Effects of Weakness on Symmetrical Bilateral Grip Force Exertion in Subjects With Hemiparesis

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Bertrand, Anne Martine, Catherine Mercier, Priscilla Lam Wai Shun, Daniel Bourbonnais, and Johanne Desrosiers. Effects of weakness on symmetrical bilateral grip force exertion in subjects with hemiparesis. J Neurophysiol 91: 1579–1585, 2004. First published November 19, 2003; 10.1152/jn.00597.2003. It has been shown that, in a bilateral force-matching task, subjects presenting weakness in one limb produce a lower force in the weakened limb even though they subjectively perceive that they are exerting the same force. The aim of this study was to verify whether subjects with hemiparesis produced asymmetrical forces during a bilateral submaximal grip task and whether this asymmetry is related to weakness of the paretic limb. Fifteen subjects with hemiparesis and 15 healthy subjects were recruited. First, the maximal voluntary force was measured for each hand. Then, subjects were asked to exert equal forces with both hands simultaneously at three submaximal force levels using two dynamometers. In the bilateral task, the force ratios (paretic/nonparetic or nondominant/dominant) differed between groups. Severely weak hemiparetic subjects produced lower force ratios than mildly weak hemiparetic subjects and healthy subjects (P < 0.000), whereas there was no difference between the force ratios produced by mildly weak hemiparetic subjects and those produced by healthy subjects. In subjects with hemiparesis, the force ratios in the bilateral task were related to the ratios of maximal voluntary forces (R² = 0.39–0.66, P ≤ 0.013) and the presence of somatosensory impairment did not affect these relationships. These results suggest that the strategy used is to compare the intensity of the motor commands on both sides and then perform the force-matching task. The use of such a strategy by subjects who have had paresis for 1 year reflects a lack of adaptation to their weakness.

Although it is recognized that under normal conditions both types of information could contribute to force perception (Cafarelli and Bigland-Ritchie 1979; Gandevia 1996; Jones 1986), there is some evidence suggesting that central information is used predominantly. Indeed, it has been shown that, in healthy subjects, the induction of weakness in one limb by fatigue (Gandevia and McCloskey 1978; Jones and Hunter 1983a,b; McCloskey et al. 1974) or by partial curarization (Gandevia and McCloskey 1977a,b) in most cases leads to an overestimation of the force produced by the weakened limb during either a weight or an isometric force-matching task.

In the presence of induced weakness, an increase in force perception and a decrease in maximal voluntary force have been shown to be related (Gandevia and McCloskey 1977a,b; Jones and Hunter 1983b). However, as noted by Gandevia (1987) and Jones (1995), the changes in magnitude of the two variables were not equivalent (i.e., not a 1:1 ratio). Indeed, with both the fatigue and the partial curarization protocols, the force perception increased less than the relative decrease of the force magnitude (Gandevia and McCloskey 1977a; Jones and Hunter 1983b). This has been attributed to either the contribution of afferent peripheral information (Cafarelli 1982) or the properties of the paralytic agents used in the different experiments (Gandevia 1987). Cafarelli and Bigland-Ritchie (1979) are the only authors that report equivalent changes in the relative force perception and the relative maximal voluntary force in healthy individuals. This was shown using a submaximal isometric force-matching procedure while the length of homologous muscles was similar or shortened on one side and lengthened on the other to alter the maximal voluntary force. The slope of the regression line between forces at both sides was nearly equal to the ratios of the maximal voluntary force measured on each side. Moreover, modifications in muscle length did not affect the relationship between the smoothed rectified electromyogram recorded for each side, suggesting that excitatory inputs were similar when the forces were perceived to be the same. Together, these results suggest that force matching was done by scaling the maximal voluntary forces, which is consistent with the central perception of force.

In subjects with poststroke hemiparesis, an increased sensation of heaviness or effort when trying to move has been documented (Brodal 1973; Gandevia 1982; Rode et al. 1996).

