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ORIGINAL ARTICLE

Interlimb Coordination During the Stance Phase of Gait in Subjects With Stroke

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Abstract

Objective: To analyze the relation between contralesional and ipsilesional limbs in subjects with stroke during step-to-step transition of walking.

Design: Observational, transversal, analytical study with a convenience sample.

Setting: Physical medicine and rehabilitation clinic.

Participants: Subjects (n=16) with poststroke hemiparesis with the ability to walk independently and healthy controls (n=22).

Interventions: Not applicable.

Main Outcome Measures: Bilateral lower limbs electromyographic activity of the soleus (SOL), gastrocnemius medialis, tibialis anterior, biceps femoris, rectus femoris, and vastus medialis (VM) muscles and the ground reaction force were analyzed during double-support and terminal stance phases of gait.

Results: The propulsive impulse of the contralesional trailing limb was negatively correlated with the braking impulse of the leading limb during double support ($r=-.639$, $P=.01$). A moderate functional relation was observed between thigh muscles ($r=-.529$, $P=.035$), and a strong and moderate dysfunctional relation was found between the plantar flexors of the ipsilesional limb and the vastus medialis of the contralesional limb, respectively (SOL-VM, $r=-.80$, $P<.001$; gastrocnemius medialis-VM, $r=-.655$, $P=.002$). Also, a functional moderate negative correlation was found between the SOL and rectus femoris muscles of the ipsilesional limb during terminal stance and between the SOL ($r=-.506$, $P=.046$) and VM ($r=-.518$, $P=.04$) muscles of the contralesional limb during loading response, respectively. The trailing limb relative impulse contribution of the contralesional limb was lower than the ipsilesional limb of subjects with stroke ($P=.02$) and lower than the relative impulse contribution of the healthy limb ($P=.008$) during double support.

Conclusions: The findings obtained suggest that the lower performance of the contralesional limb in forward propulsion during gait is related not only to contralateral supraspinal damage but also to a dysfunctional influence of the ipsilesional limb.

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Gait disorders affect a large proportion of subjects with stroke, limiting their ability to ambulate in the community.[1] The features of poststroke walking vary according to stroke severity, location of infarct, time since stroke, type of rehabilitation received, and other individual differences.[2] Also, the mechanical energy cost per stride and metabolic energy expenditure[3] are typically higher in subjects with stroke than healthy subjects.

Biomechanical models have shown the importance of interlimb relations during the double-support phase in unimpaired gait energy consumption.[4] The transition from one stance limb inverted pendulum to the next appears to be a major determinant of the mechanical work of walking.[4,5] An optimal mechanical relation between human limbs, described as the trailing limb plantar flexor action,[6,7] compensates the energy loss provoked by the leading limb during heel strike[5,8] to maintain the velocity of the body's

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center of mass. Recent studies involving healthy subjects have demonstrated that the degree of plantar flexor activity during propulsion depends on the degree of muscle activity[9] and the magnitude of the ground reaction force[10] of the contralateral limb during heel strike. This interlimb relation observed during step-to-step transition of unimpaired walking,[9,10] and also in standing-related tasks,[11,12] can be justified by the bilateral influence of group II fibers on spinal interneurons[13] and the importance of vestibulo- and reticulospinal pathways on group II fibers.[14]

After a unilateral stroke, interlimb coordination is often impaired[15-17] as a result of the primary brain lesion itself and/or adaptive changes.[18-21] Although studies about interlimb relations have been dedicated to the evaluation of upper limbs, neurophysiological and neuroanatomic findings indicate that the interlimb coordination of lower limbs can be impaired, particularly when there are subcortical injuries in the territory of the middle cerebral artery, such as in the internal capsule.[22,23]

Subjects with stroke present low kinetic energy[24,25] and an inadequate propulsion of the contralateral limb to the affected hemisphere (contralesional limb) during preswing[26] as a result of low plantar flexor strength and power.[2,27] The major metabolic cost has been associated with the mechanical work done by the ipsilesional limb, mainly to lift the center of mass.[28] However, in spite of often being described as a compensatory limb that adapts to changes in the paretic limb,[29] changes observed in the ipsilesional limb have also been attributed to a possible dysfunction of ipsilateral distributed pathways responsible for postural control.[29-33] This could help us to understand why stroke subjects present lower performance of the contralesional limb when cyclic and antiphase ankle movements are executed with both limbs.[34,35] In fact, these findings suggest that the ipsilesional limb may lead to performance changes in the contralesional limb and reinforce the idea that step-to-step transition during gait could be highly demanding in terms of energy consumption in stroke subjects because of their need to coordinate contralesional and ipsilesional limbs.

