Bilateral Level of Effort of the Plantar Flexors, Hip Flexors, and Extensors During Gait in Hemiparetic and Healthy Individuals

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Background and Purpose—Muscle weakness is recognized as a key factor in gait performance of poststroke individuals, but its impact on lower-limb muscular effort has been scarcely studied. The aims of this study were to compare the level of effort of the lower limbs of hemiparetic and able-bodied individuals and to assess the effect of side, cadence, and muscle group.

Methods—Seventeen chronic hemiparetic participants (7 females and 10 males) with a mean age of 60.5 ± 13.4 years were assessed when walking. They were compared with a group of 14 able-bodied individuals. The level of effort was estimated from the muscular utilization ratio (MUR), which relates the walking moment of a given muscle group to its maximal potential moment. Peak MUR and MURarea were used as main outcome measures.

Results—Hemiparetic individuals showed greater peak MUR values (45% to 78%) than the able-bodied subjects matched for cadence (24% to 63%). For both groups, the peak MUR values were similar between sides and increased with cadence. At self-selected cadence, the plantar flexors showed greater peak MUR values, whereas at maximal cadence, levels of effort for all muscles were equivalent. The MURarea values at the hip joint were greater for the hemiparetic group, and both groups had values that increased with cadence. Differences between sides and muscle groups were noted for the hemiparetic and healthy individuals, respectively. Large peak MUR values were associated with high MURarea values.

Conclusions—For a similar cadence, the levels of effort of hemiparetic individuals were greater than those of the able-bodied. In the presence of muscle weakness, similar bilateral levels of effort could mean that hemiparetic individuals relied on their sense of effort while walking. (Stroke. 2006;37:2070-2075.)

Key Words: gait ■ rehabilitation ■ stroke

The ability to walk can be substantially modified after a stroke. In fact, 8% to 14% of hemiparetic individuals need assistance with walking, and 22% to 37% are confined to a wheelchair at discharge of the rehabilitation settings, making the understanding of gait deficits important for achieving rehabilitation goals. During gait, the generation of energy by the hip extensors, ankle plantar flexors, and hip flexors are important to maintain or increase the forward velocity of the body. After a stroke, because of the presence of weakness of the affected lower limb, reduced moments and powers produced by these specific muscles are acknowledged, and these changes are paralleled by a lower walking speed.

Although gait moment information is useful to the comprehension of hemiparetic gait, Nadeau et al made an important contribution to the utility of these moments by proposing the muscular utilization ratio (MUR) model, which yields a profile reflecting the percentage of muscle activation that produces the moment. The MUR accounts for the speed of contraction and muscle length during gait through the use of equations previously developed from maximum muscle contractions performed at a range of velocities on an isokinetic dynamometer. Because the MUR is an index expressed relative to the maximum capability of a group of muscles, it takes into consideration the difference in absolute maximal strength of muscle groups within and between individuals. It is thus possible to make comparisons between muscle groups (eg, right versus left) and various groups of individuals (eg, hemiparetic versus healthy). In addition, findings related to the sense of effort have revealed that subjective effort appears to be calibrated in terms of the maximal strength of an individual. In this context, the MUR could represent an objective indicator of the level of effort.

The maximal levels of effort (peak MUR) of affected lower-limb muscle groups have already been investigated during hemiparetic gait. At self-selected speed, peak MUR reached values of 64%, 46%, and 33% for the plantar flexors, hip flexors, and extensors, respectively. At maximal speed,
these values increased significantly, with the hip flexors showing the biggest gain. Assessment of peak MUR furnishes useful information about the maximal level of effort of a muscle group, but it represents a single value and does not give an overview of the use of a muscle throughout its action. Calculation of the area under the curve of the MUR profile (MURrea) of various muscle groups could provide a more complete view of the level of effort during gait. Moreover, MURrea could help further the understanding of hemiparetic gait deviations and compensatory strategies. Knowing that stroke can affect, to a lesser extent, the limb ipsilateral to the brain lesion, it would be relevant to evaluate peak MUR and MURrea of the affected and unaffected plantar flexors, hip flexors, and extensors during their concentric action at self-selected and maximal gait cadences. This study aimed to determine bilaterally the lower-limb levels of effort of hemiparetic individuals while walking and to assess the influences of side, cadence, and muscle groups on these levels of effort. Values of healthy adults walking at matched cadences were used for comparison.

