoarthritis, rheumatoid arthritis, limb loss, and back pain. Arch Phys Med Rehabil 2014;95:986-95.
2. Tonmukayakul U, Shih ST, Bourke-Taylor H, et al. Systematic review of the economic impact of cerebral palsy. Res Dev Disabil 2018;80:93-101.
3. Rosenbaum P, Paneth N, Leviton A, et al. A report: the definition and classification of cerebral palsy April 2006. Dev Med Child Neurol Suppl 2007;109(Suppl 109):8-14.
4. Hirtz D, Thurman DJ, Gwinn-Hardy K, Mohamed M, Chaudhuri AR, Zalutsky R. How common are the “common” neurologic disorders? Neurology 2007;68:326-37.
5. Thurman D, Alverson C, Browne D, et al. Traumatic brain injury in the United States: a report to Congress. Atlanta, GA: Centers for Disease Control and Prevention; 1999.
6. Peden M, Scurfield R, Sleet D, et al. World Report on Road Traffic Injury Prevention. Geneva: World Health Organization; 2004.
7. Ponsford JL, Olver JH, Curran C. A profile of outcome: 2 years after traumatic brain injury. Brain Inj 1995;9:1-10.
8. Alterman DM, Heidel RE, Daley BJ, et al. Contemporary outcomes of vertebral artery injury. J Vasc Surg 2013;57:741-6 [discussion 6].
9. Ang KK, Guan C, Chua KS, et al. A clinical study of motor imagery BCI performance in stroke by including calibration data from passive movement. Conf Proc IEEE Eng Med Biol Soc 2013;2013:6603-6.
10. Bohannon RW, Andrews AW, Smith MB. Rehabilitation goals of patients with hemiplegia. Int J Rehabil Res 1988;11:181-4.
11. Wiley ME, Damiano DL. Lower-extremity strength profiles in spastic cerebral palsy. Dev Med Child Neurol 1998;40:100-7.
12. Allen NE, Canning CG, Sherrington C, et al. The effects of an exercise program on fall risk factors in people with Parkinson’s disease: a randomized controlled trial. Mov Disord 2010;25:1217-25.
13. Williams GP, Schache AG, Morris ME. Mobility after traumatic brain injury: relationships with ankle joint power generation and motor skill level. J Head Trauma Rehabil 2013;28:371-8.
14. Nadeau S, Arsenault AB, Gravel D, Bourbonnais D. Analysis of the clinical factors determining natural and maximal gait speeds in adults with a stroke. Am J Phys Med Rehabil 1999;78:123-30.
15. Williams G, Kahn M, Randall A. Strength training for walking in neurologic rehabilitation is not task specific: a focused review. Am J Phys Med Rehabil 2014;93:511-22.
16. Dorsch S, Ada L, Alloggia D. Progressive resistance training increases strength after stroke but this may not carry over to activity: a systematic review. J Physiother 2018;64:84-90.
17. Moreau NG, Bodkin AW, Bjornson K, Hobbs A, Soileau M, Lahasky K. Effectiveness of rehabilitation interventions to improve gait speed in children with cerebral palsy: systematic review and meta-analysis. Phys Ther 2016;96:1938-54.
18. Ada L, Dorsch S, Canning CG. Strengthening interventions increase strength and improve activity after stroke: a systematic review. Aust J Physiother 2006;52:241-8.
19. Morris SL, Dodd KJ, Morris ME. Outcomes of progressive resistance strength training following stroke: a systematic review. Clin Rehabil 2004;18:27-39.
20. Kjolhede T, Vissing K, Dalgas U. Multiple sclerosis and progressive resistance training: a systematic review. Mult Scler 2012;18:1215-28.
21. Winter DA. Energy generation and absorption at the ankle and knee during fast, natural, and slow cadences. Clin Orthop Relat Res 1983:147-54.
22. Winter DA. Biomechanical motor patterns in normal walking. J Mot Behav 1983;15:302-30.
23. Whittle MW. Whittle’s gait analysis. 5th ed. Philadelphia: Churchill Livingstone; 2012.
24. Ryschon TW, Fowler MD, Wysong RE, Anthony A, Balaban RS. Efficiency of human skeletal muscle in vivo: comparison of isometric, concentric, and eccentric muscle action. J Appl Physiol (1985) 1997;83:867-74.
25. Lieber RL, Friden J. Functional and clinical significance of skeletal muscle architecture. Muscle Nerve 2000;23:1647-66.
26. Biewener AA, Roberts TJ. Muscle and tendon contributions to force, work, and elastic energy savings: a comparative perspective. Exerc Sport Sci Rev 2000;28:99-107.
27. Roberts TJ. The integrated function of muscles and tendons during locomotion. Comp Biochem Physiol A Mol Integr Physiol 2002;133:1087-99.
28. Wickiewicz TL, Roy RR, Powell PL, Edgerton VR. Muscle architecture of the human lower limb. Clin Orthop Relat Res 1983:275-83.
29. Williams G, Schache AG. The distribution of positive work and power generation amongst the lower-limb joints during walking normalises following recovery from traumatic brain injury. Gait Posture 2016;43:265-9.
