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Review

The how and why of arm swing during human walking

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ABSTRACT

Humans walk bipedally, and thus, it is unclear why they swing their arms. In this paper, we will review the mechanisms and functions of arm swinging in human gait.

First, we discuss the potential advantages of having swinging arms. Second, we go into the detail on the debate whether arm swing is arising actively or passively, where we will conclude that while a large part of arm swinging is mechanically passive, there is an active contribution of muscles (i.e. an activity that is not merely caused by stretch reflexes). Third, we describe the possible function of the active muscular contribution to arm swinging in normal gait, and discuss the possibility that a Central Pattern Generator (CPG) generates this activity. Fourth, we discuss examples from pathological cases, in which arm swinging is affected. Moreover, using the ideas presented, we suggest ways in which arm swing may be used as a therapeutic aid.

We conclude that (1) arm swing should be seen as an integral part of human bipedal gait, arising mostly from passive movements, which are stabilized by active muscle control, which mostly originates from locomotor circuits in the central nervous system (2) arm swinging during normal bipedal gait most likely serves to reduce energy expenditure and (3) arm swinging may be of therapeutic value.

1. Introduction

Humans walk bipedally, and thus, it is unclear why we normally swing our arms during gait, as this has no direct function for propulsion. As a consequence, most (clinical) studies on gait tend to ignore arm swing altogether, and modeling studies often lump head (H), arms (A) and trunk (T) into a HAT unit assuming that this unit moves as one mass.

Still, some of the earliest studies on gait also included analysis of the arm movements during gait. These studies suggested that the arms swing purely passively,[2] as a consequence of the movements of the thorax, gravity, and inertia [1,2]. In addition, the first full gait analysis, performed by Braune and Fischer also included detailed descriptions of arm movements during gait [3], although these movements are merely reported, not interpreted. More than 40 years after the study by Braune and Fischer, Elftman [4] used their data to analyze arm swing during walking in detail, and concluded that since net moments in the shoulder joints were present, arm swing during gait is not passive, and driven by muscle activity. Only several years later, these ideas were confirmed by electromyographic findings by Fernandez Ballesteros [5] and Hogue [6]. Later studies however, reasoned that such active shoulder torques are only small, and suggested that arm swinging may be largely passive [7,8]. To date, the debate of *how* arm swing comes about (i.e. whether it is caused by accelerations of the shoulder girdle or muscular activity) seems to be still going on [8–11].

Apart from the question whether arm swing is actively controlled or merely passive, there seems to be no consensus on *why* humans swing their arms during gait (i.e. what the purpose of arm swing is, if it has a purpose at all). Suggested reasons include minimizing energy consumption, optimizing stability, and optimizing neural performance.

In the present review, we aim at giving an overview of *why* and *how* humans swing their arms during gait. First, we will discuss the potential (dis) advantages of having swinging arms. Second, we will go into detail on the debate whether arm swing is arising actively or passively. Third, we will describe the possible function

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[2] Actually, Gerdy is always reported as seeing arm swing during gait as entirely passive, but, upon better reading his work, one can see that he believed that sometimes arm movements were also partly active: "Je dois ajouter que parfois ils semblent, ces mouvements des bras, augmentés par l'action irréflexie du biceps brachial, et peut-être du grand pectoral et d'une portion du deltoide." [I should add that sometimes these arm movements seem increased by action of the biceps brachii, and the pectoralis major and a portion of the deltoid.], p12.

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of the active muscular contribution to arm swinging in normal gait, and discuss the possibility that a Central Pattern Generator (CPG) generates this activity. Fourth, we will discuss examples from pathological cases, in which arm swinging is affected. Lastly, using the ideas presented in earlier parts of this paper, we will suggest ways in which arm swing may be used as a therapeutic aid.

2. Arm swing: why?

Regardless of whether arm swing is passive or active, or partly passive and partly active (which seems most likely), one of the important questions is *why* humans walk with their arms swinging out of phase with the legs. Over the years, multiple reasons have been suggested, including optimizing stability, optimizing energy consumption, and maximum use of the neuronal heritage of quadrupedal gait. Below, we will outline findings of the former two ideas (i.e. arm swing to optimize stability, and arm swing to optimize energy consumption). As the last idea is also closely related to the question of *how* muscular activity during arm swing is controlled, we will discuss it in Section 3.

