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INTERLIMB COORDINATION DURING STEP-TO-STEP TRANSITION AND GAIT PERFORMANCE

Abstract

Most energy spent in walking is due to step-to-step transitions. During this phase, the interlimb coordination assumes a crucial role to meet the demands of postural and movement control. This work reviews studies that have been carried out regarding the interlimb coordination during gait as well as the basic biomechanical and neurophysiological principles of the interlimb coordination. The knowledge gathered from these studies is useful for understanding step-to-step transition during gait from a motor control perspective and for interpreting walking impairments and inefficiency related to pathologies, like stroke. This review shows that unimpaired walking is characterised by a consistent and reciprocal interlimb influence that is supported by biomechanical models, and spinal and supraspinal mechanisms. This interlimb coordination is perturbed in subjects with stroke.

Keywords: Interlimb coordination, step-to-step transition, gait, energy expenditure, biomechanical, neurophysiology, spinal and supraspinal mechanisms, stroke

1. Introduction

The neural process in postural control is necessary for all motor actions that induce dynamic and inter-segmental forces and also shifts of the centre of mass (CoM) (Massion, 1998). Therefore, voluntary actions may be considered self-inflicted postural perturbations that may be predicted, to a certain degree, by the central nervous system (CNS), which adjusts the activity of postural muscles both prior to the actual movement and in response to it (Aruin, 2002). Two different views have been proposed to explain how the CNS manages both movement and postural control. The first considers two descending control pathways, one accounting for movement control and the other for balance maintenance (Massion, 1992). The second considers the existence of a common controller for focal and postural commands (Aruin & Latash, 1995a, 1995b; Latash, Aruin, & Shapiro, 1995). According to this second view, changes in the activity of postural muscles are not an addition to but an inherent part of a control process for an action (Latash, 1998).

Complex movements such as gait are a considerable challenge to our understanding, because a large number of body segments are involved and many tasks are taking place simultaneously, i.e., balance, body support and forward progression, some of which are collaborative and others competitive (Winter & Eng, 1995). Apart from these factors, walking in humans also requires a close coordination of muscle activation between the two legs (Dietz, 2002), which has been strongly associated with gait economy (Donelan, Kram, & Kuo, 2002a; Kuo, Donelan, & Ruina, 2007).

The understanding of interlimb coordination, i.e. the timing of motor cycles of the limbs in relation to one another (Swinnen & Carson, 2002), requires knowledge from the neurophysiological and biomechanical domains related to postural and movement control, as well as concepts related to gait efficiency. Neurophysiologists tend to focus on the principles of organisation of the central networks that generate muscle activity patterns. On the other hand, biomechanical researchers focus mainly on movement mechanics, including limb and body kinematics, kinetics and energy cost. Although complementary, these two approaches have not frequently been coupled to bring about interlimb coordination results. The conclusions obtained in each field combined could contribute more significantly to the construction of scientific knowledge about interlimb coordination. In fact, the importance of studying gait interlimb coordination is based on its impact on the metabolic cost of walking (Donelan, et al., 2002a; Donelan, Kram, & Kuo, 2002c; Kuo, Donelan, & Ruina, 2005; Kuo, et al., 2007), and is supported by biomechanical evidence (Donelan, et al., 2002a, 2002c; Kuo, et al., 2007; Winter & Eng, 1995), and neurophysiological factors at the spinal (Bajwa, Edgley, & Harrison, 1992; Corna, Galante, Grasso, Nardone, & Schieppati, 1996; Dietz, 1992) and supraspinal levels (Drew, Prentice, & Schepens, 2004; Matsuyama et al., 2004).

However, despite the importance of interlimb coordination in the metabolic cost of walking, the interlimb coordination has been poorly explored. This can probably be explained by the fact that walking is an energy-cheap activity for healthy subjects, because interlimb coordination is optimised and integrated. Yet, this interlimb coordination can be impaired directly or indirectly as a consequence of lesions in specific supraspinal neuronal structures (Fries, Danek, Scheidtmann, & Hamburger, 1993; Marque, Simonetta-Moreau, Maupas, & Roques, 2001; Maupas, Marque, Roques, & Simonetta-Moreau, 2004; Nardone & Schieppati, 2005). Also, the interlimb coordination is affected by gait symmetry (Krasovsky & Levin, 2009). Consequently, comprehension of interlimb coordination in individuals presenting asymmetric lower limb motor impairment, such as subjects with stroke, is necessary to

understand the atypical behaviour in the pathology. After unilateral stroke, interlimb coordination is often impaired (Dietz & Berger, 1984; Roerdink, Lamoth, Kwakkel, & van Wieringen, 2007; Wu et al., 2009) due to the primary brain lesion itself and/or resulting from adaptive changes (Crone, Johnsen, Biering-Sorensen, & Nielson, 2003; Lamy et al., 2009; Murase, Duque, Mazzocchio, & Cohen, 2004) in other connected central structures. Knowledge concerning interlimb coordination can provide a basis for answering clinical questions related to: how the movement control system changes for specific cases, how to look for alterations in performance, what changes to look for during movement analysis and most important, how outcomes of interventions may be quantified.

This review aims to describe the role of interlimb coordination on forward progression and postural control of walking and its impact on gait efficiency, as well the neurophysiological and biomechanical mechanisms that are involved. This overall review of interlimb coordination adds to the pool of knowledge for research in the field of motor control. This study not only brings together the neurophysiological and biomechanical perspectives that have more frequently been discussed independently, but also it provides important insights into post-stroke rehabilitation, taking into account that walking ability becomes impaired in more than 80% of subjects with stroke (Duncan et al., 2005; Wevers, van de Port, Vermue, Mead, & Kwakkel, 2009). The interlimb coordination process which is reviewed here takes into account healthy subjects and subjects with stroke.

2. Gait asymmetry and interlimb coordination impairment in subjects with stroke: postural and movement control requirements

Walking efficiently does require bilateral symmetry; however, symmetry and coordination are often compromised, especially in post-stroke gait (Brandstater, de Bruin, Gowland, & Clark, 1983; Olney & Richards, 1996; Wall & Turnbull, 1986). Following stroke, typical motor impairments include impaired balance (Mizrahi, Solzi, Ring, & Nisell, 1989; Olney & Richards, 1996), disorganised postural control synergies and excessive muscle co-contraction, weight shift toward the ipsilesional side, and compensatory movement patterns such as excessive hip and knee movements during gait (Chen, Patten, Kothari, & Zajac, 2005; Olney & Richards, 1996; Paillex & So, 2003). All these generate an asymmetric walking pattern associated to impaired interlimb coordination. In fact, gait energy expenditure may be increased in subjects with stroke due to the reduction in strength (force generation capacity) and impaired coordination of the affected leg or legs (Kuo & Donelan, 2010). Interlimb coordination, especially the maintenance of reciprocal, out of phase motions of the limbs, is particularly critical for stable human

(bipedal) walking, predominantly during step-to-step transition, because the transition from one stance limb inverted pendulum to the next appears to be a major determinant of the mechanical work of walking (Donelan, et al., 2002c; Kuo, et al., 2007).

In terms of postural control, the support base, during the double support periods, is not very stable since one foot is carrying the weight on the small area of the heel while the other is pushing off on the forepart of the foot (Winter, 1995; Yang, Winter, & Wells, 1990). During double support, stability depends not only on the activity of each limb, but also on the relation between them to keep the CoM within the safe limits of the support base (Freitas, Freitas, Duarte, Latash, & Zatsiorsky, 2009; Jacobs, 1997; Kiemel, Elahi, & Jeka, 2008; Morasso & Schieppati, 1999; Nicholas, Doxey-Gasway, & Paloski, 1998; van der Kooij, Jacobs, Koopman, & Grootenboer, 1999). Stability also depends on controlling the CoM in terms of the environment conditions, including the gravitational forces, reaction forces from the supporting surfaces, imposed accelerations and obstacles (Dietz, Gollhofer, Kleiber, & Trippel, 1992; Latash, 1998). According to motor control theories, the system adjusts muscle activation thresholds of the trailing limb to guarantee dynamic gait stability (Feldman, Krasovsky, Baniña, Lamontagne, & Levin, 2011). Consistent with mathematical models, the energy dissipation due to non-elastic foot-ground interaction during the heel strike may be an essential element of legged locomotion rather than an accidental imperfection (Ahn & Hogan, 2012). It may not only provide indispensable sensory cues from foot contact of the leading leg (reflecting cutaneous input or load –related afferents) to coordinate locomotor patterns, but may also be a key mechanical factor that determines the stability of locomotion (Ahn & Hogan, 2012) as medio-lateral stability is mainly ensured by foot placement (‘stepping strategy’) (Hof, Vermerris, & Gjaltema, 2010). The importance of double support phase is also linked to the relation between postural stability, interlimb coordination and the metabolic cost of walking (Donelan, Shipman, Kram, & Kuo, 2004; Holt, Jeng, Ratcliffe, & Hamill, 1995; Krasovsky et al., 2012).

In terms of movement control, the double support phase has been described as one of the most determinant in the metabolic cost of walking (Donelan, et al., 2002a). The generation of energy at one joint and the absorption at another joint that occurs mainly during the double support phase of gait is associated with increased energy expenditure. Indeed, the energy increase of the push-off leg takes place as the weight-accepting leg absorbs energy (Winter, 2005). Also, to redirect and accelerate the CoM through step-to-step transition, the amount of energy spent on each collision between the foot and the ground at heel-strike must be replaced by contralateral limb propulsion (Donelan, et al., 2002a; Kuo, et

al., 2005, 2007; Neptune, Kautz, & Zajac, 2004) to redirect the CoM upward and forward (Donelan, et al., 2002a). In fact, it has been demonstrated that the work performed to propel the CoM forward during final stance constitutes a significant portion of the net metabolic cost of normal walking (Donelan, et al., 2002a; Gottschall & Kram, 2003; Grabowski, Farley, & Kram, 2005).

