Functional Resistance Training Methods for Targeting Patient-Specific Gait Deficits: A Review of Devices and their Effects on Muscle Activation, Neural Control, and Gait Mechanics

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Abstract

Background: Injuries to the neuromusculoskeletal system often result in weakness and gait impairments. Functional resistance training during walking—where patients walk while a device increases loading on the leg—is an emerging approach to combat these symptoms. However, there are many methods that can be used to resist the patient, which may alter the biomechanics of the training. Thus, all methods may not address patient-specific deficits.
Methods: We performed a comprehensive electronic database search to identify articles that acutely (i.e., after a single training session) examined how functional resistance training during walking alters muscle activation, gait biomechanics, and neural plasticity. Only articles that examined these effects during training or following the removal of resistance (i.e., aftereffects) were included.
Findings: We found 41 studies that matched these criteria. Most studies (24) used passive devices (e.g., weighted cuffs or resistance bands) while the remainder used robotic devices. Devices varied on if they were wearable (14) or externally tethered, and the type of resistance they applied (i.e., inertial [14], elastic [8], viscous [7], or customized [12]). Notably, these methods provided device-specific changes in muscle activation, biomechanics, and spatiotemporal and kinematic aftereffects. Some evidence suggests this training results in task-specific increases in neural excitability.
Interpretation: These findings suggest that careful selection of resistive strategies could help target patient-specific strength deficits and gait impairments. Also, many

approaches are low-cost and feasible for clinical or in-home use. The results provide new insights for clinicians on selecting an appropriate functional resistance training strategy to target patient-specific needs.

Keywords: Physical Therapy, Rehabilitation, Spinal Cord Injury, Stroke, Cerebral Palsy, Transcranial Magnetic Stimulation

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1. Introduction

Walking is a motor skill that is intrinsically learned at a young age; however, this seemingly basic skill is actually carried out by a complex network of interdependent pathways in the neural and muscular systems. Hence, damage to these systems due to neurological or orthopedic conditions (e.g., stroke, spinal cord injury, cerebral palsy, osteoarthritis, etc.) often results in gait abnormalities or disability [1, 2, 3, 4]. Unfortunately, current trends in public health—such as the increase in the ageing population—suggest that the prevalence of many of the conditions will grow [5].

Individuals with these neurological or orthopedic conditions typically exhibit motor impairments, with the most common being muscle weakness [6, 7, 8]. Strength is highly correlated with functional activity performance [9, 10, 11], and therapists frequently prescribe resistance training with the goal of improving walking [8, 12, 13, 14]. While resistance training alone can improve walking function (e.g., increased walking velocity or endurance) [15, 13, 16, 14], it has also been shown that resistance training has limited transfer to functional activities [17, 18]. Rather, functional activities, such as walking, are better improved using task-specific training (e.g., training patients to walk by specifically practicing walking overground or on a treadmill) [17, 18, 19]. This is not surprising considering that task-specific training is a key determinant for inducing plastic changes in the nervous system [20, 21, 22, 19]. Given the unique contributions that task-specific and resistive training offer for gait rehabilitation, therapeutic interventions that combine these two training types may be more effective than either training type by itself [23].

Functional resistance training (FRT) is essentially a fusion of resistive and task-specific training principles, and is administered by having a patient perform a task-specific training against an applied resistance. As such, it is specifically designed to improve functional ability by: 1) increasing voluntary muscle force throughout the range of motion for a task and 2) modulating force in muscle groups appropriate for the activity being trained [24, 25]. Historically, FRT principles have been widely applied for training sport performance, such as when a sprinter trains by running with a parachute attached to their waist. By comparison, these training techniques have only recently been adapted by the rehabilitation community for gait training.

In this context, FRT during walking is applied by having the patient walk with a resistance applied to their lower-extremity. Resistance can be applied to the legs using many different strategies, which vary based on the type of device used, how that device interfaces with the user, and the type of resistance that the device supplies. Notably, the characteristics of the resistance—such as the force profile, the timing relative to the gait cycle, and the muscles that are targeted—vary greatly depending on strategy that is being used. Ultimately, the resistive strategy selected for FRT during walking could greatly affect the outcomes of the training.

In this review, we highlight the types of devices that have been used to apply external loads for FRT during walking, as well as the characteristics of the unique resistances provided by each device. We also discuss potential trade-offs and the different effects that may occur due to acute training (i.e., a single training session) with these various resistive strategies. Specifically, we review how FRT has been applied during walking to alter joint moments and muscle activation, how training has elicited kinematic and spatiotemporal aftereffects once resistance is removed, and how it has altered neural control of walking. These findings can be used by clinicians when selecting a resistive strategy to treat their patients' specific impairments and functional goals. Throughout the review, we also raise attention to many areas where future research is required to advance our understanding of FRT.

2. Methods

2.1. Literature Search

The literature searches were performed in MEDLINE via PubMed, Web of Science, Embase, and Science Direct using the following permutations of the text and keyword combinations (Fig. 1). Relating to the functional task we searched for "gait" and "walking", along with the type of training being "resistance". The search was also conducted based on the variables measured, which included "electromyography", "kinematics", "transcranial magnetic stimulation", "spatiotemporal", "spatial", and "temporal" along with relevant abbreviations. The references found from this computerized search were manually inspected to identify other potential studies that fit our inclusion criteria. All databases were searched for relevant articles up until August 4, 2020.

We found 1,638 articles that matched these criteria. We then removed all duplicate articles to produce 910 unique articles. From these articles, we selected those that met our inclusion criteria. Mainly, studies were included if they were original investigations related to FRT during walking (see the operational definition below), published as peer-reviewed journal articles (i.e., excluding conference proceedings), and designed to measure the acute effects/adaptations (i.e., excluding clinical trials) of FRT during walking on adult human subjects (i.e., excluding trials on infants or animals). Additionally, studies were only included if they had appropriate statistical analysis (i.e., excluding case studies and series). Eligible articles were reviewed to see if they collected at least one of the following variables: muscle activation or joint moments before and during training; spatiotemporal gait parameters or kinematic variables before training and after removing the resistance (i.e., aftereffects from washout periods or catch trials); or transcranial magnetic stimulation variables before and during training, or before and after training. Additional articles were excluded because they only measured from the unresisted leg or presented variables as asymmetries. In total, 41 articles met all of our criteria (Table 1).

From these articles, we extracted the population that was trained, the type of device that was used to apply resistance (i.e., whether it was a passive device or an active motorized robot), the mode that was used to apply the resistance (i.e., tethered to a point on the participant [point-based] or directly to the participant's joint [joint-based]), the resistance type (e.g., whether the resistance was inertial, elastic, viscous, etc.), and the movement that the device was resisting. For all of our variables of interest (muscle activations, joint moments, kinematics, spatiotemporal gait parameters, and transcranial magnetic stimulation), we report all of the statistically significant findings relative to baseline (i.e., normal walking) and indicate the direction of change with an arrow pointing upwards (variable increased) or downwards (variable decreased).

2.2. Functional Resistance Training Operational Definition

During screening, studies were excluded based on whether they performed FRT during walking. We defined this based on whether the study used a device to increase the loading experienced by the leg during walking beyond what would be experienced during normal unassisted walking. We would like to note that many abstractions of existing therapies could be viewed as FRT but were not included in this review. Examples include body-weight supported treadmill training, split-belt treadmill training, stair climbing, inclined walking, electrical stimulation, perturbation research, and prosthesis research. Lastly, we have not reviewed many studies that examined the effects of ankle-foot orthoses because these studies often aim to assist the user, report the net moments from both the user and device, and do not make comparisons to walking without the device. Additionally, the biomechanical effects of walking with compliant ankle-foot orthoses have been reviewed elsewhere [26].

3. Results

3.1. Populations Being Researched

While FRT during walking is often motivated for use in populations with neurological injuries, a majority of this acute research has actually been performed on able-bodied individuals (30/41 studies). This is likely due to the ease of recruiting able-bodied participants, and the need to validate methods before testing on patients. The remainder of the studies were performed on individuals with neurological injuries, including spinal cord injuries (5/41 studies), strokes (5/41 studies), and cerebral palsy (4/41 studies). A single study was performed in individuals with knee osteoarthritis, an orthopedic condition.

3.2. Devices for Functional Resistance Training

The devices that have been applied for FRT during walking range from simple passive devices to advanced active rehabilitation robots (Fig. 2). We refer to these devices as active or passive based on how energy flows between the device and user. Active rehabilitation robots use active actuators (e.g., motors), which add external energy to the user in order to provide resistance. Meanwhile, passive devices—including weighted cuffs/vests, elastic bands, and brakes—do not add external energy to the user. Rather, resistance is produced in passive devices when the user exerts their own internal energy on the device. In some cases, the energy put into the device can be stored and returned to the user; however, this is not external power as it was originally input by the user.

