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FASCIA SCIENCE AND CLINICAL APPLICATIONS: REVIEW & COMMENTARY

The influence of walking-aids on the plasticity of spinal interneuronal networks, central-pattern-generators and the recovery of gait post-stroke. A literature review and scholarly discussion

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Summary *Background:* Many aspects of post-stroke gait-rehabilitation are based on low-level evidence or expert opinion. Neuroscientific principles are often not considered when evaluating the impact of interventions. The use of walking-aids including canes and rollators, although widely used for long periods, has primarily been investigated to assess the immediate kinetic, kinematic or physiological effects. The long-term impact on neural structures und functions remains unclear.
Methods: A literature review of the function of and factors affecting plasticity of spinal interneuronal-networks and central-pattern-generators (CPG) in healthy and post-stroke patients. The relevance of these mechanisms for gait recovery and the potential impact of walking-aids is discussed.
Results: Afferent-input to spinal-networks influences motor-output and spinal and cortical plasticity. Disrupted input may adversely affect post-stroke plasticity and functional recovery. Joint and muscle unloading and decoupling from four-limb CPG control may be particularly relevant.

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Conclusions: Canes and rollators disrupt afferent-input and may negatively affect the recovery of gait.

Introduction

The most effective treatments for post-stroke rehabilitation, when considering Clinical Practice Guidelines and systematic reviews, are those whose development was based on sound knowledge of basic neuroscience (Veerbeek et al., 2014). Despite this, information from basic science is not routinely considered in many aspects of gait rehabilitation. Clinical practice is often based on low level evidence or expert opinion (Kollen et al., 2009; Lennon, 2003; States et al., 2009). Walking aids, including canes and rollators, although widely used and often for long periods, have not been investigated regarding impact on neural and neuromuscular mechanisms. To date, studies have primarily been limited to the immediate effects on kinetic, kinematic or physiological outcomes in cross-sectional studies (Jeong et al., 2015; Polese et al., 2012).

We review spinal neuronal networks (SINs), central pattern generators (CPGs) and the influence of afferent feedback on these structures in healthy and post-stroke subjects. We discuss possible influences of walking aids on the control and recovery of these systems and gait function, the potential consequences for rehabilitation and areas requiring future research.

Spinal interneurons (SINs)

Neuronal networks are groups of neurones, each with potentially different input and output relationships and intrinsic properties, which work co-operatively and in parallel (Getting, 1989). They are distributed throughout the central nervous system, forming for example cortical, vestibular, cerebellar and spinal neural networks.

Spinal interneuronal networks, SINs, are thought to represent the functional link translating higher centre commands and integrating peripheral feedback to achieve orchestrated output at the motor neurones (MNs) (Squire et al., 2013). This enables coordinated muscle activity to achieve motor goals. SINs are involved in all levels of movement control, from simple reflex responses to complex voluntary tasks (Jankowska and Hammar, 2002). They play an important role in turning the "space based" representation of movement in the motor cortex (e.g. hand to mouth) (Capaday et al., 2013) into specific muscle activity via MNs. They seem to be decisive in reducing the redundancy inherent in cortical movement maps and generating specific patterns of activity (Harel et al., 2008).

Locomotor CPGs represent one form of hereditary, stereotyped although flexible SIN (Squire et al., 2013). The function of CPGs in gait control and the relevance for rehabilitation has been considered primarily for patients with spinal cord injury (SCI) (Wirz et al., 2001). The importance for stroke rehabilitation has been sparsely considered (Arya and Pandian, 2014; Sist et al., 2014) and to our knowledge not at all for the prescription of walking aids.

Structure of SINS

This paper uses a functional classification of SINs (Edgley, 2001).

SINs consist of 1. Input neurones from various sources including supraspinal, peripheral afferents and interneurons (INs) from other SINs. 2. Numerous types of INs which process and integrate the inputs. 3. Target output neurones which may be MNs, the interneurons of other SINs, or supraspinal structures (Jankowska, 2008) (Fig. 1).

Input neurons

Supraspinal input neurones include cortical, vestibular, reticular, cerebellar and rubrospinal sources. Peripheral inputs arise from muscle, tendon, cutaneous, joint, osseous and pain fibres (Kandel et al., 2013).

The proportion of inputs from different sources varies depending on the spinal segment. MNs directing hand and finger movement receive the most direct corticospinal inputs, the proportion is nevertheless estimated to be 10% or less. Tracing of corticospinal pathways suggests that most fibres terminate directly onto INs rather than MNs (Shinoda et al., 1981), emphasising the integrative importance of these structures. The synaptic strength of cortical-MN connections is also weaker than cortical-IN and IN—MN

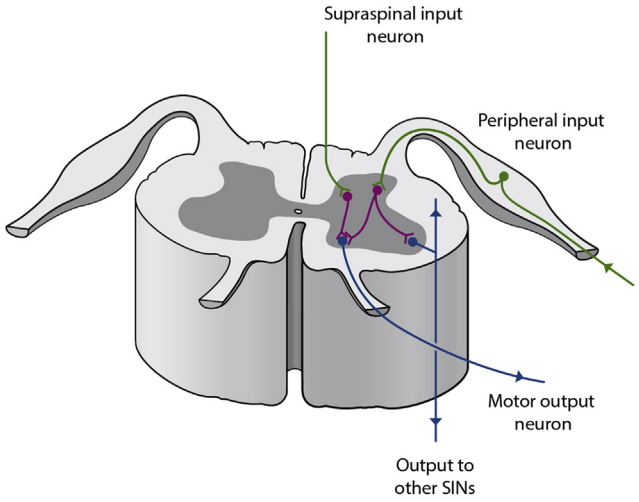

Figure 1 Spinal interneuronal network (SIN).

connections. This supports the hypothesis that INs participate in the process of translating cortical commands into muscle activity.

Divergence of input

Afferent neurons form divergent connections with large numbers of INs (Kandel et al., 2013). This simultaneous delivery of information to multiple effectors supports a holistic and coordinated response.