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Using a weight-matching task, Gandevia and McCloskey (1977b) showed that subjects with hemiparesis without somatosensory impairment overestimated weights lifted with the weakened limb, as in experimentally induced weakness. In addition, a significant correlation was found between the over-estimation of the lifted weights and weakness. The latter authors proposed that subjects with hemiparesis relied on the sense of effort and that the overestimation resulted from the increased motor command needed to overcome the reduced motor outflow of the paretic muscles. However, the impact of this altered force perception on the ability of hemiparetic subjects to perform a task requiring equal bilateral force exertion has not been specifically investigated yet.

This study proposes a simple model to account for the asymmetry of forces between the two sides in subjects with hemiparesis. According to this model, the force exerted by each muscle group involved in a bilateral task is determined as a percentage of its maximal voluntary force. The model is based on the assumption that subjects rely on the sense of effort to match the forces, whether the peripheral sensory system is impaired or intact. However, since it is recognized that peripheral information could contribute to force perception, the effect of somatosensory impairment needs to be verified. The general objectives of this study was to test the proposed model. Three specific objectives were determined: 1) to verify that subjects with poststroke hemiparesis produce asymmetrical forces during a force-matching task as compared with healthy subjects; 2) to evaluate whether the asymmetry between the forces on both sides is stable over time; and 3) to determine whether this asymmetry is associated with the relative weakness of the paretic side and whether this relationship is affected by the integrity of somatosensory feedback.

METHODS

Participants

Two convenience groups participated in this study. The first one consisted of 15 subjects with poststroke hemiparesis, while the second was composed of 15 age- and gender-matched healthy subjects. To be included in the study, all subjects had to meet the following eligibility criteria: 1) no upper-extremity orthopedic or neurological deficits (except those related to the paresis) and 2) upper-extremity pain intensity of <2 cm on a 10-cm visual analog scale (Huskisson 1983). Subjects with hemiparesis had to meet additional specific criteria: 1) paresis of the upper extremity resulting from a first unilateral cerebrovascular accident that occurred at least 1 year earlier; 2) motor impairment scored at stage 3 or more in the hand section of the Chedoke McMaster Stroke Assessment (Gowland et al. 1993); and 3) no severe cognitive deficits, as demonstrated by a Mini-mental State Examination score better than 24/30 (Folstein et al. 1975; Hébert and Girouard 1992).

The study was approved by the research ethics committee of the two rehabilitation centers where the subjects were recruited and each participant gave his/her informed consent before the study.

Procedure and instruments

Subjects were evaluated in a single session. All clinical evaluations were administered to subjects with hemiparesis by an experienced occupational therapist. The motor impairment of the arm and hand was evaluated with the Chedoke McMaster Stroke Assessment (Gowland et al. 1993), which allowed the impairment to be classified according to the ability to perform the movement within or out of abnormal synergy patterns. To identify subjects presenting somatosensory hand impairment, three submodalities were evaluated: touch/pressure, two-point discrimination, and kinesthesia. The touch/pressure threshold was estimated at the distal phalanx of the index using Semmes-Weinstein monofilaments and following the procedure described by Bell-Krotoski (1990). Static and moving two-point discrimination thresholds were also measured at the distal phalanx of the index using the Mackinnon-Dellon Disk-Criminator (Dellon et al. 1987). Finally, the kinesthesia was evaluated at the interphalangeal joint of the thumbs following the procedure described by Desrosiers and colleagues (1996). Based on norms established for healthy older adults (Desrosiers et al. 1996), subjects were classified as presenting somatosensory impairment on the paretic side if they failed to meet one of the following criteria: 1) they could not feel the monofilament no. 3.61; 2) they could not feel two ends separated by a distance of 6 mm; or 3) they could not correctly indicate the movement direction at least eight times on 10 trials.