2.1. Arm swing to optimize stability

When discussing the effects of arm swing on gait stability, it is necessary to start with a definition of gait stability. In steady-state gait, infinitesimally small perturbations are ever present, and the system's response to such perturbations may be called local stability. When gait is externally perturbed, global stability can be assessed by quantifying the response to such a perturbation. Following Bruijn et al. [12], in human gait, this response may be divided into two phases: an initial phase, which is dependent upon both the steady state of the system (as it was before the perturbation) and the system's intrinsic mechanical properties (e.g. inertia, stiffness), and a second, reactive phase ('recovery'), which is mainly dependent on active control and reflexes. Thus, when discussing stability, we will make a distinction between steady state gait stability, and the ability to recover from a larger perturbation.

Ortega et al. [13] used lateral stabilization to study the contribution of the arms to steady state gait stability. They found that elastic cords attached to hip-belt reduced energy expenditure more when subjects walked without arm swing than when they walked with their natural swing. From this, the authors concluded that arm swing contributes to lateral stabilization. However, an alternative explanation is that the elastic cords counteracted the angular momentum about the vertical (see below), which could also have led to larger decreases in energy expenditure when walking without arm swing. Indeed, Collins et al. [10] found no effects of arm swing on steady state gait stability in a simple passive dynamic walking model. Moreover, Pijnappels et al. [14], and Bruijn et al. [12], using perturbation experiments, even found negative effects of arm swing on steady state gait stability.

It should be noted that, in contrast, it is clear that the arms may aid in recovery of the gait pattern after a perturbation [15]. Indeed, studies finding negative effects of arm swing on steady state gait stability reported that arm movements after a perturbation do help to recover the gait pattern once it is perturbed [12,14,16]. This may also be the reason why Curtze et al. [17] reported that the lateral velocity of arm swing played a vital role in the control of dynamic balance in amputees; these subjects may have been perturbed so much, that arm movements actually became beneficial.

Apart from the swinging motion of the arms, the posture of the arms has been suggested to be related to stability as well. For instance, in toddlers [18,19], and children with CP [20] guard positions of the arms during walking have been found, which have been suggested to be a compensatory strategy to maintain balance. Clearly, such a guard position is useful when preparing for a fall. Still, it is as of yet unclear how such a guard position would improve stability.

All in all, the effects of arm swing on gait stability are equivocal, but it is clear that the arms may help in regaining balance after a perturbation, and that guard postures may be adopted by those at risk of falling.

2.2. Arm swing to minimize energy consumption

While not directly investigating the effects of arm swing on energy consumption per se, Elftman [4] was the first study that suggested that arm swing may minimize energy consumption during gait. This study reported that arm swing decreased angular momentum about the vertical. As such a decrease will lead to a decrease in vertical ground reaction moment (at least, when stride times remain similar), it is likely to be accompanied by a decrease in energy consumption of the legs, since a smaller ground reaction moment needs to be generated by the leg muscles. Still, it could be that swinging the arms would cost more energy than the reduced energy demands of the legs. Later studies however, confirmed that arm swing decreased angular momentum about the vertical [10,21–25], and vertical ground reaction moment [10,26], and, most importantly, actual energy consumption, as measured using oxygen consumption [10,13,27,28], for which estimates range up to 8% decreased energy consumption, when compared to walking with constrained arms [27].

3. Arm swing: how?

As outlined in the introduction, the question whether arm swing is passive or active was one of the first questions asked when arm swing was studied. An obvious first step is to calculate net joint moments in the shoulder during gait. Elftman [4] was the first to do so, and reported shoulder moments up to 7.5 Nm. These findings have later been confirmed by several authors [10,29,30], although reported shoulder moment peaks vary as much as 6 fold (e.g. 2.2 Nm reported by Collins et al. [10], vs. 12 Nm reported by Hinrichs [30]). This suggests that there are forces other than the accelerations of the shoulder girdle and gravity that cause the movements of the arms during gait.

