Bilateral Reach-to-Grasp Movement Asymmetries after Human Spinal Cord Injury

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Abstract

Cervical spinal cord injury (SCI) in humans typically damages both sides of the spinal cord resulting in asymmetrical 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 multi-channel electromyographic (EMG) recordings we studied unilateral and bilateral reach-to-grasp movements of a small and large cylinder in individuals with asymmetric arm impairments due to cervical SCI and age-matched controls. We found that the stronger arm of SCI subjects showed movement durations longer than controls 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, inter-limb coordination was reduced compared with controls, 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.
**Introduction**

Most of our daily motor behaviors involve bilateral arm movements. This ability is largely impaired in individuals with cervical spinal cord injury (SCI; Spooren et al. 2009; Herrmann et al. 2011). Bilateral arm movements entail anatomical and physiological interactions between neuronal structures crossing the body midline (Swinnen and Wenderoth 2004; Jankowska 2008; Alstermark and Isa, 2012). 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 interneurones (Fenrich et al. 2007; Fenrich and Rose 2009) which cross the midline and play a role in the modulation of bilateral motor behaviors (Carmel and Martin 2014). In humans, most injuries to the spinal cord result in bilateral anatomical damage (Kakulas 2004; Bunge et al. 1993) 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 (Field-Fote and Hoffman 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 controls, that movement with one arm affects spatial and temporal kinematics variables of the movement of the contralateral arm. Evidence showed that bilateral reach-to-grasp movements have longer reaction time and movement duration, lower peak arm velocities and larger grip apertures than unilateral movements (Kelso et al. 1979; Castiello et al. 1993; Jackson et al. 1999). The extent of upper extremity paresis also affects bilateral reach-to-grasp movements. For example, it was shown in individuals with stroke that the paretic arm substantially delayed movement of the contralateral non-paretic arm during bilateral trials (Rice and Newell 2004; Platz et al. 2001; Cunningham et
al. 2002; Rose and Winstein 2005). Although little is known about bimanual movements and
inter-limb coordination between arms after SCI, some studies allow some predictions. For
example, 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 and Perez 2012; Bunday et al. 2013) and spinal motoneurone
(Zidjewind et al. 2012) excitability in arm muscles on one side by voluntary contraction of the
contralateral arm compared with controls. Furthermore, crossed reflexes, which may play a role
in interlimb coordination via cervical commissural interneurons (Soteropulos et al. 2013), are
impaired after SCI (Calancie et al. 2005). 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. We also expected that inter-
limb coordination between arms will be reduced in humans with cervical SCI compared with
controls. 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 years; Table 1) and 20 age-matched uninjured controls (mean age=48.4±18.1 years, p=0.26, 7 female) 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 year), cervical injury (C3-C8), an intact (score=2) or impaired (score=1) but not absent innervation in dermatomes C6 using 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 out of 16 SCI subjects were categorized by the American Spinal Cord Injuries 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 (SCI\text{strong}) and weaker (SCI\text{weak}) arm in SCI participants was determined by averaging the maximum isometric voluntary contraction (MVC) quantified using 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; controls, n=10). The strength of each arm was confirmed by asking individual subjects which was the stronger and weaker arm according to their estimation, which matched the MVC results in all but one subject. This subject reported a left stronger 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 controls. To ensure that the determination of the stronger and weaker arm 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 (controls dominant arm=0.26±0.01 mV, controls non-dominant arm=0.25±0.01 mV, SCI\text{strong}=0.21±0.03 mV, SCI\text{weak}=0.16±0.02 mV; F(3,68)=4.7, p=0.005). MVCs were lower in the SCI subjects weaker compared to the stronger arm (p<0.01) and controls (p<0.001). No differences were found in MVCs between the dominant and non-dominant arm in controls (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 2-3 brief MVCs for 3-5 s with all muscles tested separated by 30 to 60 s of rest. All subjects participated in 2 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 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°, forearms in the neutral position with the tip of the index finger and thumb touching each other positioned 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 was 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 seconds 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 using eight OptiTrack Natural Point V100 cameras (120 Hz) positioned in front and 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 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). Inter-limb 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 (20–1000 Hz), and sampled at 2 kHz for off-line analysis (CED 1401 with Spike2 software, Cambridge Electronic Design, UK, off-line analysis in MATLAB, The MathWorks Inc, Natick, MA). Mean rectified EMG activity was smoothed with a Gaussian smoothing kernel (σ=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 to which extent 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 using a Shapiro-Wilk’s test for homogeneous variance with Levene’s test of equality and for sphericity using Mauchy’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 males and females), 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 (controls dominant, SCIstrong, SCIweak), OBJECT (small, large), and a between subject factor GROUP (controls, SCI) and interactions among them on reaction time, peak arm velocity, maximum hand aperture, total movement duration, and inter-limb coordination. We also tested the effect of within-subject factors PHASE (acceleration, hand opening, and hand closing), SIDE, OBJECT, and a 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 using a 2-sample, unpaired t-test applied to each 100 ms time window in the EMG time course with the alpha level Bonferroni-corrected for multiple comparisons. Additional repeated measures ANOVAs and t-tests were performed on each group separately. Correlation values used to assess inter-limb coordination were converted using the Fisher z-transform for
statistical analyses. The significance level was set at $P<0.05$ and group data are presented as mean±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 controls and in both arms of SCI subjects peak arm velocity decreased during bilateral compared with unilateral trials when reaching for a large (controls: $p<0.001$, SCI\text{strong}: $p<0.01$; SCI\text{weak}: $p=0.04$; Fig. 2A) and a small (controls: $p<0.01$, SCI\text{strong}: $p<0.001$; SCI\text{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 to 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 controls.

