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Exploring How the Arms Can Help the Legs in Facilitating Gait Rehabilitation

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Inspired by the ideas from the fields of gait rehabilitation, neuroscience, and locomotion biomechanics and energetics, a body of work is reviewed that has led to propose a conceptual framework for novel "self-assistive" walking devices that could further promote walking recovery from incomplete spinal cord injuries. The underlying rationale is based on a neural coupling mechanism that governs the coordinated movements of the arms and legs during walking, and that the excitability of these neural pathways can be exploited by actively engaging the arms during locomotor training. Self-assistive treadmill walking rehabilitation devices are envisioned as an approach that would allow an individual to actively use their arms to help the legs during walking. It is hoped that the conceptual framework inspires the design and use of self-assistive walking devices that are tailored to assist individuals with an incomplete spinal cord injury to regain their functional walking ability.

1. Introduction

Advancements in neuroscience research have shifted the goal of gait rehabilitation from a compensatory approach to that of promoting full walking recovery for individuals with an incomplete spinal cord injury (iSCI).[1] This is a grand challenge for the field of gait rehabilitation because a spinal cord injury disrupts nerve communication to and from the brain which can severely impair normal walking function. Historically, it was assumed that an individual without the ability to control their legs due to a spinal cord injury would have little to no chance of walking again. Thus, rehabilitation has focused on the use of external assisted devices such as wheelchairs and exoskeletons designed to provide compensatory strategies for locomotion. Over the years, research has shown that the spinal cord has the ability to reorganize its structure, function, and neural connections in response to training, and this ability is referred to as neural plasticity or neuroplasticity.[2–4] However, there is still more work to be done to achieve the goal of full walking recovery for individuals with iSCI.

Inspired by this concept of neural plasticity, this paper explores how actively using the arms during gait rehabilitation could help promote walking recovery after an iSCI. Our primary research and experience are in the basic science of locomotion biomechanics and metabolic energetics, but we have long been intrigued by the evolving field of gait rehabilitation. In particular, we have come to recognize the fundamental importance of a neural coupling mechanism that coordinates arm and leg movements during walking and its functional significance for gait rehabilitation. We believe that the benefits of arm and leg neural coupling can be translated into practical gait rehabilitation walking devices. In fact, we recently investigated how mechanically linking the arms and legs affects the biomechanics and energetics of walking in healthy adults.[5] However, to continue making progress, inspire collaborations, and help translate these findings into a clinical setting, a conceptual framework with an interdisciplinary perspective is needed. Here we propose an interdisciplinary conceptual framework for how and why such novel devices might aid in gait rehabilitation.

Central to our proposed conceptual framework is the understanding that the coupling behavior of arm and leg movements during walking has both basic and clinical significance. With this in mind, this perspective piece is organized into four main sections to connect key insights from the fields of gait rehabilitation, neuroscience, and locomotion biomechanics and energetics. Section I reviews the neural coupling mechanisms that govern the rhythmic behavior of arm and leg movements and explains why the coordinated action of the arms and legs is critical for developing optimal gait rehabilitation strategies. Section II reviews two distinct, but complementary frameworks (i.e., task-by-task and dynamic walking) that help explain the biomechanical basis for the metabolic cost of walking. They share a similar finding in that the net metabolic power required for human walking can be primarily explained by the mechanical demands placed on the legs. Understanding the mechanical demands that explain the metabolic cost of walking sets the foundation for Section III, which offers a mechanistic explanation to understand why the metabolic cost of arm swing is absent from these biomechanical frameworks. More importantly, in Section IV, we discuss how these insights have inspired us to design and build a

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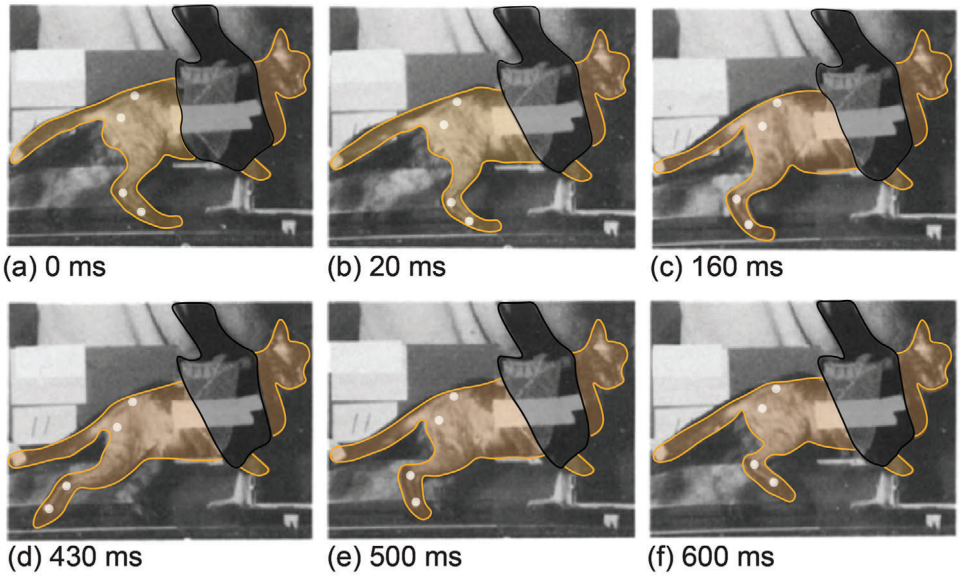

Figure 1. Photographs of selected positions in the step cycle of an adult spinal cat (outlined in orange) walking on a treadmill at a speed of 0.6 m s^{-1}. A vest (outlined in black) supported the shoulder girdle and chest. The cat's forepaws were placed on a platform 2.5 cm above the moving belt. The positions shown are: a) initial treadmill contact, b) initial posterior movement of the paw, c) support phase, d) initial ankle flexion, e) dragging the paw during the swing phase, and f)initial extension phase at the ankle. Adapted with permission.[9] Copyright 1986, Elsevier.

simple assistive device that allows an individual to mechanically couple their active arm movements to help the legs in facilitating the mechanical demands of walking.[5] And lastly, we integrate the key ideas outlined in this review into a conceptual framework that has scientific and practical value. This conceptual framework will require refinement through iterative experiments and testing. Nonetheless, we present it with the intent to inspire other interdisciplinary scientists.

2. Neurological Basis of Coordinating the Arms and Legs during Gait Rehabilitation

The idea of exploiting the neural coupling between the arms and legs for gait rehabilitation was pioneered by Behrman and Harkema in a series of case studies.[6] Prior to their seminal work and the seminal work of others around that time,[7,8] it was shown by Lovely and co-workers that cats could be trained to recover their hindlimb stepping motion after a spinal cord transection at the level of the T12–T13, which severs brain and spinal cord communication.[9] It is important to note that the cats' forelimbs were supported by a platform positioned in front of them, and their torsos were supported by an overhead system that allowed their hindlimbs to walk on a treadmill (**Figure 1**). Thus, Lovely and co-workers at that time did not focus on forelimb and hindlimb coordination, but they and others[10–12] made the critical observation that there exists a range of sensory inputs that could be used to facilitate the correct stepping pattern. In a sense, the idea of "sensory cueing," as noted by Edgerton et al., was born from these key insights.[13] In the experiment by Lovely et al., the cats started their locomotor training program with assistance from human trainers, who manually facilitated the motion of the hindlimbs through the stance and swing phases of walking. Investigator-provided sensory cues were critical for re-learning the correct stepping mechanics. One sensory cue included pinching the tail to increase the excitatory activation of the extensor hindlimb muscles to facilitate proper stance phases. Another sensory cue focused on lifting the hind paws and hyperextending the metatarsophalangeal joint during its swing phase. Such assistance enhanced the activation of the hindlimb and digital flexors, allowing for proper foot placement for the next support phase. They also found that after just two months of repetitive training, 16 of the 18 cats were able to step independently and continuously with their hindlimbs. Insights from these types of locomotor training studies offered a scientific basis for translating this type of locomotor training approach to humans.