We found that most studies performed FRT during walking using passive devices (24/41 studies). This majority likely stems from the accessibility and affordability of these devices, many of which are already possessed by rehabilitation clinics (e.g., weighted cuffs and resistance bands). However, several studies have also used active robots (17/41 studies). Typically, these studies have used custom devices built for research purposes or programmed commercially available rehabilitation robots to be resistive.

3.3. Modes of Interfacing with the Limb

Within each of these classes of devices (i.e., active robots and passive devices), there are two separate modes that can be used to interface with the limb. By modes, we are referring to whether the resistance is applied at a point on the user (i.e., attached externally to a segment on the body, as is typically done with weights, resistance bands, or tethered robots; sometimes referred to as an end-effector based) or directly to the joints of the user (as is common with wearable braces or exoskeleton robots). Ultimately, the differences between these two modes can affect how a device is able to resist the user during training, as point loads make it more difficult to target specific joints (Fig. 3). Despite this, we found that most studies applied resistance through point loads (28/41 studies), while only 14 studies used joint loads.

3.4. Types of Resistances

While the mode of applying the resistance dictates how the device is attached to the user, the type of resistance largely dictates the characteristics of the resistance. Generally, resistances can be characterized as inertial, elastic, viscous, frictional, or any combination thereof. In passive devices, the type of resistance is inherent to the type of passive element that the device uses (e.g., mass, spring, damper, etc.). In active robots, the motors can potentially be programmed to emulate any of these resistance types, or provide customized (i.e., user-defined) resistances that are not possible with passive elements. All of these resistance types will provide different resistance profiles based on the mechanics of the movement: inertial resistance depends on acceleration, elastic resistance scales based on position, viscous resistance depends on velocity, and friction provides a constant resistance (Fig. 4A). Notably, the resistance type employed by the device will also determine the type of muscle contraction (i.e., concentric or eccentric) that can be trained (Fig. 4B). While most devices can engage the user's muscles concentrically, eccentric contractions can only be elicited by a device that can exert energy on the user (i.e., active robots, or inertial and elastic devices returning stored energy to the user).

We found that most of the studies we examined used inertial resistances (14/41 studies) by attaching a weight at some point on the body. In comparison, eight studies used viscous resistances and 7 studied elastic resistances. Several studies also examined more customized robotic resistances (12/41 studies). Many of these studies used the robot to emulate a system of passive devices (creating a viscoelastic resistance), while others used closed-loop control to create a constant resistance or one that was proportional to some other variable.

3.5. Joint Moments and Muscle Activation During Training

It is important to note that the mode and type of resistance cannot be viewed independently—every resistive device must utilize both—and the combination of these factors determines the resistance that the patient experiences. Further, because gait is a repetitive task with stereotypical kinematics, each resistive strategy is going to be stereotypical in its ability to resist the user. Hence, the FRT strategy largely dictates the muscles groups, types of muscle contraction, joint action, and the phase of gait when a device is able to apply resistance. This section examines all of the studies that have measured muscle activation or joint moments while providing FRT (Table 2). For reference, Supplemental Fig. 1 depicts internal joint moments and muscle activation changes with different FRT strategies using a computer-based simulation [27].

3.5.1. Inertial Point Resistances

Typically, point-based inertial resistances have been administered by placing weights on the foot/shank, thigh, pelvis, or torso. When attached to the foot/shank, weighted cuffs increased hip extension and flexion moments during the stance phase, as well as hip flexion and knee flexion moments during the swing phase [28, 29, 30]. This strategy also increased muscle activation of the quadriceps at the transition between stance and swing [28], the hamstrings during swing [31], and the triceps surae during stance [28]. Weighted cuffs attached to the thigh or pelvis had no significant effects on joint moments; however, triceps surae activation increased during the stance phase [28, 32]. Weights attached to the torso (e.g., using a backpack) [33, 34, 35, 36, 37] significantly increased hip extension, knee flexion and extension, and ankle dorsi and plantarflexion moments during the stance phase [34, 35, 37]. This strategy also increased muscle activation of the quadriceps, hamstrings, and triceps surae during the stance and swing phases [35, 36]. Inertial resistance pulling backwards on the shank increased muscle activation of the quadriceps during the pre-swing phase of gait [38].

3.5.2. Elastic Point Resistances

Pulling forward on the foot/shank with an elastic resistance band increased muscle activation of the hamstrings during the early–mid swing phase [39, 40]. However, when the band was placed proximally on the shank, hamstring activation decreased during the stance phase [41]. Pulling backwards on the pelvis increased muscle activation of the triceps surae muscles during the terminal stance and pre-swing phases of gait [42].

3.5.3. Custom Point Resistances

An active robotic cable device that pulled backwards on the shank with a viscoelastic resistance [43, 44] increased muscle activation of the tibialis anterior during the swing phase [43], and it would likely increase quadriceps activation as well if tested on less impaired individuals. A robotic walker that pulled backwards on the pelvis with a constant force [45] increased muscle activation of the quadriceps, tibialis anterior, gluteus maximus, and adductor longus muscles during the stance phase of gait. Yet another motorized cable device pulled downwards on the pelvis with a constant force [46]; however, this strategy did not significantly alter muscle activation.

3.5.4. Elastic Joint Resistances

An ankle orthosis with elastic tubing between the heel and calf has been used to resist to ankle dorsiflexion during walking [47]. This strategy increased muscle activation of the tibialis anterior muscle during pre- and initial-swing [47]. Future research in this area has large potential given the availability of elastic ankle-foot orthoses.

3.5.5. Viscous Joint Resistances

Viscous resistances have been applied to the hip and/or knee joints using active robotic exoskeletons (i.e., the Lokomat) [48, 31, 49, 50, 51] and passive braces [52, 53]. In each instance, the resistance has been applied to both flexion and extension of the joint (i.e., bidirectionally). When applied to the hip, this strategy increased muscle activation of the rectus femoris and tibialis anterior during the swing phase of gait [50, 49]. When applied to the knee, this strategy mainly increased muscle activation of the quadriceps, hamstrings, and tibialis anterior during the swing phase [52, 53]. However, this strategy also increased activation of the triceps surae and gluteus medius during the swing phase, as well as the quadriceps, hamstrings, and gluteus medius during the stance phase [52]. Resisting both the hip and knee increased muscle activation of the hamstrings during pre-swing, and the rectus femoris, medial hamstring, and tibialis anterior during mid-swing [48, 51]. These effects were absent when tested in individuals with spinal cord injury [31].

3.5.6. Custom Joint Resistances

Several active robotic exoskeletons have been programmed to provide custom resistances. One device provided a constant torque to resist either knee flexion or extension [54]. With this device, resisting extension increased activation of the quadriceps muscles and resisting flexion reduced activation of the vastus medialis [54]. An electrohydraulic ankle foot orthosis has also been programmed resist to ankle dorsiflexion during the early swing phase [55]. This strategy increased muscle activation of the tibialis anterior muscle from pre- to mid-swing [55]. Lastly, a wearable, soft robot has been used to resist ankle plantar flexion [56]. The resistance provided by this robot was unique because the torque was proportional to the real-time ankle moment; thus, mimicking normal joint loading. During training, this strategy increased muscle activation of the soleus while decreasing muscle activation of the tibialis anterior during the stance phase [56].

3.6. Aftereffects Following the Removal of Resistance

Aftereffects are typically measured when studying motor adaptation. Motor adaptation occurs when a movement (in this case, walking) is practiced in the presence of a perturbation [57, 58], such as the extra loading presented by a resistive device. During practice with the perturbation, one's perception of the movement gets altered and the nervous system gradually creates a new set of controls for the movement. Finally, once the perturbation is removed, some aspects of the modified movement persist, which are referred to as aftereffects. These aftereffects contain information about how the nervous system is being driven to adapt [59, 60] and may indicate potential gains a particular training can produce, as aftereffects have been seen to transfer to overground walking after training [61, 62, 63, 64, 53]. In this section, we examine how different strategies for FRT during walking have produced acute kinematic and spatiotemporal aftereffects (i.e., following a single session of training) (Table 3).