However, it could well be that these net joint moments are generated by passive structures alone (e.g. tendons, ligaments), and thus, it is necessary to check whether there is rhythmic EMG activity in arm muscles. Such activity has indeed been recorded by various authors [5,6,9,11,31]. Summarizing the findings of these studies, it seems that arm swing during gait is accompanied by activity in several muscles, including the deltoid, latissimus dorsi, and trapezius muscles. Fig. 1 illustrates when in the gait cycle which muscles are active. From this figure, it can be seen that for several muscles, the patterns of activity are double peaked, with activity both driving, and damping the arm swing. This pattern of activity is not necessarily associated with active driving of arm swing by the arm muscles, as was explicitly mentioned by Pontzer et al. [11]; it could also be that the function of the arm muscles is to stabilize the unstable shoulder joint during impacts, in which case stiffness could be responsible for the net joint moments. To adequately investigate the role of the muscles in arm swing during gait one would have to exclude muscle activity altogether.

Since it is hard to exclude muscle activity in experiments on humans, such investigations have usually applied a modeling approach. The first authors to do so were Jackson et al. [7], who used a double pendulum model to investigate the contribution of shoulder accelerations and muscle torques in driving arm swing. They concluded that if arm swing during gait would not involve any muscle activity, the motion of the arms would "vary greatly for

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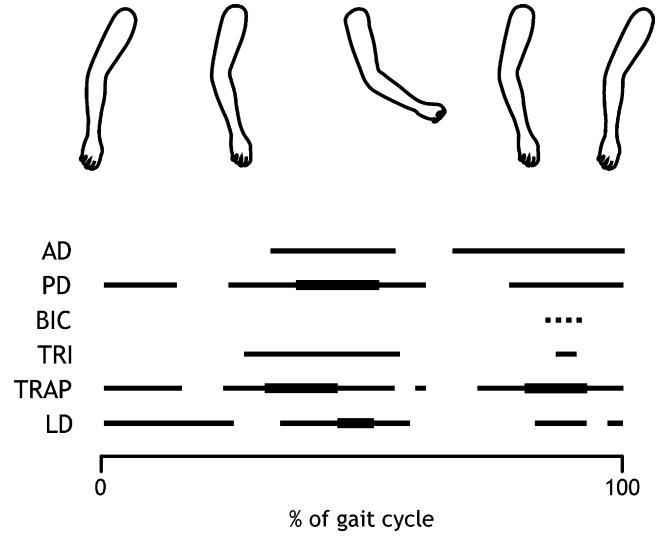

Fig. 1. Periods of muscle activity during Normal walking with free arm swing(Normal, 6 km/h). Thick bars indicate EMG activity of anterior deltoid (AD), posterior deltoid (PD), Triceps (TRI) exceeding 5% MVC or, respectively, activity of trapezius (TRAP) and lattisumus dorsi (LD) exceeding 10% MVC. Thin bars denote weaker EMG activity, i.e. >1% MVC for AD, PD, TRI and, respectively, >3% for TRAP and LD. Mean BIC activity (dotted line) stayed below 1% MVC. Data are based on grand averaged EMG profiles of the 20 participants (adapted from Kuhtz-Buschbeck et al., 2008).

various cadences and contribute an undesirable jerkiness to locomotion" [7]. However, while their model was elaborate at the time, it contained a multitude of parameters that were only roughly estimated. In later work, Webb et al. [32] investigated in how far a driven pendulum model could be used to predict the switch from 2:1 arm to leg swing ratios (which occur at lower walking speeds), to 1:1 arm to leg swing ratios (as occur at medium and high speed walking; see further). Results showed that this model was well able to predict this transition. These findings were later replicated by Kubo et al. [8], using a double pendulum model. In another study, Gutnik et al. [33] reported that the motion of the arms (both in terms of period of motion and of angular velocity) during normal walking could not be described by a simple pendulum model, and concluded that muscle forces must be responsible for this discrepancy. However, the pendulum they compared their movements to, was a passive pendulum, without a driving acceleration at the hinge, which seems unrealistic. In a more simple passive dynamic walking model, Collins et al. [10] showed that arm swing may occur passively, and may show different phase relationships to the legs. Collins et al. [10] extended these findings in a physical model, consisting of artificial "arms" (i.e. pieces of rope or metal) attached to the shoulder by means of a hinge, showing that these "arms" could show different phase relationship with the legs, suggesting that no muscle activity is needed to swing the arms. Still, these findings were not quantified in an objective manner.