Traditionally, gait rehabilitation for iSCI patients involved both the arms and legs. One widely used strategy was for patients to practice their stepping motions on a treadmill while holding on to left and right parallel bars.[14] This allowed the patient to use their arms to partially support and stabilize the body, alleviating some of the mechanical burden on the legs. However, the use of parallel bars elicited asymmetric walking patterns, leading patients to overcompensate by relying more heavily on the less affected or unaffected leg. It was found that freeing the arms from providing body weight support helped patients achieve a more normal-like walking pattern, characterized by muscle activity and leg movements that were similar to walking of healthy adults. Thus, the use of parallel bars faded, and instead, upward-lifting harness suspension systems that provide body weight support emerged and are now widely integrated with locomotor training. In the transition from parallel bars to body weight support, the potential utility of exploring different methods of actively engaging the arms during locomotor training was seemingly forgotten.

The principles underlying modern locomotor training remain based on the idea that just like cats, humans with a spinal cord injury are capable of re-learning how to walk again, but one must

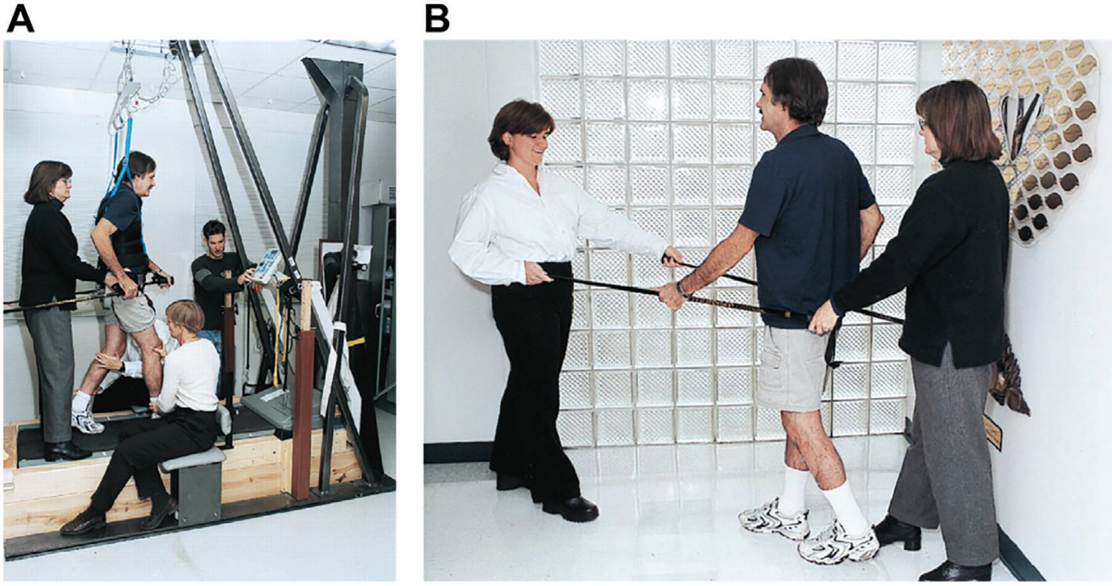

Figure 2. Fundamental principles of locomotor training include coordinating arm and leg movements during walking. In this context, physical therapists passively guide the back-and-forth motion of the patient's arms during locomotor training, which includes A) treadmill walking and B) overground walking. Adapted with permission.[6] Copyright 2000, Oxford University Press.

provide the spinal cord with the correct sensory cues.[6,13] As shown in **Figure 2**, providing the spinal cord with the correct sensory cues involves external assistance from physical therapists (or robotic devices to drive the stepping motion of the patient's legs). This rhythmic stepping motion provides the spinal cord with the critical sensory cues of limb loading and unloading and hip position.[6,15–17] While the repetitive stepping motion of the legs forms the foundation for locomotor training as we see it today, Behrman and Harkema did list the act of coordinating the swinging motion of the arms with that of the legs as a critical sensory cue.[6] In a series of case studies involving locomotor training, Behrman and Harkema provided the sensory cue of arm swing by having their patients hold onto horizontal poles that were guided by a physical therapist. The physical therapist would move the poles back and forth to facilitate the passive, reciprocal motion of the arms during locomotor training. While the coordinated action of the arms has been recognized as an integral component of sensory cueing, we contemplated the following: could *active* arm movements be more beneficial than *passive* arm movements during locomotor training?

The idea that arm swing acts as a sensory cue for the spinal cord arises from the observation that the coupling behavior of human arm and leg movements originate from the time our evolutionary ancestors transitioned from quadrupedal (four limbs) to bipedal (two limbs) locomotion.[18,19] When transitioning from quadrupedal to bipedal locomotion, the forelimbs were freed from the mechanical burden of supporting and accelerating the body during walking. However, humans have retained the neural circuity originally programmed for quadrupedal interlimb coordination and thus, still use the strong neural coupling pathways between the arms and legs during bipedal walking.[18–21] This has been demonstrated by Dietz and co-workers, who showed that stimulating the right distal tibial nerve during walking elicited a spinal reflex response in both the right leg's tibialis anterior muscle and the left arm's triceps muscle (**Figure 3A**).[20] This finding demonstrated that these neural connections share a common pathway that converges onto the spinal cord, allowing the arms and legs to communicate. Even more surprising, Dietz and colleagues could not elicit the same spinal reflex response in the arm's triceps muscle when subjects were swinging the arms while standing (Figure 3B) nor when subjects were sitting and writing (Figure 3C). These insights led Dietz and colleagues to propose that this neural coupled pathway is normally "closed" and can only be "opened" when the swinging arms are coordinated with the stepping motion of the legs during walking (as illustrated in Figure 3D,E).[18] These findings suggest that incorporating the correct sensory cues to stimulate the neural coupled pathway of the arms and legs may strengthen or create new neural connections via neural plasticity that could help regain walking function. These findings also suggest that the arms must be coordinated with the stepping motion of the legs to maximize re-learning in the injured spinal cord.

The discoveries by Dietz and co-workers[20] and those of others[21] inspired new ways of thinking and led to the idea that these neural coupled pathways could be further exploited by *mechanically* coupling arm and leg movements. Indeed, the ability to tap into the excitability of these neural coupling pathways was demonstrated by the recumbent stepping experiments on neurologically intact individuals carried out by Huang and Ferris.[22] The subjects in this study sat on a bicycle-like machine and were instructed to use their arms to drive the cyclic stepping-like motion of their legs by pushing and pulling handles that mechanically linked their arm and leg movements. Several findings from that study are worth noting. First, having subjects actively use their arms to drive their leg motion (self-driven condition) increased the rhythmicity and amplitude of the electromyographic (EMG) activity measured in the passively driven leg muscles. This increase was with respect to their externally