Methodology

Participants

Hemiparetic participants were included in the study if they had a chronic (6 months or more) unilateral stroke, could walk 10 meters independently with or without a cane, presented residual weakness of the affected lower limb, and had a minimal activity tolerance of 2 hours with rest. Any participant presenting with comprehensive aphasia, incontinence, an unstable medical condition, history of injury, and anesthesia of the lower limbs was excluded. Also, 14 healthy participants, evaluated from a previous study on level of effort, were included for comparison. Informed consent was obtained before the evaluation session, and the ethics board approved the study.

Clinical Evaluation

Demographic data for all participants were gathered by a physical therapist. In addition, for the hemiparetic group, lower-limb physical impairment was assessed with the lower-extremity component (leg and foot) of the Chedoke-McMaster Stroke Assessment, and spasticity at the ankle was measured by the Composite Spasticity Index. The perception threshold of touch-pressure was evaluated with calibrated Simmes-Weinstein filaments, and balance was assessed with the Berg Balance Scale. The self-selected and maximal clinical gait speeds were quantified by means of the 5-m walking test.

Calculation of MUR

The MUR is a ratio between the walking moment produced by a muscle group during gait at a given time and its maximal potential moment. The ratio is then multiplied by 100 to give a percentage. A biomechanical analysis of gait allows the walking moment (numerator) to be calculated while the denominator is estimated from a regression equation. The regression equation is derived from velocity, torque, and joint angle data arising from the performance of maximum isokinetic contractions of each muscle group at various dynamometer velocities. Thus, for a given side, 3 equations (1 for each muscle group) were computed for each participant. By entering the angles and the velocities found during the gait cycle into the equation, the denominator of the MUR can be estimated (for more details, see Nadeau et al7 and Requiao et al11). In the present study, 2 indices of effort were derived from calculations based on the MUR data: peak MUR, corresponding to the maximal value of the MUR curve, and MURrea, representing the area under the curve of the MUR. These indices, expressed as a percentage and as a percentage×seconds, were obtained bilaterally for the plantar flexors, hip flexors, and extensors during their concentric action in gait (energy generation phase). The duration (in seconds) of the energy generation phase was also quantified to better interpret the MURrea value.

Gait Assessment and Determination of the MUR Numerator

Gait parameters were collected during 5 gait cycles at self-selected and maximal speeds for the hemiparetic group and at 4 cadences for the healthy group (60, 80, self-selected, and 120 steps/min). These cadences were chosen so that they would cover the range of cadences of stroke participants for later matching. Kinematic (angles) and kinetic (ground reaction forces) data were used to estimate the net moments (MUR numerator) at the ankle and hip joints with an inverse dynamic approach. The concentric action (energy generation) of the muscles was identified when the angular velocity multiplied by the local net moment at the ankle and hip joints presented the same polarity (for more details, see Milot et al9). Three main phases of energy generation, conventionally named A2 for the plantar flexors, H1 for the hip extensors, and H3 for the hip flexors, were retained. The beginning and end of these 3 phases as well as their duration in seconds were analyzed. The 3 trials showing the most similar values of speed and cadence were averaged and then used for the calculation of the MUR numerator.

Strength Assessment and Determination of the MUR Denominator

The maximal voluntary concentric strength in plantar flexion, hip flexion, and extension was measured with a Biodex dynamometer (Biodex Medical Systems) bilaterally for both groups. For the ankle, the range of motion was set at maximal dorsiflexion and plantar flexion for each participant. Participants were then asked to contract as hard and as fast as possible in plantar flexion at velocities of 30° and 180°/s until the apparatus stopped. A maximal isotonic contraction with a constant low torque was also performed to reach higher velocities of movement. For the hip, the range of motion was set at a minimum of 45° of flexion to maximal extension. Participants performed maximal concentric movements in extension and flexion at velocities of 30°, 90°, and 120°/s for the hemiparetic participants and 30°, 90°, and 180°/s for the able-bodied. For each testing condition, 2 trials were performed for each muscle group, and the trial showing the highest torque value was retained. Data were corrected for the gravity effect at each angle. A detailed description of the strength assessment has been presented in a previous article.9 From the strength data collected at various angles and velocities, a regression equation was derived bilaterally for each muscle group and each participant. These equations allowed the MUR denominator to be determined.
Statistical Analysis