30. Ratamess NA, Alvar BA, Evetoch TK, et al. Progression models in resistance training for healthy adults. Med Sci Sports Exerc 2009;41:687-708.
31. Neptune RR, Sasaki K, Kautz SA. The effect of walking speed on muscle function and mechanical energetics. Gait Posture 2008;28:135-43.
32. van der Krogt MM, Delp SL, Schwartz MH. How robust is human gait to muscle weakness? Gait Posture 2012;36:113-9.
33. DeVita P, Helseth J, Hortobagyi T. Muscles do more positive than negative work in human locomotion. J Exp Biol 2007;210:3361-73.
34. Mentiplay BF, Banky M, Clark RA, Kahn MB, Williams G. Lower limb angular velocity during walking at various speeds. Gait Posture 2018;65:190-6.
35. Schwartz MH, Rozumalski A, Trost JP. The effect of walking speed on the gait of typically developing children. J Biomech 2008;41:1639-50.
36. Fukunaga T, Kubo K, Kawakami Y, Fukashiro S, Kanehisa H, Maganaris CN. In vivo behaviour of human muscle tendon during walking. Proc Biol Sci 2001;268:229-33.
37. Sawicki GS, Lewis CL, Ferris DP. It pays to have a spring in your step. Exerc Sport Sci Rev 2009;37.
38. Ishikawa M, Komi PV, Grey MJ, Lepola V, Bruggemann G-P. Muscle-tendon interaction and elastic energy usage in human walking. J Appl Physiol 2005;99:603-8.
39. Franz JR, Slane LC, Rasske K, Thelen DG. Non-uniform in vivo deformations of the human Achilles tendon during walking. Gait Posture 2015;41:192-7.
40. Häkkinen K, Komi P. Effect of explosive type strength training on electromyographic and force production characteristics of leg extensor muscles during concentric and various stretch-shortening cycle exercises. Scand J Sports Sci 1985;7:65-76.
41. Newton RU, Kraemer WJ. Developing explosive muscular power: implications for a mixed methods training strategy. Strength Cond J 1994;16:20-31.
42. Schache AG, Dorn TW, Williams GP, Brown NA, Pandy MG. Lower-limb muscular strategies for increasing running speed. J Orthop Sports Phys Ther 2014;44:813-24.
43. Williams GP, Schache AG. Evaluation of a conceptual framework for retraining high-level mobility following traumatic brain injury: two case reports. J Head Trauma Rehabil 2010;25:164-72.
44. Sugisaki N, Kanehisa H, Kawakami Y, Fukunaga T. Behavior of fascicle and tendinous tissue of medial gastrocnemius muscle during rebound exercise of ankle joint. Int J Sport Health Sci 2005;3:100-9.
45. Williams GP, Clark RAP, Hansson JB, Paterson KP. Feasibility of ballistic strengthening exercises in neurologic rehabilitation. Am J Phys Med Rehabil 2014;96:828-33.
46. Kudo S, Hisada T, Sato T. Determination of the fascicle length of the gastrocnemius muscle during calf raise exercise using ultrasonography. J Phys Ther Sci 2015;27:3763-6.

47. Mehrholz J, Rutte K, Pohl M. Jump training is feasible for nearly ambulatory patients after stroke. Clin Rehabil 2006;20:406-12.
48. Hendrey G, Clark RA, Holland AE, et al. Feasibility of ballistic strength training in subacute stroke: a randomized, controlled, assessor-blinded pilot study. Arch Phys Med Rehabil 2018;99: 2430-46.
49. Johnson BA, Salzberg C, MacWilliams BA, Shuckra AL, D'Astous JL. Plyometric training: effectiveness and optimal duration for children with unilateral cerebral palsy. Pediatr Phys Ther 2014; 26:169-79.
50. Johnson BA, Salzberg CL, Stevenson DA. Effects of a plyometric training program for 3 children with neurofibromatosis type 1. Pediatr Phys Ther 2012;24:199-208.
51. van Vulpen LF, de Groot S, Rameckers E, Becher JG, Dallmeijer AJ. Improved walking capacity and muscle strength after functional power-training in young children with cerebral palsy. Neurorehabil Neural Repair 2017;31:827-41.
52. Morgan P, Embry A, Perry L, Holthaus K, Gregory CM. Feasibility of lower-limb muscle power training to enhance locomotor function poststroke. J Rehabil Res Dev 2015;52:77-84.
53. Hunnicutt JL, Aaron SE, Embry AE, et al. The effects of POWER training in young and older adults after stroke. Stroke Res Treat 2016;2016:5.
54. Wilson GJ, Murphy AJ, Walshe AD. Performance benefits from weight and plyometric training: effects of initial strength level. Coach Sports Sci J 1997;2:3-8.
55. Delecluse C, Van Coppenolle H, Willems E, Van Leemputte M, Diels R, Goris M. Influence of high-resistance and high-velocity training on sprint performance. Med Sci Sports Exerc 1995;27: 1203-9.