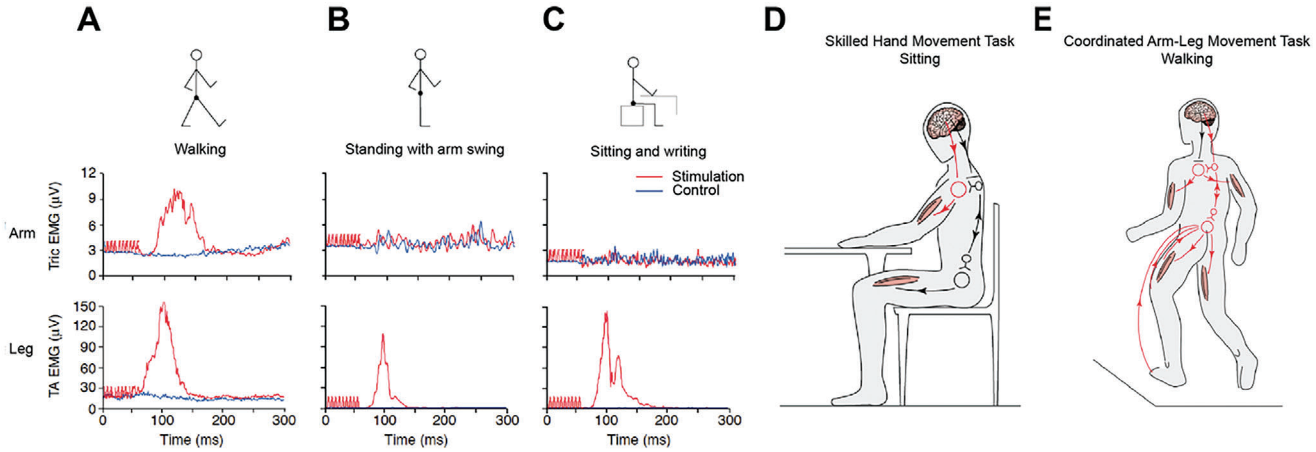

Figure 3. Interlimb reflexes are compared between walking, standing, and sitting. Interlimb reflexes were induced by applying a train of electrical stimuli to the right distal tibial nerve during walking (A; $n = 100$ responses), standing with voluntary arm swing (B; $n = 20$ responses) and sitting while writing (C; $n = 20$ responses). The data are from a single subject where control EMG recordings without stimulation (blue) are displayed for comparison. During walking, right tibial nerve stimulation was followed by EMG responses (red) of the leg's tibialis anterior (TA) and arm's triceps (Tric) muscles. However, arm muscle response was absent when stimuli were applied during standing and sitting. This suggests that the proximal arm muscle reflex response is associated with swinging of the arm during walking as a residual function of quadrupedal locomotion. Movement control during different motor tasks. According to the research cited in the review by Dietz et al. 2002, neuronal control of arm movement is task-dependent. During skilled hand movements (D), strong direct cortical-motoneuronal excitation is predominant (red lines) and the cervical propriospinal neuronal system is inhibited. During walking (E), it is assumed that the brain command is predominantly mediated by interneurons. Cervical and thoracolumbar propriospinal systems become coupled and coordinate arm and leg movements (red lines). Data originally reported in Dietz et al.[20] Adapted with permission.[18] Copyright 2002, Elsevier.

driven condition where an experimenter moved the subject's relaxed arms and legs, which were strapped to the handlebars and pedals, respectively. Second, exerting greater arm effort increased the EMG activity of the passively driven leg muscles. This is worth noting because the same patterns of leg EMG activity could not be elicited during the externally driven condition. From these findings on neurologically intact individuals, we can infer that there are at least two gait rehabilitation strategies that are key to exploiting the neural coupled pathways that exist between the arms and legs, which are 1) incorporate assistance but allow the user to help drive their own stepping-like leg motion with their arms and 2) allow the user to vary their level of arm effort.

These findings were intriguing, but the question remained as to whether the same behavior could be evoked in individuals recovering from an iSCI. The idea behind this question is depicted in **Figure 4**, a conceptual framework proposed by Ferris and co-workers.[23] It is important to note that our understanding of the neural circuitry underlying arm-leg coupling, left-right limb coordination, and control of locomotion has advanced significantly over the years[24,25] and thus more complex than depicted in Figure 4. Nonetheless, it is useful to explain how the conceptual framework by Ferris and colleagues helped to understand the possible pathways that would allow an increase in arm muscle activity to facilitate an increase in leg muscle activity in those with an iSCI. In pathway A, actively engaging the arms could excite neural connections that recruit motor units within the legs that are not otherwise excitable through direct motor cortex innervation. In individuals with an iSCI, the ability to recruit motor units within the lower limbs is severely limited. Yet, direct motor cortex innervation could excite arm spinal interneurons (pathway B,C) or a core set of spinal interneurons (pathway D,E)

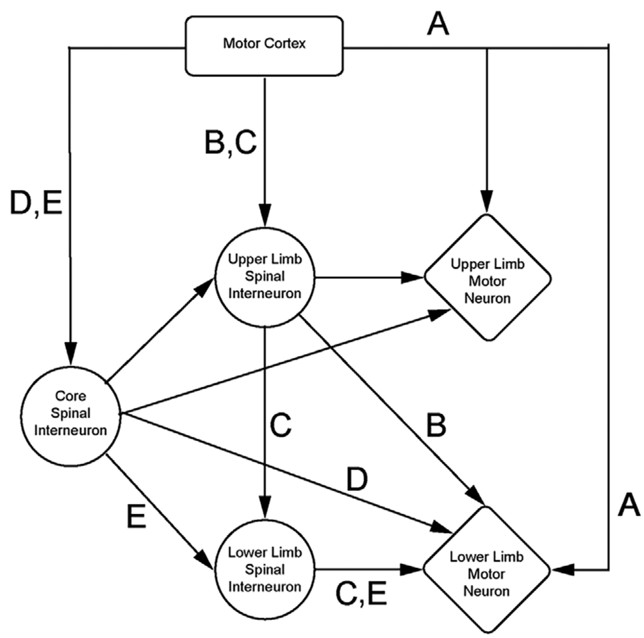

Figure 4. Schematic of possible neural pathways responsible for lower limb (i.e., legs) muscle excitation from upper limb (i.e., arms) exertion. There are five potential pathways A–E) for lower limb muscle excitation. Excitatory connections between the motor cortex and upper limb motor neurons could branch off to A) lower limb motor neurons. Excitatory connections between the motor cortex and upper limb interneurons could then excite connections to B) lower limb motor neurons or C) interneurons. Alternatively, a group of common core interneurons (e.g., central pattern generator) could excite D) lower limb motor neurons or E) interneurons. Unlabeled arrows show pathways for upper limb muscle excitation. Adapted with permission.[23] Copyright 2006, Wolters Kluwer Health, Inc.

