Bilateral reach-to-grasp movement asymmetries after human spinal cord injury

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Calabro FJ, Perez MA. Bilateral reach-to-grasp movement asymmetries after human spinal cord injury. J Neurophysiol 115: 157–167, 2016. First published October 14, 2015; doi:10.1152/jn.00692.2015.—Cervical spinal cord injury (SCI) in humans typically damages both sides of the spinal cord, resulting in asymmetric functional impairments in the arms. Despite this well-accepted notion and the growing emphasis on the use of bimanual training strategies, how movement of one arm affects the motion of the contralateral arm after SCI remains unknown. Using kinematics and multichannel electromyographic (EMG) recordings we studied unilateral and bilateral reach-to-grasp movements to a small and a large cylinder in individuals with asymmetric arm impairments due to cervical SCI and age-matched control subjects. We found that the stronger arm of SCI subjects showed movement durations longer than control subjects during bilateral compared with unilateral trials. Specifically, movement duration was prolonged when opening and closing the hand when reaching for a large and a small object, respectively, accompanied by deficient activation of finger flexor and extensor muscles. In subjects with SCI interlimb coordination was reduced compared with control subjects, and individuals with lesser coordination between hands were those who showed prolonged times to open the hand. Although the weaker arm showed movement durations during bilateral compared with unilateral trials that were proportional to controls, the stronger arm was excessively delayed during bilateral reaching. Altogether, our findings demonstrate that during bilateral reach-to-grasp movements the more impaired arm has detrimental effects on hand opening and closing of the less impaired arm and that they are related, at least in part, to deficient control of EMG activity of hand muscles. We suggest that hand opening might provide a time to drive bimanual coordination adjustments after human SCI.

reaching and grasping; voluntary drive; corticospinal drive; unilateral movements; bilateral movements; spinal cord injury

MOST OF OUR DAILY MOTOR BEHAVIORS involve bilateral arm movements. This ability is largely impaired in individuals with cervical spinal cord injury (SCI) (Herrmann et al. 2011; Spooren et al. 2009). Bilateral arm movements entail anatomical and physiological interactions between neuronal structures crossing the body midline (Alstermark and Isa 2012; Jankowska 2008; Swinnen and Wenderoth 2004). Animal models showed that SCI significantly damages neural circuits at the body midline (Oudega and Perez 2012), resulting in extensive sprouting of corticospinal (Bareyre et al. 2004; Rosenzweig et al. 2010) and spinal (Fenrich et al. 2007; Fenrich and Rose 2009) interneurons, which cross the midline and might play a role in the modulation of bilateral motor behaviors. In humans, most injuries to the spinal cord result in bilateral anatomical damage (Bunge et al. 1993; Kakulas 2004) and functional impairments in both arms (Spooren et al. 2009). Despite this well-accepted notion and the growing emphasis on the use of bimanual training strategies (Hoffman and Field-Fote 2010, 2013), the effect of movement of one arm on the motion of the contralateral arm after SCI remains unknown.

It is well established, for bilateral reaching in uninjured control subjects, that movement with one arm affects spatial and temporal kinematics variables of the movement of the contralateral arm. For example, evidence has shown that bilateral reach-to-grasp movements have longer reaction time and movement duration, lower peak arm velocities, and larger grip apertures than unilateral movements (Castiello et al. 1993; Jackson et al. 1999; Kelso et al. 1979). The extent of upper extremity paresis also affects bilateral reach-to-grasp movements. It was shown in individuals with stroke that the paretic arm substantially delayed movement of the contralateral non-paretic arm during bilateral trials (Cunningham et al. 2002; Platz et al. 2001; Rice and Newell 2004; Rose and Winstein 2005). Although little is known about bimanual movements and interlimb coordination between arms after SCI, some studies allow some predictions. A number of individuals with cervical SCI showed an impaired ability to maintain trunk stability in the sitting position (Curtis et al. 1995; Murphy et al. 2014), which can compromise performance of bilateral arm movements (Kukke and Triolo 2004). SCI subjects also show impaired crossed facilitatory interactions between arm muscles with a decreased ability to facilitate corticospinal (Bunday et al. 2013; Bunday and Perez 2012) and spinal (Zidjewind et al. 2012) motoneuron excitability in arm muscles on one side by voluntary contraction of the contralateral arm compared with control subjects. Thus we hypothesized that abnormalities in movement kinematics and electromyographic (EMG) activation during bilateral reach-to-grasp movements after SCI will affect the reaching and grasping phases of the task. Furthermore, crossed reflexes, which may play a role in interlimb coordination via cervical commissural interneurons (Sotopoulos et al. 2013), are impaired after SCI (Calancie et al. 2005). Therefore, we also expected that interlimb coordination between arms will be reduced in humans with cervical SCI compared with control subjects. To test our hypotheses, we examined unilateral and bilateral reach-to-grasp movements to objects of different sizes because differences have been reported in muscle activation patterns when reaching for small and large objects after incomplete cervical SCI (Stahl et al. 2015).
MATERIALS AND METHODS