Considering the aforementioned, lower limb asymmetry in subjects with stroke involving movement and postural control dysfunction (Olney, Griffin, Monga, & McBride, 1991; Olney & Richards, 1996; Ryerson, Byl, Brown, Wong, & Hidler, 2008; Silva, Sousa, Tavares, et al., 2012) is associated with interlimb coordination impairments (Sousa, Silva, Santos, Sousa, & Tavares, 2013). In fact, few correlations were observed in electromyographic and kinematic variables between lower limbs in subjects with stroke (Sousa, Silva, Santos, et al., 2013) comparing to healthy subjects (Sousa, Silva, & Tavares, 2013).

3. The impact of decreased interlimb coordination on gait efficiency in subjects with stroke

In patients recovering from stroke, mechanical work measurements suggest that the contralesional leg performs much less push-off work and that both legs perform more total mechanical work than speed-matched healthy individuals (Kim & Eng, 2004; Olney & Richards, 1996). This increase in work suggests that patients recovering from stroke experience an elevated metabolic cost because step-to-step transitions require more mechanical work (Kuo & Donelan, 2010). According to the double-inverted pendulum model (Donelan, et al., 2002a; Kuo, et al., 2007), a major energy expenditure in walking is due to step-to-step transitions (Donelan, et al., 2002a), as the forces of the two legs need to redirect the CoM velocity from a downward and forward direction, to an upward and forward direction. The leading leg strikes the ground, performing negative work on the CoM and the energy spent may be restored through positive work by the trailing leg. The double-inverted pendulum model predicts that the trailing leg restores mechanical work through a powerful plantar flexion at the time of the initial contact and loading response of the contra-lateral limb (Kuo, 2002; Kuo, et al., 2005). The larger the heel strike cost in the leading leg during the initial contact, the higher the metabolic cost of walking, i.e. the energy dissipated during step-to-step transition explains 29% of the variance in the metabolic energy cost of walking (Doets, Vergouw, Veeger, & Houdijk, 2009). Transition between steps reaches an optimum level when the propulsion and the initial contact-loading response have the same magnitude and a short duration (Kuo, et al., 2007).

A lower push off work by the contralesional limb of subjects with stroke (Kim & Eng, 2004; Olney & Richards, 1996; Sousa, Silva, Santos, et al., 2013) is associated with higher energy expenditure since higher push-off work must be performed by the ipsilesional limb in the next step (Sousa, Silva, Santos, et al., 2013). Besides this, a higher negative work performed by the leading limb during initial contact and loading response (Sousa, Silva, Santos, et al., 2013) also leads to a higher need of push-off work. This is probably related to increased plantar flexion at initial contact (Olney & Richards, 1996) caused not only by weakness in the contralesional limb muscles (Richards, Malouin, Dumas, & Lamontagne, 1998), but also due to postural control dysfunction (Ikai, Kamikubo, Takehara, Nishi, & Miyano, 2003). The similarities in ankle postural control strategies between the first half of stance and standing (Yang, et al., 1990) highlight the impact of ankle postural control dysfunction on the negative work performed during initial contact. This makes sense when the importance of the role of ankle plantar flexors in upright standing is taken into account (Fitzpatrick, Douglas, & McCloskey, 1994; Loram, Maganaris, & Lakie, 2005). Finally, a decrease in the ability of the trailing limb to adjust its activity according to the actions of the leading limb can also decrease step-to-step transition efficiency. Therefore, the importance of exploring interlimb coordination in stroke patients relies not only on understanding the impact of the limb contralateral to the affected hemisphere (contralesional limb) on the ipsilateral limb (ipsilesional limb), but also the impact of the ipsilesional limb on the actions of the contralesional limb. This happens because, depending on the location of the lesion (Matsuyama, et al., 2004), the performance of the contralesional limb can be affected by neural pathways responsible for movement control while the performance of the ipsilesional limb can be affected by the ipsilaterally distributed neural pathways responsible for postural control (Latash, 1998; Matsuyama, et al., 2004). Also, changes in the motor function have been demonstrated in the contralesional limb (Olney & Richards, 1996) and in the ipsilesional limb (Cramer et al., 1997; Genthon et al., 2008).

Although biomechanical characteristics of stroke walking have been widely explored and described (Chen, et al., 2005; Goldie, Matyas, & Evans, 2001; Kim & Eng, 2004; Lamontagne, Malouin, Richards, & Dumas, 2002; Lamontagne, Richards, & Malouin, 2000; Lamontagne, Stephenson, & Fung, 2007; Lin, Yang, Cheng, & Wang, 2006; Olney, Griffin, & McBride, 1994; Olney & Richards, 1996; Shiavi, Bugle, & Limbird, 1987; Verma, Arya, Sharma, & Garg, 2012; Woolley, 2001), only recently has the interlimb coordination been a subject for study.

4. Neurophysiological mechanisms involved in interlimb coordination impairment in subjects with stroke

The territory of the middle cerebral artery is the most frequently affected arterial territory in stroke (Mohr, Lazar, & Marshall, 2004). This artery supplies either the cortical and the sub-cortical structures (Crafton, Mark, & Cramer, 2003; Schiemanck, Kwakkel, Post, Kappelle, & Prevo, 2006), particularly the internal capsule. Lesions at the internal capsule level have the potential to affect the contralesional disposed dorsolateral system and the ipsilesional disposed ventromedial system highlighted in Figure 1. The role of the cortico-ponto-reticulospinal-spinal interneuronal system in controlling interlimb relations has been highlighted (Figure 1) (Jankowska, Hammar, Slawinska, Maleszak, & Edgley, 2003; Matsuyama, et al., 2004). The corticoreticular axons originate primarily from regions of the sensorimotor cortex (mostly area 6), and descend with the corticospinal axons through the internal capsule and cerebral peduncle (subcortical level). These corticoreticular axons, some of which arise as collaterals of corticospinal axons, terminate bilaterally in the pontomedullary reticular formation from which the long-descending reticulospinal axons originate. The pontine and medullary reticulospinal axons descend mostly ipsilaterally throughout the spinal cord influencing spinal motoneurons and interneurons and are related to postural control. The corticospinal tract is responsible for movement in the contralateral side (Matsuyama, et al., 2004).

Studies involving healthy subjects demonstrated that neural circuits controlling each leg are coupled. When both limbs have a supportive role, the perturbation of one limb evokes a purposeful bilateral response pattern, with similar muscular onset latency on both limbs (Bajwa, et al., 1992; Nardone, Grasso, Giordano, & Schieppati, 1996). This response is thought to be mediated at the spinal level but under supraspinal control (Berger, Dietz, & Quintern, 1984; Dietz, 1992). In fact, experiments have demonstrated the existence of a group of interneurons (Edgley, Jankowska, Krutki, & Hammar, 2003; Jankowska & Noga, 1990) that receive supraspinal inputs from the vestibulo- and reticulo-spinal pathways and the corticospinal tract (Davies & Edgley, 1994; Jankowska, Edgley, Krutki, & Hammar, 2005; Jankowska, Stecina, Cabaj, Pettersson, & Edgley, 2006) and they also receive bilateral peripheral inputs from group Ia, group II afferents (Jankowska, et al., 2005) and cutaneous afferents (Edgley & Aggelopoulos, 2006). A contribution from the cerebellum to this spinal interlimb coordination via reticulospinal neurons has been suggested for both cats (ItoBonnet, Gurfinkel, Lipchits, & Popov,

1984/1976) and humans (Dietz, Zijlstra, & Duysens, 1994; Stubbs & Mrachacz-Kersting, 2009). Also, there is evidence of bilateral interlimb coordination in the homonymous muscle groups in the human, as each limb affects the strength of muscle activation and the time-space behaviour of the other (Dietz, et al., 1994; Stubbs & Mrachacz-Kersting, 2009).

Based on the neuroanatomic fundamentals previous mentioned, it can be expected that lesions at the subcortical level are associated with the dysfunction of the bilateral limb response (Dietz, Quintern, Boos, & Berger, 1986), when both limbs are performing a supportive role (Dietz & Berger, 1984; Marchand-Pauvert, Nicolas, Marque, Iglesias, & Pierrot-Deseilligny, 2005). The deregulation of the group II pathways demonstrated in the contralesional limb of subjects with stroke (Marque, et al., 2001; Nardone & Schieppati, 2005) can also explain their interlimb coordination problems. The information provided by spindle group II fibres has an important role in postural control circuits (Morasso, Baratto, Capra, & Spada, 1999; Nardone, Corrà, & Schieppati, 1990; Nardone, Giordano, Corrà, & Schieppati, 1990; Schieppati, Nardone, Siliotto, & Grasso, 1995). Some authors go further arguing that both legs and foot muscles are the site of postural control segmental reflexes (Schieppati, et al., 1995), mainly because of spindle group II fibres (Grey, Ladouceur, Andersen, Nielsen, & Sinkjær, 2001; Grey, Van Doornik, & Sinkjær, 2002; Nielsen & Sinkjær, 2002; Schieppati & Nardone, 1997; Sinkjær, Andersen, Ladouceur, Christensen, & Nielsen, 2000).