Descriptive statistics (mean and SD) were calculated for the demographic and anthropometric data. Differences in cadence and speed parameters between self-selected and maximal gait speeds were compared with paired t tests. A 3-way repeated-measures ANOVA with a “group of subjects” between factor compared the main effects of muscle group, cadence, and side on peak MUR and MUR\textsubscript{area} values. A 2-way repeated-measures ANOVA with a “group of subjects” between factor compared the main effects of cadence and side on the duration of the energy generation phase for each muscle. For any significant ANOVA ($P<0.05$), a planned contrast with adjusted probability values was performed to locate the difference. The degree of the relation between peak MUR and MUR\textsubscript{area} was examined with Pearson product-moment correlation coefficients. Last, a paired t test was used to assess the difference in muscle strength between sides. From the 30°/s torque-angle curves, strength values were extracted at the first angle reached by all participants. These angles were 7° of dorsiflexion, 0° (hip in neutral position), and 40° of hip flexion for the plantar flexors, hip flexors, and hip extensors, respectively.

Results

Participants

For the hemiparetic individuals, a convenience sample of 17 participants (7 females, 10 males) met the inclusion criteria of the study. Their mean age, height, body mass, and time since stroke were 60.5 ± 13.4 years, 167.4 ± 8.8 cm, 75.7 ± 9.5 kg, and 77.6 ± 106.2 months, respectively. Six had right hemiparesis of the lower limb and 11 had left hemiparesis. No participants used a cane or wore an orthosis during gait assessment. The 14 healthy participants (7 females, 7 males) included for comparison had a mean age, height, and mass of 46.2 ± 13.3 years, 170 ± 0.1 cm, and 72.0 ± 14.9 kg, respectively.

Clinical Evaluation

The Chedoke-McMaster Stroke Assessment displayed a mean score of 5.47 for the leg and 4.87 for the foot. The Composite Spasticity Index revealed mild spasticity at the ankle, with a mean score of 5.5/6. One hemiparetic participant had hypoesthesia of the foot. The Berg Balance Scale evaluation revealed a mean score of 52.4/56, and the clinical self-selected and speed parameters between self-selected and maximal gait speeds were 0.39 m/s and cadences (85.6 ± 11.7 versus 118.8 ± 18.5 steps/min; $P<0.001$). When healthy participants walking at imposed cadences were observed, it was found that the 80 and 120 steps/min cadences best matched the self-selected and maximal gait cadences of hemiparetic participants, respectively (86 versus 84 steps/min and 119 versus 115 steps/min).

Predictive Equation and Estimation of MUR Values

The predictive equation computed from the dynamometric assessment had coefficients of determination ranging from 0.79 to 0.99, 0.65 to 0.99, and 0.88 to 0.99 for the affected plantar flexors, hip flexors, and hip extensors, respectively. The corresponding values for the unaffected side were 0.89 to 0.99, 0.69 to 0.99, and 0.87 to 0.99. For the healthy participants, the coefficients of determination for both sides ranged from 0.84 to 0.99, 0.67 to 0.99, and 0.84 to 0.99 for the plantar flexors, hip flexors, and extensors, respectively. Overall, the coefficient of determination showed an adequate fit of the torque curves, suggesting an appropriate estimation of the MUR denominator.

Peak MUR

For all muscles tested, the hemiparetic participants presented with greater peak MUR values on both sides than the able-bodied controls matched for cadence (between-group $P=0.004$). Also, for both groups, no side difference was noted, and the peak MUR of all muscle groups increased significantly with cadence ($P<0.001$). However, the changes in peak MUR with cadence were not similar between all muscle groups (muscle×cadence interaction, $P<0.001$). The hip muscles showed the largest increment with gait cadence (the Figure).

In addition, whatever the side and group of participants, the plantar flexors were the most-used muscle group ($P<0.001$) at self-selected cadence (80 steps/min for healthy participants), whereas no significant difference in the peak MUR was found between the hip flexors and extensors (hemiparetic $P=0.211$; healthy $P=0.141$). At maximal cadence (120 steps/min for healthy participants), the peak MUR values became equivalent between muscles for both groups of participants (the Figure).