Subjects. Sixteen participants with SCI (mean age = 54.3 ± 12.8 yr; Table 1) and 20 age-matched uninjured control subjects (mean age = 48.4 ± 18.1 yr; P = 0.26, 7 women, 13 men) participated in the study. All subjects gave informed consent to experimental procedures, which were approved by the local ethics committee at the University of Pittsburgh. SCI participants had a chronic (>1 yr) cervical injury (C2-C7), an intact (score = 2) or impaired (score = 1) but not absent innervation in dermatomes C5 by the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) sensory scores, and residual hand and arm motor function. Participants had the ability to reach and grasp with the index finger and thumb without compensatory trunk movements. To ensure that no compensatory movements were present, the trunk was securely strapped to the testing chair as needed. Two of 16 SCI subjects were categorized by the American Spinal Injury Association Impairment Scale (AIS) as AIS A (complete injury) due to the lack of sacral sparing, despite being able to elicit voluntary force with arm muscles. Fourteen subjects were classified as incomplete AIS C and D. The stronger (SCIstrong) and weaker (SCIweak) arms in SCI participants were determined by averaging the maximum isometric voluntary contraction (MVC) quantified with background EMG activity in all muscles tested including the first dorsal interosseous (FDI), abductor pollicis brevis (APB), extensor (ECR) and flexor (FCR) carpi radialis, and anterior deltoid (AD; Fig. 1A, Table 1). We also recorded from the extensor digitorum communis (EDC) and flexor digitorum superficialis (FDS) in a subgroup of subjects (SCI, n = 8; control, n = 10). The strength of each arm was confirmed by asking individual subjects which was the stronger and the weaker arm according to their estimation, which matched the MVC results in all but one subject. This subject reported a stronger left arm but MVCs were stronger in the right arm, and therefore the right side was considered as the stronger side for analysis. His report might have been influenced by the left APB MVC values found to be above the mean of control subjects. To ensure that the determination of the stronger and weaker arms of subjects was not influenced by the number and size of muscles tested, we also quantified side differences by comparing MVCs in the FDI and APB muscles bilaterally, and similar results were obtained. Participants’ average level of MVCs in all muscles tested was different across groups [control dominant arm = 0.26 ± 0.01 mV, control nondominant arm = 0.25 ± 0.01 mV, SCIstrong = 0.21 ± 0.03 mV, SCIweak = 0.16 ± 0.02 mV; F(3,60) = 4.7, P = 0.005]. MVCs were lower in the SCI subjects’ weaker arm compared with the stronger arm (P < 0.01) and control subjects (P < 0.001). No differences were found in MVCs between the dominant and nondominant arms in control subjects (P = 0.3).

Experimental setup. Subjects were seated in a custom chair with both arms flexed at the elbow by 90° resting comfortably on an attached table top. At the start of the experiment, subjects performed two or three brief MVCs for 3–5 s with all muscles tested separated by 30–60 s of rest. All subjects participated in two randomized sessions. In one session, subjects completed unilateral and bilateral reach-to-grasp movements to a small (10-mm diameter) cylinder, and in the other session subjects completed the same movements to a large (75-mm diameter) cylinder. Subjects were instructed to reach and grasp at a comfortable self-paced speed with the index finger and thumb, but not lift, a small and a large cylinder located in front of them. Subjects were not allowed to slide the hand/forearm on the table to perform the movement. Objects were affixed to a table top at a distance that required subjects to maximally extend their arms without leaning forward and at a height that required individuals to flex the shoulder by ~90°. The height of the table was adjusted to the arm length, such that all participants began the experiment with the arms positioned in the same configuration. The starting position for each trial was with the elbows at 90° and the forearms in the neutral position with the tip of the index finger and thumb touching each other on top of a testing table. A computer positioned in front of the subject provided an auditory GO cue (lasting 200 ms) at the start of each trial by playing a sound file of the word “Left” (unilateral left), “Right” (unilateral right), or “Both” (bilateral left and right), indicating which condition the subject needed to perform. Subjects were instructed to reach and grasp with the index finger and thumb on force sensors located at each side of each cylinder and hold the position for ~3 s until another auditory cue (“Return”) was provided. After the “Return” cue the instruction was to return their arms to the initial position. Subjects performed two 45-trial blocks; in each block 15 Left, 15 Right, and 15 Both trials were randomly presented.