The control of interlimb coordination during the antiphase pattern for locomotion has been interpreted as evidence that existing spinal circuits controlling the predominant antiphase pattern are either selectively recruited or disinhibited. However, the additional muscle activation associated with moving the nonparetic ankle in an antiphase mode strongly degraded paretic ankle movements compared with a unilateral performance (Kautz & Brown, 1998; Kautz & Patten, 2005; Tseng & Morton, 2010). These findings cannot be explained by the central pattern generator dysfunction in subjects with stroke.

5. Interlimb coordination between ipsilesional and contralesional lower limbs in subjects with stroke during gait

While interlimb coordination between the terminal stance propulsion and the initial contact and loading response is perfectly integrated in healthy subjects (Sousa, Santos, Oliveira, Carvalho, & Tavares, 2012; Sousa, Silva, & Tavares, 2013), in subjects with stroke at the subcortical level (internal capsule),

limited evidence indicates that only the activity of the contralesional limb is influenced by the activity of the ipsilesional limb (Sousa, Silva, Santos, et al., 2013).

Results obtained in healthy subjects indicate that the activity of the major muscles acting on terminal stance propulsion (Liu, Anderson, Pandey, & Delp, 2006; Neptune, et al., 2004; Zajac, Neptune, & Kautz, 2003) of the trailing limb is positively correlated to the anteroposterior and vertical ground reaction forces during initial contact and loading response (Sousa, et al., 2012) to replace energy spent during the heel strike by the contralateral limb (Donelan, Kram, & Kuo, 2002b; Donelan, et al., 2002c; Kuo, et al., 2005). Mathematical models argue that the energy expenditure can be reduced through the application of a propulsion impulse in the trailing limb immediately before collision of the leading limb (Kuo, 2002; Kuo, et al., 2007). This out-of-phase interlimb relation is also perfectly justifiable from a postural control perspective, as the onset of anticipatory postural adjustments may be time-locked with certain events within the locomotor cycle rather than the onset of the prime mover (Nashner & Forssberg, 1986). Also, the activity of the main muscles responsible for impact reduction during heel strike (tibialis anterior, biceps femoris and vastus) (Liu, et al., 2006; Neptune, et al., 2004; Perry, 1992; Sadeghi et al., 2002; Wakeling & Nigg, 2001a, 2001b; Whittle, 2007) is inversely related to the activity of the same muscles and positively related to the soleus activity during contralateral terminal propulsion (Sousa, Silva, & Tavares, 2013). In healthy subjects, there is a reciprocal influence between the leading limb during double support and the trailing limb during terminal stance propulsion, as proprioceptive information related to ground reaction force can be used to create feedforward commands to regulate contralateral plantar flexor activity in the preceding subphase of walking, and also because the main responsible muscles for impact reduction during heel strike are influenced by the homologous activity and by the soleus of the contralateral limb during terminal stance propulsion (Sousa, et al., 2012; Sousa, Silva, & Tavares, 2013).

The lack of correlation between the propulsive impulse of the ipsilesional limb and the braking impulse of the contralesional limb (Sousa, Silva, Santos, et al., 2013) leads to a lower efficiency in interlimb coordination in subjects with stroke since the CNS does not seem to consider proprioceptive information from the contralesional limb to adjust the ipsilesional propulsive activity. Sensory dysfunction is estimated to be present in more than half of stroke survivors (Carey, 1995; Carey, Oke, & Matyas, 1996; Tyson, Hanley, Chillala, Selley, & Tallis, 2008). A deregulation of the group II pathways demonstrated in the contralesional limb of subjects with stroke can be the origin of unilateral interlimb

coordination (Marque, et al., 2001; Nardone & Schieppati, 2005). In fact, the alteration of muscle tone in a paretic limb (Eng, Kim, & MacIntyre, 2002; Olney & Richards, 1996) may have an impact on proprioceptors in muscles and tendons even if the fibre tracts of the proprioceptive system itself have not been affected by the brain lesion (Thiel, Aleksic, LKlein, Rudolf, & Heiss, 2007). A possible dysfunctional information provided by plantar cutaneous receptors during initial contact and loading response of the contralesional limb could also explain the unilateral interlimb coordination (Edgley & Aggelopoulos, 2006). This afferent was demonstrated to be related to the parameters of the ground reaction forces (Kavounoudias, Roll, & Roll, 1998; Zehr, Komiyama, & Stein, 1997), to assist placing and weight acceptance at the beginning of stance (Zehr & Stein, 1999), and it also has an important role in balance maintenance during walking (Van Wezel, Ottenhoff, & Duysens, 1997; Zehr, et al., 1997; Zehr & Stein, 1999). However, a tactile sensation deficit of the plantar cutaneous receptors was not related to the incidence of falls (Marigold & Eng, 2006) neither to standing instability in subjects with stroke (Marigold, Eng, Tokuno, & Donnelly, 2004). Besides, load perception during initial contact and loading response is likely to be easier than on the other stance subphases in subjects with stroke (Chu, Hornby, & Schmit, 2014). While the perception of an impact force is primarily sensory in nature, the perception of a self-generated force also involves the motor system, thus complicating perception (Shergill, Bays, C.D., & Wolpert, 2003). The higher deficit in load perception during terminal stance and pre swing (Chu, et al., 2014) emphasises the role of proprioceptive impairment on interlimb deficit in subjects with stroke. On the other hand, the growing body of evidence suggesting that load information provided by group 1b afferents contributes substantially to ongoing unilateral muscle activity in late stance (Grey, Nielsen, Mazzaro, & Sinkjaer, 2007; Pearson & Collins, 1993), highlights the importance of information provided by type II fibres in adjusting trailing limb muscle activity during late stance according to leading limb muscle activity during initial contact and loading response. Impairment of the reticular system in the subcortical stroke may also explain interlimb coordination impairment in subjects with stroke considering its relevance during the moment of touchdown in matching the muscle activity of both legs with the ground surface (Sousa, Silva, & Tavares, 2013) and the strong influence of this system over interneurons that mediate information by the group II afferents of both lower limbs during walking (Davies & Edgley, 1994; Jankowska, et al., 2003; Matsuyama, et al., 2004).

Although motor control deficits have been described in the contralesional limb when promoting forward propulsion (Olney & Richards, 1996), there is evidence that the contralesional propulsive

impulse is adaptable due to the braking impulse of the ipsilesional limb during initial contact and loading response (Sousa, Silva, Santos, et al., 2013). These findings indicate that the neural control of contralesional limb motor patterns may be substantially influenced by the ipsilesional leg sensorimotor state during the bilateral lower limb function. Based on this, more “appropriate” sensorimotor information from the ipsilesional limb, i.e. from the less affected limb, would be integrated by the nervous system and would contribute to a more appropriate contralesional pattern. During the push-off phase of the gait cycle, the increase in sensory gating associated with volition may contribute to the poorer performance in load perception of the contralesional limb (Chu, et al.). In fact, subjects with stroke (Sousa, Silva, Santos, et al., 2013), like healthy subjects (Sousa, Silva, & Tavares, 2013), present an inverse relation between the activity of muscles responsible for impact reduction during leading initial contact (Liu, et al., 2006; Neptune, et al., 2004; Perry, 1992; Sadeghi, et al., 2002; Wakeling & Nigg, 2001a, 2001b; Whittle, 2007) and the main agonists during pre-swing (Neptune, Kautz, & Zajac, 2001; Neptune, et al., 2004). The results obtained in healthy subjects indicate that despite being the primary cause for the leg energy absorption and consequent negative work (Winter, 2005), the higher activity of the vastus medialis, biceps femoris and tibialis anterior can reduce the leading limb heel strike impact (Liu, et al., 2006; Neptune, et al., 2004; Perry, 1992; Sadeghi, et al., 2002; Wakeling & Nigg, 2001a, 2001b; Whittle, 2007), decreasing the positive work needed by the trailing limb. This was demonstrated through a decreased muscle activity of the main responsible muscles for forward propulsion (Neptune, et al., 2001; Neptune, et al., 2004; Sousa, Silva, & Tavares, 2013; Winter, 2005). The positive work for forward progression of the trailing limb depends strongly on the negative work performed by the leading limb, and these components have a significant impact in the metabolic cost of walking (Sousa, Silva, & Tavares, 2013). These findings are in accordance with the biomechanical models proposed for step-to-step transition (Kuo, et al., 2007) since the energy dissipated is related to an inelastic collision of the swing leg with the ground, leading to changes in velocities of the legs and the CoM that need to be compensated for active work of the trailing limb. The importance of the role of the plantar flexors in restoring energy expenditure during step-to-step transition is highlighted by the higher magnitude of positive mechanical work compared to the magnitude of the negative work (DeVita, Helseth, & Hortobagyi, 2007; Sousa, Silva, & Tavares, 2013).