Convergence of input

SINs simultaneously receive input from many different sources (Edgley, 2001). Final output will depend on the weighting and integration of received signals. This integrative function appears to be the main task of interneurons (Jankowska and Edgley, 1993).

Interneurons

Intra-limb control

Inhibition

1. Reciprocal inhibition.

Reciprocal inhibition refers to the intra-limb, intermuscular inhibition of antagonist musculature during agonistic activation.

Presynaptic reciprocal inhibition-stretch reflex
For example, due to the stretch reflex a sudden stretch of an extensor muscle triggers its reflex contraction thereby stretching the antagonistic flexor. This could trigger a stretch reflex in the flexor muscle, potentially creating a series of agonist—antagonist reflex contractions. To prevent this, 1b afferents from the antagonistic muscles are simultaneously and "reciprocally" inhibited during the agonist reflex contraction. This inhibition prevents the antagonistic MNs from receiving the information that a stretch has occurred and therefore from firing (Kiehn et al., 2010). This is an example of pre-synaptic inhibition and is mediated by ipsilateral spinal INs.

Postsynaptic reciprocal inhibition-gait control
Reciprocal inhibition during walking is important for coordinated limb control, although mediated by a different mechanism than the stretch reflex. Agonistic 1a afferents synapse onto 1a INs which use post-synaptic rather than pre-synaptic inhibition. These 1a INs synapse directly onto the soma of antagonistic MNs therefore inhibiting the MN itself and not it's afferent (Squire et al., 2013). These antagonistic inhibitory neurons are activated during all agonistic activations even without a stretch reflex. If 1a INs is blocked, agonist—antagonist co-contraction occurs (Windhorst, 2007). These networks are primarily ipsilateral as they remain intact in the hemi cord (Kiehn, 2006). Reciprocal inhibition therefore provides a principle mechanism by which muscles can be linked and coordinated (Kandel et al., 2013) (Fig. 2).

2. Non-reciprocal inhibition

Animal experiments demonstrate that non-reciprocal inhibition is governed by 1b INs. These are activated by muscle and cutaneous afferents, joint receptors and cortical inputs and can project to both agonistic and antagonistic muscle groups (Purves et al., 2012). This enables intra-limb muscular inhibition providing a protective mechanism and allowing supra-spinal influence of muscular activity levels.

Non-reciprocal inhibition — autogenic inhibition (Golgi tendon reflex)
This reflex is the opposite of the stretch reflex. 1b afferent fibres from Golgi Tendon organs fire during muscle contractions signalling tension in the muscle. The fibres synapse onto 1b inhibitory INs of their own MN. If signals from 1b afferents indicate that muscle tension is high, then 1b INs increase firing rate thereby increasing inhibition at their homologous MN. This reduces activity thus having a protective effect (Purves et al., 2012; Windhorst, 2007).

This circuit operates not only as a protective reflex, but also at lower levels of muscle tension. The inhibition of MNs via 1b INs can be reduced or increased, depending on the requirements of the motor task (Purves et al., 2012). As the 1b INs receive multiple inputs, the final output, whether a reduction or an increase in inhibition, will depend on the integration of incoming information. In the stance phase of gait, despite increased extensor muscle activity which will increase 1b afferent signals, a further increase not a decrease in extensor activity occurs (Conway et al., 1987; Dietz et al., 1992). The integration of inputs from various sources e.g. joint load receptors, influences final output. SIN output therefore adapts depending on motor goal (Jankowska, 1992).

Non-reciprocal inhibition — recurrent inhibition
Renshaw cells (RCs) are inhibitory cells located ventrally in the spinal cord. During firing of MNs, the signal is also forwarded, by axon collaterals from the MN, to the Renshaw cell. This stimulates the inhibitory output of the RC which makes synaptic connections to the stimulating MN, to several other synergistic MNs in adjacent segments and to 1a inhibitory neurones (Kandel et al., 2013; Nishimaru et al., 2006). This creates a negative feedback loop, in which increasing activity of the MN increases signals to the inhibitory RC, thus reducing the MN output. This process plays an important role in the termination of MN burst during locomotion. Connections to the 1a inhibitory neurones may regulate the strength of reciprocal inhibition (Kandel et al., 2013; Nishimaru et al., 2006). Connections to other local MNs causes a generalised, not muscle specific, inhibitory effect. These processes are termed recurrent inhibition (Alvarez and Fyffe, 2007). Recurrent inhibition is strongest among proximal postural muscles during postural control and locomotion (Kandel et al., 2013; Nishimaru et al., 2006). In contrast, recurrent inhibition is weak or absent in MN pools concerned with