Kinematic recordings. Reach-to-grasp movements were recorded with eight OptiTrack Natural Point V100 cameras (120 Hz) positioned in front and at sides of subjects. Five reflective markers (4 mm) were placed on each arm on the following locations: tip of the thumb and index finger, top of the middle knuckle, inner side of the wrist, and dorsal side of the forearm. Force sensors placed on the cylinders were synchronized with the cameras by recording the time at which the

Table 1. Subject characteristics

<table>
<thead>
<tr>
<th>SCI Subject</th>
<th>Age, yr</th>
<th>Sex</th>
<th>Level</th>
<th>AIS Score</th>
<th>Etiology</th>
<th>Time Since Original Injury, yr</th>
<th>Stronger Side (self-report)</th>
<th>MVC SCIstrong mV</th>
<th>MVC SCIweak mV</th>
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<td>C5</td>
<td>D</td>
<td>T</td>
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<td>L</td>
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<tr>
<td>2</td>
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<td>D</td>
<td>T</td>
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<td>R</td>
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<td>0.14 (L)</td>
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<td>C</td>
<td>NT</td>
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<td>R</td>
<td>0.33 (R)</td>
<td>0.31 (L)</td>
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<td>F</td>
<td>C7</td>
<td>C</td>
<td>T</td>
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<td>L</td>
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<td>D</td>
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<td>L</td>
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<td>0.10 (R)</td>
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</table>

SCI, spinal cord injury; M: male; F: female; AIS, American Spinal Injury Association Impairment Scale; T, traumatic; NT, nontraumatic; MVC, maximum voluntary contraction [averaged across muscles first dorsal interosseous (FDI); abductor pollicis brevis (APB), extensor carpi radialis (ECR), flexor carpi radialis (FCR), extensor digitorum communis (EDC), flexor digitorum superficialis (FDS), anterior deltoid (AD)]; L, left; R, right; SCIstrong, SCIweak, less and more impaired sides, respectively, based on MVC and self-report.
thumb and index finger first made contact with each cylinder. The spatial variables measured included (Fig. 1B) peak arm velocity and maximum aperture (measured relative to the final position of the fingers on the object to control for differences in marker placement). The temporal variables measured included (Fig. 1B) 1 reaction time: time between auditory GO signal and movement onset (defined as the first forward movement of the arm); 2 total movement duration: time between movement onset and grasp (time when both the index finger and thumb contacted the cylinder); 3 arm acceleration: time between movement onset and peak arm velocity; 4 hand opening: time between hand opening onset and maximum aperture between the index finger and thumb; 5 hand closing: time between the maximum aperture between the index finger and thumb and grasping the object. Note that temporal variables were not compared directly, as measures of total phase duration. Rather, changes in interval duration were compared across subjects. In other words, movement duration for unilateral trials was subtracted from movement duration for bilateral trials, in each time interval tested. In this way, movement duration was compared at each movement phase of the task (i.e., arm acceleration, hand opening, and hand closing) and during the total duration of the task (total movement duration). Interlimb coordination was measured at the end of hand opening (at the time to reach maximum hand aperture) and hand closing (at the time when the index finger made contact with the object) by quantifying peak desynchronization (defined as the absolute time difference when each limb reached the end of each of the tested events). A high value indicates that the limbs tended to reach the kinematic event at different times, whereas a value close to zero indicates that the limbs tended to reach the kinematic events simultaneously.

**EMG recordings.** EMG was recorded from the FDI, APB, ECR, FCR, EDC, FDS, and AD in both groups through surface electrodes secured to the skin over the belly of each muscle (Ag-AgCl, 10-mm diameter). The signals were amplified, filtered (20-1,000 Hz), and sampled at 2 kHz for off-line analysis (CED 1401 with Spike2 software, Cambridge Electronic Design, Cambridge, UK; off-line analysis in MATLAB, The MathWorks, Natick, MA.). Mean rectified EMG activity was smoothed with a Gaussian smoothing kernel ($\sigma = 20$ ms), normalized to the MVC in each muscle and subject tested. Time courses were aligned to each kinematic event to determine the amount of EMG activity associated with each part of the movement, averaged at 100-ms intervals (Cavanagh and Komi 1979). To determine the extent to which flexor (F) and extensor (E) muscles were activated at each phase of the task we calculated a ratio of the difference between mean rectified EMG activity in the E and F over the sum of the mean E and F activity ($(E - F)/(E + F)$; muscle activation ratio) measured in 100-ms time windows (Stahl et al. 2015).