Despite subjects with stroke present functional interlimb coordination synergies between ipsilesional heel strike and loading response and contralesional propulsion similar to that observed in

healthy subjects (Sousa, et al., 2012; Sousa, Silva, Santos, et al., 2013; Sousa, Silva, & Tavares, 2013), only the ipsilesional limb afferents from the BF muscle during initial contact and loading response in related to the forward propulsion activity of contralesional limb during pre-swing. The afferents from ipsilesional ankle plantar flexor during initial contact impair contralesional propulsive activity during pre-swing (Sousa, Silva, Santos, et al., 2013). Although the ipsilesional limb has been frequently defined as the non-affected limb, motor impairments have been reported in both the upper (Colebatch & Gandevia, 1989; Desrosiers, Bourbonnais, Bravo, Roy, & Guay, 1996; Jones, Donaldson, & Parkin, 1989) and lower extremities (Adams, Gandevia, & Skuse, 1990; Genthon, et al., 2008; Lindmark & Hamrin, 1995). These motor impairments are considered to be the result of adaptations to function deficits of the contralateral limb (contralesional limb) (Aruin, 2006), caused by disuse, as well as from neuronal damage depending on the anatomical region of vascular disruption (Matsuyama, et al., 2004). According to some authors, ipsilesional disorders related to lower soleus activity levels, higher ankle coactivation values, changes in feedforward mechanisms and increased centre of pressure dispersion under the ipsilesional limb are related to a dysfunction of the ventral-medial system in sub-cortical injuries located at the internal capsule level (Genthon, et al., 2008; Silva, Sousa, Pinheiro, Ferraz, et al., 2012; Silva, Sousa, Pinheiro, Tavares, et al., 2012; Silva, Sousa, Tavares, et al., 2012). Based on studies involving subjects with stroke (Silva, Sousa, Pinheiro, Ferraz, et al., 2012; Silva, Sousa, Pinheiro, Tavares, et al., 2012; Silva, Sousa, Tavares, et al., 2012; Sousa, Silva, Santos, et al., 2013), it can be argued that the negative influence of the ipsilesional limb over the contralesional limb can be attributed to postural control deficits of the ipsilesional limb. These findings support the argument for the dysfunction of the ventral-medial system over the ipsilesional limb as one of the causes for the impaired interlimb relation in subjects with stroke.

6. Clinical implications

Rehabilitation of subjects with stroke in a chronic stage is associated with elevated costs (Gorelick, 1994). However, there is a lack of scientific knowledge supporting rehabilitation guidelines to promote interlimb coordination, enhancing the gait economy. The importance of studying subjects with stroke in a chronic stage is also sustained by the evidence of functional improvement beyond the acute phase after stroke (6 months) (Ferrucci et al., 1993), which can be explained by knowledge about neuroplasticity physiology (Hallett, 2001).

Paresis of ankle plantar flexor muscles have been demonstrated to be the main cause of the reduced forward propulsion of the contralesional limb during the stance phase of gait (Knarr, Kesar,

Reisman, Binder-Macleod, & Higginson, 2013; Lamontagne, et al., 2002; Neptune, et al., 2001; Olney, et al., 1991; Olney & Richards, 1996). Based on interlimb coordination knowledge, it can be argued that the lower performance of contralesional propulsion in subjects with stroke in a chronic stage is not only explained by the neuronal damage but also by the influence of the ipsilesional limb. This recent evidence is of significant relevance for clinical rehabilitation of subjects with stroke. Specifically, in subjects with stroke in the middle anterior cerebral artery involving subcortical areas such as the internal capsule and the corona radiata. Strategies to improve postural control in the ipsilesional limb should be adopted not only to decrease the ipsilesional postural control deficit, but also to decrease its negative impact on controlling the movements of the contralesional limb. Rehabilitation approaches should focus on proprioceptive facilitation techniques (Nudo, 1999; Taub, Uswatte, & Elbert, 2002; Ward & Cohen, 2004). Rehabilitation of sensorimotor integration deficits has been shown to improve postural control in subjects with stroke (Bayouk, Boucher, & Leroux, 2006; Smania, Picelli, Gandolfi, Fiaschi, & Tinazzi, 2008). While performance advantages associated with bilateral arm movements after stroke have been reported (Cunningham, Stoykov, & Walter, 2002; Harris-Love, Waller, & Whittall, 2005; Rose & Winstein, 2005), supporting bimanual upper extremity training protocols for recovery of arm movements after stroke (Luft, McCombe-Waller, Whittall, & et al., 2004; Mudie & Matyas, 1996, 2000; Whittall, McCombe, Silver, & Macko, 2000), studies of lower limb coordination do not seem to support bilateral protocols to improve interlimb coordination during locomotion (Kautz & Brown, 1998; Kautz & Patten, 2005; Sousa, Silva, Santos, et al., 2013; Tseng & Morton, 2010).

Walking after stroke is characterised by slow gait speed (Olney & Richards, 1996; Sousa, Silva, Santos, et al., 2013; von Schroeder, Coutts, Lyden, Billings, & Nickel, 1995), poor endurance (Dean, Richards, & Malouin, 2001) and a reduced ability to adapt to the task and to environment constraints (Said, Goldie, Patla, Sparrow, & Martin, 1999). Motor impairments are believed to be the primary cause for this poor walking ability as suggested by the association between muscle weakness of specific muscle groups, such as the plantar flexors on the contralesional side, and the slow speed (Nadeau, Gravel, Arsenault, & Bourbonnais, 1999; Olney, et al., 1994). Whereas studies using correlation analysis have revealed that some electromyographic abnormalities such as spasticity (Lamontagne, Malouin, & Richards, 2001), altered coactivation (Lamontagne, et al., 2000), and muscle paresis (Lamontagne, et al., 2002) are more pronounced in subjects with low gait speed, a cause-effect relationship of some of these abnormalities with poor locomotor performance (Detrembleur, Dierick, Stoquart, Chantaine, & Lejeune,

2003) remains difficult to establish. The study of the interlimb relation during the stance phase of gait in subjects with stroke can give significant insights into the understanding of the low performance of stroke gait, considering the importance of step-to-step transition performance in global gait efficiency.

7. Concluding remarks

The role of the interlimb coordination on the forward progression and postural control of walking and its impact on gait efficiency has been clearly demonstrated in biomechanical studies. Its importance is sustained not only by biomechanical models but also by neuroanatomy and neurophysiology studies, as well as by experimental studies involving animals but also humans. Unimpaired walking is characterised by a consistent and reciprocal interlimb coordination which is not observed in subjects with stroke. In addition to decreased interlimb coordination, a dysfunctional influence of the ipsilesional limb over the contralesional forward propulsion was observed. This suggests that the lower performance of contralesional forward propulsion is not only related to the contralateral supraspinal damage, but also to a negative influence of the ipsilesional limb. The knowledge gathered from this review as to the interlimb coordination is useful to promote understanding about gait step-to-step transition from a motor control perspective and for interpreting the walking impairments and inefficiency related to pathologies involving unilateral or bilateral asymmetric impairment of lower limbs. Taking into account that stroke is a prevalent disorder, the study of this pathological condition is important to gain a better understanding about the performance deficits and the potential for functional recovery, as well as to develop intervention strategies that maximise recovery.

This study presents an overview about the interlimb coordination and its impact in gait performance; however, it is not a systematic review. Taking into account that a systematic review gives a clear and consistent overview about a particular research topic, including information that allows to draw relevant conclusions and stress the demand for more research, systematic reviews regarding the interlimb coordination and its impact in gait performance are suggested as they can lead to important insights into this topic.

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References

- Adams, R.W., Gandevia, S.C., & Skuse, N.F. (1990). The distribution of muscle weakness in upper motoneuron lesions affecting the lower limb. *Brain*, 113(5), 1459-1476. doi: 10.1093/brain/113.5.1459
- Ahn, J., & Hogan, N. (2012). A Simple State-Determined Model Reproduces Entrainment and Phase-Locking of Human Walking. *PLoS ONE*, 7(11), e47963. doi: 10.1371/journal.pone.0047963
- Aruin, A. (2002). The organization of anticipatory postural adjustments. *Journal of Automatic Control*, 12(1), 31-37.
- Aruin, A. (2006). The effect of asymmetry of posture on anticipatory postural adjustments. *Neuroscience Letters*, 401(1-2), 150-153. doi: 10.1016/j.neulet.2006.03.007
- Aruin, A., & Latash, M. (1995a). Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. *Experimental Brain Research*, 103(2), 323-332.
- Aruin, A., & Latash, M. (1995b). The role of motor action in anticipatory postural adjustments studied with self-induced and externally triggered perturbations. *Experimental Brain Research*, 106(2), 291-300.
- Bajwa, S., Edgley, S.A., & Harrison, P.J. (1992). Crossed actions on group II-activated interneurons in the midlumbar segments of the cat spinal cord. *The Journal of Physiology*, 455(1), 205-217.
- Bayouk, J.-F., Boucher, J.P., & Leroux, A. (2006). Balance training following stroke: effects of task-oriented exercises with and without altered sensory input. *International Journal of Rehabilitation Research*, 29(1), 51-59.
- Berger, W., Dietz, V., & Quintern, J. (1984). Corrective reactions to stumbling in man: neuronal co-ordination of bilateral leg muscle activity during gait. *Journal of Physiology*, 357, 109-125.
- Brandstater, M.E., de Bruin, H., Gowland, C., & Clark, B.M. (1983). Hemiplegic gait: analysis of temporal variables. *Archives of Physical Medicine and Rehabilitation*, 64(12), 583-587.
- Carey, L.M. (1995). Somatosensory loss after stroke. *Critical Reviews in Physical and Rehabilitation Medicine*, 7(1), 51-91.
- Carey, L.M., Oke, L.E., & Matyas, T.A. (1996). Impaired limb position sense after stroke: A quantitative test for clinical use. *Archives of Physical Medicine and Rehabilitation*, 77(12), 1271-1278. doi: [http://dx.doi.org/10.1016/S0003-9993\(96\)90192-6](http://dx.doi.org/10.1016/S0003-9993(96)90192-6)
- Chen, G., Patten, C., Kothari, D.H., & Zajac, F.E. (2005). Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. *Gait & Posture*, 22(1), 51-56. doi: 10.1016/j.gaitpost.2004.06.009
- Chu, V.W., Hornby, T.G., & Schmit, B.D. (2014). Perception of lower extremity loads in stroke survivors. *Clinical Neurophysiology*. doi: <http://dx.doi.org/10.1016/j.clinph.2014.06.047>
- Colebatch, J.G., & Gandevia, S.C. (1989). The distribution of muscular weakness in upper motor neuron lesions affecting the arm. *Brain*, 112(3), 749-763. doi: 10.1093/brain/112.3.749
- Corna, S., Galante, M., Grasso, M., Nardone, A., & Schieppati, M. (1996). Unilateral displacement of lower limb evokes bilateral EMG responses in leg and foot