3.6.1. Inertial Point Resistances

Aftereffects have been measured with inertial resistances by placing weighted cuffs on the shank [30, 62, 31, 65]. Once resistance was removed with this strategy, individuals walked with increased knee flexion [31, 65]. Spatiotemporally, this resulted in increased overground gait speed and step length [62] and foot clearance when walking on a treadmill [30]. Pulling backwards on the shank with an inertial resistance [38, 66, 63] increased hip flexion and reduced hip extension once the resistance was removed [38]. Spatiotemporally, this strategy increased step length and single leg support time while reducing swing time [38, 66]. It also increased overground gait speed and stride length [63].

3.6.2. Elastic Point Resistances

Pulling forward on the foot with an elastic resistance band decreased foot velocity once the resistance was removed [40]. A passive device that pulled downward on the pelvis did not have an effect on sagittal plane hip, knee, or ankle kinematics [67].

3.6.3. Custom Point Resistances

Several studies have provided a viscoelastic resistance using a cable robot to pull backwards on the shank [43, 68, 69, 44] and thigh [64]. While none of these studies have measured kinematic aftereffects, spatiotemporally, this strategy increased overground gait speed [64] and step/stride length [43, 68, 69, 64, 44]. Another active robot has been used to pull downward on the pelvis with a custom force [46]. With this strategy, hip range of motion and cadence were unchanged once the resistance was removed; however, the stance phase duration increased.

3.6.4. Elastic Joint Resistances

Walking with resistance to ankle dorsiflexion during the swing phase [47] resulted in an aftereffect of increased ankle range of motion.

3.6.5. Viscous Joint Resistances

A bidirectional viscous resistance at the hip produced a kinematic aftereffect of increased hip and knee flexion [50, 49]. Spatiotemporally, these aftereffects presented as increased stride length and foot clearance [50, 49]. When applied at the knee, this strategy produced aftereffects of increased hip and knee excursions [52, 53] and increased overground gait speed [53]. When applied to the hip and knee concurrently, viscous resistances produced a kinematic aftereffect of increased hip and knee flexion [48].

3.6.6. Custom Joint Resistances

Walking with an active ankle-foot orthosis that resisted ankle dorsiflexion during the swing phase significantly increased ankle dorsiflexion angle during the mid-swing phase once the resistance was removed [55]. Joint-based resistances that emulated pulling backwards on the shank were found to increase step length [70, 71].

3.7. Neural Adaptations to Functional Resistance Training

Very few articles have studied the neural effects of this training [72, 47, 73, 74] and findings have been mixed. Refer to supplemental section 1 for details.

4. Discussion

FRT during walking is an emerging technique for rehabilitation following neuromusculoskeletal injury. As such, there are several different strategies that have been used to apply resistance, which vary based on the type of device used, how the device interfaces with the user, and the type of resistance that the device supplies. Hence, we examined the different strategies that have been used to apply FRT during walking, and how the characteristics of each resistive strategy altered the acute effects of training (i.e., after a single training session). Specifically, we reviewed how FRT has been applied during walking to alter joint moments and muscle activation, how training has elicited kinematic and spatiotemporal aftereffects once resistance is removed, and how it has altered neural control of walking. In this section, we will discuss the significance of our findings, as well as any potential trade-offs to consider when applying this training.

4.1. Patient Populations that May Benefit

While the majority of acute research on FRT during walking was performed on able-bodied individuals, these studies were often motivated for individuals with neurological injuries, including spinal cord injury, stroke, and cerebral palsy. This is understandable, as FRT is largely based on principles of experience dependent neural plasticity [20, 21, 22, 19]. However, we found that training strategies often had more evident effects in able-bodied participants than individuals with neurological injuries [48, 31, 43, 44]. This may have occurred because many participants with neurological injuries were too impaired to overcome the resistance. Hence, it has been suggested that patients with severe impairments following injuries could be better served with assistive training rather than FRT [75].

Notably, patients with orthopedic injuries are underrepresented in this research. We only found a single study trained individuals with osteoarthritis [33]. However, following orthopedic injury or reconstructive surgery, most patients present with muscle weakness, altered neural control, and functional impairments, which extend to gait [2, 76]. Hence, individuals with orthopedic injuries could be prime beneficiaries of this training, and future studies should be performed on these populations. Indeed, preliminary evidence from pilot clinical trials indicate that FRT during walking could have positive effects in individuals with anterior cruciate ligament (ACL) injuries [77, 78].

4.2. Types of Devices for Functional Resistance Training

We found that most studies have either used active rehabilitation robots or passive devices to apply FRT during walking. While there are benefits to both types of devices, there are also several trade-offs that must be considered when selecting a device for training. In this section, we will discuss this broad spectrum of devices (Fig. 2) and the practicality of their application for FRT during walking. Additionally, we will introduce a third type of device that has the potential to alter how this training is applied.

4.2.1. Active Robots

We will first consider active rehabilitation robots; we refer to this set of robots as active because they use active actuators capable of either assisting or resisting movement. There is large potential for training with active robots because the motors can be controlled to provide unique force environments to the user. Additionally, sensors on the robot allow therapists to track the progress of a patient throughout training and offer opportunities to provide real-time feedback to the user through interactive games. Given this upside, it is understandable that active robots have been widely applied for FRT during walking.

However, a major issue with most active robots is that they are not very accessible for patients or clinicians. First, a majority of these robots are custom-built, which requires an investment and expertise. Second, commercially available robots are very expensive, which prevents their widespread use in-home or in small clinics [79]. Lastly, the commercial versions of these devices are typically used for assistive training on heavily impaired individuals, and resistance settings are not available for routine clinical use. For these reasons, clinicians are more likely to use the more cost-effective passive devices instead of active robots.

4.2.2. Passive Devices

A majority of the studies in this review used passive devices for training. This was likely because passive devices are very practical—they have the inherent ability to provide large resistances at a fraction of the cost of a robot [80, 81]. Moreover, they can be purchased at a local sporting goods store, which increases the feasibility of in-home use by the patient. The downside to these passive devices is that they are not controllable, so resistance must be scaled by manually adjusting the device. Further, these devices are not typically instrumented with encoders and load cells, which limits a clinician's ability to monitor the patient's compliance or recovery throughout the training process, especially if the device is being used at home. Without these capabilities, patients must be intrinsically motivated to train. Some of these issues could potentially be remedied if the devices were instrumented in order to track movement (e.g., using encoders or inertial sensors) or, as we will see in the next section, if the passive elements were made controllable.

4.2.3. Semi-Passive Robots

There is another class of devices that exist in the middle ground between active robots and passive devices (Fig. 2), which we refer to as semi-passive rehabilitation robots [81]. These robots draw inspiration from passive devices by employing passive elements to provide resistance to the patient; however, like with active robots, the passive elements can be controlled by a computer. Thus, the resulting robotic devices balance the cost and portability of passive devices, while still allowing for patient monitoring and interactive treatment. Although removing motors typically sacrifices the ability to assist the user during training, semi-passive robots may offer a cost-effective way to provide FRT. While none of the articles we reviewed were semi-passive, simple modified could be made to make some of these devices controllable [82].

4.3. Differences in Modes of Interfacing With the Limb

In this review, we distinguished devices based on how they interfaced with the limb. That is, if they attached the resistive element to a point on the user (i.e., a point-based resistance), or if the resistance was applied as a torque directly at the joint (i.e., a joint-based resistance). From a mechanical viewpoint this distinction is largely semantic, as point resistances can be applied to emulate a desired joint-based resistance (i.e., torques) and vice versa (Fig. 3) [70]. However, in practice, the differences between these two modes can have a profound effect on how a device is able to resist the user during training and how exercise using that device should be administered.

Joint-based resistances are desireable because they can be easily applied to target patient-specific weaknesses. During rehabilitation, strength is typically measured at the joint level using dynamometry or graded scales such as manual muscle testing [83]. Hence, with a joint-based approach, muscle weakness can be detected at a specific joint and a resistive torque can be prescribed to target the weakened muscle group. While point-based approach can still provide targeted treatment, it is more difficult. For example, 1) the torques experienced at the joints due to a point-based resistance are often coupled with one another, 2) joints more proximal point where the resistance is applied (i.e., with a larger lever arm) experience larger resistances, and 3) the resistance with point-based loads is more dependent on anatomy and gait kinematics (i.e., segment lengths and joint angles) (Fig. 3). Despite these limitations, point-based devices can still provide utility for FRT. Additionally, we found that a majority of the studies in this review actually used point-based device (28/41 studies). Hence, there are other factors to be considered when distinguishing between these two modes.