Thus, despite the finding of EMG activity in arm muscles, it appears that a part of arm swing may be explained by passive dynamics. How large this part is, however, has never been properly explored. Using modeling techniques, one should be able to show what the arms would do when there is no active drive of muscles, or when only the moments caused by muscles are there. Future studies could thus provide better insight into the question as to what extent arm swing during walking is passive.

4. Neural control of arm swing

If we assume that the arms swing is partly passive, the question arises as to *why* there is arm muscle activity during gait (persisting even when the arms are constrained; see [5,9]). Arm muscle activation may come about by the way the nervous system (more particularly the spinal cord) is built, with interconnected Central Pattern Generators (CPG) generating locomotion patterns [34]. In a leading review, Dietz [35] has argued that bipedal and quadrupedal locomotion share common spinal neuronal control mechanisms (see also [35–37]). The basic assumption is that during evolution, man started to walk bipedally at a given point, and that the circuitry, previously used for the arms during locomotion, did not disappear overnight but remained operational to assist arm swing during gait (including the control needed to guide the passive component of the swing). Interestingly, our closest neighbor species in evolution, other primates, do not appear to show swinging arms when they walk bipedally (e.g. see Fig. 2 in two papers by Mori and coworkers [38,39]), but this may be related to the somewhat uncommon mode of walking for these animals. An intermediate form of gait, termed "knuckle" walking, is seen in gorillas. The EMGs in the arm muscles show strikingly similar basic features in this type of walking when compared to walking in man [40].

The basic idea of CPG's being responsible for arm swing during locomotion goes back to suggestions of Jackson and colleagues [7,41,42] but evidence in support of this contention has only been accumulated recently. Obviously it is not easy to prove this notion of CPG control of arm swing, since direct evidence is lacking. Briefly, the indirect arguments on which this idea is based are the following.

First, there is the observation that the coordination between arms and legs conforms to strict rules, as if they are "hard-wired" within the CNS as a remnant of privileged connections used in locomotion. For example, Wannier et al. [43] showed that the coupling between arms and legs in various locomotor activities (swimming, walking) always has the arms move at either the same frequency or at a multiple of this frequency. Furthermore, the privileged mode of quadrupedal interlimb coordination in other animals is the diagonal mode and one would expect this mode to be dominant as well when walking bipedally. If quadrupedal coordination is deeply embedded in the human nervous system then one might expect this to be revealed in conditions when there is a conflict between voluntary arm movements and walking. For example, Muzii et al. [44] combined a walking and a clapping task at preferred rates. Hand clapping was found to be tightly coupled to heel strike. When instructed to walk and clap at different rates (e.g. walk normally but clap faster) the subjects were not able to perform this task, implying that the walking rhythm dominated the coordination. Hence coupling is fairly robust, a finding that was confirmed by the observation that the typical 1:1 diagonal coordination during gait is maintained even when either one of the limbs involved is loaded with an extra 2 kg [45].

The second piece(s) of evidence for the notion of CPGs being responsible for arm muscle activity during gait comes from the study of interlimb connections and reflexes. In the cat, the girdles are known to be connected by long propriospinal neurons and these are thought to be involved in the spinal mechanism for interlimb coordination [46]. Evidence in this direction was obtained when it was shown that transmission in these propriospinal pathways is facilitated by the injection of substances, known to be able to activate spinal CPGs [47]. It is thought that such interconnections underlie interlimb coordination during gait. This coordination usually takes the form of an in-phase synchronization between diagonal limbs (trot) in a variety of quadrupeds [46,48]. Other patterns include pacing and galopping. It is thought that all these types of coordination somehow rely on long fibers, interconnecting the CPGs either directly or indirectly [49–51]. Evidence for the presence of such long propriospinal tracts exist both in cat [48,52,53] and in rat [54–56]. These

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connections can explain the experimental finding that cyclic or tonic stimulation of low-threshold afferents from a single hindlimb or forelimb is able to activate locomotor rhythmic bursting at both lumbar and cervical cord levels [57–59]. This lead to the suggestion that "sensory input from a given limb is not only able to influence its adjacent segmental circuitry, but also has access to the distant constitutive components of the spinal locomotor network ensemble". However, the coupling remains intact even when afferent input is absent (as was shown in the deafferented cat by Orsal et al. [60]).