- muscles in standing humans. *Experimental Brain Research*, 109(1), 83-91.
- Crafton, K.R., Mark, A.N., & Cramer, S.C. (2003). Improved understanding of cortical injury by incorporating measures of functional anatomy. *Brain*, 126(7), 1650-1659. doi: 10.1093/brain/awg159
- Cramer, S.C., Nelles, G., Benson, R.R., Kaplan, J.D., Parker, R.A., Kwong, K.K., . . . Rosen, B.R. (1997). A functional MRI study of subjects recovered from hemiparetic stroke. *Stroke*, 28(12), 2518-2527. doi: 10.1161/01.str.28.12.2518
- Crone, C., Johnsen, L.L., Biering-Sorensen, F., & Nielson, J.B. (2003). Appearance of reciprocal facilitation of ankle extensors from ankle flexors in patients with stroke or spinal cord injury. *Brain*, 126, 495-507.
- Cunningham, C.L., Stoykov, M.E., & Walter, C.B. (2002). Bilateral facilitation of motor control in chronic hemiplegia. *Acta Psychologica*, 110, 321-337.
- Davies, H.E., & Edgley, S.A. (1994). Inputs to group II-activated midlumbar interneurons from descending motor pathways in the cat. *The Journal of Physiology*, 479(Pt 3), 463-473.
- Dean, C.M., Richards, C.L., & Malouin, F. (2001). Walking speed over 10 metres overestimates locomotor capacity after stroke. *Clinical Rehabilitation*, 15(4), 415-421. doi: 10.1191/026921501678310216
- Desrosiers, J., Bourbonnais, D., Bravo, G., Roy, P.-M., & Guay, M. (1996). Performance of the 'unaffected' upper extremity of elderly stroke patients. *Stroke*, 27(9), 1564-1570. doi: 10.1161/01.str.27.9.1564
- Detrembleur, C., Dierick, F., Stoquart, G., Chantaine, F., & Lejeune, T. (2003). Energy cost, mechanical work, and efficiency of hemiparetic walking. *Gait & Posture*, 18(2), 47-55.
- DeVita, P., Helseth, J., & Hortobagyi, T. (2007). Muscles do more positive than negative work in human locomotion. *Journal of Experimental Biology*, 210(19), 3361-3373. doi: 10.1242/jeb.003970
- Dietz, V. (1992). Human neuronal control of automatic functional movements: interaction between central programs and afferent input. *Physiological Reviews*, 72(1), 33-69.
- Dietz, V. (2002). Do human bipeds use quadrupedal coordination? *Trends in Neurosciences*, 25(9), 462-467. doi: 10.1016/s0166-2236(02)02229-4
- Dietz, V., & Berger, W. (1984). Interlimb coordination of posture in patients with spastic paresis. *Brain*, 107(3), 965-978.
- Dietz, V., Gollhofer, A., Kleiber, M., & Trippel, M. (1992). Regulation of bipedal stance: dependency on "load" receptors. *Experimental Brain Research*, 89(1), 229-231. doi: 10.1007/bf00229020
- Dietz, V., Quintern, J., Boos, G., & Berger, W. (1986). Obstruction of the swing phase during gait: phase-dependent bilateral leg muscle coordination. *Brain Research*, 384(1), 166-169. doi: [http://dx.doi.org/10.1016/0006-8993\(86\)91233-3](http://dx.doi.org/10.1016/0006-8993(86)91233-3)
- Dietz, V., Zijlstra, W., & Duysens, J. (1994). Human neuronal interlimb coordination during split-belt locomotion. *Experimental Brain Research*, 101(3), 513-520. doi: 10.1007/bf00227344
- Doets, H.C., Vergouw, D., Veeger, H.E.J., & Houdijk, H. (2009). Metabolic cost and mechanical work for the step-to-step transition in walking after successful total ankle arthroplasty. *Human Movement Science*, 28(6), 786-797.
- Donelan, J.M., Kram, R., & Kuo, A.D. (2002a). Mechanical work for step-to-step transition is a major determinant of the metabolic cost. *Journal of Experimental Biology*, 205, 3717-3727.
- Donelan, J.M., Kram, R., & Kuo, A.D. (2002b). Mechanical work for step-to-step

- transition is a major determinant of the metabolic cost. *Journal of Experimental Biology*, 205(1), 3717-3727.
- Donelan, J.M., Kram, R., & Kuo, A.D. (2002c). Simultaneous positive and negative external mechanical work in human walking. *Journal of Biomechanics*, 35(1), 117-124.
- Donelan, J.M., Shipman, D.W., Kram, R., & Kuo, A.D. (2004). Mechanical and metabolic requirements for active lateral stabilization in human walking. *Journal of Biomechanics*, 37(6), 827-835. doi: 10.1016/j.jbiomech.2003.06.002
- Drew, T., Prentice, S., & Schepens, B. (2004). Cortical and brainstem control of locomotion. In Douglas G. Stuart Shigemi Mori & Wiesendanger Mario (Eds.), *Progress in Brain Research* (Vol. Volume 143, pp. 251-261): Elsevier.
- Duncan, P., Zorowitz, R., Bates, B., Choi, J., Glasberg, J., Graham, G., . . . Reker, D. (2005). Management of adult stroke rehabilitation care: a clinical practice guideline. *Stroke*, 36(9), e100-e143.
- Edgley, S.A., & Aggelopoulos, N.C. (2006). Short latency crossed inhibitory reflex actions evoked from cutaneous afferents. *Experimental Brain Research*, 171(4), 541-550. doi: 10.1007/s00221-005-0302-9
- Edgley, S.A., Jankowska, E., Krutki, P., & Hammar, I. (2003). Both dorsal horn and lamina VIII interneurons contribute to crossed reflexes from feline group II muscle afferents. *The Journal of Physiology*, 552(3), 961-974. doi: 10.1113/jphysiol.2003.048009
- Eng, J.J., Kim, C.M., & MacIntyre, D.L. (2002). Reliability of lower extremity strength measures in persons with chronic stroke. *Archives of Physical Medicine and Rehabilitation*, 83(3), 322-328. doi: <http://dx.doi.org/10.1053/apmr.2002.29622>
- Feldman, A., Krasovsky, T., Baniña, M., Lamontagne, A., & Levin, M. (2011). Changes in the referent body location and configuration may underlie human gait, as confirmed by findings of multi-muscle activity minimizations and phase resetting. *Experimental Brain Research*, 210(1), 91-115. doi: 10.1007/s00221-011-2608-0
- Ferrucci, L., Bandinelli, S., Guralnik, J.M., Lamponi, M., Bertini, C., Falchini, M., & Baroni, A. (1993). Recovery of functional status after stroke. A post-rehabilitation follow-up study. *Stroke*, 24(2), 200-205. doi: 10.1161/01.str.24.2.200
- Fitzpatrick, R., Douglas, K., & McCloskey, D. (1994). Stable human standing with lower-limb muscle afferents providing the only sensory input. *Journal of Physiology*, 2536, 395-403.
- Freitas, P.B.d., Freitas, S.M.S.F., Duarte, M., Latash, M.L., & Zatsiorsky, V.M. (2009). Effects of joint immobilization on standing balance. *Human Movement Science*, 28(4), 515-528. doi: 10.1016/j.humov.2009.02.001
- Fries, W., Danek, A., Scheidtmann, K., & Hamburger, C. (1993). Motor recovery following capsular stroke: Role of descending pathways from multiple motor areas. *Brain*, 116(2), 369-382. doi: 10.1093/brain/116.2.369
- Gentton, N., Rougier, P., Gissot, A.-S., Froger, J., Pélissier, J., & Pérennou, D. (2008). Contribution of each lower limb to upright standing in stroke patients. *Stroke*, 39(6), 1793-1799.
- Goldie, P.A., Matyas, T.A., & Evans, O.M. (2001). Gait after stroke: Initial deficit and changes in temporal patterns for each gait phase. *Archives of Physical Medicine and Rehabilitation*, 82(8), 1057-1065. doi: 10.1053/apmr.2001.25085
- Gorelick, P.B. (1994). Stroke prevention. An opportunity for efficient utilization of health care resources during the coming decade. *Stroke*, 25(1), 220-224. doi:

10.1161/01.str.25.1.220

- Gottschall, J.S., & Kram, R. (2003). Energy cost and muscular activity required for propulsion during walking. *Journal of Applied Physiology*, 94(5), 1766-1772.
- Grabowski, A., Farley, C.T., & Kram, R. (2005). Independent metabolic costs of supporting body weight and accelerating body mass during walking. *Journal of Applied Physiology*, 98(2), 579-583. doi: 10.1152/japplphysiol.00734.2004
- Grey, M.J., Ladouceur, M., Andersen, J.B., Nielsen, J.B., & Sinkjær, T. (2001). Group II muscle afferents probably contribute to the medium latency soleus stretch reflex during walking in humans. *The Journal of Physiology*, 534(3), 925-933.
- Grey, M.J., Nielsen, J.B., Mazzaro, N., & Sinkjaer, T. (2007). Positive force feedback in human walking. *Journal of Physiology*, 581(1), 99-105.
- Grey, M.J., Van Doornik, J., & Sinkjær, T. (2002). Plantar flexor stretch reflex responses to whole body loading/unloading during human walking. *European Journal of Neuroscience*, 16(10), 2001-2007.
- Hallett, M. (2001). Plasticity of the human motor cortex and recovery from stroke. *Brain Research Reviews*, 36, 169-174.
- Harris-Love, M.L., Waller, S.M., & Whittall, J. (2005). Exploiting Interlimb Coupling to Improve Paretic Arm Reaching Performance in People With Chronic Stroke. *Archives of Physical Medicine and Rehabilitation*, 86(11), 2131-2137. doi: <http://dx.doi.org/10.1016/j.apmr.2005.05.006>
- Hof, A.L., Vermerris, S.M., & Gjaltema, W.A. (2010). Balance responses to lateral perturbations in human treadmill walking. *The Journal of Experimental Biology*, 2013, 2655-2664.
- Holt, K.G., Jeng, S.F., Ratcliffe, R., & Hamill, J. (1995). Energetic cost and stability during human walking at the preferred stride frequency. *Journal of Motor Behavior*, 27(2), 164-178. doi: 10.1080/00222895.1995.9941708
- Ikai, T., Kamikubo, T., Takehara, I., Nishi, M., & Miyano, S. (2003). Dynamic Postural Control in Patients with Hemiparesis. *American Journal of Physical Medicine & Rehabilitation*, 82(6), 463-469
410.1097/1001.PHM.0000069192.0000032183.A0000069197.
- ItoBonnet, M., Gurfinkel, S., Lipchits, M., & Popov, K. (1984/1976). *The Cerebellum and Neural Control Central programming of lower limb muscle activity in the standing man* (Vol. 17): Raven Press.
- Jacobs, R. (1997). Control model of human stance using fuzzy logic. *Biological Cybernetics*, 77(1), 63-70. doi: 10.1007/s004220050367
- Jankowska, E., Edgley, S.A., Krutki, P., & Hammar, I. (2005). Functional differentiation and organization of feline midlumbar commissural interneurons. *The Journal of Physiology*, 565(2), 645-658. doi: 10.1113/jphysiol.2005.083014
- Jankowska, E., Hammar, I., Slawinska, U., Maleszak, K., & Edgley, S.A. (2003). Neuronal basis of crossed actions from the reticular formation on feline hindlimb motoneurons. *The Journal of neuroscience: the official journal of the Society for Neuroscience*, 23(5), 1867-1878.
- Jankowska, E., & Noga, B.R. (1990). Contralaterally projecting lamina VIII interneurons in middle lumbar segments in the cat. *Brain Research*, 535(2), 327-330. doi: [http://dx.doi.org/10.1016/0006-8993\(90\)91618-Q](http://dx.doi.org/10.1016/0006-8993(90)91618-Q)
- Jankowska, E., Stecina, K., Cabaj, A., Pettersson, L.-G., & Edgley, S.A. (2006). Neuronal relays in double crossed pathways between feline motor cortex and ipsilateral hindlimb motoneurons. *The Journal of Physiology*, 575(2), 527-541. doi: 10.1113/jphysiol.2006.112425
- Jones, R.D., Donaldson, I.M., & Parkin, P.J. (1989). Impairment and recovery of

- ipsilateral sensory-motor function following unilateral cerebral infarction. *Brain*, 112(1), 113-132. doi: 10.1093/brain/112.1.113
- Kautz, S.A., & Brown, D.A. (1998). Relationships between timing of muscle excitation and impaired motor performance during cyclical lower extremity movement in post-stroke hemiplegia. *Brain*, 121, 515-526.
- Kautz, S.A., & Patten, C. (2005). *Interlimb Influences on Paretic Leg Function in Poststroke Hemiparesis* (Vol. 93).
- Kavounoudias, A., Roll, R., & Roll, J.-P. (1998). The plantar sole is a 'dynamometric map' for human balance control. *NeuroReport*, 9(14), 3247-3252.
- Kiemel, T., Elahi, A.J., & Jeka, J.J. (2008). Identification of the plant for upright stance in humans: multiple movement patterns from a single neural strategy. *Journal of Neurophysiology*, 100(6), 3394-3406. doi: 10.1152/jn.01272.2007
- Kim, C.M., & Eng, J.J. (2004). Magnitude and pattern of 3D kinematic and kinetic gait profiles in persons with stroke: relationship to walking speed. *Gait & Posture*, 20(2), 140-146. doi: 10.1016/j.gaitpost.2003.07.002
- Knarr, B.A., Kesar, T.A., Reisman, D.S., Binder-Macleod, S.A., & Higginson, J.S. (2013). Changes in the activation and function of the ankle plantar flexor muscles due to gait retraining in chronic stroke survivors. *Journal of NeuroEngineering and Rehabilitation*, 10(12).
- Krasovsky, T., Baniña, M.C., Hacmon, R., Feldman, A.G., Lamontagne, A., & Levin, M.F. (2012). Stability of gait and interlimb coordination in older adults. *Journal of Neurophysiology*, 107(9), 2560-2569. doi: 10.1152/jn.00950.2011
- Krasovsky, T., & Levin, M.F. (2009). Toward a Better Understanding of Coordination in Healthy and Poststroke Gait. *Neurorehabilitation and Neural Repair*, 24(3), 213-224. doi: 10.1177/1545968309348509
- Kuo, A.D. (2002). Energetics of actively powered locomotion using the simplest walking model. *Journal of Biomechanical Engineering*, 124(1), 113-120.
- Kuo, A.D., & Donelan, J.M. (2010). Dynamic principles of gait and their clinical implications. *Physical Therapy*, 90(2), 157-174. doi: 10.2522/ptj.20090125
- Kuo, A.D., Donelan, M., & Ruina, A. (2005). Energetic consequences of walking like an inverted pendulum: step-to-step transitions. *Exercise Sports Science Review*, 33(2), 88-97.
- Kuo, A.D., Donelan, M., & Ruina, A. (2007). The six determinants of gait in the inverted pendulum analogy: a dynamic walking perspective. *Human Movement Science*, 26(4), 617-656.
- Lamontagne, A., Malouin, F., & Richards, C.L. (2001). Locomotor-specific measure of spasticity of plantarflexor muscles after stroke. *Archives of Physical Medicine and Rehabilitation*, 82(12), 1696-1704. doi: <http://dx.doi.org/10.1053/apmr.2001.26810>
- Lamontagne, A., Malouin, F., Richards, C.L., & Dumas, F. (2002). Mechanisms of disturbed motor control in ankle weakness during gait after stroke. *Gait & Posture*, 15(3), 244-255. doi: 10.1016/s0966-6362(01)00190-4
- Lamontagne, A., Richards, C.L., & Malouin, F. (2000). Coactivation during gait as an adaptive behavior after stroke. *Journal of Electromyography and Kinesiology*, 10(6), 407-415. doi: 10.1016/s1050-6411(00)00028-6
- Lamontagne, A., Stephenson, J.L., & Fung, J. (2007). Physiological evaluation of gait disturbances post stroke. *Clinical Neurophysiology*, 118(4), 717-729. doi: 10.1016/j.clinph.2006.12.013
- Lamy, J.C., Wargon, I., Mazevet, D., Ghanim, Z., Pradat-Diehl, P., & Katz, R. (2009). Impaired efficacy of spinal presynaptic mechanisms in spastic stroke patients.

- Brain*, 132, 734-748.
- Latash, M. (1998). *Neurophysiological basis of movement*. USA: Human Kinetics.
- Latash, M., Aruin, A., & Shapiro, A. (1995). The relation between posture and movement: A study of a simple synergy in a two-joint task. *Human Movement Science*, 14(1), 79-107. doi: 10.1016/0167-9457(94)00046-h
- Lin, P.-Y., Yang, Y.-R., Cheng, S.-J., & Wang, R.-Y. (2006). The relation between ankle impairments and gait velocity and symmetry in people with stroke. *Archives of Physical Medicine and Rehabilitation*, 87(4), 562-568. doi: 10.1016/j.apmr.2005.12.042
- Lindmark, B., & Hamrin, E. (1995). Relation between gait speed, knee muscle torque and motor scores in post-stroke patients. *Scandinavian journal of caring sciences*, 9(4), 195-202.
- Liu, M., Anderson, F., Pandey, M., & Delp, S. (2006). Muscles that support the body also modulate forward progression during walking. *Journal of Biomechanics*, 39(14), 2623-2630.
- Loram, I., Maganaris, C., & Lakie, M. (2005). Human postural sway results from frequent, ballistic bias impulses by soleus and gastrocnemius. *Journal of Physiology*, 564(1), 295-311. doi: 10.1113/jphysiol.2004.076307
- Luft, A.R., McCombe-Waller, S., Whittall, J., & et al. (2004). Repetitive bilateral arm training and motor cortex activation in chronic stroke: A randomized controlled trial. *JAMA*, 292(15), 1853-1861. doi: 10.1001/jama.292.15.1853
- Marchand-Pauvert, V., Nicolas, G., Marque, P., Iglesias, C., & Pierrot-Deseilligny, E. (2005). Increase in group II excitation from ankle muscles to thigh motoneurons during human standing. *The Journal of Physiology*, 566(1), 257-271.
- Marigold, D., & Eng, J. (2006). Altered timing of postural reflexes contributes to falling in persons with chronic stroke. *Experimental Brain Research*, 171(4), 459-468. doi: 10.1007/s00221-005-0293-6
- Marigold, D.S., Eng, J.J., Tokuno, C.D., & Donnelly, C.A. (2004). Reliability of lower extremity strength measures in persons with chronic stroke. *Neurorehabilitation and Neural Repair*, 18(4), 222-229.
- Marque, P., Simonetta-Moreau, M., Maupas, E., & Roques, C.F. (2001). Facilitation of transmission in heteronymous group II pathways in spastic hemiplegic patients. *Journal of Neurology, Neurosurgery & Psychiatry*, 70(1), 36-42. doi: 10.1136/jnnp.70.1.36
- Massion, J. (1992). Movement, posture and equilibrium: interaction and coordination. *Progress in Neurobiology* 38(1), 35-56.
- Massion, J. (1998). Postural control systems in developmental perspective. *Neuroscience Biobehavioral Review*, 22(4), 465-472.
- Matsuyama, K., Mori, F., Nakajima, K., Drew, T., Aoki, M., & Mori, S. (2004). Locomotor role of the corticoreticular-reticulospinal-spinal interneuronal system. In Douglas G. Stuart Shigemi Mori & Wiesendanger Mario (Eds.), *Progress in Brain Research* (pp. 239-249). London: Elsevier.
- Maupas, E., Marque, P., Roques, C.F., & Simonetta-Moreau, M. (2004). Modulation of the transmission in group II heteronymous pathways by tizanidine in spastic hemiplegic patients. *Journal of Neurology, Neurosurgery & Psychiatry*, 75(1), 130-135.
- Mizrahi, J., Solzi, P., Ring, H., & Nisell, R. (1989). Postural stability in stroke patients: Vectorial expression of asymmetry, sway activity and relative sequence of reactive forces. *Medical and Biological Engineering and Computing*, 27(2),