In the experimental conditions, subjects were seated on a chair with elbows positioned at approximately 90° of flexion and forearms resting on a height-adjustable table while holding a static dynamometer in each hand. They wore cycling gloves that did not cover the distal and middle phalans and comprised gel pads located over the metacarpophalangeal joints. The gloves were used to try to avoid a possible reduction of force due to pain caused by the pressure. The same two static-grip dynamometers were used for all force measurements. Each dynamometer was made of two rigid aluminum bars fixed on a force transducer. The force transducers had four strain gauges that measured the resultant force independently of the site of its application on the rigid bars. The signals were amplified (low-pass filter, set at 50 Hz) and sampled with an A/D conversion card (AT-MIO 16-E10, National Instruments) at a frequency of 100 Hz before being stored on the hard disk of a desktop computer. A computer program created with Labview 5.0 (National Instruments) was used for data acquisition.

The subjects had to produce three maximal voluntary grip exertions with each hand alternately, beginning with the nonparetic or dominant hand. A 1-min rest period was provided between the trials and a 5-min rest period was given at the end of the measurements. The subjects were then asked to exert equal grip forces with both hands simultaneously at three submaximal force levels. These force levels corresponded approximately to 25, 50, and 65% of the highest value obtained from the three maximal voluntary grip exertions at the paretic or nondominant side. Since attainment of this target force level was verified for the nonparetic side, the forces were low enough to allow the production of equal forces in hemiparetic subjects. Three consecutive trials were performed for each force level, with a rest period of 15 s between them. Two signal tones, separated by 4 s indicated the beginning and end of the trials. Instructions were given as follows: “When you hear a first sound, exert low (or medium or high) equal forces by squeezing the handles with both hands. Try to maintain these equal forces until you hear the second sound and then release them.” In addition, they were instructed to evaluate their performance at the end of each trial and to say if they perceived the exerted forces as equal. When a subject reported that he or she did not perceive the forces as equal, the trial was cancelled and repeated.

Visual feedback was provided to the evaluator to make sure that the trials were done at the fixed force levels. A target corresponding to the force level requested, as well as the force exerted by the subject’s nonparetic or dominant hand only, were displayed on a computer screen. Thus the evaluator could reject a trial if the targeted force level was not reached but had no information on the symmetry of the forces. This was done to prevent a bias related to the experimenter’s expectations when rejecting trials. Finally, since the subjects had no visual feedback, the acceptable range around the targeted force levels was large enough (between 15 and 35% for the low force level, between 40 and 60% for the medium force level, and between 60 and 80% for the high force level) to avoid too many repetitions.
The bilateral task was repeated twice, 1 h apart, in subjects with hemiparesis to determine the test–retest reliability of the symmetry between forces.

Data analysis

During the bilateral task, the force in each hand was recorded for 6 s (including 1 s preceding and following the tones). However, only the values between the 3rd and 5th seconds of acquisition (200 points), which corresponded to the force maintenance, were extracted and kept for analysis (see Fig. 1). For each point, the force values were converted into ratios (paretic/nonparetic for subjects with hemiparesis and nondominant/dominant for healthy subjects), which were then averaged over time. A global mean force ratio (FR) was subsequently calculated for each subject by averaging the three force values obtained during the three maximal force exertions on each side and by dividing the mean of one side by that of the other side (paretic/nonparetic). Finally, the presence or absence of somatosensory impairment was quantified using a dichotomous variable (0, without impairment; 1, impairment). Subjects were classified as presenting a somatosensory impairment according to the criteria presented above (see Procedure and Instruments).