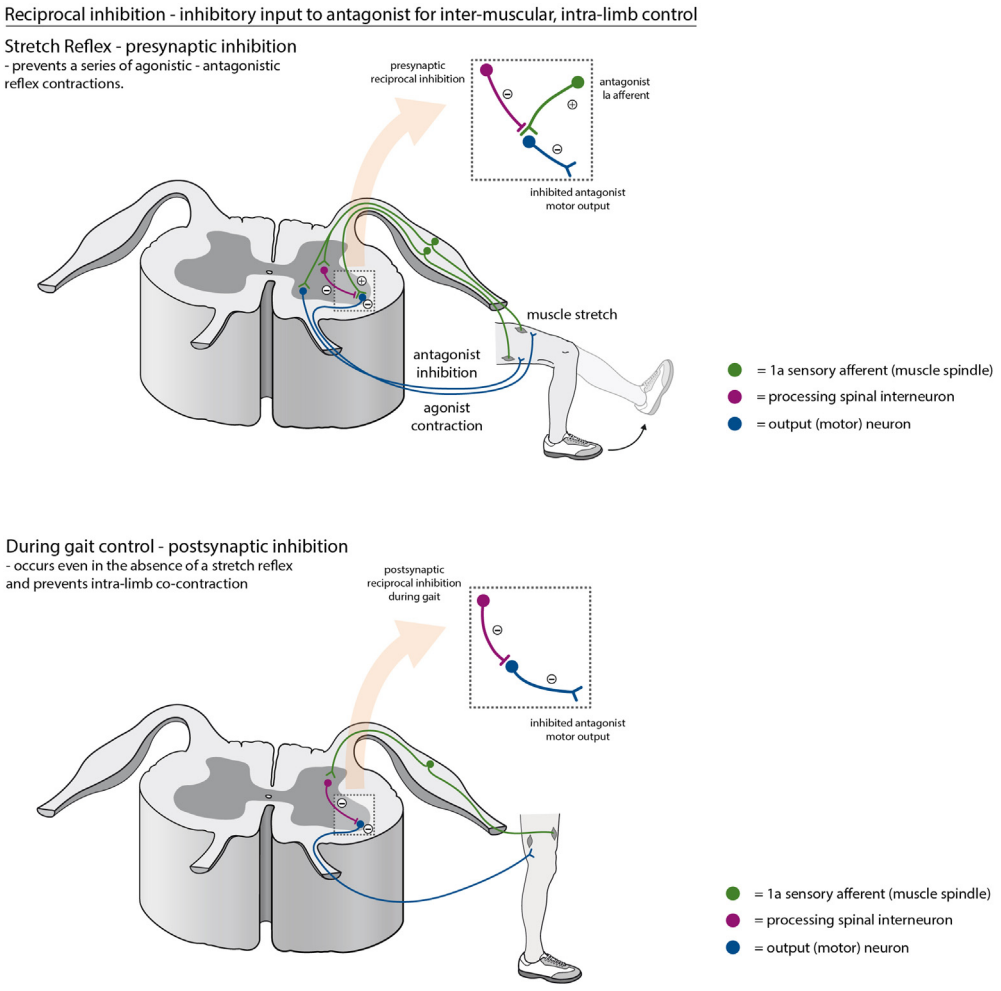

Figure 2 Reciprocal inhibition — inhibitory input to antaonist for inter-muscular, intra-limb control.

precise, distal voluntary movement (Windhorst, 2007). This may reflect the diffuse nature of RC inhibition which is adequate for postural control but not for the exactitude required for skilled voluntary movement.

Animal models demonstrate that RCs also receive input from descending pathways, commissural INs (from the contralateral side) and during walking from the ipsilateral locomotor networks (Nishimaru et al., 2006) (Fig. 3).

Excitation

Afferent inputs

Direct connections from group 1a and II muscle afferents onto MNs provide excitatory inputs. The strength of these connections varies depending on the motor task and the afferent fibre. The strongest connections arise from 1a afferents during postural tasks of antigravity muscles (Windhorst, 2007). Evidence shows convergent excitation from cutaneous, joint and group III muscle afferents. Excitatory inputs from supraspinal structures selectively increase activity in SINs. Signals from the "brainstem command centres" such as the Mesencephalic Locomotor Region which is involved in the initiation of gait and control of muscle tone, as well as direct cortico-spinal excitatory inputs (Takakusaki, 2013).

Excitatory spinal INs

In animal studies at least four types of INs have been shown to release the excitatory neurotransmitter glutamate and target MNs as well as commissural INs (CINs). The influence on commissural INs suggests an important role for left—-right coordination. They also appear to be involved in rhythm generation during gait through rhythmic and repetitive firing (Zhang et al., 2008).

Inter-limb control

Inter-limb coordination is an important aspect of gait and balance control. For example initiation of swing phase is dependent on ipsilateral signals indicating the end of stance phase and contralateral signals indicating stance. Equally, if one leg is displaced during standing or walking a coordinated bilateral response occurs (Dietz, 2003). This is achieved by both CINs(Takakusaki, 2013) and supraspinal inputs involving the corpus callosum (Arya and Pandian, 2014). A further example is the polysynaptic flexor withdrawl reflex (Sandrini et al., 2005).

Commissural interneurones

"Commissural interneurons" (CINs) have been identified in animal studies and can have axonal projections which are

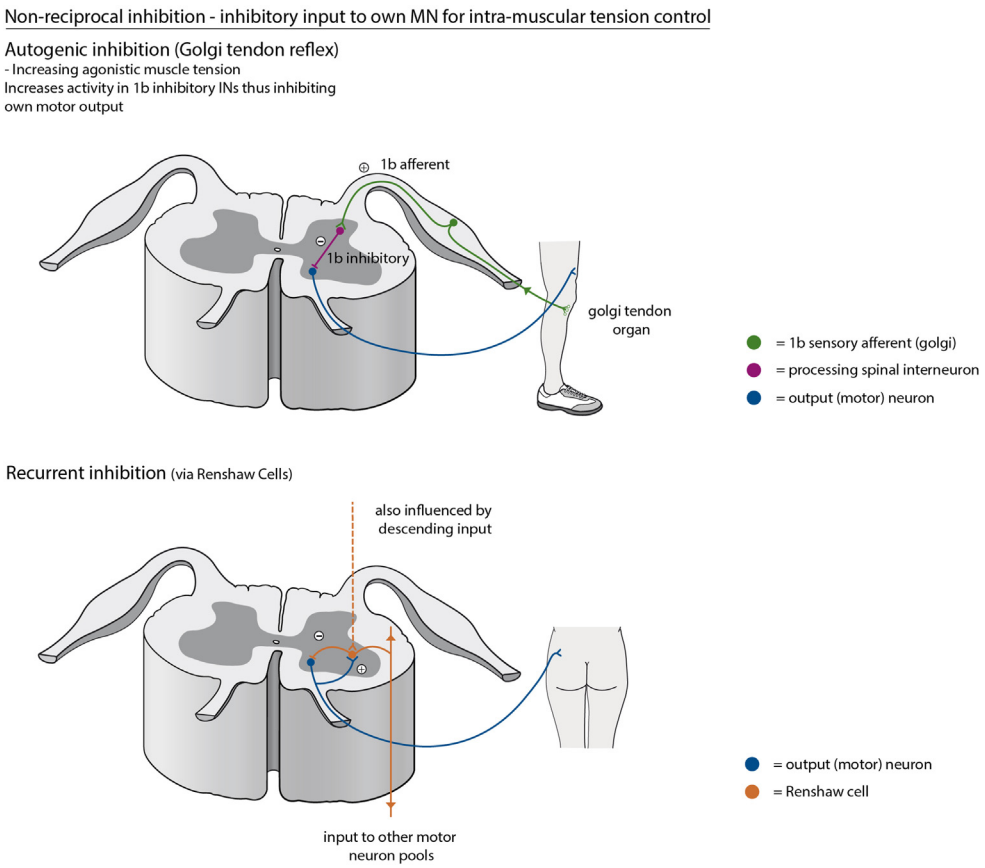

Figure 3 Non-reciprocal inhibition — inhibitory input to own MNs for intra-muscular tension control.