Although the connections go both ways it is clear that in rats the caudorostral connections seem to be the most powerful ones. For example, Juvin et al. [57] showed that the hindlimb CPGs strongly activated forelimb CPGs in rats. In the absence of lumbar CPG activity one can elicit cervical CPG rhythmicity with lumbar afferent stimulation, whereas cervical dorsal root inputs are unable to drive the lumbar generators without cervical CPG activity. Similarly in the cat, Akay et al. [61] obtained evidence for a strong lumbar to cervical drive (using decerebrate cats walking on a transversely-split treadmill). In fact, these authors proposed that antero-posterior coordinations depend basically on ascending excitatory and descending inhibitory fibers. Furthermore these intraspinal interconnections seem to favor the diagonal coupling (right forelimb and left hindlimb synchronized). For example, the isolated spinal cord of the rat usually shows diagonally coupled bursting that corresponds to quadrupedal walking [57,58]. The same is true for fictive locomotion in the cat, although occasionally other forms of coordination are observed as well [60].

In humans, there is sufficient evidence to indicate that spinal CPGs exist as in other species [62] and that there exist the same kind of long propriospinal connections as described in other species [63]. The coordination of arm and leg movements takes the form of an in-phase relationship between diagonal limbs [64]. The dominance of the lumbosacral girdle over the cervicothoracic is probably preserved in humans as well. For example, Sakamoto et al. [65] showed that during combined arm and leg cycling, the cadence of the arms was significantly altered when leg cycling cadence was changed. The opposite, however, was not true, i.e. the arms did not affect the leg cadence.

Nevertheless, some action in the other direction remains possible and this is of utmost importance in the context of gait rehabilitation, since it is important to know whether arm swing can assist locomotor movements of the legs (see further). In normal subjects, it was found that upper limb movement influences the recruitment of lower limb motoneurons during locomotor-like rhythmic activity on a recumbent stepper [66,67]. In contrast, later work did not provide further evidence for facilitation [68]. Upper limb effort did not increase maximal voluntary muscle activation of the legs. This latter result, however, could have been due to a ceiling effect (i.e. the authors proposed to repeat the experiments with submaximal contractions).

Evidence for interactions between the girdles was even more difficult to obtain in SCI subjects because of intersubject variability. Nevertheless, in a study of cervical incomplete SCI subjects it was found that upper limb movements generally increased soleus EMG activity in the movement phase that corresponded to the stance phase in normal gait [69]. From this, the authors concluded that "the neural signal induced by the upper limb movements contributes not merely to enhance, but to shape the lower limb locomotive motor output, possibly through interlimb neural pathways". Again, such facilitation was not seen in SCI when maximal contractions were used for leg muscles [68].

So far the emphasis has been on the spinal mechanisms underlying interlimb coordination during gait. Nevertheless, one should keep in mind that interlimb coordination is more sturdy when the spinal cord is connected to the brainstem (as in decerebrate cats, see [51]). Higher order regulation of interlimb coordination can be achieved at brainstem and cortical level [51,70]. This explains why one does not necessarily have to walk with natural swinging arms, but can perform other actions as well with the arms (i.e. texting, holding a book, etc.). Moreover, even for the natural swinging of the arms, it has been shown that cortical contributions may be present [31].

5. Arm swing and pathology

As outlined in Section 1, arm swing during gait has an important role in decreasing energetic cost of locomotion. Several pathologies may lead to various abnormalities in arm movements during walking. It may therefore be expected that pathological gait is energetically more demanding, not only because of the pathology, but also because of affected arm movements. Indeed, it has been reported that preventing arm swing during gait does change the gait pattern in healthy adults, in particular with respect to the interlimb coordination, and cadence [41,42,71,72].

In patients, impairments in arm swing can be secondary to a deficit in leg movements (as for example in orthopedic patients). However, the focus of the present review is on pathologies that directly affect arm swing, as in patients with central neurological pathologies (e.g. stroke, Parkinson's disease, Cerebral Palsy, Spinal Cord Injury).