Statistical analysis

To ascertain that the force ratios were not affected by fatigue due to the successive trials in subjects with hemiparesis, a two-way repeated-measures ANOVA was first performed using FR as the dependent variable. The within-subject factors were the trial (1–3) and the level of force [low (25%), medium (50%), high (65%)]. To confirm whether the subjects with hemiparesis produced asymmetrical grip forces in the bilateral task compared with the control subjects (objective 1), a two-way repeated-measures ANOVA was also performed. The within-subject factor was the level of force while the between-subject factor was the group (subjects with hemiparesis and healthy subjects). Significant interactions and main effects were further analyzed with one-way repeated-measures ANOVA or independent t-tests and the significance level was then adjusted for multiple comparisons using the Bonferroni method. When the assumption of sphericity was violated in the ANOVA analysis, the Huynh-Feldt epsilon was used to adjust the degrees of freedom. When Levene’s test was significant, t-tests were performed using a model that does not assume equal variances between groups.

Intraclass correlation coefficients (ICC) and their 95% confidence intervals were computed to estimate the test–retest reliability of the FR measurements at each force level in the bilateral task. In addition, paired t-tests were also conducted on the grip FR obtained for each force level to verify that there was no systematic bias between the measuring sessions (objective 2). Finally, to verify whether the symmetry of forces produced by subjects with hemiparesis during the bilateral task is related to the weakness of the paretic side and whether the somatosensory impairment affected this relationship, simple and multiple linear regression models were performed for each of the three force levels (objective 3). The FR in the bilateral task was then used as the dependent variable whereas the MVFR and somatosensory impairment were the independent variables. For all analyses, the statistical significance level was fixed at 0.05.

Results

Sample description

The mean age for the group of subjects with hemiparesis was 52.0 ± 12.4 yr and for the healthy group was 47.7 ± 11.5 yr. All subjects were right-handed except one in the healthy group. Characteristics of subjects with hemiparesis are reported in Table 1. Five subjects with hemiparesis were classified as presenting a somatosensory impairment.

Attainment of force target level and stability of grip force ratios across trials

During the bilateral task, few trials were discarded and repeated (<10%) due to nonattainment of the target force level or to the dissatisfaction of the subjects regarding the equality of forces. Since there was no practice trial, the first trial was mainly the one that needed to be cancelled and repeated. Computations of the means and SDs of the forces exerted on the nonparetic or dominant side revealed that a magnitude near the targeted force level was reached (the forces corresponded to 27 ± 6 or 25 ± 6%, 48 ± 8 or 45 ± 5%, and 72 ± 9 or 65 ± 5% of the maximal force measured on the paretic or nondominant side, respectively). The grip force ratios were stable across trials in subjects with hemiparesis since there was no interaction between the Trial and Level of force factors [F(2.27,31.72) = 0.46, P = 0.66] and no main effect for the factor Trial [F(2,56) = 1.04, P = 0.37].

Symmetry of grip forces during the bilateral task

An example of a typical force recording measured in a subject with hemiparesis during the bilateral task is illustrated in Fig. 1. The group mean of grip force ratios and the SD at each force level for both groups are presented in Fig. 2. No interaction between the Level of force and Group factors was found [F(1.19,33.21) = 1.39, P = 0.25]. However, there was a main effect for the Level of force factor [F(1.19,33.21) = 6.23, P = 0.014]. Contrast analyses (adjusted significance level = 0.017) indicated that the grip force ratios in both groups were higher at the low than at the medium force level [F(1,29) = 6.77, P = 0.014] and there was a trend suggesting that the grip force ratios were also higher at the low force level compared with the high force level [F(1,29) = 6.29, P = 0.018]. However, there was no significant difference in the grip force ratios produced at the medium and higher force levels.
TABLE 1. Characteristics of subjects with hemiparesis