both intra- and intersegmental (level of each spinal nerve), descending and ascending (Squire et al., 2013). CINs are widely interconnected thus acting as building blocks of complex networks (Jankowska, 2008). They integrate information from supraspinal and peripheral sources and provide direct excitation, direct and indirect inhibition to ipsi and contralateral MNs (Fig. 4).

Alternating and synchronous limb movement

A dual inhibitory system is involved in left-right alternating patterns (anti-phase movement in walking) and synchronous bilateral patterns (in-phase movement such as jumping with two legs) (Kiehn et al., 2010). During alternating movement, ipsilateral activation and contralateral inhibition occur simultaneously via a direct inhibitory pathway, mediated by inhibitory GABAergic INs, which project onto contralateral motor neurones and an indirect pathway provided by excitatory glutametergic INs, which synapse onto contralateral inhibitory Renshaw cells.

Excitatory CINs can simultaneously synapse onto MNs and Renshaw cells. This is thought to be important during synchronous activity when both limbs perform the same task (Kiehn et al., 2010) (Fig. 5).

Afferent input

Direct connections exist between CINs and higher centres. Reticulospinal and vestibulospinal connections illustrate that CINs are involved in postural adjustments. Inputs from the pyramidal tract and the mesencephalic

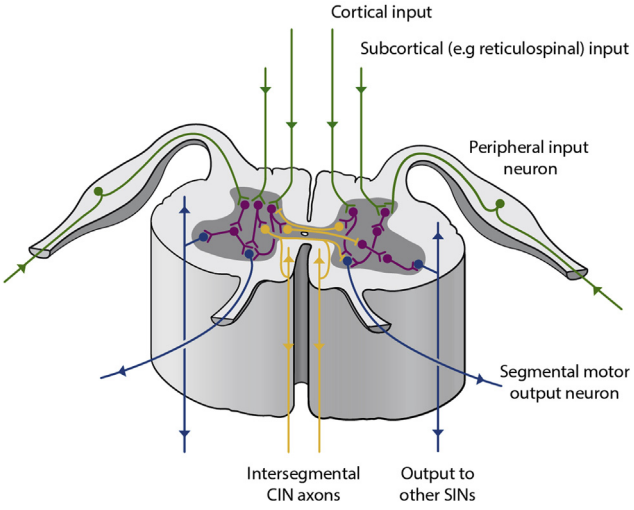

Figure 4 Commisural Interneurons (CINs).

locomotor region (MLR) indicate involvement in gait initiation (Jankowska, 2008) and with the cortex, in the earliest stages of movement preparation (Fetz et al., 2002). Input from fastigial neurons from the cerebellum indicates involvement in feedforward adaptation and motor learning (Jankowska, 2008). Connections from muscle afferents indicate integration of peripheral afferent signals.

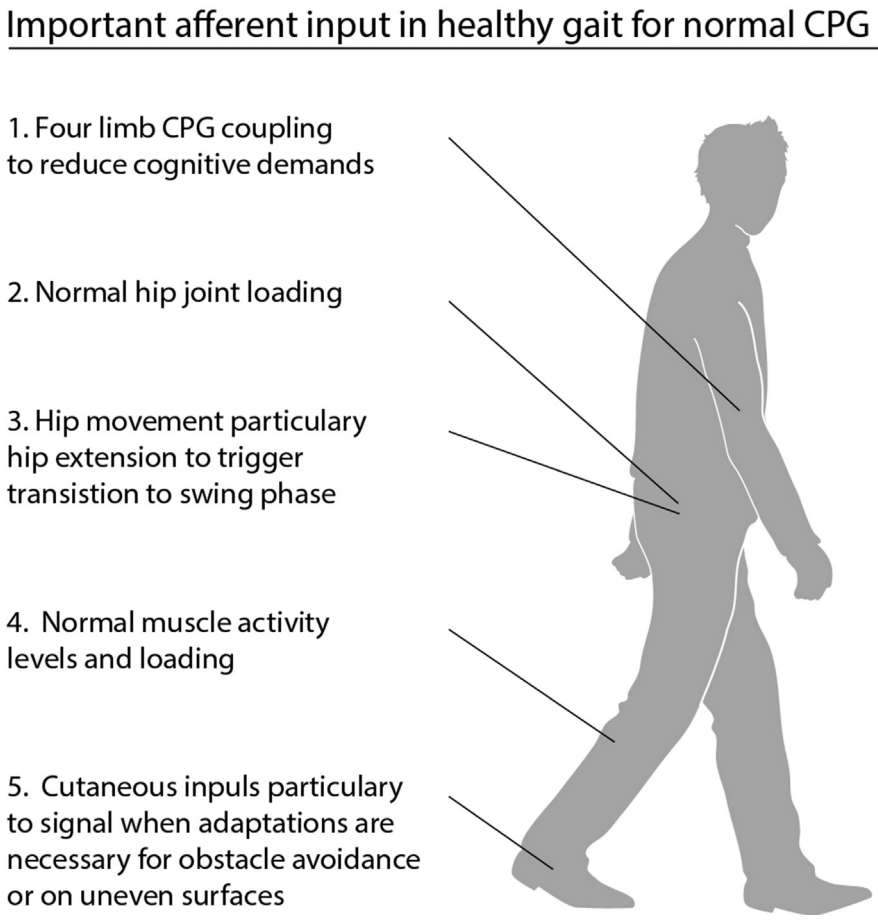

Figure 5 Alternating and synchronous inter-limb control.