**Data analysis.** Data in both groups were tested for normal distribution with a Shapiro-Wilk test for homogeneous variance with Levene’s test of equality and for sphericity using Mauchly’s test. Since in control subjects no differences were found in any of the kinematic variables measured in the left and right arms (and between men and women), we only report data acquired from the dominant right arm in all subjects. Repeated-measures ANOVAs were performed to determine the effects of within-subject factors TASK (unilateral, bilateral), SIDE (control dominant, SCI, and SCIwasm), and OBJECT (small, large), between-subject factor GROUP (controls, SCI), and interactions among them on reaction time, peak arm velocity, maximum hand aperture, total movement duration, and interlimb coordination. We also tested the effect of within-subject factors PHASE (arm acceleration, hand opening, and hand closing), SIDE, and OBJECT and between-subject factor GROUP on movement duration (bilateral – unilateral). Post hoc tests were performed.
with Bonferroni corrections for multiple comparisons. EMG activity between groups was compared with a two-sample, unpaired t-test applied to each 100-ms time window in the EMG time course with the α-level Bonferroni-corrected for multiple comparisons. Additional repeated-measures ANOVAs and t-tests were performed on each group separately. Correlation values used to assess interlimb coordination were converted with the Fisher z-transform for statistical analyses. The significance level was set at \( P < 0.05 \), and group data are presented as means ± SD in the text.

RESULTS

Peak arm velocity. Figure 2 illustrates arm velocity traces from representative participants. Repeated-measures ANOVA showed a significant effect of TASK \([F_{(1,34)} = 96.9, P < 0.001]\) and OBJECT \([F_{(1,34)} = 4.1, P = 0.05]\) but no effect of GROUP \([F_{(1,34)} = 0.03, P = 0.8]\) on peak arm velocity. Note that in control subjects and in both arms of SCI subjects peak arm velocity decreased during bilateral compared with unilateral trials when reaching for a large (control: \( P < 0.001, \) SCI\textsubscript{strong}: \( P < 0.01, \) SCI\textsubscript{weak}: \( P = 0.04; \) Fig. 2A) and a small (control: \( P < 0.01, \) SCI\textsubscript{strong}: \( P < 0.001, \) SCI\textsubscript{weak}: \( P = 0.02; \) Fig. 2B) object, suggesting that no impairments were present at this early part of the reach-to-grasp movement.

Maximum aperture size. Figure 3 illustrates aperture size traces from representative participants. Here, note that in the control subject and in both arms of the SCI subject, maximum hand aperture increased during bilateral compared with unilateral trials when reaching for a small but not a large object, suggesting that individuals with SCI were able to scale the hand aperture to a similar extent as control subjects.

Repeated-measures ANOVA showed a significant effect of TASK \([F_{(1,19)} = 71.2, P = 0.001]\) and OBJECT \([F_{(1,19)} = 11.4, P = 0.003]\) and in the interaction between GROUP and OBJECT \([F_{(1,33)} = 6.9, P = 0.01]\) on maximum hand aperture. We found that maximum hand aperture increased during bilateral compared with unilateral trials in control subjects (unilateral = 28.6 ± 2.2 mm, bilateral = 32.6 ± 2.5 mm, \( P < 0.001 \)) and in both arms of SCI subjects (SCI\textsubscript{strong}: unilateral = 36.7 ± 2.9 mm, bilateral = 39.4 ± 3.3 mm, \( P = 0.01; \) SCI\textsubscript{weak}, unilateral = 32.0 ± 3.0 mm, bilateral = 35.0 ± 3.1 mm, \( P = 0.03 \)) when reaching for a small object. No differences were observed in maximum hand aperture when reaching for a large object (control \( P = 0.2, \) SCI\textsubscript{strong} \( P = 0.4, \) SCI\textsubscript{weak} \( P = 0.3 \)).

Reaction time and total movement duration. Reaction times were longer during bilateral compared with unilateral trials in control subjects and in both arms of SCI subjects when reaching for both objects (\( P < 0.01 \)). Although individuals with SCI showed longer reaction times in both arms compared with control subjects, we found that differences in reaction time during bilateral compared with unilateral trials were larger in control subjects and in the stronger arm of SCI subjects compared with the weaker arm of SCI subjects when reaching for a large \([F_{(1,33)} = 3.8, P = 0.05; \) Fig. 4C] and a small \([F_{(1,33)} = 3.8, P = 0.05; \) Fig. 4D] object.