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age, yr</th>
<th>Gender</th>
<th>Delay Post-CVA, mo</th>
<th>Side of Paresis</th>
<th>CM (hand, arm)</th>
<th>SW (P, NP)</th>
<th>MDD static / moving (P, NP)</th>
<th>Thumb kinesthesia (P, NP)</th>
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<tr>
<td>1*</td>
<td>60</td>
<td>M</td>
<td>105</td>
<td>R</td>
<td>3, 4</td>
<td>†, 2.83</td>
<td>‡, 5 / ‡, 5</td>
<td>1, 10</td>
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<tr>
<td>2</td>
<td>25</td>
<td>F</td>
<td>41</td>
<td>R</td>
<td>3, 4</td>
<td>2.83, 2.83</td>
<td>3, / 2, 2</td>
<td>10, 10</td>
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<tr>
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<td>16</td>
<td>L</td>
<td>3, 5</td>
<td>4.56, 2.83</td>
<td>‡, 4 / ‡, 4</td>
<td>3, 10</td>
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<tr>
<td>4</td>
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<td>M</td>
<td>29</td>
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<td>113</td>
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<td>2, / 5, 4</td>
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<tr>
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<td>105</td>
<td>R</td>
<td>5, 5</td>
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<td>58</td>
<td>M</td>
<td>76</td>
<td>R</td>
<td>5, 5</td>
<td>2.83, 2.83</td>
<td>3, / 4, 3</td>
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<td>78</td>
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<td>6.65, 2.83</td>
<td>‡, 3 / ‡, 4</td>
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<tr>
<td>9</td>
<td>54</td>
<td>M</td>
<td>37</td>
<td>L</td>
<td>6, 6</td>
<td>2.83, 2.83</td>
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<td>R</td>
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<td>15, / 3, ‡</td>
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<td>R</td>
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<td>F</td>
<td>30</td>
<td>R</td>
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<td>L</td>
<td>7, 7</td>
<td>3.61, 2.83</td>
<td>6, / 2, 2</td>
<td>10, 10</td>
</tr>
</tbody>
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CVA, cerebrovascular accident; CM, Chedoke-McMaster Stoke Assessment; SW, Semmes-Weinstein monofilaments; MDD, Mackinnon-Dellon Disk-Criminator; NP, nonparetic; P, paretic; M, male; F, female; L, left; R, right. *Subjects who showed somatosensory impairment; †subjects who indicated that they did not feel the largest monofilament; ‡subjects who indicated that they felt one end for all two-point distances.

Although the grip force ratios of the subjects with hemiparesis were smaller than those of the healthy subjects, the difference did not reach the significance level \( F(1,29) = 2.43, P = 0.130 \). The force ratios of the subjects with hemiparesis were smaller than those of the healthy subjects \( F(1,28) = 3.89, P = 0.059 \). To determine whether this nonsignificant result arises from mildly weak hemiparetic subjects, the analysis was repeated with the hemiparetic group divided into two subgroups, one consisting of 10 subjects presenting a severe weakness (ratio of maximal voluntary forces lower than 0.70) and the other of 5 mildly weak subjects (ratio of maximal voluntary forces higher than 0.70). This analysis revealed that there was still an effect for the Level of force factor \( F(1,25,33.81) = 10.70, P = 0.001 \) and no interaction between the Level of force and Group factors \( F(2.50,33.81) = 2.43, P = 0.09 \). However, contrary to the first analysis, there was an effect for the Group factor \( F(2.27) = 25.70, P < 0.000 \). Contrast analyses (adjusted significance level = 0.017) indicated that severely weak hemiparetic subjects produced lower grip force ratios than mildly weak hemiparetic subjects (\( t_{1,41} = -4.22, P = 0.011 \)) and healthy subjects (\( t_{23} = -7.38, P < 0.000 \)). However, there was no difference in the force ratios produced by mildly weak hemiparetic subjects and those produced by healthy subjects (\( t_{4,61} = 1.46, P = 0.21 \)).

Test–retest reliability

The ICCs and their 95% confidence intervals are presented in Table 2. Good temporal stability was demonstrated between measurements, especially for the low and high force levels.