Studies demonstrate that supraspinal inputs are essential for the correct functioning of CINs and lower limb coupling (Dietz et al., 2002). Passive facilitation of walking in one leg with a Dynamic-Gait-Orthosis induced muscle activity in the opposite (still) leg in healthy subjects but not in SCI subjects.

SIN output

To motor neurones

"The majority of inputs to spinal MNs originate from premotor SINs." (Edgley, 2001) Motor neurones are large cells, each one receiving between 50 and 150 K synaptic inputs, approximately 40% of which are excitatory, 60% inhibitory (Harel et al., 2008). They receive signals from diverse sources including local segmental afferent information and remote inputs from distant segments and descending pathways.

To ascending fibres

Ascending fibres to supraspinal centres contribute to the monitoring of motor output, inter-limb coordination and to the perception of limb position (Purves et al., 2012).

To other SINs

Output to other SINs enables connectivity and coordinated control.

Locomotor CPGs

CPGs hereditary, stereotyped but flexible SINs

CPG's have been extensively investigated in animals and indirectly in humans (Dietz, 2012; Dietz et al., 2002; Grillner, 2011; Nielsen, 2003; Squire et al., 2008). They are genetically determined networks whose structure and function are modulated through experience (Molinari, 2009). CPGs in the brainstem control breathing and swallowing and spinal cord CPGs control walking (Cheron et al., 2012). Spinal CPGs influence three aspects of locomotion 1. Rhythm and cycle 2. Intra-limb agonist—antagonist coordination 3. Inter-limb coordination (Squire et al., 2008).

The basic structure of CPGs consists of agonist and antagonist "half-centres", or task-specific sub-populations of INs, which are mutually inhibitory (van Hedel and Dietz, 2010). These are mediated by reciprocal inhibition through 1a INs. Animal studies show that half-centres exist for specific joints and are situated on each side of the spinal cord for each limb (Squire et al., 2008). It is suggested that

half-centres, work together to coordinate movement across joints (Squire et al., 2008). This organisation enables flexible combinations of motor actions thus facilitating task specific recruitment of muscle activity. Different models describe how this coordination occurs. One commonly cited model (Grillner, 1985) suggests that multi-joint coordination is controlled via SINs connecting joint specific half-centres. All forms of bipedal locomotion in humans, from very slow walking to fast running, appear to be controlled by the flexible combination of four to five CPGs (Cappellini et al., 2006). The strength of excitation and inhibition at each unit is modulated according to the motor task thus allowing flexible and context dependent motor output (Danner et al., 2015).

Half-centres are further subdivided. One part determines timing and muscle activation during stance and the transition to swing. The other during swing phase (Danner et al., 2015).

Although the basic pattern and rhythm of walking can be produced by CPGs alone, for the skilled and context dependent adaptations of gait required in daily activity, input from supraspinal centres and peripheral afferents is crucial. These inputs determine which components of CPGs are combined to achieve a motor goal thus influencing the timing and level of muscle activation.

Upper and lower limb co-ordination

In some situations e.g. swimming, coordination between all four limbs is required. CINs connecting the cervical and lumbar enlargements of the spinal cord appear to be responsible for upper and lower limb co-ordination (Delwaide and Crenna, 1984; Dietz, 2003). However, unique to humans, due to bipedal stance and skilled hand movements, is the ability to disengage the upper limbs from four limb CPG control when skilled hand movements are required. Dietz et al. have demonstrated that when the lower extremities are stimulated, EMG responses are monitored in the arms when the subject is walking but not when sitting and writing (Dietz, 2001). This implies a «task-dependent neuronal coupling» between upper and lower limbs in which spinal circuits can enable four-limb co-ordination or can be gated via cortical activity to free arm control for skilled movements (Dietz, 2002, 2003). This implies that tasks requiring upper limb activity outside the cyclical control of spinal CPGs require increased cortical input. fMRI studies indicate that the cortical supplementary motor area (SMA) is involved in this control (Debaere et al., 2001).

Influence of peripheral afferents on gait

Studies in individuals with complete SCI demonstrate that stepping patterns can be driven solely by information from peripheral sensory afferents (Harkema, 2008). Information from load receptors, hip joint movement, cutaneous and muscular proprioceptors appear to be particularly influential in determining final motor output (Dietz et al., 2002; Grillner, 2011; Takakusaki, 2013).

Dietz et al. (2002) demonstrated that passive physiological gait movements alone, without joint loading (facilitated with a Driven-Gait-Orthosis) did not induce muscle activity in healthy or SCI subjects. These results confirm earlier findings which show that load receptors are essential to trigger extensor muscle activity during walking in humans (Dietz et al., 1992). Flexor activity appears to be less influenced by load receptors, probably due to more central control during walking (Dietz, 2012; Dietz et al., 2002).

This study (Dietz et al., 2002) also showed that isolated, loaded hip movement without movement at the knees or ankles, induced normal walking activity patterns in healthy and SCI subjects. Isolated loaded knee or ankle movement did not induce walking patterns. Therefore, sensory feedback from both joint load and hip movement receptors appears to be decisive to facilitate normal CPG activity. These findings were confirmed by Pearson et al. who found that preventing hip extension can inhibit the transition to swing phase (Pearson, 2004). Stretch at the hip flexor musculature signalling the end of stance phase may influence the initiation of swing phase. As CPGs are functionally divided into parts that control i) stance and transition to swing and ii) swing phase (Danner et al., 2015), it appears that joint load, hip movement and hip flexor stretch receptors are important in the stance and transition phase. The swing phase appears to be more influenced by central, cortical control (Petersen et al., 2012).

Muscle afferents also influence activity in SINs. Swing phase is not initiated until intra-limb plantar flexor activity is low and the muscle is unloaded (Pearson et al., 1998).