Total movement duration was longer during bilateral compared with unilateral trials in both groups, regardless of side or

Fig. 2. Peak arm velocity. Raw traces show tangential velocity of the dominant arm of control subjects (unilateral, black traces; bilateral, gray traces) and in the stronger (SCI\textsubscript{strong}: unilateral, red traces; bilateral, light red traces) and weaker (SCI\textsubscript{weak}: unilateral, green traces, bilateral, light green traces) arms of individuals with SCI when reaching for a large (A) and a small (B) object. Dotted squares show the time at which peak arm velocity was reached, and arrow points to an amplification of the same time period. Black triangles show movement onset, and colored triangles indicate the time at which peak arm velocity was reached in each of the conditions tested. Graphs show the group data [control, \( n = 20 \); spinal cord injury (SCI), \( n = 16 \)]. x-Axis shows all groups tested [control (dominant arm), SCI\textsubscript{strong}, and SCI\textsubscript{weak}]. y-Axis shows peak arm velocity expressed in meters per second. Note the decreased in peak arm velocity in both groups during bilateral compared with unilateral trials when reaching for both objects. Error bars indicate SEs. *\( P < 0.05 \).
object being tested \( [F_{(1,34)} = 139.7, P < 0.001; \text{Fig. 4, C and D}] \). Note that total movement duration was longer in the stronger arm of SCI subjects compared with control subjects and the weaker arm of subjects when reaching for a large \( (P = 0.02; \text{Fig. 4C}) \) and a small \( (P = 0.01; \text{Fig. 4D}) \) object.

**Movement duration at different phases of the movement.** In control subjects, movement duration during bilateral compared with unilateral trials was prolonged during hand closing compared with hand opening when reaching for both objects \( [F_{(1,38)} = 35.4, P < 0.001] \). Also, movement duration (bilateral compared with unilateral) was prolonged during hand opening compared with arm acceleration for both objects \( [F_{(1,38)} = 34.3, P < 0.001] \).

Repeated-measures ANOVA showed a significant effect of PHASE \( [F_{(1,34)} = 99.7, P < 0.001] \) and in the interaction between GROUP and SIDE \( [F_{(1,34)} = 12.6, P = 0.001] \) on movement duration during bilateral compared with unilateral trials. We found an increased movement duration in the stronger arm of SCI subjects during hand opening when reaching for a large object \( (P = 0.03; \text{Fig. 4A and E}) \) and during hand closing when reaching for a small object \( (P = 0.02; \text{Fig. 4B and F}) \). Note that the majority of subjects \( (13/16) \) showed increased movement durations in the stronger arm during hand opening for the large object and during hand closing for the small object compared with control subjects. Notably, no differences were found in the weaker arm across conditions compared with the control subjects \( (P = 0.1) \). Also, no differences were found in arm acceleration between groups and conditions \( (P = 0.4) \).

**Interlimb coordination.** Repeated-measures ANOVA showed an effect of GROUP on peak desynchronization measured at maximum hand aperture \( [F_{(1,34)} = 15.9, P < 0.001] \) and index finger contact \( [F_{(1,34)} = 12.5, P = 0.001; \text{Fig. 5}] \). Here we found that SCI individuals showed higher peak desynchronization compared with control subjects when reaching for a large \( (\text{control} = 93 \pm 12 \text{ ms}, \text{SCI} = 282 \pm 51 \text{ ms}, P = 0.002) \) and a small \( (\text{control} = 74 \pm 5 \text{ ms}, \text{SCI} = 154 \pm 29 \text{ ms}, P = 0.01) \) object at maximum hand aperture. Similarly, peak desynchronization was higher at the time when the index finger made contact with the object in SCI individuals compared with control subjects when reaching for both objects \( (\text{large: control} = 156 \pm 22 \text{ ms}, \text{SCI} = 286 \pm 38 \text{ ms}, P = 0.006; \text{small: control} = 176 \pm 22 \text{ ms}, \text{SCI} = 323 \pm 56 \text{ ms}, P = 0.02; \text{Fig. 5}) \). Note that peak desynchronization in SCI subjects was higher when reaching for a large compared with a small object during maximum hand aperture \( (P = 0.004) \) but not during index finger contact \( (P = 0.5) \). Also note that in control subjects values of peak desynchronization were similar for both object sizes at both kinematic events \( (P = 0.9) \). Thus our results indicate that the hands of SCI subjects tended to reach kinematic events at different times (higher desynchronization) compared with control subjects, who had the tendency to reach these events with both hands at a closer time. A positive correlation was found between peak desynchronization at max-
imum hand aperture and movement duration (bilateral − unilateral) during hand opening when reaching for a large ($r = 0.65, P = 0.005$; Fig. 6A) but not a small ($r = 0.15, P = 0.5$; Fig. 6A) object. Also, peak desynchronization during index finger contact correlated with movement duration (bilateral − unilateral) during hand closing when reaching for a large ($r = 0.71, P = 0.002$; Fig. 6B) but not a small ($r = 0.2, P = 0.4$; Fig. 6B) object.