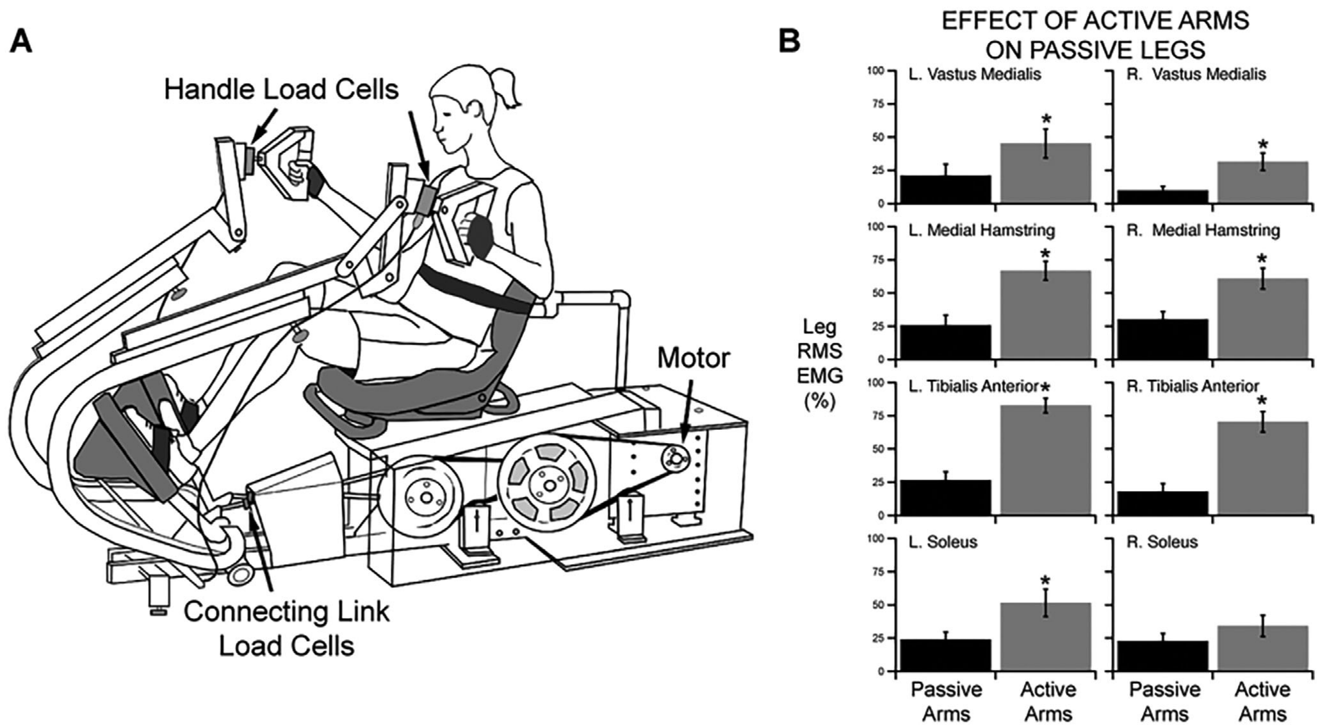

Figure 5. A) A recumbent stepping machine (modified TRS 4000; NuStep, Inc) allowed individuals with an iSCI to fully engage their arms to push and pull the handles while the legs were fully engaged or while allowing the legs to be driven passively by arm movements. Adapted with permission.[26a] Copyright 2009, Wolters Kluwer Health, Inc. B) Normalized EMG data reveals that fully engaging the arms increased the muscle activity of the passively driven left (L.) and right (R.) legs (* indicated $p < 0.05$). Error bars are standard error about the means. Original data was extracted from Huang and Ferris.[26b] using WebPlotDigitizer[28] to recreate the modified plots. Adapted with permission.[26b] Copyright 2009, Elsevier.

that are coupled with and excite lower limb interneurons, leading to greater leg muscle activity.

With this conceptual framework in mind, Huang and Ferris followed up with a study on individuals with an iSCI.[26b] These individuals ($n = 15$) were classified according to the American Spinal Injury Association Impairment Scale (ASIA[27]), with $C = 6$, $D = 8$, and $E = 1$. Following a similar experimental approach and a modified recumbent stepper (**Figure 5A**) from their previous study, they performed different combinations of active and passive arm and leg movements to understand the extent to which the excitability of the arm-leg neural coupled pathways could be modulated. They found that engaging the arms with maximal voluntary effort increased the muscle activity of the passively driven legs (Figure 5B). An important takeaway from these recumbent stepping experiments is that it showed it was possible to increase the excitability of these neural coupled pathways by allowing individuals with an iSCI to actively use their arms to move their passively behaving legs. This seminal study gave credence to the possibility that, in humans, actively engaging the arms during gait rehabilitation could be a key strategy for helping the injured spinal cord learn how to walk again.

Since the insights of Huang and Ferris,[22,23,26] other devices that allow for coordinated passive and active limb movements have been proposed as gait rehabilitation strategies. However, only a few devices such as an arm-leg cycle ergometer[29] and an EasyStand Glider[30] have demonstrated a neural coupling behavior in individuals with an iSCI. For instance, Kawashima and co-workers compared individuals with either an *incomplete* cervical SCI ($n = 7$, ASIA scale $C = 4$ and $D = 3$) or a complete thoracic SCI ($n = 5$, ASIA scale $A = 4$, $B = 1$) to understand if leg muscle activity can be modulated by the passive motion of the arms using a modified EasyStand Glider (**Figure 6A**).[30] This is an important comparison because individuals with an *incomplete* cervical SCI have preserved the interlimb neural connections between the arms and legs whereas those with a *complete* thoracic SCI have not. Those with a complete thoracic SCI would not be able to use greater levels of arm effort to excite lower limb muscles via neural coupled connections as depicted in Figure 4, such as those connections that branch off from upper limb motor neurons (pathway A), upper limb spinal interneurons (pathway B,C), or common core spinal interneurons (pathway D,E).

To test this idea with the modified EasyStand Glider, the experimenter used the handle to move the legs passively in an alternating motion, thereby mimicking the walking-like motion of the legs. In many individuals with an incomplete cervical SCI, they found that engaging the arms passively or actively increased the muscle activity of the soleus and tibialis anterior leg muscles. This provides evidence in support of the idea proposed by Dietz[18] in which the cervical and thoraco-lumbar propriospinal systems became coupled as the arms and legs move in a locomotion-like coordinated manner as illustrated in Figure 3. In those with a complete thoracic SCI, the muscle activity in same leg muscles did *not change*, confirming that the neural connections between the arms and legs were indeed lost (as shown by an example data set in Figure 6B–D).

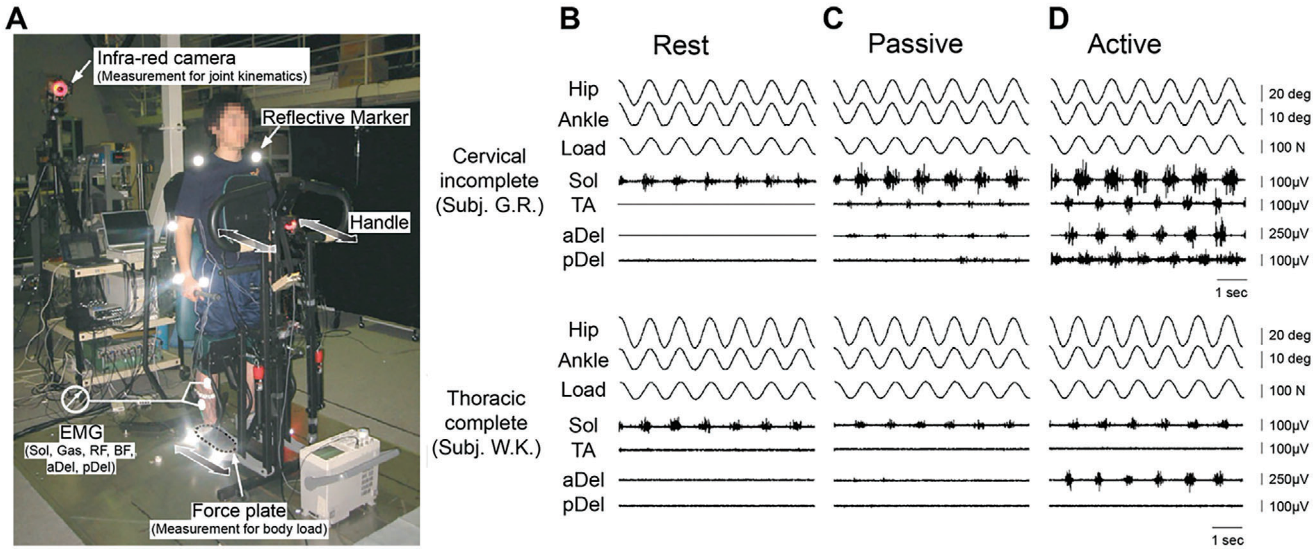

Figure 6. A) During the experiment, subject's with a spinal cord injury (SCI) stood securely on a EasyStand Glider 6000 device (Altimate Medical). B–D) Representative data for hip and ankle joint motion, the load on the leg, and arm and leg EMG activity recorded from subjects G.R. (top) and W.K (bottom). All data were recorded during passive alternate leg movement (1 Hz pace) under the following experimental conditions. B) Rest condition—subjects hands placed on fixed bar while arms remained relaxed. C) Passive condition—each hand strapped to handle while experimenter moved handles in alternate back-and-forth motion. D) Active condition—subjects exerted some arm effort while experimenter moved handles alternate back-and-forth motion. Sol, soleus; TA, tibialis anterior; aDel, anterior deltoid; pDel, posterior deltoid. Adapted with permission.[30] Copyright 2008, American Physiological Society.