Point and joint-based resistances can also differ based on their cost and ease of use. Devices that provide point-based resistances are typically lower cost and easier to set up than joint-based devices, especially if they are passive devices. This stems from how they attach to the user with a simple strap/cuff; hence, more time can be spent on training and a single device can be used on multiple patients. This is in contrast with braces and exoskeletons, as care must be taken to fit the device to the patient or it will not perform as intended. For these reasons, clinicians may choose to train their patients using point- rather than joint-based devices. Hence, the decision of which resistance mode to use may be based on pragmatic choices.

4.4. How the Type of Resistance Could Affect Training

While numerous types of resistive loads were identified by this review, it is difficult to make comparisons between studies due to differences in the methods and variables analyzed. As such, it is still unclear how altering the type of resistance affects training outcomes. Undoubtedly there are differences in the resistance profiles that are generated by different types of resistive elements (Fig. 4A), but only a single study in this review tested multiple resistance types (inertial and viscous) [31]. Without a larger number of acute studies, computer based analyses [27], or even randomized controlled clinical trials, the role of resistance type for FRT will remain unclear.

We do know that the type of resistance dictates the type of muscle contractions that can be elicited during training (Fig. 4B) and how the resistance feels to the user. Inertial, elastic, and customized robotic resistances permit concentric, eccentric, and even isometric muscle contractions during training, while friction and viscous resistances only permit concentric muscle contraction [84]. The ability to provide eccentric training may be an advantage, as eccentric training can better promote strength when compared with concentric training [85, 86, 87]. However, strength also increases when training involves concentric muscle contractions [88]. It has been speculated that viscous resistances could benefit power training, as the peak force requirements when using a viscous resistance coincide with the peak velocity profile of the movement (Fig. 4A) [89]. While FRT during walking is generally regarded as safe, the same mechanism that allows for eccentric contractions also poses a potential safety risk, as the momentum of the weight, recoil of the spring, or unvalidated programming in a robot could hyperextend the user's limb during training. For this reason, resistance types that do not exert energy on the user (i.e., viscous and friction) may be the safest options.

The feeling of the resistance (i.e., the haptics) also affects how widely a device will be adopted. Inertial, elastic, and viscous resistances have different haptics but feel smooth because the resistance scales with the mechanics of the movement. Notably, none of the studies in this review applied friction based resistance training during walking. This is likely because friction based resistance feels jerky due to instability at the beginning and end of a movement (often referred to as stiction) (Fig. 4A). Stiction occurs because the coefficient of friction (the constant that determines the magnitude of the resistance) is different when an object is at rest (where the coefficient is larger) or in motion. In order to avoid this unpleasant feeling, friction is often minimized in mechanical systems. However, the haptics of resistance types is a potential area for future research, and it is possible that all resistance types have a role to play.

4.5. Applying Biomechanics and Aftereffects Results

The main goal of this review was to examine different strategies that have been used to apply resistance during walking and how these strategies alter the outcomes of acute training. Generally, we found that different resistive strategies varied in their ability to alter gait biomechanics (i.e., muscle activations and moments) during training and aftereffects following the removal of the resistance. Given that muscle strength and functional deficits vary between patients, we do not believe that there is a single resistive strategy that can be applied uniformly. Instead, clinicians must select a resistive strategy that will work for their patient given their current impairments (e.g., strength deficits and kinematic abnormalities) and functional goals (e.g., to reduce fall risk or increase gait speed), while remaining feasible for use in their clinic or home. We hope the information within this review can serve as a reference to inform these decisions.

Interpreting biomechanics data is relatively straightforward. When prescribing FRT during walking, we suggest that a strategy be applied based on patient-specific strength deficits. Once strength deficits are identified, we would suggest applying a resistive strategy that has been shown to increase the joint moment of the specific action that is weakened, or in the muscles that contribute to that joint moment (Table 2). A similar logic can be applied to aftereffects. That is, we would suggest that any kinematic or spatiotemporal deficits be identified using either motion capture, inertial measurement units, a gait mat, etc. Once the desired outcome is identified, Table 3 can be used to identify a resistive strategy has produced increases in that particular outcome. When referring to the tables in this review, please note that all variables were not measured by each study. Hence, it is possible that a resistive strategy could have an effect that is not indicated simply because it has not been measured.

We must note that using aftereffects to predict the outcomes for rehabilitation is an active area of research. As such, it is not yet certain whether the aftereffects observed after an acute training are retained in the patient's normal walking pattern following an intervention [90]. While acute aftereffects have been seen to persist in overground walking following training [61, 62, 63, 64, 53], patients typically deadapt once the resistance is removed. Clinical trials have found that aftereffects are present after an intervention and can persist for months [91, 92, 93, 94, 95], but it is unclear if this is an improvement over the standard of care [96, 93]. At the very least, aftereffects are a surrogate variable that represent the muscles that are being trained. For example, pulling backwards on the shank increases activation of the rectus femoris during training, which produces an aftereffect of increased step length [38]. Hence, even if aftereffects do not represent cumulative gains from a training, they still indicate that the muscles integral to that task are being trained.

4.6. Interpreting Neural Adaptations using TMS

More studies are needed to elucidate the effects that FRT during walking has on neural excitability. Refer to supplemental section 2 for in-depth discussion.

4.7. Feedback during Training

Feedback was seldomly applied in conjunction with FRT, while recent studies have found that feedback increases the intensity of training several fold [82]. Hence, feedback/coaching may bolster the effects of this training for future studies (see supplemental section 3 for details).

5. Conclusion

This review examined the strategies that have been used to apply FRT during walking, and characterized how resistive strategies altered the acute effects of training—including biomechanics during training, aftereffects once resistance was removed, and neural excitability. We found that strategies varied in their ability to alter gait biomechanics (i.e., muscle activations and moments) during training and aftereffects following the removal of the resistance. Overall we believe that resistive strategies can be selected to target patient specific strength deficits and gait impairments, but this selection should also account for affordability and ease of use of the device. Additionally, more research is needed to understand how this training can alter neural control of walking.

6. Conflict of Interest Statement

The authors have no financial or personal relationships with other people or organizations that could inappropriately influence (bias) their work.

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List of Figures

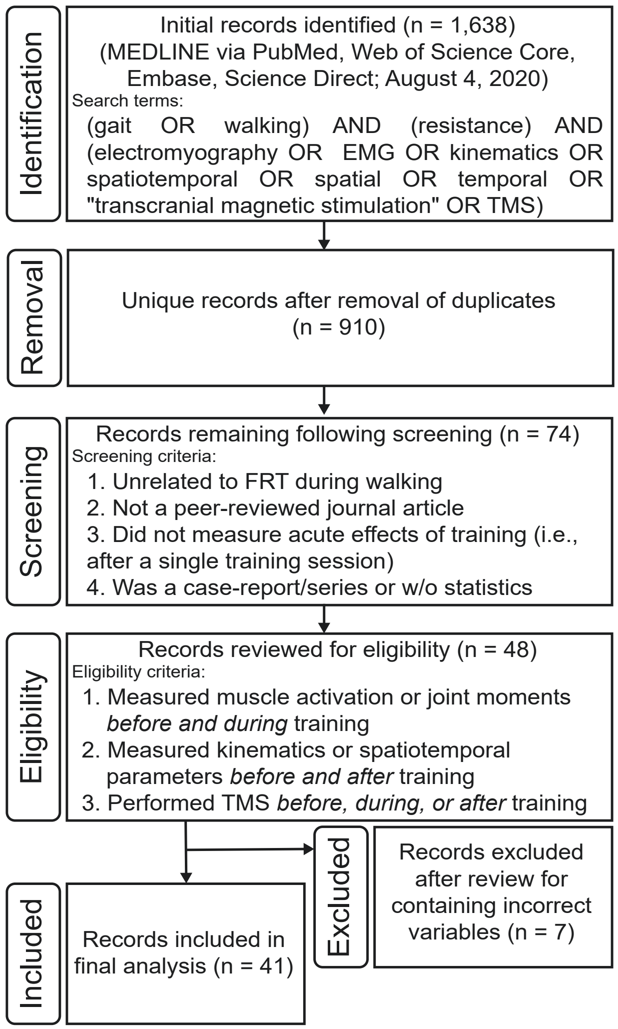

Figure 1: Flow diagram depicting study identification.