**EMG activity.** We focus our EMG analysis on FDI, EDC, and FDS since these muscles showed changes during the phases of the task with kinematic differences across groups.

First, we observed an increase in movement duration during bilateral compared with unilateral trials during hand opening in the stronger arm of SCI subjects when reaching for a large object. In this phase, EDC ($P < 0.01$) and FDS ($P < 0.01$) muscle activation in both arms of SCI subjects was larger compared with control subjects during unilateral and bilateral trials.

Figure 7, A and B, illustrate EMG activity in EDC and FDS muscles during hand opening in representative participants when reaching for a large object. Repeated-measures ANOVA showed a significant effect of GROUP [$F_{(1,16)} = 4.2, P = 0.04$] and TASK [$F_{(1,16)} = 4.9, P = 0.04$] and in the interaction between GROUP, TASK, and SIDE [$F_{(1,16)} = 4.2, P = 0.04$] on EDC and FDS muscle activation ratio. In control subjects, this ratio decreased during bilateral compared with unilateral trials during hand opening when reaching for a large ($P = 0.03$; Fig. 7C) and a small ($P < 0.01$; Fig. 7F) object. Note that...
the ratio decreased because of a decrease in EDC muscle activity (large: by 12.1 ± 2.9%, \( P = 0.004 \); small: by 14.9 ± 3.8%, \( P = 0.001 \)) while FDS activity remained similar during bilateral compared with unilateral trials. In contrast, this ratio increased in the stronger arm of SCI subjects during bilateral compared with unilateral trials when reaching for a large (\( P = 0.04 \); Fig. 7D) but not a small (\( P = 0.7 \); Fig. 7G) object. Here, the ratio increased because EMG activity decreased in FDS (by 13.2 ± 5.2%) and EDC (by 10.1 ± 3.1%) muscles during bilateral compared with unilateral trials. The ratio did not change in the weaker arm when reaching for both objects (large: \( P = 0.7 \); Fig. 7E; small: \( P = 0.2 \); Fig. 7H).

Second, we found an increase in movement duration during bilateral compared with unilateral trials when closing the hand in the stronger arm of SCI participants when reaching for a small object. Repeated-measures ANOVA showed a significant effect of GROUP \( [F_{(1,30)} = 15.0, P < 0.01] \), OBJECT \( [F_{(1,30)} = 4.4, P = 0.04] \), and TASK \( [F_{(1,30)} = 30.9, P < 0.001] \) and in their interaction \( [F_{(1,30)} = 7.1, P = 0.01] \) on mean rectified FDI EMG. In control subjects, EMG activity in the FDI decreased during bilateral compared with unilateral trials when reaching for a large (by 16.9%, \( P < 0.01 \); Fig. 8A) and a small (by 24.7%, \( P < 0.001 \); Fig. 8B) object. In SCI subjects, EMG activity decreased in the FDI muscle in the stronger and weaker arms during bilateral compared with unilateral trials when reaching for a large object (SCI\textsubscript{strong}: by 17.1%, \( P = 0.01 \); Fig. 8C; SCI\textsubscript{weak}: by 17.9%, \( P < 0.01 \); Fig. 8E). When reaching for a small object, EMG activity decreased in the stronger (SCI\textsubscript{strong}: by 12.2%, \( P = 0.04 \); Fig. 8D) but not weaker (SCI\textsubscript{weak}: by 3.5%, \( P = 0.5 \); Fig. 8F) arm. Note that the suppression of FDI muscle activity in the stronger arm of SCI subjects was lesser than controls (\( P < 0.01 \)) matched the interval in which we observed abnormal kinematic movement duration differences.