These results are promising but it is important to note that the neural coupling response will depend on the level, duration, and severity of the spinal cord injury. This is demonstrated in **Figure 7**, which highlights the different neural coupling responses between the arms and legs of two subjects with an incomplete cervical SCI. Subject T.T. has a spinal cord lesion at level C3 and subject O.O. has a lesion at level C4. Subject T.T. shows that engaging the arms passively or actively elicits a systematic increase in soleus and tibialis anterior EMG activity. Yet, this type of neural response was absent in Subject O.O. So, although subjects can have similar types of injury (e.g., incomplete cervical SCI), the location of the lesion and severity can influence their neural response. While the device used in this study shows promise as a rehabilitation tool, experiments studying its long-term effects and benefits in individuals with an iSCI are still needed.

The key insights from the studies of Huang and Ferris and Kawashima and co-workers have inspired us to think about what kind of devices and training approaches could help humans recover from an iSCI.[22,30] What is currently absent in the field of gait rehabilitation is a task-specific training approach that allows a patient to actively engage and coordinate their own arms to help drive the stepping motion of their legs while walking. It is also important that such a training approach should be flexible to accommodate an individual's functional capabilities. Engaging the arms during walking will require muscular effort to meet these mechanical demands and thus, incur a metabolic cost. In the ideal scenario, the active use of the arms would provide a benefit by helping the legs carry some of the mechanical burden of supporting and accelerating the body, as if reverting to an analogous form of quadrupedal locomotion. To get a practical sense of whether this might be possible, it is helpful to understand the biomechanical basis for the metabolic cost of walking. A fundamental understanding can provide insight as to whether the active use of the arms during walking might require a high metabolic cost. In those with an iSCI, the active use of the arms during walking could cause muscular fatigue and thus, may be too exhausting of a task to adopt as a gait rehabilitation approach. Before discussing the active use of the arms in the context of gait rehabilitation (to be discussed in Section III), we first provide a brief review of the determinants that explain the metabolic cost of walking in the next section and use these insights to show that the metabolic cost of swinging the arms is relatively cheap. This will lay the foundation as to why the active use of the arms during walking is possible and key to developing a framework that promotes and enhances walking recovery in individuals with an iSCI.

3. Partitioning the Net Metabolic Power Required for Walking: A Brief Overview

The biomechanical determinants that explain the net metabolic power required for walking have been captured by the dynamic walking and task-by-task approaches. A visual summary of how each framework breaks down the net metabolic power required for walking is shown in **Figure 8**, along with their respective terminology for consistency with the original research. The theoretical origins of Dynamic Walking can be traced back to the work of Mochon and McMahon (1980), McMahon (1984), and McGeer (1990).[31–33] These insights gave birth to the theory of passive dynamic walking and was later advanced by the notable work of others to which is now referred to as dynamic walking.[34–42] The dynamic walking approach estimates that the mechanical work required for step-to-step transitions and the cyclic muscle forces required for leg swinging comprise ≈60%–70% and ≈33% of the

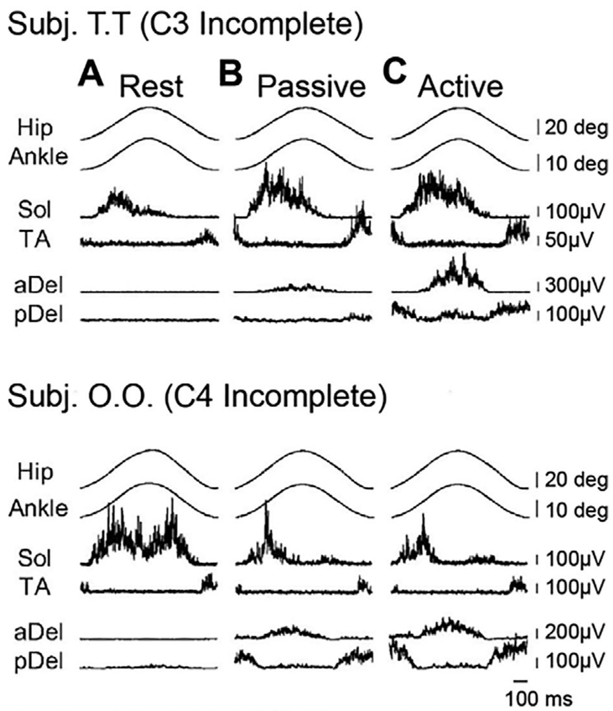

Figure 7. The averaged waveforms over 30 cycles of the hip and ankle joint motion, the load on the leg, and the induced EMG activities of arm and leg muscles recorded from two subjects with a cervical iSCI. Reproduced with permission.[30] Copyright 2008, American Physiological Society.

net metabolic power required for walking, respectively.[40–42] In the context of dynamic walking, the step-to-step transition can be understood as the period when the trailing and leading legs must re-direct the body's center of mass (COM) so that its path flows from a forward and downward trajectory to a forward and upward trajectory. The task-by-task approach originates from the work of Kram and co-workers, and estimates that the leg forces required for body weight support, forward propulsion, leg swing, and lateral balance comprise 28%, 45–47%, 10%, and 3–6% of the net metabolic power required for walking, respectively.[43–47] While we focus on these two approaches in this review, it is important to note that other approaches exist, and they have also deepened our understanding of the mechanical basis that explains the metabolic cost of walking.[48–52] Regardless of how each approach partitions the net metabolic power required for walking, they share the common finding that the metabolic cost of walking can be almost entirely explained by the mechanical demands placed on the legs, suggesting that arm swing has a negligible cost.

It seems reasonable to think that arm swing would exact a metabolic cost since muscular forces and torques generated by the shoulder are needed to swing the arms at sufficient frequencies and amplitudes.[53–56] It is tempting to think that the cost of arm swinging has been overlooked by both the dynamic walking and task-by-task approaches. However, bridging insights from the mechanical and neural coupling mechanisms that underlie the motion of the arms and legs will help to understand why the dynamic walking and task-by-task approaches can explain the metabolic cost of walking without including arm swing.

4. The Swinging Arms during Human Walking: Muscles, Pendulums, and Metabolic Cost

The arms were historically believed to play no role in the mechanics of walking, and likened the back-and-forth motion of the arms to passive swinging pendulums.[57,58] However, experiments within the past few decades have revealed the functional significance of the arms to be deeply embedded into the mechanics and neural control underlying human walking behavior. In 1965, Ballesteros et al. conducted the first study to probe the EMG activity of the arm muscles using needle electrodes during overground walking.[59] Representative data from Ballesteros et al. (**Figure 9A**) shows clear bursts of EMG activity for several muscles, most notably the posterior deltoid, latissimus dorsi, and trapezius. The activation patterns of these muscles indicate that they facilitate the back-and-forth motion of the arms during walking, but it is difficult to gauge how much muscular effort is needed because Ballesteros et al. did not express the EMG activity relative to the EMG activity measured from each muscle's maximum voluntary contraction (MVC). This was resolved in 2012 by Kuhtz-Buschbeck and Jing.[60] When walking at a comfortable speed of 1.0 m s^{-1}, Figure 9B shows that only two of the seven muscles exhibit peak EMG activities that range between 5 and 10% MVC, suggesting that swinging the pendulum-like arms requires relatively little muscular effort.

The reason why swinging the arms requires little muscular effort can be answered by the insightful experiments carried out by Collins and co-workers.[62] They built artificial arms made of either wood or rope to mimic the passive mechanical properties of pendulums and attached them to humans using a light frame fitted and supported around the neck and shoulders. Remarkably, when individuals walked (1.25 m s^{-1}) with these purely passive, pendulum-like arms, they swung back and forth just like biological arms, but without the need for neuromuscular control. This signifies that the act of walking itself can induce the back-and-forth motion of our biological arms. Furthermore, under the right initial conditions, these pendulum-like arms could swing out-of-phase with the stepping motion of the legs, just like our biological arms. Given these insights and those of others,[63,64] we can infer that little muscular effort is required to swing the arms because at preferred walking speeds, they are dominated by passive pendulum dynamics. Thus, we can conclude that the metabolic cost to swing the arms during human walking is negligible.