Relationships between weakness and asymmetry in forces

Simple regression models were first performed separately for each independent variable (MVFR and somatosensory impairment). The models revealed that the MVFR was related to the FR for each force level \( (R^2 = 0.39–0.66, P \leq 0.013) \) while somatosensory impairment showed no such relationship at any force level \( (P = 0.81 to 1.00) \). To examine whether somatosensory impairment could affect the relationship between MVFR and FR, multiple regression models were performed at each of the three force levels. Although there is a trend at the medium level, there was no significant effect (low, \( P = 0.48 \); medium, \( P = 0.09 \); high, \( P = 0.10 \)) related to the variable somatosensory impairment. In addition, no interactions between somatosensory impairment and MVFR proved to be significant (low, \( P = 0.29 \); medium, \( P = 0.36 \); high, \( P = 0.11 \)). Consequently, the models retained were those that included only the variable MVFR. In these simple regression models, the MVFR accounted for nearly 40% of the variance of the FR at the low force level, 55% at the medium force level, and 66% at the high force level. Furthermore, the parameter estimates (i.e., slope and intercept values) of the regression equations calculated at each force level indicated that changes in both MVFR and FR were equivalent at the medium and high levels (slope values = 1.07; 0.98). At the low force level, the slope was higher (1.40), but strongly influenced by high grip force ratio values (see Fig. 3).

![Grip force ratio chart](chart.png)
This study aimed to verify whether the force exerted by each muscle group involved in a bilateral task is determined as a percentage of its maximal voluntary force. It was found that subjects with poststroke hemiparesis tended to exert asymmetrical forces on both sides when they were asked to exert equal forces and that the asymmetry was stable over time. The asymmetry in grip forces was obvious in subjects who were severely weak. In addition, in subjects with hemiparesis, the ratios of forces in the bilateral task were related to the ratios of the maximal voluntary forces.

Symmetry of grip forces in subjects with hemiparesis

The results show that subjects with hemiparesis as a group tended to produce asymmetrical grip forces as opposed to healthy subjects. The nonsignificant difference between groups may be attributed to a few mildly weak subjects. Indeed when the subjects with hemiparesis are separated into two subgroups, it appears that severely weak subjects produced asymmetrical forces compared with those of the healthy subjects and those of the mildly weak subjects. In the latter group, some subjects produced very high grip force ratios. Examination of individual data reveals that three subjects produced grip force ratios $\geq 1$, notably at the low force level (between 1.30 and 1.85). The reason for these high grip force ratios is not obvious but it was observed that they were produced by subjects with the highest MVFRs (Fig. 3). We also noted that these three subjects reproduced similar grip force ratios at the second time measurement, suggesting that their strategy was stable. Overall, the subjects with hemiparesis tended to produce asymmetrical grip forces compared with healthy subjects, although the higher grip force ratios generated by some subjects attenuated the difference between groups.

All subjects produced higher grip force ratios at the low force level. However, as suggested by the interaction between the Group and Level of force factors, which verges on the significant, it was observed that the difference in force ratios at the low force level and the other two force levels was not the same between groups. Indeed, the difference was small in both the healthy group and the group of severely weak hemiparetic subjects whereas the difference was greater in the group of mildly weak hemiparetic subjects. In the latter group, the difference in force ratios between the low force level and the other two force levels seems to result from the three subjects having produced high grip force ratios.

The reproducibility of perceived heaviness proved to be moderate to good, depending on the muscles involved and the magnitude of the lifted weight (Gandevia and Kilbreath 1990; Kilbreath and Gandevia 1993). However, to our knowledge, no study has ever specifically evaluated the test–retest reliability of the measurements in a force-matching task. In the present study, the asymmetry of grip forces was shown to be reliable between two measurements in hemiparetic subjects. Both at the