The main purpose of this study was to analyze the relation between ipsilesional and contralesional limbs during gait step-to-step transition in terms of individual muscle activity and global kinetic values in subjects with stroke. Taking into account the changes observed in both contralesional[26,27] and ipsilesional[30] limbs during gait, a dysfunctional interlimb relation was hypothesized compared with interlimb relation patterns observed in healthy subjects.[9] Specifically, a higher dysfunctional relation would be expected between the ipsilesional heel strike limb and the contralesional propulsion limb. This hypothesis is based on the role of the ipsilateral and contralateral pathways because the former is more related to postural control, highlighted in the moment of touchdown, and the latter is more associated with movement control, highlighted during propulsion.[22]

To our knowledge, no previous study has evaluated the interlimb relation during an asymmetric task, implying a supportive role for the 2 limbs in subjects with stroke. Whereas correlation analyses have revealed that some electromyographic abnormalities, such as spasticity,[36] altered cocontraction,[37] and muscle paresis,[29] are higher in subjects with severe stroke, a cause-effect relation of some of these abnormalities with poor locomotor performance[3] remains difficult to establish. The study of interlimb relations during step-to-step transition in subjects with stroke can give significant insights to improve our understanding of the low performance of stroke gait, considering the importance of step-to-step transition performance in global gait efficiency. Restoring gait is one of the major goals in stroke rehabilitation; therefore, understanding the interlimb relation is extremely beneficial for designing effective locomotor interventions.

List of abbreviations:

BF	**biceps femoris**
GM	**gastrocnemius medialis**
RF	**rectus femoris**
SOL	**soleus**
TA	**tibialis anterior**
VM	**vastus medialis**

Methods

Participants

Sixteen (8 women, 8 men) patients who had suffered a stroke at least 6 months earlier and 22 healthy subjects (12 women, 10 men) participated in this study (table 1). For the subjects with stroke, the mean time ± SD between their stroke and the time of inclusion was 26±9 months. All subjects suffered an ischemic stroke: 11 of them had suffered an infarction in their left hemisphere, whereas 5 had suffered an infarction in their right hemisphere. To be included, patients were required to (1) have suffered an ischemic first-ever stroke involving the territory of the middle cerebral artery, as revealed by computed tomography, resulting in hemiparesis; (2) have a Fugl-Meyer Assessment of Sensorimotor Recovery After Stroke scale score in the motor subsection <34; (3) have the ability to walk 10m, with close supervision if necessary, but without physical assistance, as judged by the treating physiotherapist; and (4) have provided written or verbal informed consent. Patients were excluded for one of the following reasons: (1) cognitive deficit that could hinder communication and cooperation (assessed by the Mini-Mental State Examination); (2) history of orthopedic or neurologic (other than stroke) disorders known to affect walking performance; (3) history of stroke involving the brainstem or cerebellar areas; and (4) taking medication that could affect motor performance. Given the possibility of spastic hypertonus, an experienced neurologic physical therapist (A.F.S.) assessed all subjects by testing limb resistance to passive movement; considering the definition of spastic hypertonus, all subjects included in the study were considered as not having spastic hypertonus in the lower extremity. Gait data of the group of subjects with stroke were compared with data obtained from the 22 healthy control subjects. All control group subjects were sedentary and were selected according to the same exclusion criteria applied to the stroke group and were also excluded if they

Table 1 Mean ± SD values of age, height, and weight of the healthy and stroke groups and the average values of the self-selected walking speeds adopted by each group

Variables	Stroke Group	Control Group	*P*
Age (y)	53.87±7.17	49.24±7.69	.070
Height (m)	1.65±0.10	1.66±0.09	.942
Body weight (kg)	75.29±7.03	67.40±8.76	.006
Self-selected gait speed ($m \cdot s^{-1}$)	0.57±0.13	1.00±0.03	<.001

NOTE. Values are mean ± SD or as otherwise indicated.

had suffered any neurologic disorder. The study was approved by the local ethics committee and implemented according to the Declaration of Helsinki.