MUR\textsubscript{area}

As with the peak MUR, the MUR\textsubscript{area} values for the hemiparetic participants were greater than those for the healthy individuals (between-group $P=0.004$). However, an exception was found for the MUR\textsubscript{area} of plantar flexors, which showed similar values between the 2 groups with no cadence effect (the Figure). For the hemiparetic group, MUR\textsubscript{area} of the affected hip flexors was greater than that of the unaffected hip flexors at maximal cadence ($P=0.05$). For the able-bodied, despite a small difference, MUR\textsubscript{area} of the hip flexors on the right side presented greater values than on the left side (4.3±1.5 versus 3.3±1.3%); at 80 steps/min ($P=0.002$). For the hip extensors, the unaffected MUR\textsubscript{area} value was greater than the affected one at self-selected cadence ($P=0.05$), whereas...
no significant difference was observed for the healthy individuals. With cadence, an increase in the MUR$_{area}$ was noted for the hip flexor muscles in both groups of participants ($P$/H11021 0.004) and for the hip extensors, for the hemiparetic individuals only ($P$/H11005 0.002).

In addition, regardless of side and cadence, the MUR$_{area}$ values for the hemiparetic participants were similar for all muscle groups ($P$/H11022 0.05). Inversely, for both sides, healthy participants showed greater MUR$_{area}$ values for plantar flexors than for hip flexors or extensors at the imposed cadence of 80 steps/min. At the imposed 120 steps/min cadence, the MUR$_{area}$ values for the plantar flexors and hip flexors became equivalent and were greater than those for the hip extensors (the Figure).

For the duration of the energy generation phase, the hemiparetic participants presented significantly greater values for both the hip flexors (between-group $P=0.002$) and the extensors (between-group $P=0.032$) than the able-bodied at both cadences. No difference was detected for the plantar flexors (between-group $P=0.690$; the Figure). Though not significant, a trend toward a longer energy generation duration was observed on the affected hip flexors and unaffected hip extensors when compared with the opposite side for both cadences. Also, for both groups, a significant cadence effect ($P<0.05$) was acknowledged for the plantar flexors and hip flexors, with duration values decreasing with cadence.

**Correlation Between Peak MUR and MUR$_{area}$**

For the hemiparetic participants, the Pearson product-moment correlation between peak MUR and MUR$_{area}$ values was significant for all muscle groups of both sides and at both cadences (0.517$<r<0.901$). For the healthy participants, a significant association was noted for the plantar flexor muscles on the right side at 80 steps/min ($r=0.809$) and 120 steps/min ($r=0.597$), whereas other correlations were not significant.

**Discussion**

**Clinical Evaluation**

On the basis of the results of this study, the hemiparetic participants were a high-functioning group, showing mild spasticity at the ankle and motor recovery at the affected lower limb that did not conform to synergetic patterns. Nonetheless, their clinical self-selected gait speed showed a decrease of $\approx 34\%$ when compared with healthy participants, whereas their maximal clinical gait speed was near the self-selected speed of the able-bodied.11

As shown in previous studies, more pronounced weaknesses in the distal musculature were revealed by the current dynamometric testing. Inversely, the fact that the strength of the affected hip muscles was identical to that of the unaffected one is not consistent with the results of some research
studies that have highlighted strength deficits between sides of \( \approx 24\% \) to \( 37\% \). However, it is consistent with a study by Hsu et al, who stated that some hemiparetic participants showed a comparable strength deficit between affected and unaffected sides for the hip flexor muscles.

In comparison to the strength data (weighted arithmetic mean) of the able-bodied, the affected and unaffected plantar flexor strength showed a decline of 46% and 24%, respectively. The deficit at the hip ranged from 7% to 35% of the able-bodied strength values, regardless of side. These strength deficits indicated the presence of bilateral weakness, further supporting findings of other studies.

**Peak MUR**

At both cadences, the peak MUR of the affected and unaffected plantar flexors, hip flexors, and hip extensors were greater than those of the able-bodied walking at matched cadences. Because the walking moments (numerator of MUR) of the hemiparetic participants were comparable to (hip) or slightly lower than (ankle) those of the able-bodied matched for cadences (data not presented), the differences in peak MUR could be explained by the presence of bilateral weakness of the lower limbs. The hemiparetic participants generated less torque than did the healthy participants during the dynamometric assessment, leading to a lower value of the MUR denominator. Consequently, when walking at their self-selected or maximal cadences, the hemiparetic participants had to produce a greater level of effort than the able-bodied walking at similar cadences.