Sinkjaer et al. showed that during stance phase, unloading the ankle extensors reduced soleus activity by 50% in early and mid-stance (Sinkjaer et al., 2000). McCrea (2001) showed in animal studies that depending on timing, stimulation of ankle extensor afferents could cause "a premature initiation of the extension phase, entrain the locomotor stepping frequency, alter the period of the flexion and extension phases or increase extensor motoneuron activity."

Cutaneous afferents also impact CPG activity and are important for correct foot placement and obstacle avoidance (Pearson, 2003; Rossignol et al., 2006). Cutaneous afferents stimulated in cats in opposite phases of gait induce opposite postural reactions. If the cutaneous plantar-flexor paw surface is stimulated during swing phase, flexion activity is increased suggesting obstacle avoidance strategies. If the same surface is stimulated during stance phase, extensor activity is increased (Takakusaki, 2013). Drew et al. (2004) suggest this response may be due to cutaneous inputs being relayed to the reticular formation in the brainstem. This input triggers reticulospinal neurones which converge onto spinal CPGs and "will tend to re-inforce activity in muscles that are already active" (Drew et al., 2004).

Speed of displacement, signalled from numerous peripheral afferents simultaneously, influences the activity level of synergistic muscle responses (Dietz et al., 1989).

The above points illustrate several important roles of sensory feedback. Firstly to help direct the activity of the motor neurones and secondly to contribute to adaptive and corrective responses in challenging situations or following perturbation (Nielsen, 2003). Thirdly sensory receptors

send error signals in the ascending tracts to inform supraspinal structures to what extent completed movements resemble intended movements. This is important for adjustment of future movements i.e. for fine motor tuning and motor learning (Nielsen, 2003). It has been suggested that "The rhythm and pattern are transmitted back to the supraspinal structures by the spinothalamic, -reticular, and -cerebellar tracts, so that the supraspinal structures monitor all events in the spinal cord." (Takakusaki, 2013) (Fig. 6).

Modification and co-operation between sins as motor tasks change

Studies indicate that the functions of SINs adapt depending on the motor goal (Jankowska and Edgley, 1993; Kearney et al., 1999; Sinkjaer et al., 1996). For example following position change from supine to standing the soleus stretch reflex decreases by 10—15% although there is a general increase in background soleus EMG (Mynark and Koceja, 1997). It appears that spinal circuits have simultaneously enabled an increase in activity and a decrease in reactivity. This could be achieved by increased presynaptic inhibition of group I muscle afferents together with a direct increase in excitation of the MN. Optimal movement control therefore requires the ability to adapt interneuronal activity between postures and movements.

SINs may facilitate change between feedforward and feedback control

Peripheral afferent information can be blocked due to presynaptic inhibition from GABA-ergic INs whilst at the same time excitability of the post-synaptic cell (e.g.MN) is unaffected. This reduction of afferent information has been shown to take place directly before movement onset (Voss et al., 2006) and the command originates in the SMA (Haggard and Whitford, 2004). This allows changes in the weighting of descending and peripheral inputs influencing MNs. Motor control can switch from feedforward, supraspinal control during movement onset to more feedback, peripherally influenced on-line control during movement (Harel et al., 2008).

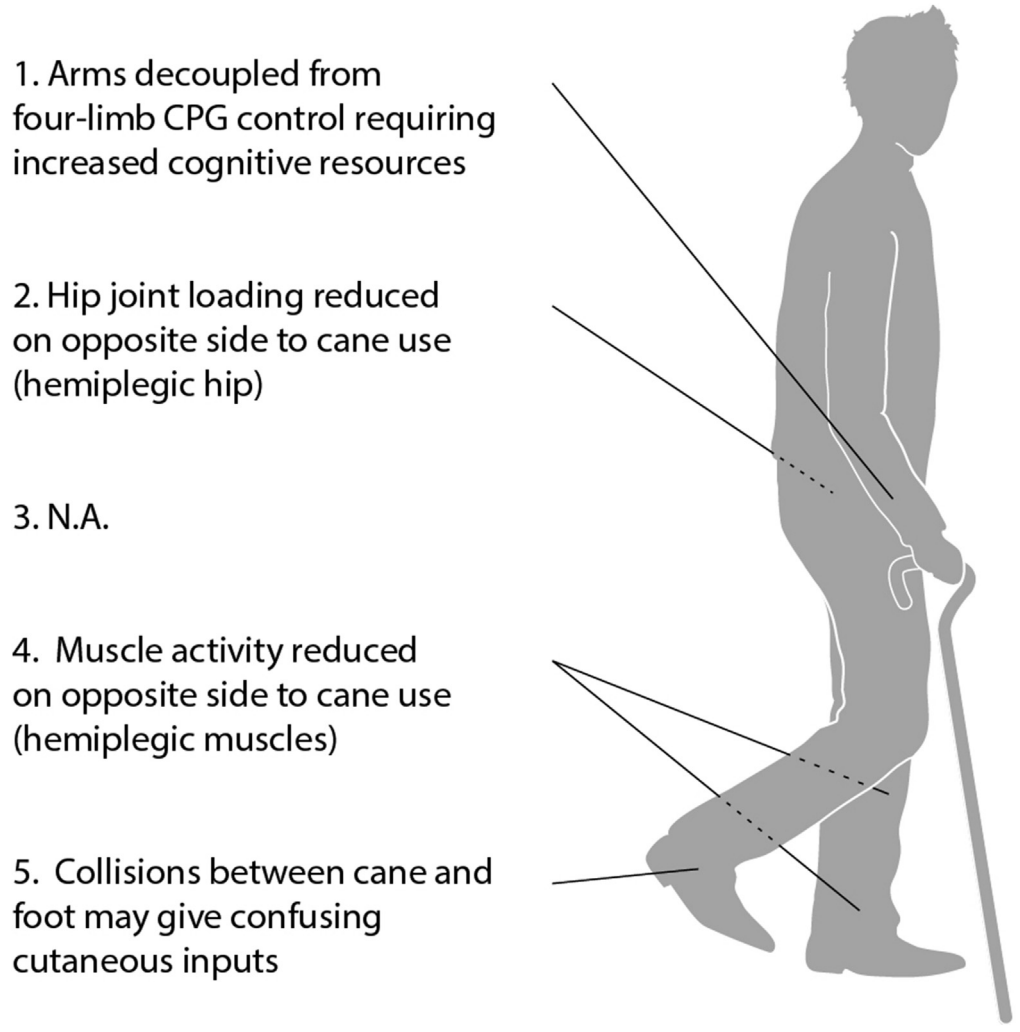

Figure 6 Important afferent input delivered in healthy gait for normal CPG activity and motor output.