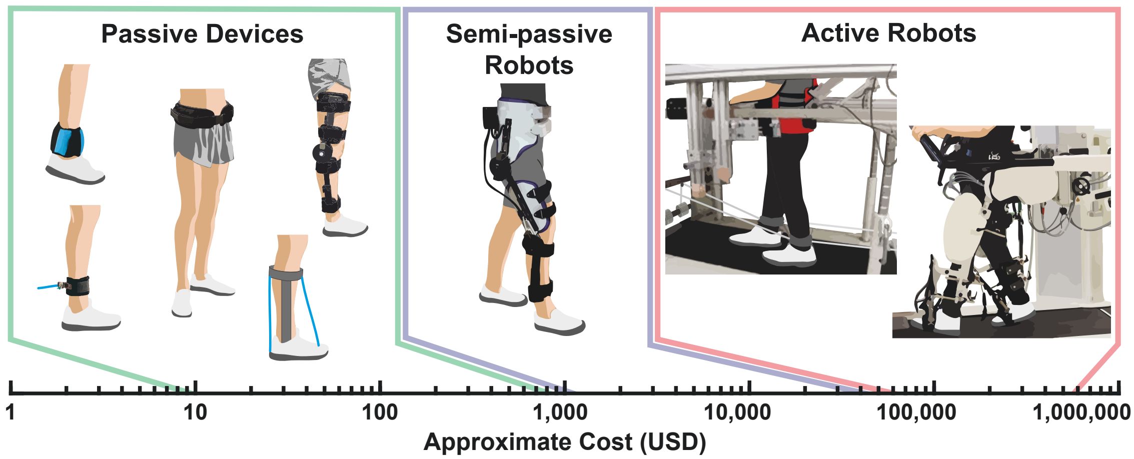

Figure 2: The spectrum of devices used for functional strength training during gait and their relative costs. Active robots provide exceptional control over the rehabilitation setting, but are also the most expensive to acquire. Meanwhile, passive devices (e.g., weighted cuffs/belts, elastic bands, and passive braces) are the most cost-effective option but offer no real-time control. While not widely studied in functional resistance training, semi-passive robots utilize controllable passive elements (e.g., controllable brakes) in order to provide a limited set of controls but at a modest price.

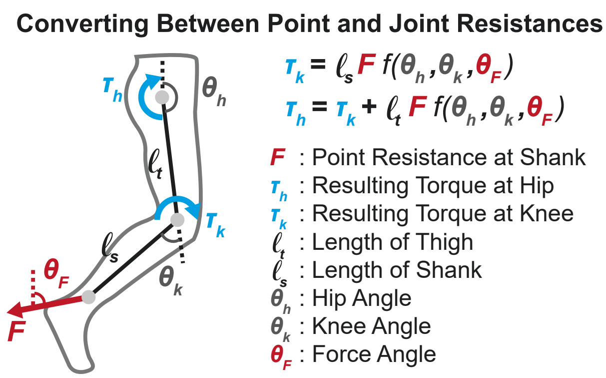

Figure 3: Schematic depicting how a point-based resistance applied to the shank translates to torques at the hip and knee (i.e., joint-based resistances) during the swing phase. Equations can describe the relationship between point- and joint-based resistances, and indicate that the resulting torques depend on the limb lengths and joint angles. Additionally, the torques at the hip and knee are coupled with one another. The notation f(θ) denotes a function of θ.

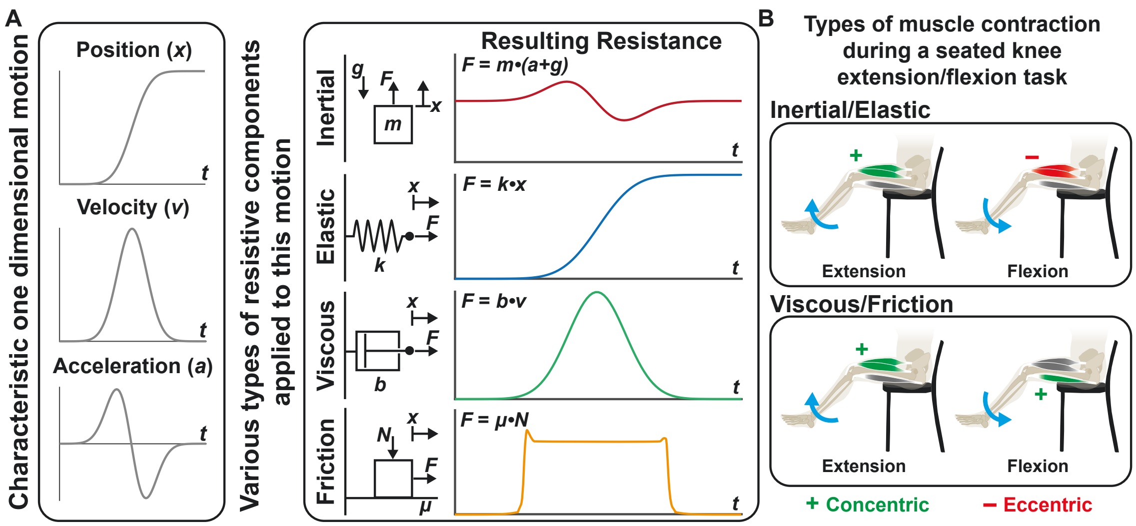

Figure 4: (A) Resistance types and the resulting forces when they are applied to a one dimensional motion. The left panel characterizes this simple motion. Maintaining these characteristics, the right panel shows the force F that would be required to: lift a weight with mass m against gravity g; deform an elastic spring with stiffness k; deform a viscous damper with a damping coefficient b; or move along a surface with a coefficient of friction μ. Most passive devices will provide one of these resistance types, and active robots can emulate these components or provide customized resistances. (B) Resistances types differ in the types of muscle contractions (e.g., concentric and eccentric) that they can elicit. During the seated knee extension/flexion task depicted, inertial and elastic resistances elicit concentric contraction when extending the leg and eccentric contraction when flexing the leg. During the same task, viscous and friction based resistances require concentric contraction during both extension and flexion.

List of Tables

Table 1: Summary of all of the studies and the variables they measured

Reference	Population	# Subj	Age	Device	Mode	Type	Resisting	MA	Mom	Kin	Spat	Neur
Browning et al. [28]	AB	5 (0F)	A	Passive	Point	Inertial	Foot Shank Thigh Pelvis	Yes	Yes			
Noble & Prentice [30]	AB	8 (5F)	YA	Passive	Point	Inertial	Shank		Yes	Yes	Yes	
Simão et al. [65]	CP	20 (10F)	9	Passive	Point	Inertial	Shank			Yes	Yes	
Lam et al. [31]	SCI	6 (NS) 7 (NS)	65 62	Passive Active	Point Joint	Inertial Viscous	Shank Hip+Knee	Yes		Yes		
Duclos et al. [29]	Stroke	10 (5F)	56	Passive	Point	Inertial	Shank		Yes			
Savin et al. [38]	AB	10 (9F)	26	Passive	Point	Inertial	Shank Back	Yes		Yes	Yes	
McGowan et al. [32]	AB	10 (5F)	21–45	Passive	Point	Inertial	Pelvis	Yes				
Krupenvich et al. [34]	AB	22 (11F)	20	Passive	Point	Inertial	Torso		Yes			
Kubinski & Higginson [33]	AB Knee OA	20 (12F) 20 (12 F)	64 62	Passive	Point	Inertial	Torso		Yes			
Silder et al. [35]	AB	29 (12F)	33	Passive	Point	Inertial	Torso	Yes	Yes			
Simpson et al. [36]	AB	15 (0F)	22	Passive	Point	Inertial	Torso	Yes				
Chow et al. [37]	AB	22 (22F)	13	Passive	Point	Inertial	Torso		Yes			
Blanchette & Bouyer [39]	AB	10 (7F)	22	Passive	Point	Elastic	Foot Front	Yes			Yes	
Blanchette et al. [40]	AB	10 (5F)	25	Passive	Point	Elastic	Foot Front	Yes			Yes	
Shin et al. [41]	AB CP	7 (2F) 7 (1F)	12 13	Passive	Point	Elastic	Shank Front	Yes				
Gottschall & Kram [42]	AB	10 (5F)	27	Passive	Point	Elastic	Pelvis Back	Yes				
Tang et al. [44]	CP	11 (5F)	12	Active	Point	Viscoelastic	Shank Back	Yes			Yes	
Yen et al. [43]	SCI	12 (NS)	48	Active	Point	Viscoelastic	Shank Back	Yes			Yes	
Mun et al. [45]	AB	11 (3F)	24	Active	Point	Constant	Pelvis Back	Yes				
Vashista et al. [46]	AB	9 (0F)	27	Active	Point	Constant	Pelvis Down	Yes		Yes	Yes	
Barthélemy et al. [47]	AB	10 (5F)	27	Passive	Joint	Elastic	Ankle Dorsi	Yes		Yes		Yes
Washabaugh et al. [52]	AB	7 (NS)	NS	Passive	Joint	Viscous	Knee Bi	Yes		Yes		
Washabaugh & Krishnan [53]	Stroke	6 (3F)	58	Passive	Joint	Viscous	Knee Bi	Yes		Yes	Yes	
Houldin et al. [50]	AB SCI	17 (NS) 9 (2F)	22–75 22–66	Active	Joint	Viscous	Hip Bi	Yes		Yes	Yes	
Houldin et al. [49]	AB	20 (13F)	25	Active	Joint	Viscous	Hip Bi	Yes		Yes	Yes	
Klarner et al. [51]	AB	20 (10F)	22–37	Active	Joint	Viscous	Hip+Knee Bi	Yes				
Lam et al. [48]	AB	20 (10F)	26	Active	Joint	Viscous	Hip+Knee Bi	Yes		Yes		
Diaz et al. [54]	AB	19 (9F)	31	Active	Joint	Constant	Knee Flex Knee Ext	Yes				
Blanchette et al. [55]	AB	12 (NS)	28	Active	Joint	Custom	Ankle Dorsi	Yes		Yes		
Conner et al. [56]	CP	8 (1F)	14	Active	Joint	Custom	Ankle Plantar	Yes				
Gama et al. [62]	AB	18 (12F)	21	Passive	Point	Inertial	Shank				Yes	
Savin et al. [63]	AB Stroke	10 (7F) 10 (7F)	62 63	Passive	Point	Inertial	Shank Back				Yes	
Savin et al. [66]	Stroke	14 (7F)	63	Passive	Point	Inertial	Shank Back				Yes	
Vashista et al. [67]	AB	8 (0F)	27	Passive	Point	Elastic	Pelvis Down			Yes		
Yen et al. [43]	SCI	10 (NS)	48	Active	Point	Viscoelastic	Shank Back				Yes	
Yen et al. [69]	Stroke	10 (NS)	59	Active	Point	Viscoelastic	Shank Back				Yes	
Yen et al. [68]	SCI	10 (NS)	50	Active	Point	Viscoelastic	Thigh Back				Yes	
Cajigas et al. [70]	AB	15 (5F)	33	Active	Joint	Custom	Shank Back				Yes	
Severini et al. [71]	AB	9 (3F)	28	Active	Joint	Custom	Shank Back				Yes	
Zabukovec et al. [73]	AB	40 (27F)	26	Active	Joint	Viscous	Hip+Knee Bi					Yes
Bonnard et al. [72]	AB	10 (NS)	22–28	Passive	Point	Elastic	Foot Up					Yes