Although the arms tend to swing like passive pendulums, is it possible that the arms could play a more active role such that they could be used to help the legs meet the mechanical demands required for economical walking? Exploiting the active use of the arms during walking could be a simple and effective training strategy for those recovering from an iSCI. However, it is unknown whether such a strategy would greatly elevate the metabolic cost of walking, leading to premature fatigue and limited ability to practice their stepping pattern. To put this into context, the net metabolic power required for walking for both healthy individuals and those with an iSCI can be compared at similar walking speeds using the findings reported by two independent studies, which are those from Israel and co-workers and Adeyeri and co-workers.[65,66] At a walking speed of 0.83 m s^{-1}, Israel and co-workers report an average net metabolic power demand of 3.1 W kg^{-1} for individuals with an iSCI.[65] At the

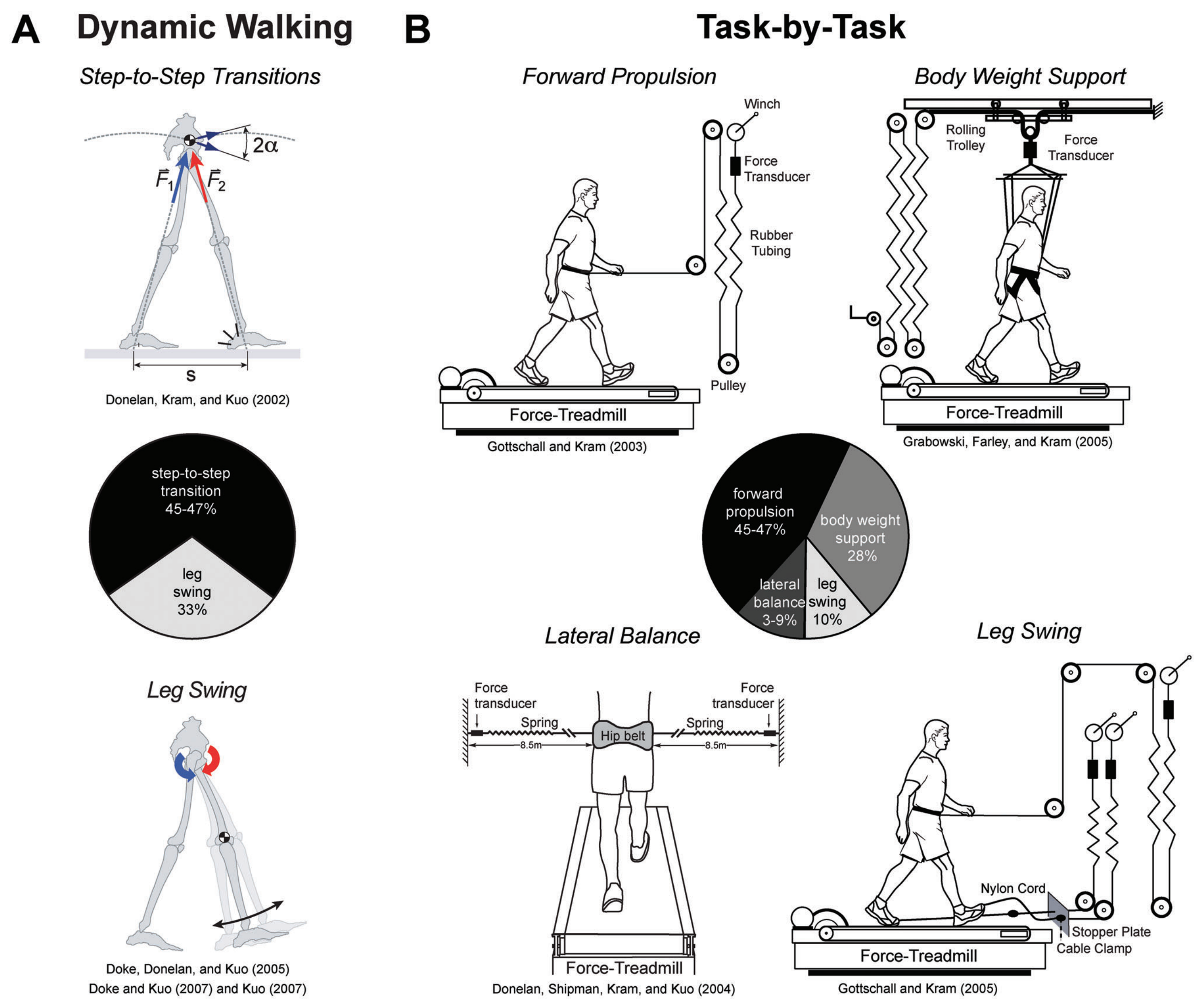

Figure 8. The field of locomotion biomechanics and metabolic energetics has been advanced by insights from the perspectives of A) dynamic walking and B) task-by-task approaches. They are recognized in this review as two scientific frameworks that have independently evolved since the early 1990s and that elegantly offer a mechanistic explanation as to the biomechanical basis for the net metabolic power required for human walking. Integrating the insights derived from these two independent, but complementary frameworks, is the key to developing new and optimal locomotor training solutions that involve the active use of the arms to maximize walking recovery in individuals with an iSCI. Illustrations used in the dynamic walking. Reproduced with permission.[39] Copyright 2007, Elsevier. Illustration for lateral balance. Reproduced with permission.[46] Copyright 2004, Elsevier. Illustrations for forward propulsion, body weight support and leg swing. Reproduced with permission.[43–45] American Physiological Society.

same absolute speed, Adeyeri and co-workers report an average net metabolic power demand of 1.6 W kg^{-1} for healthy, young individuals.[66] This reflects an approximately two-fold increase in the net metabolic power demand for walking at the same absolute speed, even though the subjects in the study of Israel and co-workers were provided with 30–40% body weight support and with manual lower limb and truck assistance from therapists. When combining the findings from Israel and co-workers with that of Gormon and co-workers, we estimate that locomotor training requires individuals with an iSCI to achieve average intensities that range between ≈88–95% of their peak metabolic power.[65,67] Given that these individuals have diminished aerobic capacities due to inactivity and muscle loss, they are likely to be more susceptible to muscle fatigue and exhaustion.[68,69] Therefore, if the arms are to play an active role in facilitating the mechanics of walking during locomotor training, it must incur as little of a metabolic cost as possible.

5. Recent Advancements and Future Considerations for How to Actively Use the Arms during Locomotor Training

This chain of reasoning has led us to several questions: How can we engage the arms to take on a more active role during walking? And if possible, how does the active use of the arms alter the biomechanics and metabolic cost of walking? In a proof-of-concept experiment in healthy individuals, we tested the idea