Repeated-measures ANOVA showed a significant effect of TASK ($F_{(1,19)}=71.2$, $p=0.001$), 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 controls (unilateral=28.6±2.2 mm, bilateral=32.6±2.5 mm, $p<0.001$) and in both arms of SCI subjects (SCI\text{strong}, unilateral=36.7±2.9...
mm, bilateral=39.4±3.3 mm, p=0.01; SCI_{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 (controls, p=0.2; SCI_{strong} p=0.4; SCI_{weak} p=0.3).

Reaction time and total movement duration

Reaction times were longer during bilateral compared with unilateral trials in controls 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 controls, we found that difference in reaction time during bilateral compared with unilateral trials were larger in controls and in the stronger arm of SCI subjects compared with the weaker arm of SCI subjects when reaching for a large \( F(1,33)=3.8, p=0.05; \text{Fig. 4C} \) and a small \( F(1,33)=3.8, p=0.05; \text{Fig. 4D} \) object. Total movement duration was longer during bilateral compared with unilateral trials in both groups, regardless of side or object being tested \( F(1,34)=139.7, p<0.001; \text{Fig. 4C-D} \). Note that total movement duration was longer in the stronger arm of SCI subjects compared with controls 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

Figure 4A-B illustrates traces of hand aperture size from representative participants. Note that in the stronger arm of the SCI subject movement duration increased, during bilateral compared with unilateral trials, during hand opening when reaching for a large object. Also, movement duration increased during hand closing when reaching for a small object. In controls, 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 to 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 ($p=0.03$; Fig. 4E) and during hand closing when reaching for a small object ($p=0.02$; Fig. 4F). 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 compared with controls. Notably, no differences were found in the weaker arm across conditions and interval compared with the control subject ($p=0.1$). Also, no differences were found in arm acceleration between groups and conditions ($p=0.4$).

**Inter-limb 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 ($F_{(1,34)}=12.5, p=0.001$; Fig. 5). Here we found that SCI individuals showed higher peak desynchronization compared with controls when reaching for a large (Large: controls=$93\pm12$ ms, SCI=$282\pm51$ ms, $p=0.002$) and a small (Small: controls=$74\pm5$ ms, SCI=$154\pm29$ ms, $p=0.01$) object at maximum hand aperture. Similarly, peak desynchronization was higher at the time when index finger made contact with the object in SCI individuals compared with controls when reaching for both objects (Large: controls=$156\pm22$ ms, SCI=$286\pm38$ ms, $p=0.006$; Small: controls=$176\pm22$ ms, SCI=$323\pm56$ ms, $p=0.02$; 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 controls values of peak desynchronization were similar for both object size 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 controls who had the tendency to reach these events with both hands at a closer time. A positive correlation was found between peak desynchronization at maximum 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 object (r=0.15, p=0.5, Fig. 6A). 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 object (r=0.2, p=0.4, Fig. 6B).

EMG activity

We focus our EMG analysis on FDI, EDC and FDS since no significant effects were found in the others muscles during the phases of the task with kinematic differences between SCI subjects and controls. First, we observed an increased 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 controls during unilateral and bilateral trials.