Instrumentation

The values of the vertical, anteroposterior, and mediolateral components of the ground reaction force were acquired using 2 forceplates at a sampling rate of 1000Hz (FP4060-10 and FP4060-08 models[a] connected to an AM 6300 amplifier[a] and to a 16-bit analogical-digital converter[b]). The 2 forceplates were mounted in series near the midpoint of the walkway.

The activity of the agonist muscles for propulsion (gastrocnemius medialis [GM], soleus [SOL], rectus femoris [RF][38]) and initial contact and loading response (tibialis anterior [TA], vastus medialis [VM], biceps femoris [BF][38,39]) were assessed through electromyography. The bilateral electromyographic signal of these muscles was monitored using a bioPLUX research wireless signal acquisition system.[c] The signals were collected at a sampling frequency of 1000Hz and were preamplified in each electrode and then fed into a differential amplifier with an adjustable gain setting (25−500Hz; common-mode rejection ratio: 110dB at 50Hz, input impedance of 100MΩ and gain of 1000). Self-adhesive silver chloride electromyographic electrodes were used in a bipolar configuration with a distance of 20mm between detection surface centers. The skin impedance was measured with an Electrode Impedance Checker.[d] The electromyography and force platform signals were analyzed with the Acqknowledge software.[b] The gait timing was measured using a photovoltaic system.[e] All subjects used the same shoe type, in their adequate size.

Procedures

Skin preparation and placement of electrodes

The skin surface of selected muscles of the midbelly and patella was prepared (shaved and then the dead skin cells and nonconductor elements were removed with alcohol and with an abrasive pad) to reduce the electrical resistance to <5000Ω, the electromyographic electrodes were placed according to anatomic references, and the reference electrode was placed on the patella.

Data acquisition: kinetic and electromyographic data

The electromyography and ground reaction force data were simultaneously acquired during walking. Subjects walked using standard footwear over a 10-m walkway,[40] without using any assistive devices and/or orthotics.

Before the data acquisition, sufficient time was given so that the participants became familiar with the experimental settings. They were allowed to walk over the walkway without explicit instructions. Meanwhile, we observed the starting point on the walkway from which they placed one foot on the proximal forceplate (trailing limb) and the other on the distal forceplate (leading limb) according to their natural cadence. To ensure a low intragroup gait variability[41-44] and a similar rate of energy expenditure[3] and muscle use ratios or levels of effort[45,46] between the 2 groups, the subjects walked at their self-selected speeds. Three successful trials, where the feet had full contact with the plate, were used for analysis for all subjects to reduce the within-individual variability and increase statistical power.[47] One-minute breaks were provided between trials.

Data processing: kinetic parameters

The ground reaction force data were low-pass filtered using a fourth-order Butterworth filter using a zero-phase lag with a cutoff frequency of 8Hz[48] and normalized according to body weight. In spite of occurring mainly during the double-support phase, biomechanical models suggest that energy loss during step-to-step transition can be reduced by a propulsion impulse from the trailing limb immediately before collision of the leading limb.[5] Also, studies about interlimb relations in healthy subjects demonstrate a relation between muscle activity of the trailing limb during terminal stance and biomechanical parameters of the leading limb during initial contact and loading response.[9,10] Thus, the stance phase was separated into 3 intervals (fig 1) to analyze the impulse generation at various time points in the gait cycle: (1) double-support phase corresponding to the initial contact and loading response of the contralesional limb until the start of the ipsilesional limb swing, (2) terminal stance of the contralesional and ipsilesional limbs, and (3) double-support phase corresponding to initial contact and loading response of the ipsilesional limb until the start of the contralesional limb swing. Globally, each limb was evaluated during terminal stance, preswing, and loading response. The stance phase was defined as the interval where the vertical component presents a value ≥7% of body weight,[41] the double-support phase corresponds to the time between the initiation of the leading limb stance phase and the initiation of the trailing limb swing phase, and the terminal stance was defined as the time between where the anteroposterior component assumes the value of zero and the beginning of the second double-support phase (see fig 1). Variables derived from the anteroposterior component were time integrated to assess the braking (negative anteroposterior component) and propulsive (positive anteroposterior component) impulses during each interval. The percentage of the propulsion impulse (%PI) generated by the trailing limb during the double-support phase in relation with the leading limb braking impulse was calculated according to the following equation[49]:

$$\%PI = \frac{\int Fy_{trail}}{\int Fy_{trail} + \int Fy_{lead}} \times 100,$$

where $\int Fy_{trail}$ is the integral of the anteroposterior component of the trailing limb during the double-support phase, and $\int Fy_{lead}$ is the integral of the anteroposterior component of the leading limb during the double-support phase. The percentage of propulsive contribution provides a quantitative measure of the coordinated output of each leg for forward propulsion during the double-support phase of walking.[49]