DISCUSSION

The main finding of this study is that in humans with asymmetric functional impairments in the arms due to incomplete cervical SCI the more impaired arm has a detrimental influence on the motion of the less impaired arm. Specifically, movement duration was prolonged during hand opening and closing when reaching for a large and a small object, respectively, accompanied by deficient activation of finger flexor and

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**Fig. 5.** Interlimb coordination. Group data for control subjects and SCI individuals showing peak desynchronization [the mean absolute time difference between when each hand reached maximum aperture and when each index finger made contact with the target when reaching for a large (A) and a small (B) object]. Values near 0 indicate that both limbs reach the tested interval at nearly the same time, whereas large values indicate that one arm completed the movement phase much earlier than the other, regardless of the hand. Error bars indicate SEs. *\( P < 0.05 \).

**Fig. 6.** Correlation between movement duration and interlimb coordination. Graphs show a correlation analysis between changes in movement duration (BIL - UNIL = bilateral minus unilateral) and peak desynchronization during maximum hand aperture (A) and index finger contact (B) when reaching for a large and a small object. Note that subjects with prolonged movement duration during hand opening and closing were those who showed lesser interlimb coordination at maximum hand aperture and index finger contact when reaching for a large object. Error bars indicate SEs. *\( P < 0.05 \). n.s., Not significant.
extensor muscles. Interlimb coordination was reduced in individuals with SCI compared with control subjects, and individuals with lesser coordination between hands showed prolonged times to open the hand. Notably, the weaker arm of SCI subjects showed movement durations during bilateral compared with unilateral trials that were proportional to control subjects. Thus, for the first time, we demonstrate asymmetric influences between movements of the arms after human SCI.

Bilateral reach-to-grasp movements after SCI. Our results in control subjects agree with previous findings showing that bilateral movements have longer reaction times and total movement duration, lower peak arm velocities, and larger grip apertures than unilateral movements (Castiello et al. 1993; Jackson et al. 1999, 2002; Kelso et al. 1979). In individuals with SCI, we found movement durations twofold longer than in control subjects during bilateral compared with unilateral trials in the stronger but not in the weaker arm of SCI subjects. This agrees with previous results in individuals with stroke showing that the paretic arm substantially delayed the total movement duration of the contralateral nonparetic arm (Cunningham et al. 2002; Dickstein et al. 1993; Platz et al. 2001; Rice and Newell 2004; Rose et al. 2005). Interestingly, the aberrant increases in movement duration during bilateral trials in our study arose from the time to open and close the hand but not from arm acceleration, consistent with the view that grasping is the phase where visual and proprioceptive online adjustments and corrections take place (Gentilucci et al. 1994; Jeannerod 1981). Specifically, we found that when reaching for a large object the time to open the hand was increased, whereas when reaching for a small object the time to close the hand was increased. It is important to note that in control subjects, the time to open and close the hand progressively increased during bilateral compared with unilateral trials, regardless of the object and arm tested. Thus most of the increases in movement duration
during bilateral trials in control subjects took place when closing the hand. This is consistent with the view that reach-to-grasp movements cannot be seen as a single action but rather as dissociable and largely independent components (Jeannerod 1981; Rand et al. 2008). It is possible that in control subjects the increases in movement duration during hand closing relate to the need to accurately grasp the object. This is supported by evidence showing that demand for precise control during grasping gradually increases when approaching the object (Paulignan et al. 1991) and that the degree of task difficulty increases the duration of a movement (Dohle et al. 2000). Thus, after SCI, the degree of difficulty might vary across the different phases of the reach-to-grasp task. It might be more difficult to open the hand when reaching for a large compared with a small object because of the object size, whereas when closing the hand the difficulty might be in scaling the hand aperture to accurately grasp the object, which will require more precision for the smaller than for the larger object. This is supported by the time-specific deficits in EMG activity in hand muscles during these phases of the task. For example, we observed an abnormal activation of the EDC and FDS muscles in the stronger arm of SCI subjects, compared with control subjects, when opening the hand and reaching for a large but not a small object. Note that in this part of the movement not only did SCI subjects activate the EDC and FDS to a larger extent than control subjects but also the degree to which these antagonistic muscles were activated in relation to each other was different from control subjects. We found lesser activation in the FDS muscle during bilateral compared with unilateral trials in the stronger arm of SCI subjects but not in control subjects, whereas activity in the EDC muscle changed to a similar extent in both groups. This agrees with a previous study showing a lesser activation of flexor than extensor muscles during hand aperture after SCI (Stahl et al. 2015). Lesser EMG activity is observed during slow compared with fast finger movements (Tazoe and Perez 2013); thus it is possible that lesser muscle activity in finger flexors contributed to some extent to the longer movement duration observed during hand opening. We also found that when closing the hand EMG activity in the FDI muscle decreased to a lesser extent in the stronger arm of SCI subjects compared with control subjects, when reaching for a small but not a large object. Evidence showed that deficits in proprioception particularly increased the duration of hand closure during reach-to-grasp movements (Gentilucci et al. 1994). Then, it is possible that sensory deficits in the hand after SCI contributed to the increases in movement during hand closing. Interlimb coordination must be flexible to adjust to changes in the duration of the different phases of a movement (Thibaudier and Frigon 2014). Interestingly, interlimb coordination was altered during hand opening to a larger extent when reaching for a large compared with a small object, and individuals with lesser coordination between hands were those who showed prolonged times to open the hand when reaching for a large object. It is tempting to speculate that these distinct changes in movement kinematics, muscle activity pattern, and interlimb coordination after SCI might be linked during hand opening. However, specific interactions between these variables during hand opening and closing as well as the neural mechanisms involved in these distinct patterns of EMG activity during the different phases of the task remain to be tested. It is less likely that our results were related to the divided attention of individuals during bilateral compared with unilateral trials because of the selective kinematics and EMG deficits observed across the different phases of the reach to grasp for the different objects and arms. Also, it is less likely that muscle weakness contributed to our findings, since increases in bilateral movement duration were present in the stronger but not in the weaker arm of SCI subjects. The ability to perform bilateral reach-to-grasp movements largely depends on trunk stability (Kukke and Triolo 2004; Murphy et al. 2014). Since our SCI subjects were able to perform reach-to-grasp movements without compensatory trunk movements and additional trunk support was provided as needed, it is less likely that this factor affected our results. Indeed, trunk stabilization maneuvers increase bimanual reaching capabilities after cervical SCI (Curtis et al. 1995; Kukke and Triolo 2004).