These adaptations further demonstrate the functional flexibility of spinal cord circuitry necessary for movement control.

Relevance for use of walking aids post-stroke

The decisive influence of sensory input on motor output has been demonstrated, thus offering a mechanism by which therapy can influence SIN and CPG activity. These influences have the potential to be beneficial or harmful depending on method and timing of delivery.

Hip joint loading

Limb loading, particularly of the hip joint, is essential for normal CPG activity and transition from stance to swing phase. This has been used to develop effective treatments for SCI patients. "Load- and hip-joint-related afferent input seems to be of crucial importance for both the generation of a locomotor pattern and the effectiveness of the training." (Dietz, 2009) Additionally, neurologically intact humans and primates returning from space exhibit clonus in the lower extremities. This suggests that clonus is highly influenced by loss of joint load, even when supraspinal input remains intact (Recktenwald et al., 1999).

Walking with canes in the contralateral, non-hemiplegic hand in stroke patients unloads the opposite, hemiplegic hip (Ajemian et al., 2004; Maguire et al., 2010). When walking with rollators, muscle activity is reduced in the lower extremities and is compensated for by increased use of the arms, suggesting that the hips are unloaded during rollator walking (Tung et al., 2014). These devices reduce normal hip loading, therefore altering afferent feedback to CPG circuits. Extrapolating from previous studies this suggests that CPG output may be adversely affected, particularly during the transition from stance to swing phase and regarding the development of clonus. Studies also indicate that load receptors contribute to leg extensor activity during standing and walking (Dietz et al., 1992). Reduced loading may affect this mechanism.

Rollator walking reduces hip extension range of movement (Alkjaer et al., 2006) which may inhibit normal transition from stance to swing phase (Pearson, 2004).

Changes in muscle afferent input change CPG output

As muscle afferents also affect CPG output (Pearson et al., 1998; Sinkjaer et al., 2000), reduced muscle activity due to cane (Maguire et al., 2010) and rollator use (Suica et al., 2016) and changes in muscle length due to rollator use (Alkjaer et al., 2006) may impact CPG activity. A reduction in plantar flexion activity is needed to initiate swing phase (Pearson et al., 1998). The effect of consistently reduced

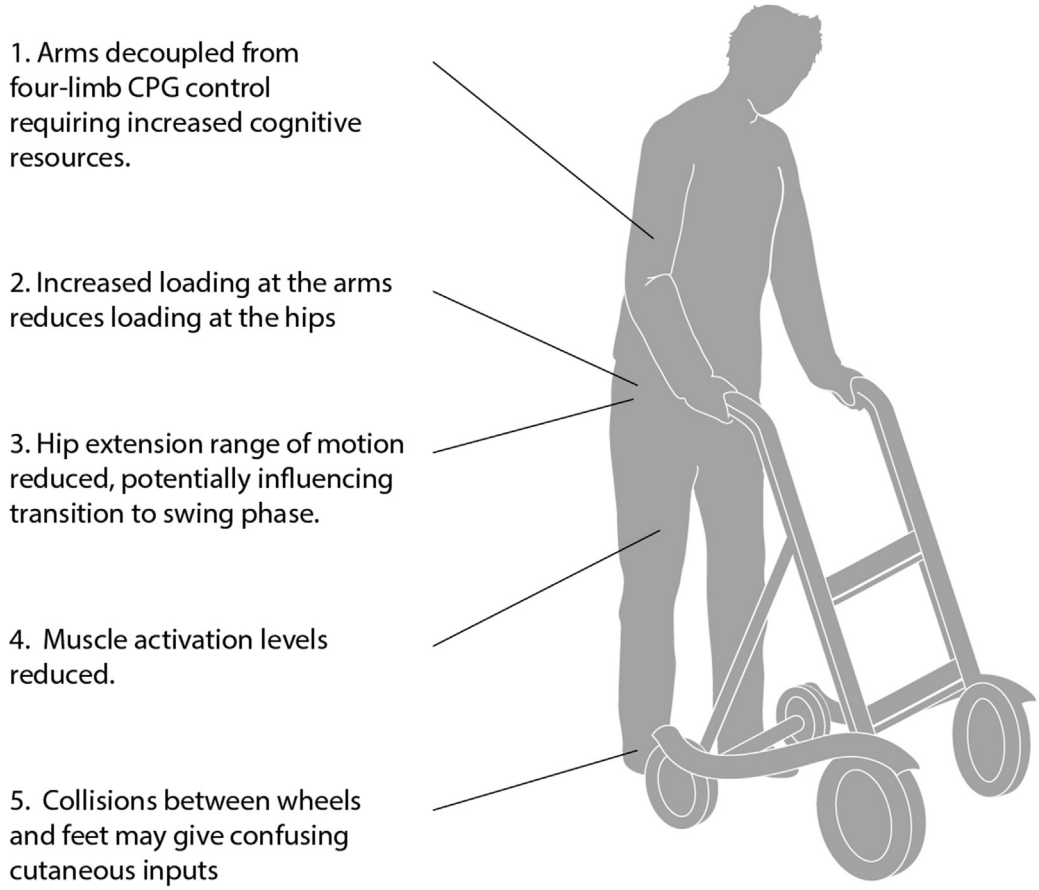

Figure 7 Alterations in afferent input when using a cane which may influence CPG activity and motor output.

muscle activity on this transition has to our knowledge not been investigated. Unloading the ankle plantar flexors during the stance phase of walking reduced soleus activity by 50% in early and mid-stance (Sinkjaer et al., 2000). As these muscles are unloaded during cane and rollator use, soleus activity may be reduced in a similar way. Although the exact effect of altered muscle afferent input due to use of these devices on CPGs remains unclear, extrapolation from other studies suggests that the altered input will change output.