Data processing: electromyographic activity

The electromyography of both limb muscles was analyzed during the intervals selected to evaluate the propulsive and braking impulse (see fig 1). The electromyographic signals were filtered using a zero-lag, second-order Butterworth filter with an effective band pass of 20 to 450Hz, and the root mean square was calculated for each interval. The electromyographic values obtained at each interval were normalized to the mean signal for each muscle over the entire gait cycle.[50] Only the electromyographic activity of the stroke subjects was analyzed because the interlimb relation in terms of electromyographic activity was analyzed in our previous study.[9]

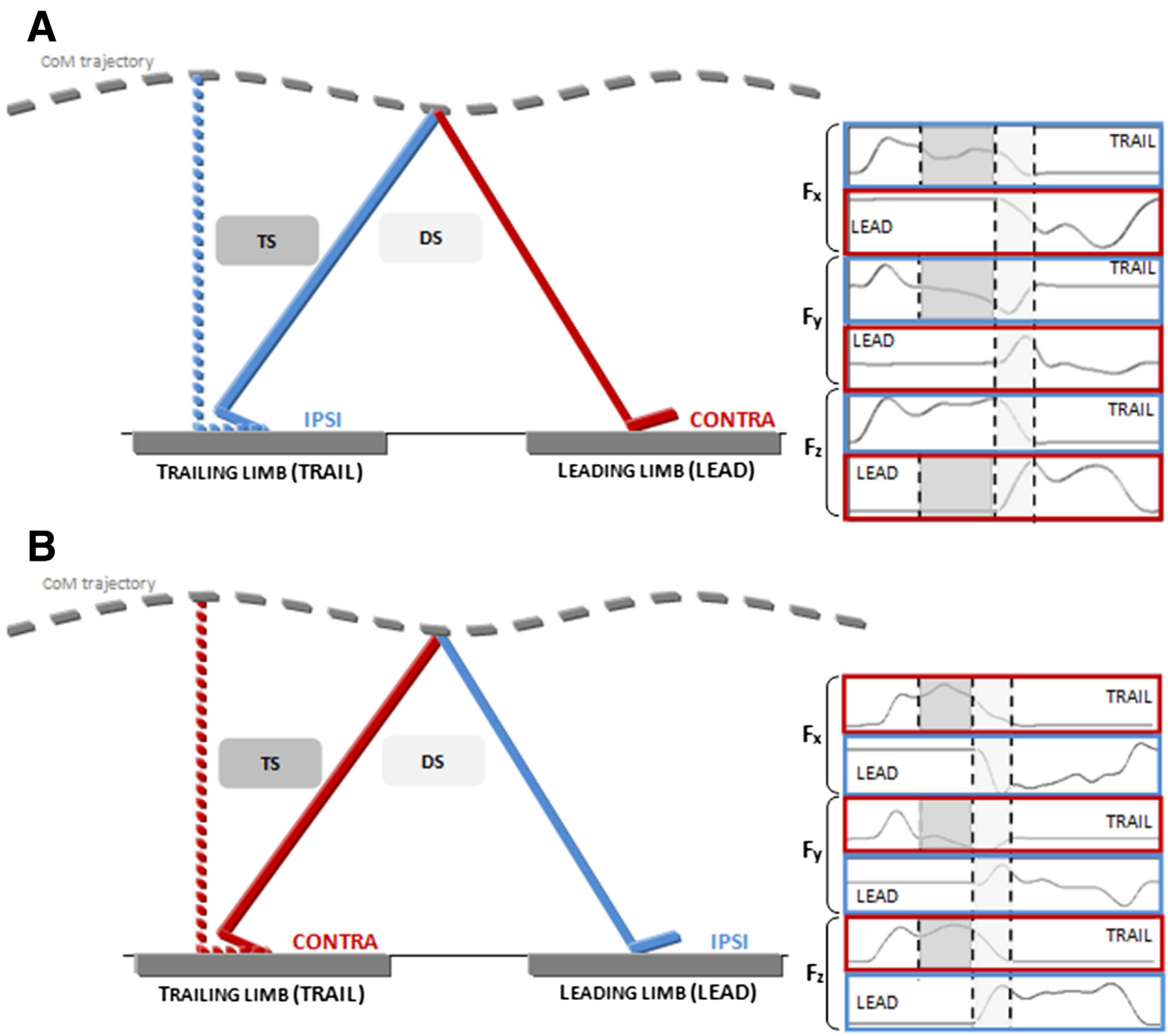

Fig 1 Intervals used to assess the interlimb relation during the stance phase of walking in stroke subjects were defined using the variation of the ground reaction force. The intervals are shown for each series: when the ipsilesional limb was the trailing limb and the contralesional limb was the leading limb (A) and when the ipsilesional limb was the leading limb and the contralesional limb was the trailing limb (B). Abbreviations: CoM, center of mass; CONTRA, contralesional limb; DS, double-support phase; F_x, mediolateral component; F_y, anteroposterior component; F_z, vertical component; IPSI, ipsilesional limb; LEAD, leading limb; TRAIL, trailing limb; TS, terminal stance.

Data analysis

The acquired data were analyzed using SPSS software.[f] Spearman and Pearson correlation coefficient tests were used to assess the relation between contralesional and ipsilesional limbs in terms of electromyography and propulsive/braking impulse, respectively. As previously mentioned, in healthy subjects, the interlimb relation was analyzed only in terms of propulsive/braking impulse. The paired-samples *t* test was used to compare the propulsive and braking impulse levels and the relative propulsive contribution between contralesional and ipsilesional limbs. To compare the propulsive impulse level between limbs of subjects with stroke and between stroke and control groups in the 3 stance subphases, the Bonferroni correction was used to reduce type I error. Statistical significance was set at $P<.05$.

Results

Interlimb relation: electromyographic activity

Figure 2 shows that during the double-support phase the higher values of the ipsilesional GM, SOL, and BF muscle activity at initial contact and loading response are associated with lower values of the contralesional VM muscle activity during preswing, whereas during the terminal stance higher values of ipsilesional SOL and RF muscle activity are associated with lower values of contralesional SOL and VM muscle activity at initial contact and loading response. The higher the contralesional VM muscle activity during preswing, the higher the RF ($r=.514$, $P=.05$) and GM muscle activity ($r=.539$, $P=.038$) for the same limb.

