Arm movements can increase leg muscle activity during submaximal recumbent stepping in neurologically intact individuals

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Arm movements can increase leg muscle activity during submaximal recumbent stepping in neurologically intact individuals. J Appl Physiol 115: 34–42, 2013. First published May 9, 2013; doi:10.1152/japplphysiol.00510.2012.—Facilitation of leg muscle activity by active arm movements during locomotor tasks could be beneficial during gait rehabilitation after spinal cord injury. The present study explored the effects of arm movements on leg muscle activity during submaximal recumbent stepping. Healthy subjects exercised on a recumbent stepping machine both with and without arm movements. Activity of five leg muscles was recorded and compared for stepping with and without arm movements. To determine which arm movements are optimal for leg muscle facilitation, subjects were instructed to step with 1) mechanically coupled vs. decoupled arm and leg movements, 2) synchronous vs. asynchronous arm movements, and 3) at 50 vs. 70 RPM. Leg muscle activity was increased by active arm movements in all muscles, except the vastus lateralis muscle. Activity of other extensors (soleus, medial gastrocnemius, and biceps femoris) was primarily increased during the extension phase, whereas activity of flexors (tibialis anterior) was also increased during the flexion phase. Facilitation was more or less consistent for both frequencies and for synchronous and asynchronous movements. For coupled arm movements, facilitation tended to be diminished or absent. The observed facilitation in the present study is probably of neuromuscular rather than biomechanical origin, since the arms are probably hardly involved in postural control or weight-bearing during recumbent stepping. Further studies in patients should explore the possibility to integrate neuromuscular facilitation in rehabilitation programs.

During walking and other rhythmic tasks, such as recumbent stepping, the lower as well as the upper limbs move in a coordinated pattern consisting of alternate flexion and extension (26). In contrast, during gait rehabilitation after a spinal cord injury (SCI), arm movements are often not involved. Generally, the arms are used for external support or for postural balance, such as during body weight-supported treadmill training (BWSTT) or when walking with assistive devices. Clinical observations suggest, however, that reciprocal swinging of the arms facilitates stepping in incomplete SCI individuals (1, 25). There is indeed some experimental evidence that arm movements can influence lower-limb muscle activity during treadmill walking (21, 22). In this study, stroke patients walked while holding onto handles that were allowed to slide along horizontal handrails (22). It was found that these arm movements influenced activity in leg muscles. However, some of these changes could be due to differences in postural stability that occurred when the rails were held. In addition, when patients had to hold onto fixed handrails, part of the body weight was supported by the arms. Arm swing primarily serves to stabilize the trunk during walking or running and to maintain body equilibrium (10, 20). However, this does not exclude a facilitation of leg muscle activity.

To circumvent this problem of postural stability and weight-bearing, some groups have opted to use an alternative locomotion-like movement, such as recumbent stepping, to demonstrate facilitation of leg muscles by arm movements (13–15). First, it was shown that muscle activity in passively moved legs was increased by maximal arm exertion (13). Arm and leg movements were mechanically decoupled to keep the biomechanical constraints for both the arms and legs similar among the experimental conditions. Arm movements did not influence muscle activity of maximally active legs (14). Comparable results were reported in a group of incomplete SCI patients (15). However, with maximum muscle activation, it is hard to prove facilitation (ceiling effect). Hence, the authors suggested that the effect on submaximally active legs should be investigated in future studies. This would be more clinically relevant as well, since the legs are usually submaximally active during gait rehabilitation, and an effect on submaximally active legs might therefore improve locomotor function.

The general aim of the present study was to explore the effect of arm movements on leg muscle recruitment during submaximal recumbent stepping. If submaximally active legs can be facilitated by arm movements, such facilitation can help to improve rehabilitation therapies where leg effort is usually submaximal as well. Since arm movements are hardly needed for weight-bearing or postural control during recumbent stepping, their effects on leg muscle activity presumably result from neural coupling rather than from biomechanical influences. The results obtained during recumbent stepping should therefore give more insight in the mechanisms of interlimb coupling during locomotor tasks. In this study, four different questions were addressed. The main question (question 1) was whether arm movements facilitate leg muscles during submaximal recumbent stepping. It was further hypothesized that such facilitation can only be present for mechanically decoupled arm and leg movements, where the mechanical work for the legs is not influenced by arm movements. For coupled arm and leg movements (as during regular recumbent stepping), arm
movements decrease the mechanical demands for the legs and, thereby, the required levels of muscle activity. To confirm this hypothesis, the next question (question 4) was whether arm movements have to be examined, namely whether arm movements would decrease leg muscle activity when arm and leg movements are mechanically coupled.