In the current study, the interlimb peak MUR values for the hemiparetic participants remained comparable between sides at maximal cadence and at the self-selected cadence, suggesting that the bilateral walking moments seem to increase in proportion to the maximal strength. One possible explanation for this observation is that the hemiparetic participants scaled their effort to their maximal strength, as shown in single or multiarticular efforts. The idea of using the sense of effort in hemiparetic gait was first presented in a previous work by the authors.

The presence of similar levels of effort between affected and unaffected sides can also provide a new explanation for the asymmetrical gait pattern observed in stroke individuals. It could be expected that the motor strategies favored by hemiparetic individuals are guided by the desire to produce similar bilateral levels of effort. To do so, the hemiparetic participants could adjust their walking moment to their remaining strength, producing different values between affected and unaffected sides (e.g., plantar flexors 74 Nm versus 85 Nm). Because the affected side has less strength than the unaffected one, this strategy could result in an asymmetrical gait pattern. This asymmetry in walking moment was observed at the ankle, the joint where the most significant strength difference between sides was noted.

The use of the sense of effort has also been noticed in studies investigating matching tasks in the upper limb of stroke individuals, where no adjustment of force production was noted for the presence of weakness on the affected side. Future studies will be needed to support the hypothesis that the sense of effort is involved in the regulation of motor control during functional activities such as gait.

**MUR**

As in the case of peak MUR, with the exception of plantar flexors, the hemiparetic participants showed greater MUR values than the able-bodied walking at similar cadence. This difference could be explained by both a greater MUR value and a greater duration of the energy generation phase of hemiparetic participants compared with healthy individuals. Note that even though a significant difference between the MUR of the right and left sides of healthy hip flexors was observed (the Figure), this difference was small (1%) and not considered to be clinically relevant. Thus, it can be noted that healthy individuals do not present a side difference in the MUR value for all muscles tested, although for the hemiparetic participants, side differences were seen at the hip joint. The difference in MUR between sides could be explained by an increment in the duration of the energy generation phase, because as mentioned earlier, the peak MUR remained similar between sides at both cadences (the Figure). As shown in the Figure, the increased MUR of the affected hip flexors was complemented by a greater, albeit not significant, duration of their concentric action, compared with the unaffected hip flexors (0.43 versus 0.37 s). The increased MUR and duration of the concentric action of the unaffected hip extensors could be a strategy to allow greater use of the contralateral hip flexors. The predominant use of the hip flexors of the affected limb gives support to previous reports that have stressed the important role of this muscle group in hemiparetic gait.

Correlation analysis revealed that hemiparetic participants presenting the greatest peak MUR also had the greatest MUR area. This finding suggests that peak MUR could provide a good estimate of the global muscle effort during gait. However, as mentioned earlier, the duration of effort could also be taken into consideration to appreciate the role of the affected and the unaffected side in gait, particularly at the hip joint. Although the peak MUR and MUR area showed a similar behavior across cadences and sides for the able-bodied, there was no significant relation between these 2 variables apart from the plantar flexors on the right side. This could be a direct effect of the lower intersubject variability observed for this group of participants.

The current study makes important and relevant contributions to the comprehension of hemiparetic gait, because it brings objective results and new concepts on the usefulness of quantifying the level of effort to further understand asymmetries in motor performance. However, there are a few limits that need to be considered. Limits related to the use of the MUR model have already been reported in previous studies (see Nadeau et al and Requiao et al). Other limits are related to the fact that the hemiparetic participants had to fulfill some specific criteria to be included in the present study. Therefore, the study had a small sample size, and hemiparetic participants presented with a relatively high functional level. Generalization of the current results should not be made to the entire population of individuals with stroke. Future studies will need to address the quantification of the level of effort in a more representative group of hemiparetic individuals.
Conclusion
Muscle weakness secondary to a stroke leads to an increased level of effort of the lower limbs during gait. However, no side difference was observed in the level of effort despite a more pronounced weakness of the affected distal muscles. An original explanation for these results is that the asymmetrical gait pattern often seen in hemiparetic gait could represent a means of preserving similar perceived sense of effort between sides as occurs in a normal state. Further research should explore the role of the sense of effort in the motor control of hemiparetic gait.

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Disclosures
None.

References
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