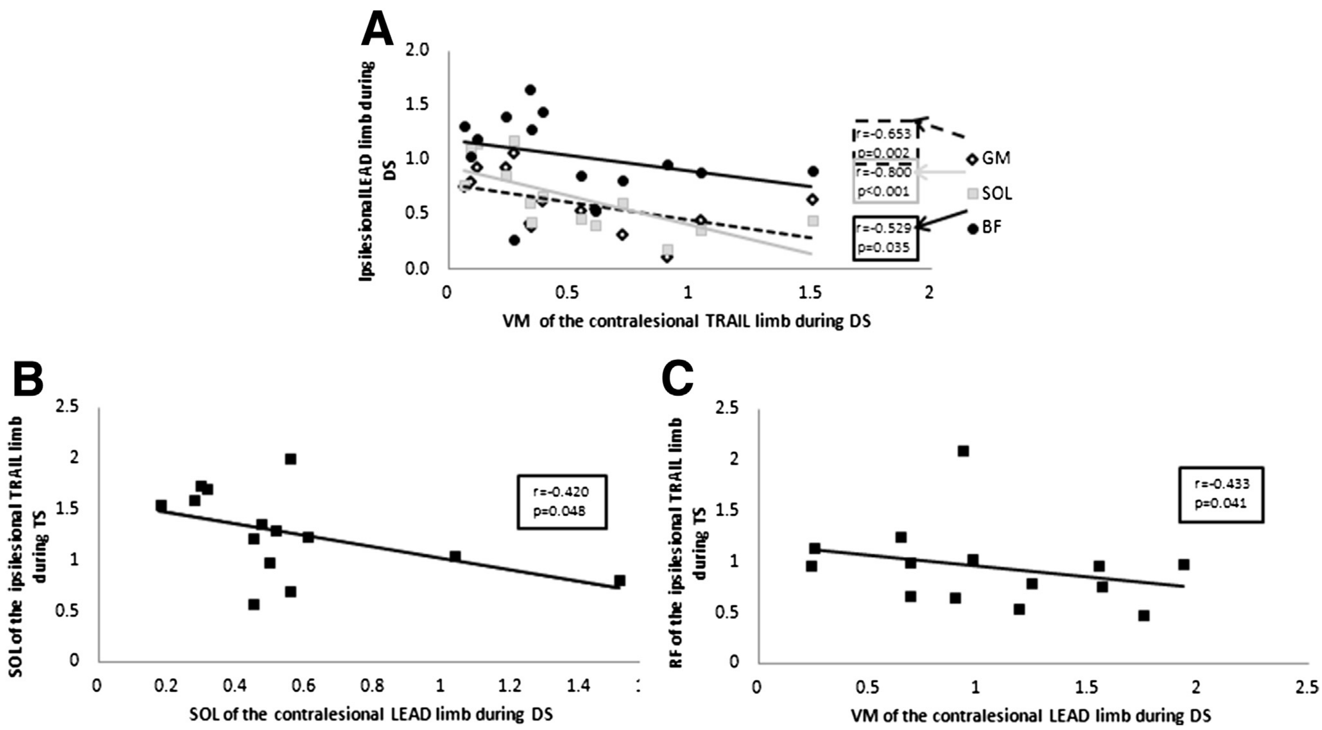

Fig 2 Representation of statistically significant correlations between limbs found in the stroke group. Statistically significant correlations occurred in electromyographic activity between the paretic trailing limb and the nonparetic leading limb during the double-support phase (A) and between the nonparetic trailing limb during terminal stance and the paretic leading limb during the double-support phase (B) and (C). Abbreviations: DS, double-support phase; LEAD, leading limb; TRAIL, trailing limb; TS, terminal stance (significant value, $P<.05$).

Interlimb relation: propulsive and braking impulse

Lower values of propulsive impulse and relative propulsive contribution were found in the contralesional limb of the stroke group during preswing, as shown in figures 3 and 4, respectively. In the control group there were statistically significant correlations between the propulsive impulse of the trailing limb and the braking impulse of the leading limb during the double-support phase ($r=-.568$, $P=.004$); however, in the stroke group, only the braking impulse of the ipsilesional leading limb was related to the propulsive impulse of the contralesional trailing limb during the double-support phase ($r=-.639$, $P=.01$).

Discussion

Healthy and stroke groups adopted different walking speeds because they were asked to walk at their own comfortable speed. The adoption of a low self-selected speed has been shown to provide stroke subjects with a rate of energy expenditure[3] and muscle use ratios or levels of effort[45,46,51] that are similar to those of healthy subjects walking at their comfortable speeds. In this sense, it can be argued that the differences observed in self-selected speed did not interfere with the results.

Each limb has been shown to affect the strength of muscle activation and time-space behavior of the other.[9,52] The results demonstrate that in subjects with stroke, the electromyography and impulse levels of the trailing limb were related to the ones of the leading limb during the double-support phase, but only when the leading limb was the ipsilesional limb and the trailing limb was the contralesional limb. The higher levels of ipsilesional BF muscle activity were associated with lower levels of contralesional VM muscle activity, which despite not developing an important role in this subphase is positively correlated with the level of activity of the GM muscle, which contributes to swing initiation,[53] and the RF muscle, which accelerates the trunk forward.[38,39] Taking into account that the BF muscle action has been related to impact reduction during initial contact and loading response,[40,54,55] the inverted indirect relation established with the GM and RF muscle activity during preswing is consistent with the inverted correlation observed between the ipsilesional braking impulse and the contralesional propulsive impulse. Based on the step-to-step transition model prediction[5] that the trailing limb propulsion compensates the energy loss of the leading limb during initial contact and loading response, these results seem to demonstrate that the ipsilesional limb improves the coordination deficits of the contralesional limb during the double-support phase. This is probably because all appropriate ipsilesional sensorimotor information can be integrated by the nervous system and contributes to a more appropriate pattern in the contralesional limb. However, the SOL muscle activity increases the horizontal energy of the trunk much more than the GM muscle, especially in the late stance,[53,56] and no influence was exerted by this muscle in the ipsilesional limb.