5.1. Impairment of arm movements

5.1.1. Arm swing amplitude

Some degree of asymmetry in arm movements during gait is physiological; significant differences between left and right arm swing amplitudes have been shown in more than half the gait trials in healthy subjects [73]. In pathological conditions, however, the asymmetry can be much larger. This increased asymmetry can have various underlying causes.

Persons with hemiplegia after stroke or with Cerebral Palsy (CP), are known to experience weakness, motor control abnormalities, and spasticity in the muscles of the involved arm(s) [74,75]. Persons with Parkinson's Disease (PD) typically suffer from symptoms such as tremor, bradykinesia, and rigidity, which also affect arm function in daily life activities [76]. In Spinal Cord Injury (SCI), one would expect the amplitude of the arm swing to vary depending on the level and extent of the lesion. In fact, in patients with a motor incomplete SCI the vast majority does not swing the arms at all during walking [77]. In other groups, the deficit is less pronounced. In patients with hemiplegia after stroke or CP the impaired (i.e. hemiplegic) arm usually swings with decreased amplitude [78,79]. Similarly, in individuals with PD, a reduced arm swing has been described [80–82]. In these patients, arm swing is especially reduced on the "most affected" side [83–85]. This asymmetry in PD was suggested to deteriorate with ongoing disease [86], and linked to the asymmetric process of nigrostriatal dopaminergic denervation [84,85]. There are no indications that patients with PD compensate by increasing the arm swing on the less affected side. This is different from other pathologies, for instance in persons with hemiplegic CP, where it was found that the arm swing amplitude of the non-hemiplegic arm exceeds that of healthy control participants [78]. This increase in non-hemiplegic arm swing in children with hemiplegic CP was found to counteract an increased angular momentum produced by the legs, suggesting it is aimed at controlling total body angular momentum [25].

In summary, typical symptoms in central neurological patients (e.g. weakness, bradykinesia, spasticity) directly impair the affected arm swing during walking. Compared to the arm swing in healthy controls, the unaffected arm may show an increased swing in persons with hemiplegia but not in PD.

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5.1.2. Arm posturing

Superimposed on arm swing during gait, there may be changes in the posture of the arms. One of the most well-known postures is used when facing unstable surroundings, namely holding the arms extended (as "balance poles") [87].

Specific arm postures are typically seen in newly-walkers (called "guard positions" [18]), and are common in CP children at a more advanced age as well [20]. Depending on the location of the brain lesion and secondary musculoskeletal deformities, a variety of locomotor patterns may emerge [88]. The type of CP is determined by the topography of the affected limbs, i.e. in children with hemiplegia one side of the body is affected more, while in children with diplegia the legs show most symptoms [89]. With respect to the arm movements during gait, children with hemiplegia can be distinguished from children with diplegia. Overall diplegic CP children have good motor control of both arms whereas hemiplegic CP children show severe disturbances of hemiplegic arm control. Even though children suffering from diplegia usually have no- or less pronounced symptoms (e.g. weakness, spasticity) in the upper extremity, they do show altered arm movements during walking compared to children with hemiplegia and age-matched controls [78]. For example, children with diplegia show greater variability in arm movements, and hold their arms more in abduction [90]. Furthermore, children with CP show specific arm postures that have often been linked to increased muscle tone, or spasticity [91]. During walking the affected upper extremity posture in children with hemiplegia typically includes an abducted, internally rotated shoulder, elbow flexion, wrist flexion, and thumb adduction [92,93]. This makes that their hemiplegic hand is held higher and more anterior during walking compared to the non-involved hand [20]. The arm posture during gait in these children was found to naturally develop toward a less impaired elbow flexion without surgical intervention [93].