- 181-190. doi: 10.1007/bf02446228
- Mohr, J., Lazar, R., & Marshall, R. (2004). Middle cerebral artery disease. In JP Mohr, RM Lazar & RS Marshall (Eds.), *Stroke: Pathophysiology, Diagnosis and Management* (pp. 123-166). New York: Elsevier.
- Morasso, P.G., Baratto, L., Capra, R., & Spada, G. (1999). Internal models in the control of posture. *Neural Networks*, 12(7-8), 1173-1180. doi: 10.1016/s0893-6080(99)00058-1
- Morasso, P.G., & Schieppati, M. (1999). Can muscle stiffness alone stabilize upright standing? *Journal of Neurophysiology*, 82(3), 1622-1626.
- Mudie, M.H., & Matyas, T.A. (1996). Upper extremity retraining following stroke: effects of bilateral practice. *Journal of Neurological Rehabilitation*, 10, 167-184.
- Mudie, M.H., & Matyas, T.A. (2000). Can simultaneous bilateral movement involve the undamaged hemisphere in reconstruction of neural networks damaged by stroke? *Disability and Rehabilitation*, 22, 23-37.
- Murase, N., Duque, J., Mazzocchio, R., & Cohen, L.G. (2004). Influence of interhemispheric interactions on motor function in chronic stroke. *Annals of Neurology*, 55(3), 400-409. doi: 10.1002/ana.10848
- Nadeau, S., Gravel, D., Arsenault, A.B., & Bourbonnais, D. (1999). Plantarflexor weakness as a limiting factor of gait speed in stroke subjects and the compensating role of hip flexors. *Clinical Biomechanics*, 14(2), 125-135.
- Nardone, A., Corrà, T., & Schieppati, M. (1990). Different activations of the soleus and gastrocnemii muscles in response to various types of stance perturbation in man. *Experimental Brain Research*, 80(2), 323-332. doi: 10.1007/bf00228159
- Nardone, A., Giordano, A., Corrà, T., & Schieppati, M. (1990). Responses of leg muscles in humans displaced while standing. Effects of types of perturbation and of postural set. *Brain*, 113(1), 65-84.
- Nardone, A., Grasso, M., Giordano, A., & Schieppati, M. (1996). Different effect of height on latency of leg and foot short- and medium-latency EMG responses to perturbation of stance in humans. *Neuroscience Letters*, 206(2-3), 89-92. doi: 10.1016/s0304-3940(96)12430-7
- Nardone, A., & Schieppati, M. (2005). Reflex contribution of spindle group Ia and II afferent input to leg muscle spasticity as revealed by tendon vibration in hemiparesis. *Clinical Neurophysiology*, 116(6), 1370-1381. doi: 10.1016/j.clinph.2005.01.015
- Nashner, L., & Forssberg, H. (1986). Phase-dependent organization of postural adjustments associated with arm movements while walking. *Journal of Neurophysiology*, 55(6), 1382-1394.
- Neptune, R., Kautz, A., & Zajac, E. (2001). Contributions of the individual ankle flexors to support, forward progression and swing initiation during normal walking. *Journal of Biomechanics*, 34(11), 1387-1398.
- Neptune, R., Kautz, S., & Zajac, F. (2004). Muscle force redistributes segmental power for body progression during walking. *Gait & Posture*, 19(2), 194-205.
- Nicholas, S., Doxey-Gasway, D., & Paloski, W. (1998). A link-segment model of upright human posture for analysis of head-trunk coordination. *Journal of Vestibular Research: Equilibrium & Orientation*, 8(3), 187-200.
- Nielsen, J., & Sinkjaer, T. (2002). Afferent feedback in the control of human gait. *Journal of Electromyography and Kinesiology*, 12(3), 213-217.
- Nudo, R.J. (1999). Recovery after damage to motor cortical areas. *Current Opinion in Neurobiology*, 9(6), 740-747. doi: [http://dx.doi.org/10.1016/S0959-4388\(99\)00027-6](http://dx.doi.org/10.1016/S0959-4388(99)00027-6)

- Olney, S.J., Griffin, M.P., & McBride, I.D. (1994). Temporal, kinematic, and kinetic variables related to gait speed in subjects with hemiplegia: a regression approach. *Physical Therapy*, 74(9), 872-885.
- Olney, S.J., Griffin, M.P., Monga, T.N., & McBride, I.D. (1991). Work and power in gait of stroke patients. *Archives of Physical Medicine and Rehabilitation*, 72(5), 309-314.
- Olney, S.J., & Richards, C. (1996). Hemiparetic gait following stroke. Part I: Characteristics. *Gait & Posture*, 4(2), 136-148. doi: 10.1016/0966-6362(96)01063-6
- Paillex, R., & So, A. (2003). Standing posture of adults: effects of a stroke. *Annales de Réadaptation et de Médecine Physique*, 46(2), 71-78.
- Pearson, K., & Collins, D. (1993). Reversal of the influence of group Ib afferents from plantaris on activity in medial gastrocnemius muscle during locomotor activity. *Journal of Neurophysiology*, 70(3), 1009-1017.
- Perry, J. (1992). *Gait Analysis. Normal and Pathological Gait*. USA: Slack Incorporated.
- Richards, C.L., Malouin, F., Dumas, F., & Lamontagne, A. (1998). Recovery of ankle and hip power during walking after stroke. *Canadian Journal of Rehabilitation*, 11, 271-273.
- Roerdink, M., Lamoth, C.J., Kwakkel, G., & van Wieringen, P.C., Beek, P.J. (2007). Gait coordination after stroke: benefits of acoustically paced treadmill walking. *Physical Therapy*, 87, 1009-1022.
- Rose, D.K., & Winstein, C.J. (2005). The co-ordination of bimanual rapid aiming movements following stroke. *Clinical Rehabilitation*, 19, 452-462.
- Ryerson, S., Byl, N.N., Brown, D.A., Wong, R.A., & Hidler, J.M. (2008). Altered Trunk Position Sense and Its Relation to Balance Functions in People Post-Stroke. *Journal of Neurologic Physical Therapy*, 32(1), 14-20
10.1097/NPT.1090b1013e3181660f3181660c.
- Sadeghi, H., Allard, P., Barbier, F., Sadeghi, S., Hinse, S., Perrault, R., & Labelle, H. (2002). Main functional roles of knee flexors/extensors in able-bodied gait using principal component analysis (I). *The Knee*, 9(1), 47-53.
- Said, C.M., Goldie, P.A., Patla, A.E., Sparrow, W.A., & Martin, K.E. (1999). Obstacle crossing in subjects with stroke. *Archives of Physical Medicine and Rehabilitation*, 80(9), 1054-1059. doi: [http://dx.doi.org/10.1016/S0003-9993\(99\)90060-6](http://dx.doi.org/10.1016/S0003-9993(99)90060-6)
- Schiemanck, S.K., Kwakkel, G., Post, M.W.M., Kappelle, L.J., & Prevo, A.J.H. (2006). Predicting long-term independency in activities of daily living after middle cerebral artery stroke. *Stroke*, 37(4), 1050-1054. doi: 10.1161/01.STR.0000206462.09410.6f
- Schieppati, M., & Nardone, A. (1997). Medium-latency stretch reflexes of foot and leg muscles analysed by cooling the lower limb in standing humans. *The Journal of Physiology*, 503(Pt 3), 691-698.
- Schieppati, M., Nardone, A., Siliotto, R., & Grasso, M. (1995). Early and late stretch responses of human foot muscles induced by perturbation of stance. *Experimental Brain Research*, 105(3), 411-422.
- Shergill, S.S., Bays, P.M., C.D., F., & Wolpert, D.M. (2003). Two eyes for an eye: the neuroscience of force escalation. *Science*, 301, 187.
- Shiavi, R., Bugle, H., & Limbird, T. (1987). Electromyographic gait assessment, Part 2: Preliminary assessment of hemiparetic synergy patterns. *J Rehabil Res Dev*, 24, 24 - 30.