Variable abbreviations: subjects (Subj), muscle activation (MA), Moments (Mom), Kinematics (Kin), Spatiotemporal (Spat), Neural (Neur); population abbreviations: AB (able-bodied), SCI (spinal cord injury), CP (cerebral palsy), OA (osteoarthritis); # Subj: the number of females in the study is noted in parentheses; age: single numbers represent the mean age in years, otherwise it is expressed as an age range; abbreviations: adult (A), young adult (YA); resisting abbreviations: Flex (flexion), Ext (extension), Plant (plantarflexion), Dorsi (dorsiflexion), Bi (Bidirectional [e.g., Flex & Ext]); Front/Back/Down indicate the direction the device was pulling. Yes indicates that a variable was measured in the study. Note, many studies had additional variables that were not of interest to this study.

Table 2: Summary of how resistance during walking has altered muscle activation and internal joint moments.

Reference	Pop	Device	Mode	Type	Resisting	Significant Outcomes [Variable (Phase)]
Browning et al. [28]	AB	Passive	Point	Inertial	Foot	**MA:** RF (PSw) ↑, TA (TSw) ↑, MG (MSt–TSt) ↑, Sol (MSt–TSt) ↑ **Moment:** H Ext (MSt) ↑, H Flex (TSt–Isw, TSw) ↑, K Flex (TSw) ↑, A Dorsi (ISw) ↑
Browning et al. [28]	AB	Passive	Point	Inertial	Shank	**MA:** MG (MSt–TSt) ↑ **Moment:** No Effect
Noble & Prentice [30]	AB	Passive	Point	Inertial	Shank	**Moment:** H Ext (TSw) ↑, H Flex (ISw) ↑, K Ext (ISw) ↑, K Flex (TSw) ↑
Lam et al. [31]	SCI	Passive	Point	Inertial	Shank	**MA:** LH (Sw) ↑
Duclos et al. [29]	Stroke	Passive	Point	Inertial	Shank	**Moment:** H Ext (LR,TSw) ↑, H Flex (TSt–PSw) ↑, K Flex (LR,TSw) ↑
Savin et al. [38]	AB	Passive	Point	Inertial	Shank Back	**MA:** RF (ISw) ↑
Browning et al. [28]	AB	Passive	Point	Inertial	Thigh	**MA:** MG (MSt–TSt) ↑, Sol (MSt–TSt) ↑ **Moment:** No Effect
Browning et al. [28]	AB	Passive	Point	Inertial	Pelvis	**MA:** MG (MSt–TSt) ↑, Sol (MSt–TSt) ↑ **Moment:** No Effect
McGowan et al. [32]	AB	Passive	Point	Inertial	Pelvis	**MA:** MG (LR–PSw) ↑, Sol (LR–PSw) ↑
Krupenvich et al. [34]	AB	Passive	Point	Inertial	Torso	**Moment:** K Ext (St) ↑, A Plant (St) ↑
Kubinski & Higginson [33]	AB	Passive	Point	Inertial	Torso	**Moment:** No Effect
Silder et al. [35]	AB	Passive	Point	Inertial	Torso	**MA:** RF (St, Sw) ↑, VM (LR–MSt, TSw) ↑, VL (LR–MSt, TSw) ↑, MH (MSw–TSw) ↑, LH (LR–MSt, MSw–TSw) ↑, MG (MSt–PSw) ↑, Sol (MSt–PSw, Sw) ↑ **Moment:** H Ext (LR - MSt) ↑, K Ext (MSt) ↑, K Flex (PSw), A Dorsi (LR) ↑, A Plant (PSw) ↑
Simpson et al. [36]	AB	Passive	Point	Inertial	Torso	**MA:** VL (LR, TSw) ↑, MG (TSt–PSw) ↑
Chow et al. [37]	AB	Passive	Point	Inertial	Torso	**Moment:** H Flex (PSw) ↑, H Abd (St) ↑, H Int (St) ↑, H Ext (St) ↑, K Ext (St) ↑, K Val (St) ↑, A Plant (St) ↑
Kubinski & Higginson [33]	Knee OA	Passive	Point	Inertial	Torso	**Moment:** No Effect
Blanchette & Bouyer [39]	AB	Passive	Point	Elastic	Foot Front	**MA:** LH (PSw–MSw) ↑, MH (PSw–MSw) ↑
Blanchette et al. [40]	AB	Passive	Point	Elastic	Foot Front	**MA:** LH (PSw–MSw) ↑, MH (PSw–MSw) ↑
Shin et al. [41]	AB	Passive	Point	Elastic	Shank Front	**MA:** Hst (LR–MSt) ↓
Shin et al. [41]	CP	Passive	Point	Elastic	Shank Front	**MA:** Hst (LR–MSt) ↓
Gottschall & Kram [42]	AB	Passive	Point	Elastic	Pelvis Back	**MA:** MG (TSt–PSw) ↑, Sol (TSt–PSw) ↑
Tang et al. [44]	CP	Active	Point	Viscoelastic	Shank Back	**MA:** No Effect
Yen et al. [43]	SCI	Active	Point	Viscoelastic	Shank Back	**MA:** TA (Psw–ISw) ↑
Mun et al. [45]	AB	Active	Point	Constant	Pelvis Back	**MA:** RF (St) ↑, VM (St) ↑, TA (St) ↑, GMax (St) ↑, AdL (St) ↑
Vashista et al. [46]	AB	Active	Point	Constant	Pelivis Down	**MA:** No Effect
Barthélemy et al. [47]	AB	Passive	Joint	Elastic	Ankle Dorsi	**MA:** TA (Sw) ↑
Washabaugh et al. [52]	AB	Passive	Joint	Viscous	Knee Bi	**MA:** RF (St, Sw) ↑, VM (St, Sw) ↑, MH (Sw)↑, LH (St, Sw) ↑, TA (Sw) ↑, MG (Sw) ↑, Sol (Sw) ↑, GMed (St, Sw) ↑
Washabaugh & Krishnan [53]	Stroke	Passive	Joint	Viscous	Knee Bi	**MA:** VM (Sw) ↑, MH (Sw) ↑, LH (Sw) ↑
Houldin et al. [50]	AB	Active	Joint	Viscous	Hip Bi	**MA:** RF (Sw) ↑
Houldin et al. [49]	AB	Active	Joint	Viscous	Hip Bi	**MA:** RF (Sw) ↑, TA (Sw) ↑
Houldin et al. [50]	SCI	Active	Joint	Viscous	Hip Bi	**MA:** RF (Sw) ↑
Klarner et al. [51]	AB	Active	Joint	Viscous	Hip+Knee Bi	**MA:** RF (ISw–MSw) ↑
Lam et al. [48]	AB	Active	Joint	Viscous	Hip+Knee Bi	**MA:** RF (MSw) ↑, MH (PSw, MSw) ↑, LH (PSw) ↑, TA (MSw) ↑
Lam et al. [31]	SCI	Active	Joint	Viscous	Hip+Knee Bi	**MA:** No Effect
Diaz et al. [54]	AB	Active	Joint	Constant	Knee Flex	**MA:** VM ↓
Diaz et al. [54]	AB	Active	Joint	Constant	Knee Ext	**MA:** RF ↑, VM ↑, VL ↑
Blanchette et al. [55]	AB	Active	Joint	Custom	Ankle Dorsi	**MA:** TA (PSw–MSw) ↑
Conner et al. [56]	CP	Active	Joint	Custom	Ankle Plant	**MA:** TA (St) ↓, Sol (St) ↑