### Table 2. Test-retest reliability of the force ratios in subjects with hemiparesis

<table>
<thead>
<tr>
<th>Force Level</th>
<th>First measurement</th>
<th>Second measurement</th>
<th>Difference between measurements</th>
<th>Paired t-test</th>
<th>Intraclass Correlation Coefficient (95% confidence interval)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>0.86 ± 0.50</td>
<td>0.79 ± 0.44</td>
<td>0.14 ± 0.23</td>
<td>0.22</td>
<td>0.92 ± 0.78–0.97</td>
</tr>
<tr>
<td>50%</td>
<td>0.72 ± 0.32</td>
<td>0.66 ± 0.37</td>
<td>0.11 ± 0.24</td>
<td>0.33</td>
<td>0.76 ± 0.41–0.91</td>
</tr>
<tr>
<td>65%</td>
<td>0.68 ± 0.27</td>
<td>0.64 ± 0.33</td>
<td>0.02 ± 0.20</td>
<td>0.14</td>
<td>0.92 ± 0.79–0.97</td>
</tr>
</tbody>
</table>

Values are means ± SD.

![Fig. 3. Grip force ratios measured during the bilateral task at each force level (A, 25%; B, 50%; C, 65%) as a function of MVFRs in subjects with hemiparesis. Regression lines, regression equations, and coefficients of determination ($R^2$) are shown.](image)
low and the high force levels, the reliability was good (high ICCs with narrow confidence intervals) but it was only moderate at the medium force level. This moderate reliability could not be explained by examining the individual data. Overall, the reliability coefficients indicate that the strategy used by the subjects to match the forces was stable across measurements.

Relationship between weakness and asymmetry in forces

The most important finding of this study is the direct relationship between the relative weakness and the asymmetry in grip forces. It is important to recall that the bilateral force-matching task was done at submaximal levels of force and that each subject had the capacity to produce grip force ratios equal to 1, since the force produced at the nonparetic limb was always lower than the maximal force of the paretic limb. According to the model proposed, the strategy used by the subjects was to match the intensity of the motor commands of each side as a percentage of the maximal voluntary force. Since the force of each hand is similar in normal subjects, the force output is close to unity. Subjects continue to use the same strategy after a stroke, even though the forces between sides differ due to the weakness. This hypothesis is supported by the relationship between MVFR and FK in subjects with hemiparesis. Nevertheless, it should be noted that, at the lowest force level, the slope deviates from 1 and the coefficient of determination ($R^2$) is reduced. At this force level, the slope seems to be largely influenced by the three highest values. Moreover, it was observed that some severely weak subjects produced larger grip force ratios at this level than at the other force levels. It could be proposed that this result from the low magnitude of the absolute forces to be exerted. Indeed, if subjects had matched the forces on both sides according to the model proposed, the magnitude of the force to be exerted by the paretic hand would have been very low. (Based on maximal voluntary force ratios, the expected forces on the paretic side would have been lower than 42 N in severely weak subjects.) Actually, some subjects correctly reported that the force to be exerted was very low. It is possible, therefore, that, although they relied on the sense of effort, they perceived a different muscular or superficial tension between hands and increased the force on their paretic side. Overall, these results are consistent with those obtained by Cafarelli and Bigland-Ritchie (1979) who reported that the ratio of forces during a force-matching task was nearly equal to the ratio of maximal voluntary forces between limbs when the maximal voluntary force was altered by varying muscle lengths in healthy individuals.

Results of multiple linear regression analyses suggest that somatosensory impairment affects neither the grip force ratios nor the relationship between these ratios and relative weakness. However, this should be interpreted with caution for at least two reasons. First, a type II error is possible because of the small sample and the limited number of subjects with a somatosensory impairment. Second, the effect of somatosensory impairment could be attenuated considering that somatosensory feedback could be reduced in all subjects by wearing cycling gloves. The effect of sensory impairment combined with weakness on force perception is not well known. Gandevia and McCloskey (1977a) have investigated the effect of partial paralysis compared with that of partial paralysis combined with anesthesia on the perceived heaviness of lifted weights with the thumb in different directions and found opposite results depending on the direction of movement. Their results also need to be considered with caution given the small number of subjects involved and the absence of statistical analyses. Therefore further research is needed to have a better understanding of the effect of somatosensory impairment associated with weakness on force perception and on the performance in bilateral force exertion.