- Silva, A., Sousa, A.S.P., Pinheiro, R., Ferraz, J., Tavares, J.M.R.S., Santos, R., & Sousa, F. (2012). Activation timing of soleus and tibialis anterior muscles during sit-to-stand and stand-to-sit in post-stroke vs healthy subjects. *Somatosensory and Motor Research*, 30(1), 48-85.
- Silva, A., Sousa, A.S.P., Pinheiro, R., Tavares, J.M.R.S., Santos, R., & Sousa, F. (2012). Soleus activity in post-stroke subjects: movement sequence from standing to sitting. *Somatosensory and Motor Research*, 29(3), 71-76.
- Silva, A., Sousa, A.S.P., Tavares, J., Tinoco, A., Santos, R., & Sousa, F. (2012). Ankle dynamic in stroke patients. Agonist vs antagonist muscle relations. *Somatosensory and Motor Research*, 29(4), 111-116.
- Sinkjær, T., Andersen, J.B., Ladouceur, M., Christensen, L.O.D., & Nielsen, J.B. (2000). Major role for sensory feedback in soleus EMG activity in the stance phase of walking in man. *The Journal of Physiology*, 523(3), 817-827.
- Smania, N., Picelli, A., Gandolfi, M., Fiaschi, A., & Tinazzi, M. (2008). Rehabilitation of sensorimotor integration deficits in balance impairment of patients with stroke hemiparesis: a before/after pilot study. *Neurological Sciences*, 29(5), 313-319.
- Sousa, A.S.P., Santos, R., Oliveira, F.P.M., Carvalho, P., & Tavares, J.M.R.S. (2012). Analysis of ground reaction force and electromyographic activity of the gastrocnemius muscle during double support. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 226(5), 397-405.
- Sousa, A.S.P., Silva, A., Santos, R., Sousa, F., & Tavares, J.M.R.S. (2013). Interlimb Coordination During the Stance Phase of Gait in Subjects With Stroke. *Archives of Physical Medicine and Rehabilitation*, 94(12), 2515-2522. doi: <http://dx.doi.org/10.1016/j.apmr.2013.06.032>
- Sousa, A.S.P., Silva, A., & Tavares, J.M.R.S. (2013). Interlimb relation during the double support phase of gait: an electromyographic, mechanical and energy based analysis. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, 227(3). doi: 10.1177/0954411912473398
- Stubbs, P.W., & Mrachacz-Kersting, N. (2009). Short-Latency Crossed Inhibitory Responses in the Human Soleus Muscle. *Journal of Neurophysiology*, 102(6), 3596-3605. doi: 10.1152/jn.00667.2009
- Swinnen, S.P., & Carson, R.G. (2002). The control and learning of patterns of interlimb coordination: past and present issues in normal and disordered control. *Acta Psychologica*, 110(2-3), 129-137. doi: [http://dx.doi.org/10.1016/S0001-6918\(02\)00030-6](http://dx.doi.org/10.1016/S0001-6918(02)00030-6)
- Taub, E., Uswatte, G., & Elbert, T. (2002). New treatments in neurorehabilitation founded on basic research. [10.1038/nrn754]. *Nat Rev Neurosci*, 3(3), 228-236.
- Thiel, A., Aleksic, B., LKlein, J.C., Rudolf, J., & Heiss, W.-D. (2007). Changes in proprioceptive systems activity during recovery from post-stroke hemiparesis. *Journal of Rehabilitation Medicine*, 39, 520-525.
- Tseng, S.-C., & Morton, S.M. (2010). Impaired Interlimb Coordination of Voluntary Leg Movements in Poststroke Hemiparesis. *Journal of Neurophysiology*, 12, 248-257.
- Tyson, S.F., Hanley, M., Chillala, J., Selley, A.B., & Tallis, R.C. (2008). Sensory loss in hospital-admitted people with stroke: Characteristics, associated factors, and relationship with function. *Neurorehabilitation and Neural Repair*, 22(2), 166-172.
- van der Kooij, H., Jacobs, R., Koopman, B., & Grootenboer, H. (1999). A multisensory

- integration model of human stance control. *Biological Cybernetics*, 80(5), 299-308. doi: 10.1007/s004220050527
- Van Wezel, B.M.H., Ottenhoff, F.A.M., & Duysens, J. (1997). Dynamic control of location-specific information in tactile cutaneous reflexes from the foot during human walking. *The Journal of Neuroscience*, 17(10), 3804-3814.
- Verma, R., Arya, K.N., Sharma, P., & Garg, R.K. (2012). Understanding gait control in post-stroke: Implications for management. *Journal of Bodywork and Movement Therapies*, 16(1), 14-21. doi: 10.1016/j.jbmt.2010.12.005
- von Schroeder, H., Coutts, R., Lyden, P., Billings, E.J., & Nickel, V. (1995). Gait parameters following stroke: a practical assessment. *Journal of Rehabilitation Research and Development*, 32(1), 25-31.
- Wakeling, J.M., & Nigg, B.M. (2001a). Modification of soft tissue vibrations in the leg by muscular activity. *Journal of Applied Physiology*, 90, 412-420.
- Wakeling, J.M., & Nigg, B.M. (2001b). Soft tissue vibrations in the quadriceps measured with skin mounted transducers. *Journal of Biomechanics*, 34, 569-543.
- Wall, J.C., & Turnbull, G.I. (1986). Gait asymmetries in residual hemiplegia. *Archives of Physical Medicine and Rehabilitation*, 67(8), 550-553.
- Ward, N.S., & Cohen, L.G. (2004). MEchanisms underlying recovery of motor function after stroke. *Archives of Neurology*, 61(12), 1844-1848. doi: 10.1001/archneur.61.12.1844
- Wevers, L., van de Port, I., Vermue, M., Mead, G., & Kwakkel, G. (2009). Effects of task-orientated circuit class training on walking competency after stroke: a systematic review. *Stroke*, 40(7), 2450-2459.
- Whitall, J., McCombe, W.S., Silver, K.H., & Macko, R.F. (2000). Repetitive bilateral arm training with rhythmic auditory cueing improves motor function in chronic hemiparetic stroke. *Stroke*, 31, 2390-2395.
- Whittle, M. (2007). *Gait Analysis: An Introduction* (4th ed. Vol. 1). USA: Elsevier.
- Winter, D.A. (1995). Human balance and posture control during standing and walking. *Gait & Posture*, 3(4), 193-214.
- Winter, D.A. (2005). *Biomechanics and motor control of human movement*. NJ: John Wiley and Sons, Inc.
- Winter, D.A., & Eng, P. (1995). Kinetics: our window into the goals and strategies of the central nervous system. *Behavioural Brain Research*, 67(2), 111-120.
- Woolley, S. (2001). Characteristics of Gait in Hemiplegia. *Topics in Stroke Rehabilitation*, 7(4), 1-18. doi: 10.1310/jb16-v04f-jal5-h1uv
- Wu, C.-Y., Chou, S.-H., Chen, C.-L., Kuo, M.-Y., Lu, T.-W., & Fu, Y.-C. (2009). Kinematic analysis of a functional and sequential bimanual task in patients with left hemiparesis: intra-limb and interlimb coordination. *Disability and Rehabilitation*, 31(12), 958-966. doi: doi:10.1080/09638280802358357
- Yang, J.F., Winter, D.A., & Wells, R.P. (1990). Postural dynamics in standing human. *Biological Cybernetics*, 62(4), 309-320.
- Zajac, F.E., Neptune, R.R., & Kautz, S.A. (2003). Biomechanics and muscle coordination of human walking: Part II: Lessons from dynamical simulations and clinical implications. *Gait & Posture*, 17(1), 1-17.
- Zehr, E.P., Komiyama, T., & Stein, R.B. (1997). Cutaneous reflexes during human gait: electromyographic and kinematic responses to electrical stimulation. *Journal of Neurophysiology*, 77(6), 3311-3325.
- Zehr, E.P., & Stein, R.B. (1999). What functions do reflexes serve during human locomotion? *Progress in Neurobiology*, 58(2), 185-205. doi: [http://dx.doi.org/10.1016/S0301-0082\(98\)00081-1](http://dx.doi.org/10.1016/S0301-0082(98)00081-1)

FIGURE CAPTIONS

Figure 1: Illustration of part of the eural systems related to postural control and movement.

FIGURES

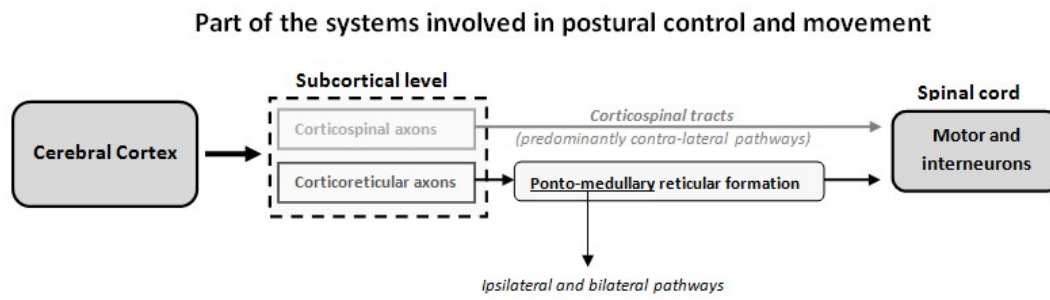


Figure 1