Figure 7A-B illustrates 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), 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 controls, 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 decreased 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. When reaching for a small object this ratio remained similar between unilateral and bilateral trials (p=0.4) and FDS activity was suppressed to a larger extent compared to trials when reaching for a large object (p=0.01). 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), 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 controls, 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 arm during bilateral compared with unilateral trials when reaching for a large object (SCIstrong: by 17.1%, p=0.01, Fig. 8C; SCIweak: by 17.9%, p<0.01, Fig. 8E). When reaching for a small object, EMG activity decreased in the stronger (SCIstrong: by 12.2%, p=0.04; Fig. 8D) but not weaker (SCIweak: by 3.5%, p=0.5; Fig. 8F) arm. Note that the lesser suppression of FDI muscle activity during bilateral movements at hand
closing for the small object on both side tested of SCI subjects (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 extensor muscles. Inter-limb coordination was reduced in individuals with SCI compared with controls 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 controls. 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 (Kelso et al. 1979; Castiello et al. 1993; Jackson et al. 1999, 2002). In individuals with SCI, we found movement durations 2-fold longer than controls during bilateral compared to 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 non-paretic arm (Dickstein et al. 1993; Rice and Newell 2004; Platz et al. 2001; Cunningham et al. 2002; 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 on-line
adjustments and corrections take place (Jeannerod 1984; Gentilucci et al. 1994). 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 to 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 compared with hand opening relates to the need to accurately grasp the object. This is supported by evidence showing that demands 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 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 controls, when opening the hand and reaching for a large but not a small object. Note that in this part of the movement SCI subjects not only activated the EDC and FDS to a larger extent than controls but also the degree to which these antagonistic muscles were activated in relation to each other was different than...
controls. We found lesser activation in the FDS muscle during bilateral compared to unilateral trials in the stronger arm of SCI subjects but not in controls whereas activity in the EDC muscle changed to 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 to 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 in controls, 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. Inter-limb coordination must be flexible to adjust to changes in the duration of the different phases of a movement (Thibaudier and Frigon 2014). Interestingly, inter-limb 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 activation pattern, and inter-limb 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 motoneurones during grasping in primates (Takei and Seki 2013) and in humans with incomplete cervical SCI (Bunday et al. 2014). The C3-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 inter-limb 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 controls. The reason why
transmission in these pathways might be more affected in one than the other direction is unclear. However, the lack or impaired modulation of EMG activity in finger flexor and extensor muscles in both arms during bilateral compared to unilateral trials, suggest that deficits after SCI reside in a decreased ability to either send and/or receive neural inputs between the limbs consistent with previous observations showing impaired bilateral cross interactions between arm muscles (Bunday and Perez 2012; Zidjewind et al. 2012; Bunday et al. 2013).

Functional significance

An increasing number of studies report the beneficial effect of bimanual training strategies in individuals with incomplete SCI (Spooren et al. 2009; Field-Fote and Hoffman 2010, 2013). 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 (Stromberg et al. 1986; Woldag et al. 2004; Reinner et al. 2005). 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 effect were observed in the more impaired arm during the motion of the less impaired arm, emphasizing that caution must be taken in extrapolations of effect of crossed interactions 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 enhance movements that are not present or decreased and/or to suppress unwanted movements. Also, decreased inter-limb coordination between the hands during hand opening and closing, might represent an outcome to consider during bimanual strategies as it is considered in other motor disorders such as stroke (Rose and Winstein 2013).
References:


Figure legends

**Figure 1. Experimental Set-up.** A. Rectified electromyographic (EMG) activity in all muscles tested including the first dorsal interosseous (FDI), abductor pollicis brevis (APB), flexor (FCR) and extensor (ECR) carpi radialis, flexor digitorum superficialis (FDS), extensor digitorum communis (EDC), and anterior deltoid (AD) during reach-to-grasp movement to a large object in a representative individual. B. Schematic of the experimental setup showing temporal and spatial kinematic variables measured during unilateral and bilateral reach-to-grasp movements. Temporal variables measured included: Reaction time (time between auditory GO signal and movement onset), Movement duration (time between movement onset and grasp), Arm acceleration (Arm accel., time between movement onset and when subjects reached peak arm velocity), Hand opening (time between the hand opening onset and maximum aperture size), Hand closing (time between the maximum aperture size and grasp). Spatial variables measured included peak arm velocity and maximum aperture size.