It has been demonstrated that SIN activity changes depending on postural sets and motor goals (Jankowska, 1992). The exact mechanisms which influence these changes remain unclear but it is likely, as with other aspects of SIN and CPG activity, that peripheral inputs play an important role. Altered multisensory afferent input could change IN inhibitory and excitatory activity.

When patients walk with assistive devices that require hands, the upper limbs must be decoupled from four limb CPG control which requires increased cortical activity (Dietz, 2002, 2003). This may have detrimental effects on patients with reduced balance, who often use more cognitive resources to maintain stability (Lamoth et al., 2011) (Figs. 7 and 8).

Plasticity of spinal circuitry

Structural and functional changes to the cerebral cortex following stroke, and the importance of neural plasticity for motor recovery have been well documented (Nudo, 2007).

Recent studies also indicate that changes in spinal cord circuitry post-stroke contribute to functional recovery (Sist et al., 2014). Animal studies have shown that improved function is associated with increased axonal sprouting from the uninjured corticospinal tract "with numerous axons observed crossing the midline in the brainstem and spinal cord and terminating in denervated grey matter". Significantly, factors which influenced these spinal plastic changes positively influenced sensorimotor recovery (Starkey et al., 2012). Although in this study the manipulating factors were chemical in nature (ChABC), the principal that elements which influence spinal plasticity can positively impact motor recovery post-stroke may be significant for physical rehabilitation. The sensory afferents discussed in this review, which have been shown to influence SIN and CPG in- and output, may provide a route to influence spinal plasticity and improve post-stroke function. It has been shown in spinal injury patients that

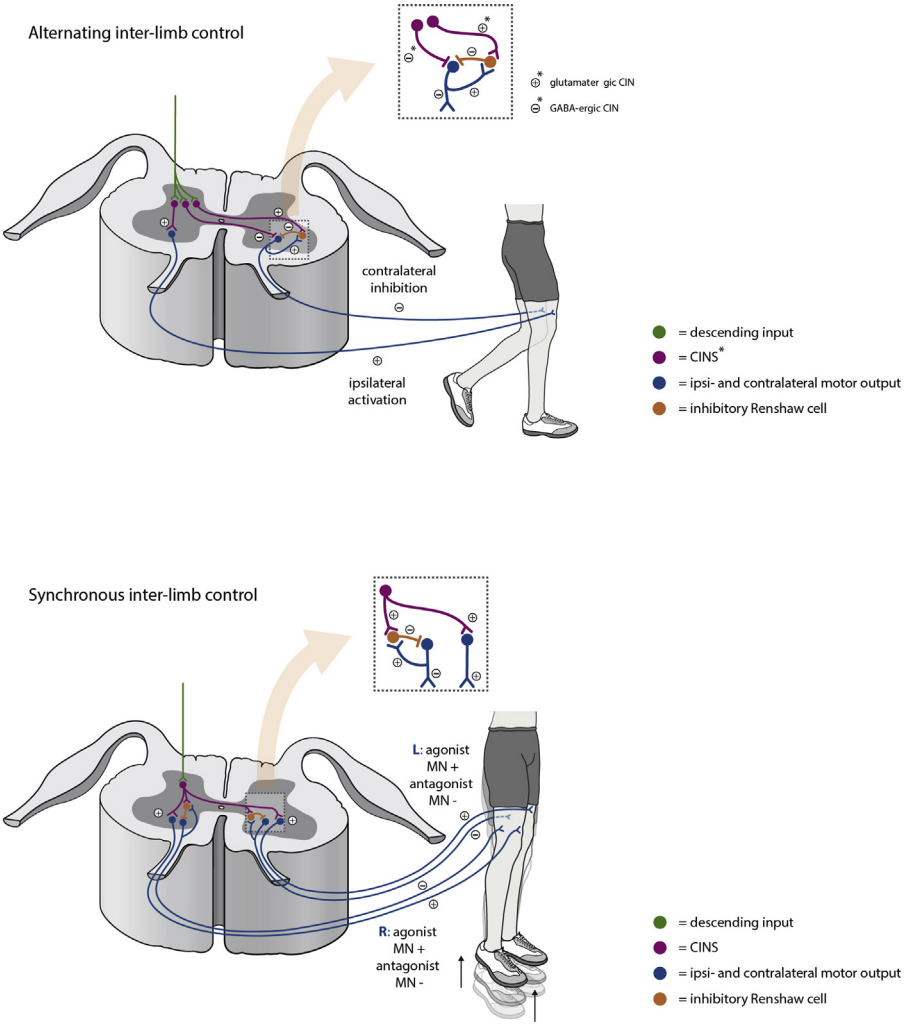

Figure 8 Alterations in afferent input when using a rollator which may influence CPG activity and motor output.

afferent influence on spinal networks can play an important role in functional reorganisation of motor output (Harkema, 2008). and that spinal and cortical plasticity is influenced by the pattern of sensory afferent feedback (Knikou, 2010).

Conclusions

These aspects of neural control and recovery should be considered during the prescription of walking-aids. It may be that assistive walking devices should allow normal joint loading, have minimal effect on muscle activity and length during walking and not require the use of hands. Some orthoses are known to fulfil these criteria (Maguire et al., 2010). These factors may enable afferent input typical of healthy gait. Normal sensory input may facilitate optimal CPG activity and therefore motor output. This may positively impact spinal plasticity and functional recovery. As walking aids are often used for long periods during the day, meaning high repetition, the influence on plasticity may be significant. Clinical research is needed to investigate these hypotheses.

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