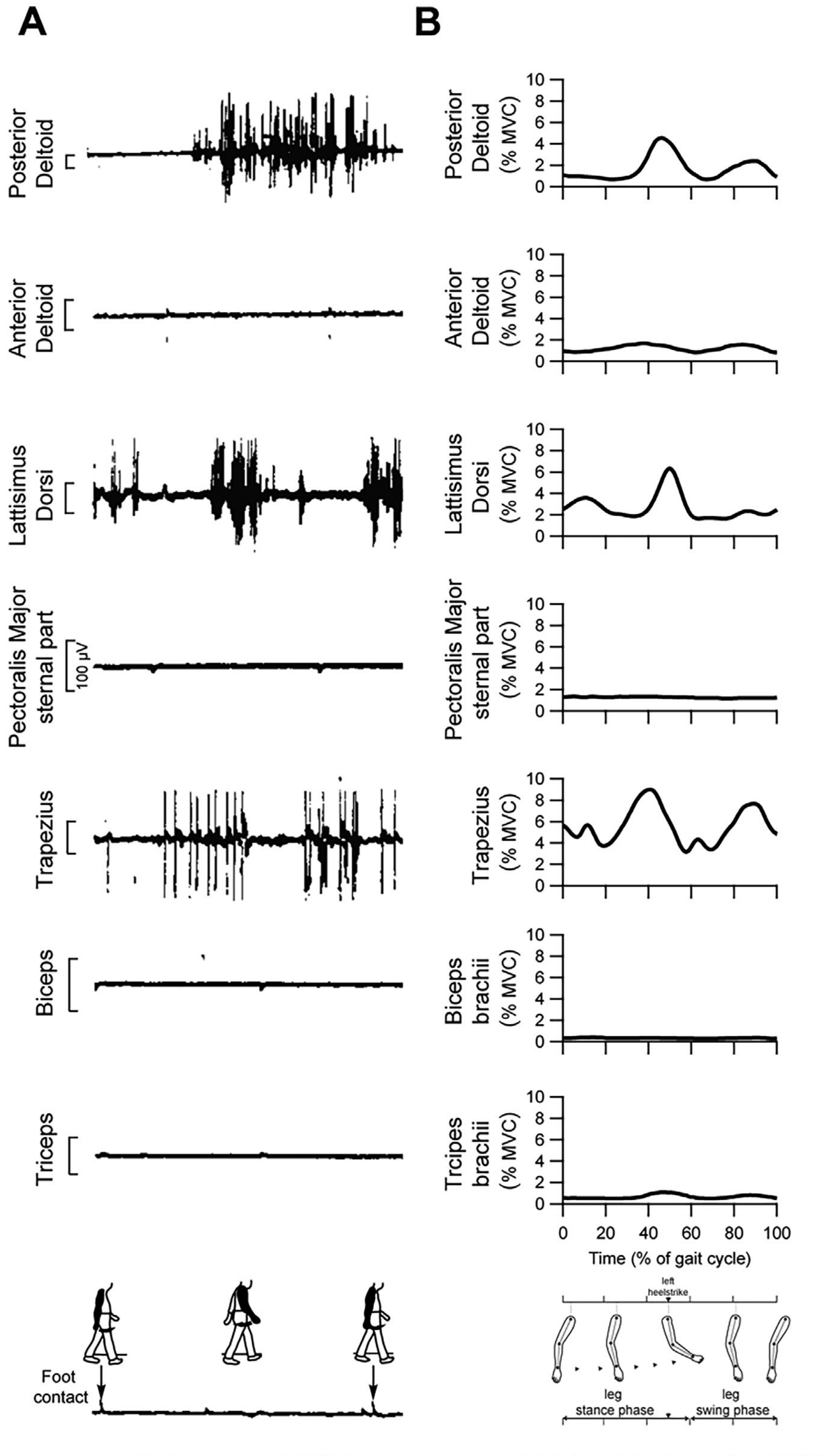

Figure 9. A) A 20-year-old male walking overground at 1.0 m s^{-1} while patterns of EMG were recorded in the muscles of the right shoulder and upper arm, as depicted by the cinematographic position of the arms. Adapted with permission.[59] Copyright 1965, Scandinavian Physiological Society. B) Grand averaged EMG curves (mean of 20 subjects) of the upper arm muscles while walking at ≈1.1 m s^{-1}. Original data was extracted from reference[60] using WebPlotDigitizer[28] to recreate the modified plots. The back-and-forth arm illustration was originally adapted from ref. [61] Adapted with permission.[60] Copyright 2011, Elsevier.

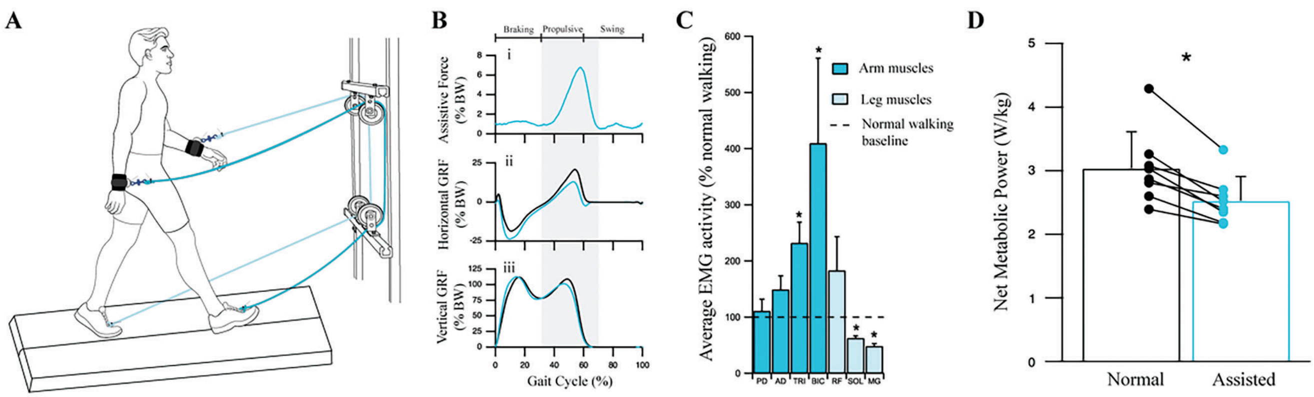

Figure 10. A) Subjects walked on a split-belt force measuring treadmill while attached to a simple self-assistive device that connects the ipsilateral arm and leg using a rope. Reflective markers and EMG sensors attached to the body captured body movements and electrical activity of key arm and legs muscles, respectively (not shown). A load cell positioned in series measured the rope tension generated by each arm. B) Mean ensemble forces demonstrate the mechanical demands during both normal (black line) and arm-assisted (blue line) walking. During ≈30–70% of the gait cycle, an assistive force (i, top trace) was generated by the same-side arm and leg rope connection (shaded gray area, $n = 7$), facilitating a decrease in the propulsive force (ii, middle trace) generated by the leg (compared to normal walking, $n = 8$). The vertical GRF (bottom trace) remained similar during both conditions ($n = 8$). C) Average EMG activity measurements, expressed relative to normal walking (100% baseline), reveal a muscular shift characterized by higher arm and lower leg muscle activity. Most notably, the arm's triceps and biceps were the primary muscles to help transmit the assistive force onto the whole body during the propulsive phase, reducing the leg's medial gastrocnemius and soleus demand (* indicates a significant difference from baseline, $p < 0.05$). D) The effect of actively using the arms coincided with a 17% reduction in the net metabolic power required for walking (mean ± SD, $n = 8$). Each line segment represents a subject, highlighting the observation that all subjects showed a reduction in net metabolic power (* indicates $p < 0.05$). Adapted with permission.[5]

that the arms could play an active role during walking by physically coupling the arms to the legs via a rope that connected the wrists of the arms to the same-sided foot of the legs.[5] We discovered that when the arms were mechanically linked to the legs (**Figure 10**), the arms could generate an assistive force that facilitated forward propulsion. The ability of the arms to facilitate forward propulsion can be seen by the reduction in the propulsive force generated by the trailing leg during the step-to-step transition, reflecting a lower mechanical demand placed on the legs during walking. During this sequence of the step-to-step transition, we also observed a neuromuscular shift characterized by an increase in the arm's EMG activity of the biceps and triceps muscles and a decrease in the leg's EMG activity of the soleus and medial gastrocnemius muscles. While the cost of actively using the arms is difficult to measure directly, our EMG measurements indicate that the arms were much more active, and thus, must have incurred a modest increase in metabolic cost. However, our findings highlight a trade-off between the need to place a greater mechanical demand on the arms so that a lower mechanical demand can be placed on the legs, which yielded a 17% reduction in the net metabolic power required for walking.

Our previous findings have inspired us to re-imagine the design possibilities of what we have conceptualized as a self-assistive device. We believe that combining principles of locomotion biomechanics and metabolic energetics (i.e., the dynamic walking and task-by-task approaches) can help guide future experimental approaches that focus on designing and using a self-assistive device that manipulates the forces acting on the body. Our goal for any self-assistive device is that it allows for individuals themselves to alter the mechanical demands placed on their arms and legs while walking. By facilitating the active use of the arms during locomotor training, an individual can actively engage in their own gait rehabilitation.