Another intriguing question is why increases in bilateral movement durations found during hand grasping were present in the stronger but not in the weaker arm of SCI subjects. The neural control of grasping in mammals has been associated with the contribution of the motor cortex and the corticospinal system (Lemon 2008). More recent studies showed that subcortical networks also contribute to modulating the excitability.
of spinal motoneurons during grasping in primates (Takei and Seki 2013) and in humans with incomplete cervical SCI (Bunday et al. 2014). The C1–C4 propriospinal system also provides an alternative and viable pathway for the control of grasping (Alstermark and Isa 2012). Furthermore, crossed spinal neuronal pathways are involved in interlimb coordination between arms muscles (Zehr et al. 2001), and some of these spinal connections might contribute to grasping and hand stabilization (Bawa et al. 2000). Importantly, crossed reflexes are impaired in individuals with incomplete cervical SCI (Calancie et al. 2005). Thus the most parsimonious explanation is that the changes and/or abnormalities in transmission in all or some of these pathways contributed to the time-specific abnormal EMG activity in finger flexors and extensor muscles compared with control subjects. The reason why transmission in these pathways might be more affected in one than the other direction is unclear. However, the lack of or impaired modulation of EMG activity in finger flexor and extensor muscles in both arms during bilateral compared with unilateral trials suggests that deficits after SCI reside in a decreased ability to send and/or receive neural inputs between the limbs consistent with previous observations showing impaired bilateral crossed interactions between arm muscles (Bunday et al. 2013; Bunday and Perez 2012; Zijderveld et al. 2012).

**Functional significance.** An increasing number of studies report the beneficial effect of bimanual training strategies in individuals with incomplete SCI (Hoffman and Field-Fote 2010, 2013; Spooren et al. 2009). Indeed, several lines of evidence suggest that crossed interactions between the arms might be beneficial in situations in which the stronger limb can be used to induce neural adaptations that facilitate motor outputs in the weaker limb in individuals with motor disorders (Renner et al. 2005; Stromberg 1986; Woldag et al. 2004). Our results show that after SCI the more impaired arm has a detrimental influence on the motion of the less impaired arm. However, no beneficial and/or detrimental effects were observed in the more impaired arm during the motion of the less impaired arm, emphasizing that caution must be taken in extrapolations of cross interaction effects across arms. Importantly, we showed that small manipulations, such as changes in the object size, might have a great impact in grasping actions during bilateral movements after SCI, which might represent a strategy to enhance movements that are not present or are decreased and/or to suppress unwanted movements. Also, interlimb coordination between arms might represent an outcome to consider during bimanual strategies, as it is considered in other motor disorders such as stroke (Rose and Winston 2013).

**REFERENCES**


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