Population abbreviations: Pop (population), AB (able-bodied), SCI (spinal cord injury), CP (cerebral palsy), OA (osteoarthritis); muscle activation (MA) abbreviations: AdL (adductor longus), GMax (gluteus maximus), GMed (gluteus medius), Hst (hamstring), LH (lateral hamstring), MH (medial hamstring), MG (medial gastrocnemius), RF (rectus femoris), Sol (soleus), TA (tibialis anterior), VL (vastus lateralis), VM (vastus medialis); resistance and internal moment abbreviations: H (Hip), K (knee), A (ankle), Flex (flexion), Ext (extension), Abd (abduction), Val (valgus), Int (internal), Plant (plantarflexion), Dorsi (dorsiflexion), Bi (Bidirectional [e.g., Flex & Ext]); gait phase abbreviations: St (stance), Sw (Swing), LR (loading response), MSt (mid-stance), TSt (terminal stance), PSw (pre-swing), ISw (initial-swing), MSw (mid-swing), TSw (terminal swing). Front/Back/Down indicate the direction the device is pulling. ↑ Indicates that the variable significantly increased during training, while ↓ indicates a significant decrease. Note, many studies had additional variables that were reported but that did not show significance.

Table 3: Summary of how strategies of providing resistance during walking produce spatiotemporal and kinematic aftereffects after acute (i.e., a single session) training.

Reference	Pop	Device	Mode	Type	Resisting	Significant Aftereffects [Variable (Phase)]
Gama et al. [62]	AB	Passive	Point	Inertial	Shank	**Spatiotemporal:** OG Gait Speed ↑, OG Step Length ↑
Noble & Prentice [30]	AB	Passive	Point	Inertial	Shank	**Spatiotemporal:** Foot Clearance ↑ **Kinematic:** No Effect
Simão et al. [65]	CP	Passive	Point	Inertial	Shank	**Spatiotemporal:** Foot Clearance ↑ **Kinematic:** H Flex (Sw) ↑, K Flex (Sw) ↑, H RoM ↑, K RoM ↑
Lam et al. [31]	SCI	Passive	Point	Inertial	Shank	**Kinematic:** K Flex (Sw) ↑
Savin et al. [38]	AB	Passive	Point	Inertial	Shank Back	**Spatiotemporal:** Step Length ↑, Swing Time ↓ **Kinematic:** Hip Flexion (Sw) ↑, Hip Extension (St) ↓
Savin et al. [63]	AB	Passive	Point	Inertial	Shank Back	**Spatiotemporal:** OG Gait Speed ↑, OG Stride Length ↑
Savin et al. [63]	Stroke	Passive	Point	Inertial	Shank Back	**Spatiotemporal:** OG Gait Speed ↑, OG Stride Length ↑
Savin et al. [66]	Stroke	Passive	Point	Inertial	Shank Back	**Spatiotemporal:** Step Length ↑, SLS Time ↑
Blanchette & Bouyer [39]	AB	Passive	Point	Elastic	Foot Front	**Spatiotemporal:** Foot Speed (Sw) ↓
Blanchette et al. [40]	AB	Passive	Point	Elastic	Foot Front	**Spatiotemporal:** Foot Speed (Sw) ↓
Vashista et al. [67]	AB	Passive	Point	Elastic	Pelvis Down	**Kinematic:** Pelvis Displacement ↑
Tang et al. [44]	CP	Active	Point	Viscoelastic	Shank Back	**Spatiotemporal:** Step Length ↑
Yen et al. [43]	SCI	Active	Point	Viscoelastic	Shank Back	**Spatiotemporal:** Stride Length ↑
Yen et al. [68]	SCI	Active	Point	Viscoelastic	Shank Back	**Spatiotemporal:** Stride Length ↑
Yen et al. [69]	Stroke	Active	Point	Viscoelastic	Shank Back	**Spatiotemporal:** Step Length ↑
Yen et al. [64]	SCI	Actve	Point	Viscoelastic	Thigh Back	**Spatiotemporal:** OG Gait Speed ↑, OG Stride Length ↑, Stride Length ↑, Stance Time ↑
Vashista et al. [46]	AB	Active	Point	Custom	Pelvis Down	**Spatiotemporal:** Stance Time ↑ **Kinematic:** No Effect
Barthélemy et al. [47]	AB	Passive	Joint	Elastic	Ankle Dorsi	**Kinematic:** A Exc ↑
Washabaugh et al. [52]	AB	Passive	Joint	Viscous	Knee Bi	**Kinematic:** H Exc ↑, K Exc ↑
Washabaugh & Krishnan [53]	Stroke	Passive	Joint	Viscous	Knee Bi	**Spatiotemporal:** OG Gait Speed ↑ **Kinematic:** H Exc ↑, K Exc ↑
Houldin et al. [50]	AB	Active	Joint	Viscous	Hip Bi	**Spatiotemporal:** Foot Clearance ↑ **Kinematic:** H Flex (Sw) ↑, K Flex (Sw) ↑
Houldin et al. [49]	AB	Active	Joint	Viscous	Hip Bi	**Spatiotemporal:** Foot Clearance ↑ **Kinematic:** H Flex (Sw) ↑, K Flex (Sw) ↑
Houldin et al. [50]	SCI	Active	Joint	Viscous	Hip Bi	**Spatiotemporal:** Step Length ↑ **Kinematic:** H Flex (Sw) ↑
Lam et al. [48]	AB	Active	Joint	Viscous	Hip+Knee Bi	**Kinematic:** H Flex (Sw) ↑, K Flex (Sw) ↑
Lam et al. [31]	SCI	Active	Joint	Viscous	Hip+Knee Bi	**Kinematic:** No Effect
Blanchette et al. [55]	AB	Active	Joint	Custom	Ankle Dorsi	**Kinematic:** A Dorsi (MSw) ↑
Cajigas et al. [70]	AB	Active	Joint	Custom	Shank Back	**Spatiotemporal:** Step Length ↑
Severini et al. [71]	AB	Active	Joint	Custom	Shank Back	**Spatiotemporal:** Step Length ↑

A full list of abbreviations can be found in Table 1. Additional abbreviations: Exc (excursion), OG (overground), SLS (single leg support), RoM (range of motion). If not specified as overground, variables were measured over a treadmill; many studies had additional variables that were reported but that did not show significance or were not variables of interest for this review.

Supplement: Functional Resistance During Walking: Review of Devices and their Effects on Muscle Activation, Neural Control, and Gait Mechanics

1. Neural Adaptations to Functional Resistance Training

Although neural adaptation is a motivator for providing FRT during walking, only a few studies that have directly investigated the neural effects of this training [1, 2, 3, 4]. A majority of these studies have analyzed neural adaptation using transcranial magnetic stimulation (TMS)—a noninvasive brain stimulation technique, where an electromagnet (referred to as a coil) is placed over the scalp to stimulate the superficial brain cortex. TMS can be used to assess neural excitability of the motor system by stimulating over a motor "hotspot" of a muscle (i.e., the area of the brain that corresponds to that muscle) then recording the output from the muscle (i.e., a motor evoked potential [MEP]) using electromyography or dynamometry. Therefore, comparing MEPs before, during, or after training can indicate an increase or decrease in excitability in the neurons that control that muscle.