Moreover, an inverted strong/moderate correlation was also observed between ipsilesional SOL and GM muscle activity during initial contact and loading response and contralesional VM activity during preswing. Considering that the SOL and GM antagonists have agonist roles in impact reduction,[57] it would be expected, according to the reciprocal inhibition mechanism, that higher SOL and GM values would be associated with higher VM levels. This nonfunctional interlimb relation could be the result of

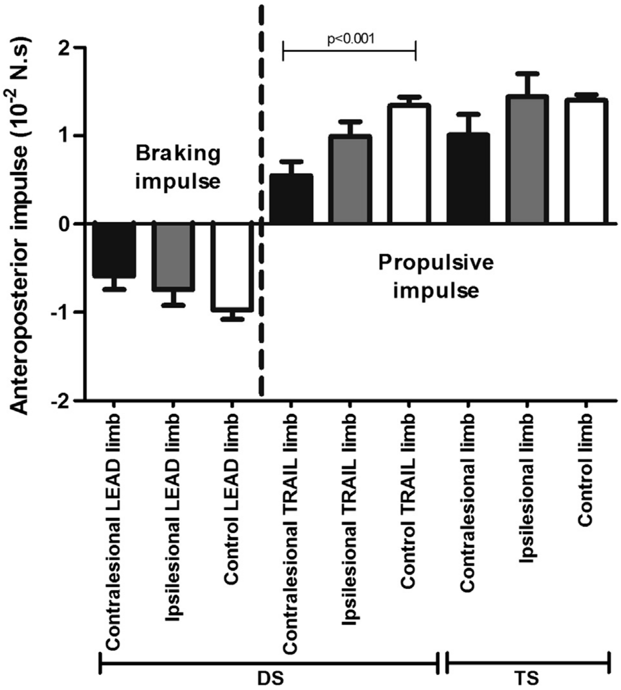

Fig 3 Mean (bars) ± SD (error bars) of propulsive and braking impulse observed in paretic and nonparetic limbs of subjects with stroke and healthy controls during the double-support phase and terminal stance. Abbreviations: DS, double-support phase; LEAD, leading limb; TRAIL, trailing limb; TS, terminal stance (significant values, $P<.05$).

excessive coactivation values of plantar flexor and dorsiflexor muscles of the ipsilesional limb,[29] as a consequence of ipsilaterally mediated effects from the neurologic lesion[30,43] and/or an adaptation for poor stability during gait.[37] However, no differences were observed in the ankle muscle coactivation between the ipsilesional limb of subjects with stroke and control subjects (Sousa, "Biomechanical analysis of human movement and postural control based on multifactorial correlation and clinical implications"; unpublished data; 2013). Another explanation could be related to recent evidence indicating that the spinal group II excitation from ankle dorsiflexors to knee extensors is particularly enhanced during poststroke in initial stance walking.[58]

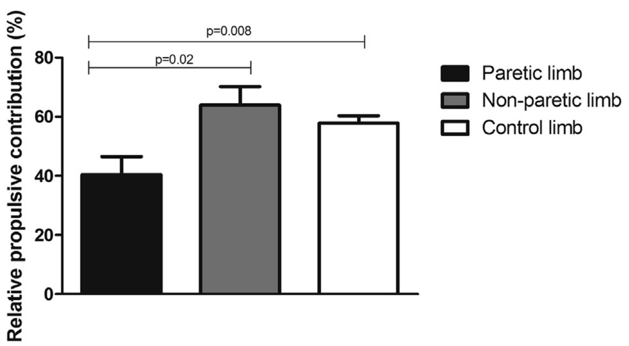

Fig 4 Mean (bars) ± SD (error bars) values of the percentage of trailing limb propulsive contribution of the paretic and nonparetic limbs of subjects with stroke and of trailing limb propulsion contribution in healthy controls during the double-support phase (significant values, $P<.05$).

Considering that most midlumbar interneuron recipients from the group II input are influenced by afferent fibers from both ipsilateral and contralateral sides,[13] a relation between ankle dorsiflexors during initial contact and loading response and contralateral knee extensors during preswing could be expected. However, the results did not support this relation.