Particular attention was paid to the instructions given to the subjects since it has been shown previously that subjects can differentiate between the forces produced and the effort felt according to the instructions (McCloskey et al. 1974; Roland and Ladegaard-Pedersen 1977). However, Jones (1983) demonstrated the predominance of the sense of effort on force perception during fatiguing contractions even when the subjects were instructed to match the forces and disregard the effort to produce them. Indeed, although subjects in some trials could produce accurate force matching, they overestimated the force to be produced most of the time. In the present study, the instructions insisted on the equality of the forces to be produced and the subjects did not receive any specific indication regarding the effort felt when producing the forces. Therefore it could be suggested that subjects with hemiparesis spontaneously rely on central information to execute the bilateral task.

Functional implications for subjects with hemiparesis

The results indicating that subjects with hemiparesis produce smaller forces on the paretic side in an isometric force-matching task are congruent with the previous observation that these subjects choose a lower weight on the paretic side in a weight-matching task (Gandevia and McCloskey 1977b). Both of these results can be explained by the use of a strategy that consists in comparing the intensity of the motor commands. This indicates that the central information can be used for either perception (comparing weights) or action (producing equal forces).

Since these results were obtained in patients with chronic hemiparesis, it appears that no adaptation occurs when motor recovery stabilizes to take the weakness into account in the strategy used. Consequently, this could have a strong impact on the performance of bimanual activities as well as on the coordination between posture and movement. Indeed, it is recognized that subjects with hemiparesis cannot always acquire adequate bilateral coordination spontaneously even if they have a useful recovery of the paretic limb and bilateral training is often needed (Carr and Shepherd 1998). Recently, it was also proposed that the increased force perception associated with isometric force exertion by the paretic upper limb and the use of a strategy based on the sense of effort could explain the higher contralateral postural stabilization forces observed in subjects with hemiparesis (Bertrand and Bourbonnais 2001). Considering the importance of bilateral actions in daily living activities, further research is needed to understand, in different contexts, the impact of using a strategy that does not take weakness into account.

Unilateral motor performance is also altered by weakness. It has been shown that weakness is strongly associated with upper-limb motor impairment and physical disability in subjects with hemiparesis (Boissy et al. 1999; Chae et al. 2002; Mercier and Bourbonnais 2004). However, it would be in-
estimating whether the weakness, lack of adaptation to the weakness, or both impairments are responsible for the reduced motor performance. The results of a recent study suggest that lack of adaptation to the weakness could also be associated with the so-called abnormal synergies on the paretic side. Lum and colleagues (2003) have suggested that the abnormal synergies are due to the imbalance between agonist and antagonist muscles, which stabilize the joints that are proximal or distal to the joint where the movement was made. The shoulder abduction movement, for instance, would be associated with an elbow flexion movement because of an imbalance between the flexors and extensors of the elbow. This could mean that the force produced in flexion is not adapted to the reduced force in extension. Lack of adaptation to the weakness needs to be considered in future research.

In summary, the results of the present study indicate that, in contrast with healthy subjects, severely weak hemiparetic subjects produce asymmetrical forces during a bilateral task. More specifically, they suggest that the strategy used to execute the task is to scale the intensity of the motor commands sent to each side as a percentage of the maximal voluntary force and that the strategy used is stable across time. These results are consistent with the hypothesis that force perception has a central origin. The results also underlie the finding that, even though the level of weakness is stable for more than a year, the strategy used by subjects with hemiparesis seems not to be adjusted to it. Further research is required to understand the mechanisms underlying bilateral force exertion in different tasks and the impact of the lack of adaptation to the weakness in functional activities in subjects with hemiparesis.

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