As the field of gait rehabilitation continues to evolve, we believe that an area of research that remains to be fully explored is understanding how to actively engage the arms so that they can lend a hand in self-assisted walking. The design of simple devices that allow self-assisted walking may prove to be a useful solution, but until such devices are designed and tested for walking, gait rehabilitation approaches will continue to rely on methods of external assistance, which may leave patients with little motivation and/or opportunity to actively engage in their own gait rehabilitation. To date, individuals with an iSCI have benefitted from training strategies that use sitting or standing devices that allow one to mechanically couple arm and leg movements, whether the arms behave passively or actively. Even though these training strategies can be categorized as non-walking tasks, the results clearly show that actively engaging the arms can modulate the excitability of the neural coupled pathways that converge onto the spinal cord. It remains unknown as to whether we could exploit this same mechanism when the arms are actively engaged during self-assisted walking. While future experiments will provide the answer, insights from past experiments suggest that it is possible, but how to effectively do so remains an open question. We have offered some insight with a preliminary design of a self-assistive device, where the arms can be used to facilitate the mechanics of walking. The approach of actively using the arms during walking described here only represents one of many potential solutions. Its simple mechanical design opens up an array of options to modify and test different hypotheses. Such design options that we are tinkering with are using the arms to apply an assistive force at the waist to facilitate forward propulsion during the step-to-step transition, adding a springy element attached in series with the rope to manipulate energy storage and release, or integrating a lever system to manipulate the mechanical advantage of the arms as they apply assistive forces to the body during walking.

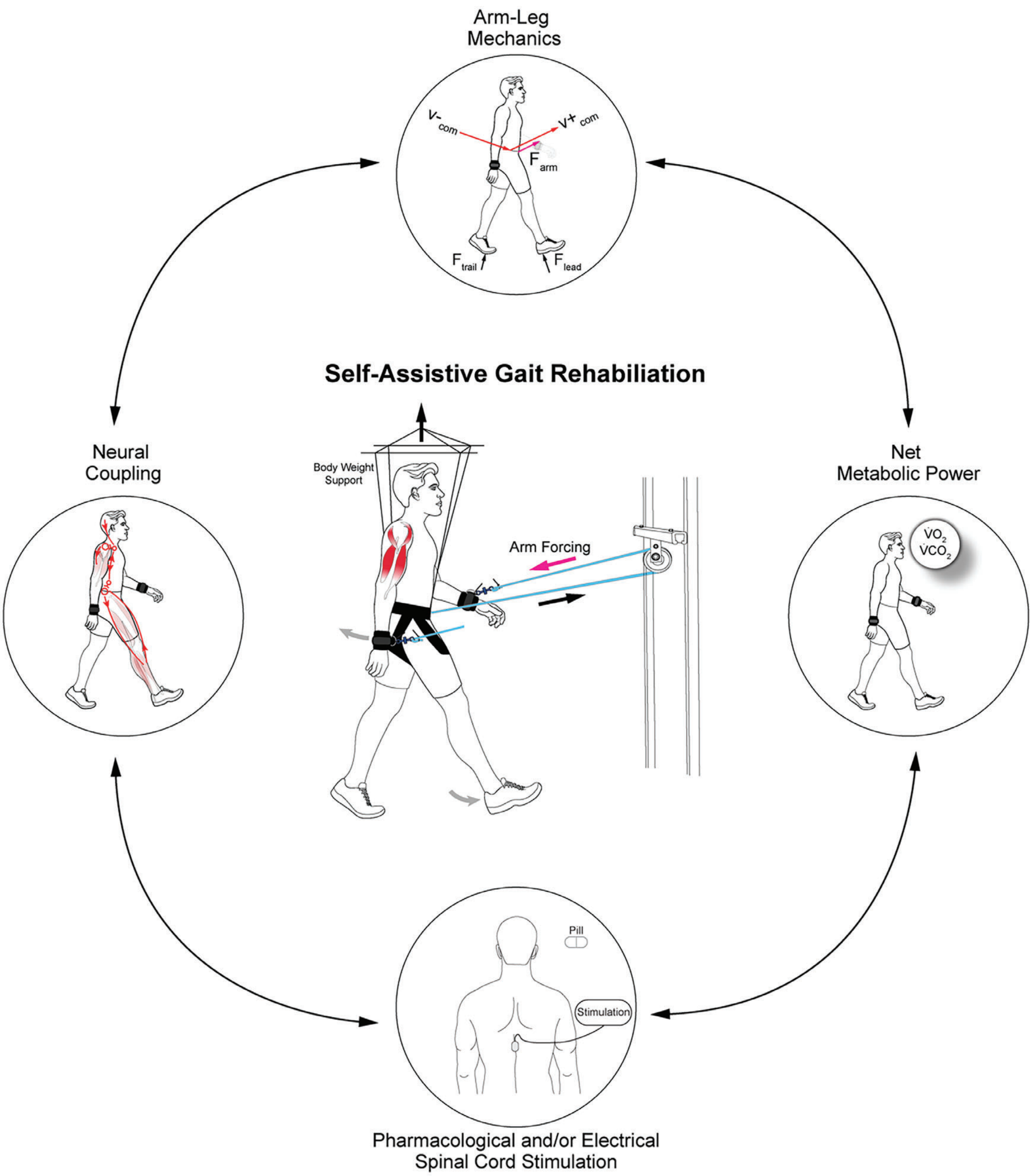

Figure 11. We envision a conceptual framework that integrates principles from the fields of locomotion biomechanics and energetics, gait rehabilitation, and neuroscience to develop self-assistive devices that could better promote walking recovery after an incomplete spinal cord injury. The self-assistive device pictured above is one of many potential solutions, but the primary goal is that such a device should allow the individual to actively use their arms so that they can help the legs with the mechanical demands of walking. Combining objective measurements that include arm-leg mechanics, metabolic power, and the excitability of the arm-leg neural coupled pathway can provide a complete picture of walking recovery. In addition, it is possible that combining the use of self-assisted walking devices with transcutaneous spinal cord stimulation could better promote walking recovery.

For the curious scientist and experimentalist, there are several approaches that one could take to solve the problem of how best to actively engage the arms during walking, but any solution should be relevant and practical in a gait rehabilitation setting.

While the emphasis on the active use of the arms has focused on benefitting individuals with an iSCI, it may be possible that a simple self-assistive device with the approach of actively using the arms may help individuals with other neurological disorders (e.g., stroke, Parkinson's disease, etc.). In addition to understanding the mechanical effects of actively using the arms during walking, there is a need to develop techniques to systematically probe the excitability of the neural coupled pathways that underlie the coordination of arm and leg movements, so that the capacity of the injured spinal cord for re-learning can be measured and tracked throughout training. We propose a conceptual framework (**Figure 11**) that combines objective measurements that include mechanics, metabolic energetics, and the excitability of the neural coupled pathways of the arms and legs during walking so that a complete picture of re-learning can be captured. In addition, integrating the use of a self-assistive device with electrical and/or pharmacological spinal cord stimulation could prove useful in promoting walking recovery.[70,71] These stimulation techniques could be used to increase the excitability of the neural connections between the arms and legs during self-assisted walking and thus, further promote walking recovery. These types of experiments will be challenging, but necessary to advance our understanding of the most effective interventions that will help individuals with an iSCI re-learn how to walk again. Overall, the simple device proposed here should not be understood as the ideal solution to locomotor training, but instead, as an example of how one can use principles of locomotion biomechanics and energetics to inspire self-assistive devices that could promote walking recovery. Our ideas on how to actively use the arms to promote walking recovery is a first step, but much work remains on understanding how to effectively exploit the arms so that they may function as built-in, smart rehabilitation motors.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

arm-leg coupling, assistive device, biomechanics, lower limb disorder, neural coupling, spinal cord injury, walking

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