The contralesional limb muscle activity during initial contact and loading response was also correlated with the ipsilesional limb muscle activity during the terminal stance. Considering that the terminal stance precedes initial contact, the results seem to indicate that higher levels of the ipsilesional limb SOL muscle could potentiate the activity of the contralesional limb TA muscle during loading response through a decrease of SOL muscle activity. This influence is close to the interlimb relation observed in healthy subjects.[9]

When comparing the electromyography results obtained with the results obtained in healthy subjects from a global point of view,[9] it is evident that the TA, BF, and VM muscles in the healthy subjects have an important role in contralateral limb activity, whereas the ipsilesional SOL muscle in the stroke subjects has consistently more influence over the contralesional limb. Besides that, the TA muscle did not have any role in interlimb relation in stroke subjects. The lack of influence that the ipsilesional limb has over the contralesional TA muscle activity can be explained by the fact that this muscle depends more strongly on motor cortex input,[59,60] which can be influenced by lesions in the internal capsule via corticospinal tract affections. The role of the SOL muscle in mediating the interlimb relation in stroke subjects can be justified by its higher dependence on sensory input in relation with supraspinal control.[61,62] However, results also demonstrated that the functional influence of the ipsilesional SOL muscle over the contralesional limb depends on its role in the task. When this muscle acts as an agonist for movement (during terminal stance it promotes forward progression of the trunk[53]), it exerts an influence over the contralesional homolog muscle, similar to the healthy subjects.[9] However, when its activity is more related with postural control, such as during loading response, it exerts a biomechanically disadvantageous influence over the contralesional limb, considering the double-inverted pendulum model and the interlimb relation observed in healthy subjects.[9] These findings support the argument for the dysfunction of the ventral-medial system over the ipsilesional limb, also hypothesized in other studies[30-32] as one of the causes for impaired interlimb relation in stroke subjects. This hypothesis assumes special relevance considering that the stroke participants in this study present lesions in the internal capsule, which can be associated with dysfunction of the corticoreticular pathway,[63] responsible for ipsilateral postural control.

According to Bowden et al,[49] the propulsive impulse provides a quantitative measure of the coordinated output of both lower limbs in stroke patients. The relative propulsive impulse of the contralesional limb was lower than that observed in the control group (∼40%), which means that the ipsilesional limb energy loss during initial contact and loading response probably may not be compensated by propulsion of the contralesional limb.[5,7] The contralesional limb of stroke subjects has been shown to produce significantly less mechanical work output than that of healthy subjects.[64] The relative propulsive impulse of the ipsilesional limb exceeds the braking impulse (∼60%) of the contralesional limb during initial contact and loading response and probably accelerates the center of mass.[5,7] In the control group, this propulsive impulse of the trailing limb was also >50%. In fact, it has been demonstrated that in healthy subjects the positive mechanical work of the trailing limb during the double-support phase exceeds the negative mechanical work performed by the leading limb.[9]

Study limitations

The relation between muscle activity and mechanical output depends on a number of nonlinear intrinsic properties, that is, on force-length-velocity relations that make the relation difficult to predict. Given this limitation, it would be important to analyze the relation of joint moment power between limbs during the double-support phase and between the propulsive and braking impulse of each limb. This knowledge would help in understanding the role of each muscle in both lower limbs of stroke subjects on gait mechanical output during step-to-step transition.

Conclusions

The results obtained in this study as to the propulsive impulse demonstrate that the contralesional limb presents lower performance in forward propulsion compared with the ipsilesional limb and the control group. Despite exerting an indirect functional influence over the activity of plantar flexors, the ipsilesional limb exerted a dysfunctional influence during initial contact and loading response over the contralesional limb during preswing. The influence of the ipsilesional limb over the contralesional limb was classified based on the interlimb relation observed in healthy subjects,[9] the double-inverted pendulum model,[5,7] and the role of individual muscles during the stance phases associated with step-to-step transition.[38,53] These findings suggest that the lower performance of the contralesional limb in forward propulsion is related not only to contralateral supraspinal damage but also to the influence of the ipsilesional limb in stance subphases of increased postural control demand.

The results here present arguments for considering an indirect impact of a postural control dysfunction of the ipsilesional limb on the performance and efficiency of gait in stroke subjects. Future work should be developed to explore this possibility because the lower performance and lower efficiency of gait in subjects with stroke have been attributed mainly to alterations in the contralesional limb.

Considering this, rehabilitation strategies should pay special attention to the ipsilesional limb to potentiate the contralesional limb activity in subjects with stroke affecting the subcortical structures in the territory of the medial cerebral artery, such as in the internal capsule. Specifically, the results obtained suggest that improving postural control of the ipsilesional limb could have positive effects over the interlimb relation during step-to-step transition and walking performance.

Suppliers

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Keywords

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