Recently, the Arm Posture Score was developed as an index to score arm posture abnormalities in children with hemiplegic CP during gait [94]. The Arm Posture Score was able to differentiate between two subgroups of children with hemiplegia; a less affected group, in which the hemiplegic moved more, but in a less controlled manner, and a more affected group, that presented a stiff arm with a limited range of motion. The less affected subgroup was suggested to have less pronounced spasticity compared to the more affected subgroup, but not have sufficient motor control of the arm. Children with hemiplegia and children with diplegia also show altered arm positions of the non-involved arms. They hold their elbow in a more flexed manner and position their (non-involved) hands higher and more in front of their body while walking when compared to healthy control subjects [20]. Children with hemiplegia, specifically, have been shown to have an abducted shoulder position in the beginning of the gait cycle [92]. The adaptations of the non-involved arms were found to be related to instability during walking in these children [20].

In summary, the position of the arms in children with CP depends on whether it is primarily affected by spasticity. If that is the case then the arm is held in the typical stiff position throughout gait, otherwise its posture is adapted to instability of gait and/or moves in a less controlled manner due to impaired motor control.

5.1.3. Interlimb coordination

Altered arm movements and positions may influence the coordination between the limbs (i.e. interlimb coordination), even in healthy gait [72]. A clear example is the frequency ratio between arm movements and leg movements. In healthy control subjects, when walking at a preferred speed, typically one arm swing is associated with one leg swing, which corresponds to a 1:1 arm-to-leg swing ratio. Only when walking slower, people adopt a 2:1 arm-to-leg swing ratio [95,96].

In subjects with central neurological deficits (stroke, PD, and CP), a 2:1 arm-to-leg swing ratio also persists at higher walking speeds [64,97]. Interestingly, in some stroke patients and children with hemiplegic CP the involved arm shows a 2:1 arm-to-leg swing ratio, while the non-involved arm shows a 1:1 arm-to-leg swing ratio [64,97], while in children with diplegia this phenomenon can occur on either side, and even on both sides simultaneously [97]. Moreover, in PD, it has been found that some patients held the 2:1 arm-to-leg swing ratio when speed increased, while others already locked on to a 1:1 arm-to-leg swing ratio from the lowest speed onwards [64]. This phenomenon has been attributed to the general inability of these patients to make transitions [64].

In contrast to the aforementioned pathologies, the majority of persons with a motor incomplete SCI do not show arm swing during stepping [77]. For the patients that did swing their arms during walking, a 1:1 arm-to-leg swing ratio was present irrespective of the maintained walking speed, like in some PD patients. This could reflect an inability to modulate specific movement patterns after SCI [98].

Most studies on gait in central neurological pathologies reported a decreased synchronization of the limbs [64,97,99–103]. In PD this decreased interlimb synchronization has been described both for de novo patients [100] and for persons in a more advanced stage of the disease [64,101–103]. The deficit in interlimb coordination between the upper and lower limbs is also present in both freezers and non-freezers [104]. Decreased synchronization in PD was suggested to be related to the presence of rigidity and bradykinesia [100].

Studies in persons after stroke and in children with CP commonly describe impairment in interlimb synchronization [64,97,99]. Both in persons after stroke and in children after hemiplegia, the hemiplegic arm constrained the ability to synchronize the limbs. In children with diplegia, on the other hand, the lower limbs limited coordination capabilities [97]. Some studies on post-stroke persons, however, also report an intact synchronization, although the authors suggested this might be due to the high level of functioning of the participants [79,105].

In children with CP, impairments in coordinative stability between the limbs have been described [97]. In children with hemiplegia, again the less stable coordination patterns originated from the hemiplegic arm (the most affected limb). In the children with diplegia, however, the non-involved limbs (i.e. arms) were found to constrain coordination stability.

Taken together, these findings suggest that interlimb coordination in central neurological pathologies is limited by the secondary affliction of the affected limbs (e.g. spasticity, rigidity). Coordinative stability, on the other hand, can also be deteriorated due to the compensating limbs.

5.2. Arm swing and gait rehabilitation

As indicated in Section 3, emerging evidence indicates that upper and lower limb movements influence each other during locomotor-like tasks. From this point of view, including arm movements in rehabilitation of gait has been proposed to be beneficial for several central neurological pathologies (e.g. stroke, spinal cord injury, cerebral palsy) [78,105,106]. In particular, it has been suggested that normalizing interlimb coordination could improve gait in patients with PD or after stroke [34], and children with CP [97]. Additionally, from a mechanical point of view it also appears useful to coordinate the limbs properly, because it is expected to lead to a normalization of the angular momentum [21] and decreased energy expenditure [10]. Most studies incorporating arm movements in gait rehabilitation, did not aim at normalizing interlimb coordination per se, but focused on increasing arm swing amplitude.