**Figure 2. Peak Arm Velocity (m/s).** Raw traces show tangential velocity of the dominant arm of controls (unilateral: black traces, bilateral: gray traces) and in the stronger (SCI_{strong}: unilateral=red traces, bilateral=light red traces) and weaker (SCI_{weak}: unilateral=green traces, bilateral=light green traces) arm of individuals with SCI when reaching for a large (A) and small (B) object. Dotted squares show the time at which peak arm velocity was reached and the arrow point 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 (controls, n=20 and SCI, n=16). The abscissa shows all groups tested [controls (dominant arm), SCI stronger (SCI_{strong}) and weaker (SCI_{weak}) arm]. The ordinate shows the peak arm velocity expressed in meters per second (m/s). 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.

**Figure 3. Maximum Aperture Size (mm).** Raw traces show angular displacement (i.e. distance in mm) of the dominant arm of controls (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) arm of SCI subjects when reaching for a large (A) and small (B) object. Dotted squares show the time at which maximum aperture between the index finger and thumb was reached and arrows show an amplification of the same time period. Black triangles show movement onset and colored triangles indicate the time point at which maximum aperture size was reached in each of the conditions tested. Group data is shown in graphs (n=20 and SCI, n=16). The abscissa shows all groups tested [controls (dominant arm), SCI stronger (SCI\textsubscript{strong}) and weaker (SCI\textsubscript{weak}) arm]. The ordinate shows the maximum aperture size in millimeters (mm) relative to the aperture size achieved during grasp. Note that maximum aperture size increased in all groups during bilateral compared to unilateral trials when reaching for a small but not a large object. Error bars indicate SEs. *p<0.05.

**Figure 4. Movement duration differences.** Raw traces show hand aperture size of the dominant arm of controls (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) arm of SCI subjects when reaching for a large (A) and small (B) object. Dotted squares show the time for hand opening (left column) and closing (right column) in representative subjects. The graphs show group data (controls, n=20 and SCI, n=16). In middle graphs, the abscissa shows the variable tested (Reaction Time, Movement Duration) in
controls (dominant arm, black bars), SCI stronger (SCIstrong, red bars) and weaker (SCIweak, green bars) arm when reaching and grasping a large (C) and a small (D) object. In lower graphs, the abscissa shows the intervals tested [Arm acceleration (Arm accel.), Hand opening and Hand closing in controls (dominant arm, black bars), SCI stronger (SCIstrong, red bars) and weaker (SCIweak, green bars) arm]. The ordinate shows the movement duration [(BIL (bilateral) – UNIL (unilateral)] in seconds (sec) at each interval. Note the pronounced increased in movement duration during hand opening when reaching for a large object and during hand closing when reaching for a small object in the stronger but not in the weaker arm of SCI subjects compared with controls. Error bars indicate SEs. *p<0.05.

**Figure 5. Inter-limb coordination.** Group data for controls (black bars) and SCI individuals (red bars) showing bilateral 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 small (B) object. Values near zero 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.

**Figure 6. Correlation between bilateral movement duration and inter-limb 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 (black circles) and small (red circles) object. Note that subjects with prolonged movement duration during hand opening and closing...
were those who showed lesser inter-limb coordination at maximum hand aperture and index finger contact when reaching for a large object. Error bars indicate SEs. *p< 0.05.

**Figure 7. EMG activity during hand opening.** Mean rectified EMG activity expressed as a % of MVC in the EDC (A) and FDS (B) in controls (black traces=unilateral, gray traces=bilateral) and in the stronger (red traces=unilateral, light red tracers=bilateral) and weaker (green traces=unilateral, light green traces=bilateral) arm of individuals with SCI when reaching for a large object. Group data (controls, n=10 and SCI, n=8) when reaching for a large (C-E) and small (F-H) object. The abscissa shows the trials tested in controls (dominant arm, black bars=unilateral, gray bars=bilateral), SCI\textsubscript{strong} (red bars=unilateral, pink bars=bilateral) and SCI\textsubscript{weak} (green bars=unilateral, light green bars=bilateral) arm and muscle activation ratio between EDC and FDS during unilateral and bilateral trials. The ordinate shows the amount of EMG activity in each muscle expressed as a percentage of the MVC in each muscle (% MVC; left side) and muscle activation ratio between EDC and FDS [calculated as a ratio of the difference between mean rectified EMG activity in the EDC (E) and FDS (F) over the sum of the mean E and F activity (E-F)/(E+F); right side]. Bars showing activation ratios are in the same color as the muscles tested but open. Note that the muscle activation ratio between EDC and FDS decreased during bilateral trials in controls (C, F) and remained unchanged in the weaker arm of SCI subjects (E, H) when reaching for both objects, whereas it increased in the stronger arm of SCI subjects when reaching for a large (D) but not a small (G) object. Error bars indicate SEs. *p<0.05.