TMS has been used to evaluate neural excitability both during training (i.e., stimulating the brain as the participant walked on the treadmill) and directly after training (i.e., with the participant seated in a chair) in able-bodied participants. Bonnard et al. [1] measured neural excitability during training, which consisted of walking with an elastic band attached between the subject's feet and shoulders (i.e., a point-based resistance pulling upwards on the foot). They found that neural excitability (i.e., the size of the MEPs) increased in the rectus femoris and lateral hamstring during the late swing phase while training. Barthélemy et al. [2] measured changes in neurological excitability both during and after training with an elastic ankle-foot orthosis (i.e., a joint-based strategy) that provided resistance to ankle dorsiflexion during the swing phase. They found that excitability increased in the tibialis anterior during the swing phase while training, but did not see any significant changes following training. Lastly, Zabukovec et al. [3] applied a joint-based viscous resistance to the hip and knee joints and measured the neural excitability after training; however, they did not see any significant changes in neural excitability. Hence, these studies have typically found that excitability increases during training [1, 2], but that these effects are not present following training [3, 2].

2. Interpreting Neural Adaptations using TMS

Surprisingly, there were very few studies that have examined the effects of FRT during walking on neural excitability. Without such information, we can only discuss the methods that have been used to measure neural excitability, highlight potential problems with interpreting these data, and stress the importance of creating larger datasets to better understand the neural mechanisms of recovery.

The results from the limited number of studies suggest that neural excitability is altered during training but not following training. However, the methods that were used to measure neural excitability were very different in these two instances. During training, TMS was performed functionally (i.e., as the participant walked on the treadmill), but following the training, TMS was applied more conventionally, with the subject in a seated posture. While functional TMS is potentially a powerful technique, it is not widely used because there are several factors that must be controlled when performing TMS, and it is difficult to control for these factors during functional tasks.

The finding that neural excitability remained unchanged when measured in a seated posture following training does not necessarily indicate that neural excitability is unchanged in the entire motor system; rather, there may not be a net change in excitability. TMS is a measure of the entire corticospinal tract—which includes the motor cortex, midbrain, brainstem, spinal cord, and all of the connections in between—as well as peripheral motor neurons and muscles. Hence, it is possible that an increase in cortical excitability is being masked by a decrease somewhere else in the system. However, techniques that are more targeted within the corticospinal tract (e.g., transcranial electrical stimulation, cervicomedullary stimulation, Hoffmann's reflex) would be required to test this theory.

It is also important to mention that an increase in excitability is not necessarily a desirable outcome, while a decrease in excitability is not necessarily undesirable. For example, decreased neural excitability has been found following strength training in uninjured subjects [5]. This does not mean that strength training should be avoided, but that an adaptive change (presumably inhibitory) is happening somewhere along the corticospinal tract, which could potentially have therapeutic value. Indeed, patients with overactive spinal reflexes (i.e., hyperreflexia), as is often seen following neurological injury, could potentially benefit from a training that induces inhibitory effects [6, 7]. Ultimately, the desired neural outcome will need to be defined by the condition being tested. Unfortunately, it is still not well understood how specific neural changes correlate with functional outcomes.

3. Feedback during Training

Feedback has rarely been provided when performing FRT during walking, however, this may be a crucial component to induce positive outcomes after an intervention [8]. Feedback can be used to increase the intensity or ensure the participant walks with normal kinematics. Typically, when a resistance is applied to the leg, subjects have a tendency to alter their walking in order to take "the path of least resistance"; but feedback can help to alert the subject that they are using an abnormal gait strategy. Studies that have directly compared training with and without visual feedback have found that feedback increased muscle activation several fold [8, 9]. The few studies that have provided feedback have typically provided the subject with a real-time depiction of their kinematics or spatiotemporal gait parameters [10, 9, 11, 8, 3, 12]. While these methods require some sort of instrumentation, a similar effect could also be obtained through verbal coaching or having the patient avoid/clear an obstacle while walking [13].

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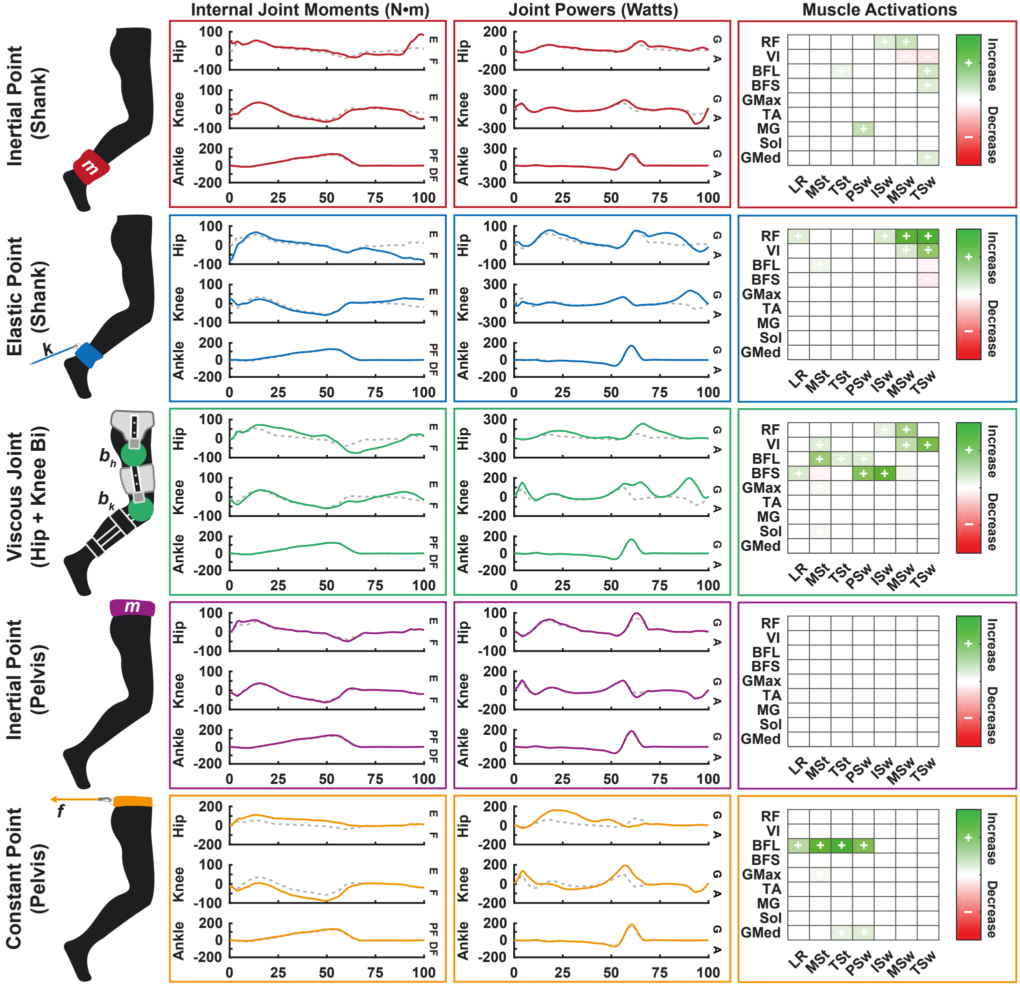

Figure S1: Representative joint moments, powers, and muscle activations resulting from common resistive strategies applied while walking. Internal joint moments and powers are plotted against the percentage of the gait cycle, where solid lines represent walking with the load and dashed lines represent normal walking. Labels to the right of the moment plots indicate the direction for extension, flexion, plantarflexion, and dorsiflexion. Labels on the power plots indicate a power generation or absorption. Muscle activations are depicted as a heat map of the muscles and the phase of the gait cycle, and indicate a change in muscle activation between resisted and normal walking. Note that these data are the result of a biomechanical computer simulation. Muscle abbreviations: RF (rectus femoris), VI (vastus intermedius), BFL (biceps femoris long head),BFS (biceps femoris short head), GMax (gluteus maximus), TA (tibialis anterior), MG (medial gastrocnemius), Sol (soleus), GMed (gluteus medius). Gait phase abbreviations: LR (loading response), MSt (mid-stance), TSt (terminal stance), PSw (pre-swing), ISw (initial-swing), MSw (mid-swing), TSw (terminal swing). Reprinted from Publication Gait & Posture, 75, Edward P. Washabaugh, Thomas E. Augenstein, Chandramouli Krishnan, Functional resistance training during walking: Mode of application differentially affects gait biomechanics and muscle activation patterns, 129-136, Copyright (2020), with permission from Elsevier. https://doi-org.proxy.lib.umich.edu/10.1016/j.gaitpost.2019.10.024