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A series of case studies in patients with SCI led to the conclusion that natural reciprocating arm movements facilitated stepping, whereas weight bearing on the arms inhibited rhythmic stepping [106]. This is important since daily use of assistive devices such as walkers can contribute to the absence of arm swinging during gait in persons after motor incomplete SCI [77]. Locomotor training that also incorporated arm swinging, promoted independent arm swing after the training in these patients [77].

Patients with stroke have also been studied to gain evidence that supports the facilitation of leg movements by including arm swinging. In adults with hemiplegia after stroke, impaired hemiplegic arm swing was found to constrain walking speed. Treating the spastic arm muscles with Botulinum toxin improved walking speed, stride-time of the paretic leg, and knee and ankle range of motion in these patients [107,108]. Interestingly, persons with hemiplegia after stroke were also able to actively increase arm swing amplitude on both sides of the body after instruction [79]. This indicates that they might be able to beneficially influence their walking by cognitively adjusting their arm movements. The latter suggestion has been confirmed since it was found that auditory cues directed at arm motion can also be used to improve arm swing amplitude and interlimb coordination in these patients [64]. Furthermore, this intervention led to the beneficial effect of lengthened strides [99]. It should also be mentioned that arm swing might have beneficial effects on leg muscle spasticity in these patients since arm cycling was found to reduce the hyperactive soleus H-reflexes in these patients [109].

Another possibility to enhance arm swing during gait rehabilitation is the use of sliding handles on handrails while training on a treadmill. This setup allowed stroke subjects to reciprocally swing the arms while walking at a faster speed than they were normally able to achieve [105]. Additionally, due to the sliding (as compared to fixed) handrails, less weight was borne by the upper limbs during treadmill training, which led to increases in lower limb muscle activation and may facilitate transfer to over ground walking [110].

In PD patients, the evidence for arm facilitation is scant. Nevertheless, these patients were found to be able to modify their walking pattern by consciously adapting one gait variable (in this case arm swing) [111]. Increasing arm swing amplitude in these patients normalized walking speed and step lengths [111].

All in all, it seems that including arm swing in rehabilitation programs may normalize gait patterns. This could have added advantage of reducing the energetic cost of gait of the patient, thereby increasing the effort he/she has to spend to walk a certain distance, and, as a consequence, increase the patient's mobility. One complication, one has to take into account is that these patients often also have changes in trunk motion and posture (e.g. children with CP show more trunk movements in all planes [90,92]; patients with PD walk with increased trunk flexion [82], and reduced trunk rotation throughout the gait cycle [80,100]). Such changes may affect arm movements indirectly and in such cases one has to avoid training these patients in the same way one would train subjects with normal trunk motions and posture.

6. Discussion and conclusion

We set out to review the *how* and *why* of arm swing during normal and pathological gait. In reviewing the literature, it becomes apparent that the question of "how" cannot be easily answered at the time, as there is as of yet no study showing in how far muscles actively generate arm swing, and what part of it is passive (i.e. generated by accelerations at the shoulder girdle, inertia, and gravity). The question of "why" however, seems to have converged on two answers. Firstly, as described in Section 2.2, by now it is clear that arm swing during human gait reduces energetic cost by as much as 8%. Secondly, there is converging evidence that swinging the arms during gait facilitates the movements of the legs.

Given these two reasons, it may seem strange that there is only a limited body of work to assess arm movements during pathological gait and to evaluate the potential role of arm swing in the rehabilitation of gait. Nevertheless, the sparse work undertaken on this topic is promising and may lead to enhanced forms of gait rehabilitation. Still, more work is needed to confirm the effectiveness of including arm swing as a rehabilitative goal. It is our hope that the rationale and evidence for paying more attention to arm movements during gait, as compiled in this review will catalyze the inclusion of arm swing analysis during normal gait analysis. After all, with modern day techniques, measuring full body does not take much more time than just the legs, and important insights may be gained.

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Conflict of interest

None of the authors has a conflict of interest.

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