**Figure 8. EMG activity during hand closing.** Graphs show group data (controls, n=20 and SCI, n=16) of mean rectified EMG activity in the FDI muscle in controls and in both arms of
individuals with SCI when reaching for a large (A, C, E) and small (B, D, F) object expressed as a % of the FDI MVC during hand closing. The abscissa shows EMG activity during hand closing (in intervals of 100 ms) during unilateral (dotted horizontal line) and bilateral trials in controls [(dominant arm, gray bars), (SCI strong, pink bars), (SCI weak, light green bars)]. The ordinate shows the amount of FDI EMG activity during bilateral compared to unilateral trials expressed as a % of MVC during unilateral trials. Note that FDI EMG decreased in all groups when reaching for a large object. However, when reaching for a small object, FDI EMG activity decreased in the stronger arm of SCI subjects to a lesser extent than controls and remained unchanged in the weaker arm of SCI participants during bilateral compared to unilateral trials. Error bars indicate SEs. *p<0.05.
Figure 2

[Diagram showing movements and velocity graphs for Controls, SCIstrong, and SCIweak, comparing peak arm velocity for large and small objects.]
Figure 3

A

Movement Onset

B

SCI_{strong}

SCI_{weak}

Aperture Size (mm), relative to grasp

LARGE OBJECT

SMALL OBJECT
Figure 4

A

Movement time diff.
Hand opening, Unilateral
Hand opening, Bilateral


SCIf

Hand opening, Unilateral
Hand opening, Bilateral


SCIw

Hand opening, Unilateral
Hand opening, Bilateral


B

Movement time diff.
Hand closing, Unilateral
Hand closing, Bilateral


C

Movement duration (BIL - UNIL - sec)
Reaction time
Total mov't duration


D

Movement duration (BIL - UNIL - sec)
Reaction time
Total mov't duration


E

Movement duration (BIL - UNIL - sec)
Arm accel.
Hand opening
Hand closing


F

Movement duration (BIL - UNIL - sec)
Arm accel.
Hand opening
Hand closing

LARGE OBJECT

SMALL OBJECT
Figure 5

A

B

Peak Desynchronization (sec)

Controls

SCI

Maximum hand aperture

Index finger contact

LARGE OBJECT

SMALL OBJECT
Figure 6

A. Maximum Hand Aperture Peak Desynchronization (sec)

B. Index Finger Contact Peak Desynchronization (sec)

- Movement duration (BIL. - UNIL., sec), Hand opening
- Movement duration (BIL. - UNIL., sec), Hand closing

- Large
- Small

p = 0.006
n.s.
p = 0.002
n.s.
Figure 7

(A) Graph showing the muscle activation ratio over time after hand opening onset (sec). Unilateral (Unil.) and bilateral (Bil.) activations are compared.

(B) Similar graph to (A) but focused on different parameters.

(C) Bar graph showing EMG activity (% MVC) for EDC and FDS muscles, with significant differences indicated (*).

(D) Bar graph similar to (C) but with additional data points for the ratio.

(E) Graph showing muscle activation ratio, with significant differences indicated (*).

(F) Similar to (C) with additional data points for the ratio.

(G) Similar to (D) with additional data points for the ratio.

(H) Graph similar to (E) with additional data points for the ratio.
Table 1

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<th>Gender</th>
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<th>AIS Score</th>
<th>Aetiology</th>
<th>Time since original injury (yrs)</th>
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<th>MVC SCI\textsubscript{strong} (mV)</th>
<th>MVC SCI\textsubscript{weak} (mV)</th>
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SCI: Spinal Cord Injury; M: male; F: female; AIS: American Spinal Injury Association impairment scale; T: traumatic; NT: non-traumatic; MVC: maximum voluntary contraction (averaged across muscles FDI: first dorsal interosseous, APB: abductor pollicis brevis, ECR: extensor carpi radialis, FCR: flexor carpi radialis, EDC: extensor digitorum communis, FDS: flexor digitorum superficialis, AD: anterior deltoid); L: left; R: right; SCI\textsubscript{strong}, SCI\textsubscript{weak}: less and more impaired sides, respectively, based on MVC and self-report.