If leg muscle facilitation occurs, it is also important to know what type of arm movement is optimal to be able to develop an effective training program. For this purpose, two more questions were addressed. The first of those two questions (question 3) was as to which frequency is optimal for leg muscle facilitation by arm movements. This question is relevant since reflex experiments have shown that neural coupling between arms and legs is influenced by movement frequency (16). During passive recumbent stepping, lower-limb muscle recruitment by arm movements was increased at higher frequencies (17). If such an effect would be present during submaximal movement frequency was increased at higher frequencies (17). If such an effect would be present during submaximal stepping, higher stepping frequencies should be recommended for rehabilitation programs. A related question (question 4) was examined, namely whether arm movements have to be alternating to be effective. More specifically, question 4 was whether asynchronous (ASYNC) arm movements are superior to synchronous arm movements (SYNC) for leg muscle facilitation. Although the fundamental locomotor coordination pattern consists of ASYNC arm movements, this mode has not been proven to be superior in the facilitation of leg muscle activity. Behavioral studies have shown that, for bimanual cyclic movements, the ASYNC movements are less stable (e.g., more difficult to perform) than SYNC movements (23). On the basis of this literature it is difficult to predict what mode of arm movements would be superior, but since ASYNC is the more natural way of interlimb coordination during gait, one would expect this mode to be slightly more advantageous.

METHODS

A group of 10 healthy subjects (2 men, 8 women; age 37.9 ± 12.1 yr) was recruited for the study. Exclusion criteria were neurological or motor disorders, reduced exercise tolerance, contraindications for exercise, medication influencing reaction time, or a pacemaker. All participants signed an informed consent, and the protocol was approved by the Medical Ethical board for the region Arnhem-Nijmegen. The study was conducted according to the Declaration of Helsinki.

Experimental setup. Throughout the experiment, subjects were seated on a recumbent stepping machine (Fig. 1; Biostep, Biostep Clinical Pro, Biodex Medical System New York). During regular recumbent stepping, the arms move 180° out of phase with the ipsilateral leg. For the legs, the extension phase of the stepping movement is equivalent to the stance phase during walking (26). Usually, arm and leg movements are mechanically coupled during recumbent stepping (Fig. 1A). To examine the neural coupling between arms and legs, there was a need to decouple the arm and leg movements mechanically. For this purpose, separate handles were mounted on both sides of the Biostep (Fig. 1B). While using these handles, arm and leg movements were mechanically decoupled, and arm movements equivalent to the ones on the stepping machine were performed without substantial external resistance. Feet and arms were attached to the pedals and separate handles with Velcro strips. Trunk movements were not restricted, since it has been demonstrated that neural interlimb coupling is more pronounced with unrestricted head and trunk movements (12).

The Biostep has 10 resistance levels and an isokinetic resistance mode. Using the isokinetic mode resistance increases when work rate increases, such that stepping frequency can be kept constant. A metronome was used to guide the subjects an idea of the intended frequency. Since an increase in muscle activity is expected to increase work rate, isokinetic resistance was used during the experiments to be able to detect differences in muscle activity without influencing movement frequency.

Surface electromyography (EMG, ZeroWire, Aurion) was recorded bilaterally of the tibialis anterior (TA), vastus lateralis (VL), biceps femoris (BF), gastrocnemius medialis (MG), soleus (SO), deltoideus anterior (DA), and deltoideus posterior (DP) muscles. On each muscle, two electrodes (Kendall ECG, 2.0-cm diameter) were placed parallel to the muscle fibers with an interelectrode distance of 2 cm. Signals were preamplified and low- (1,000 Hz) and high-pass (10 Hz) filtered. Joint angles of bilateral elbow (ELB) and knee (KNE) were registered by electrogoniometers (Goniometer System, Biometrics). A three-dimensional motion-analysis system (VICON, Oxford, UK) was used to monitor the movement of the recumbent steppers’ left pedals. These kinematic data were used to determine the start of extension and flexion phases. EMG signals were sampled with 2,000 Hz, and kinematic data were sampled with 100 Hz.

Experimental protocol. Subjects were allowed to practice on the Biostep to become familiar with recumbent stepping and isokinetic resistance. Before each condition, practice was allowed as well. A control condition with a total of 20 movement cycles, during which

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**Fig. 1.** Experimental setup for the mechanically coupled (A; regular handles) and decoupled condition (B; separate handles). Separate handles were mounted on both sides of the Biostep to allow mechanically decoupled arm movements in the synchronous (SYNC) and asynchronous (ASYNC) mode.
subjects stepped at 50 RPM at the lowest resistance level, was recorded. These recordings were used for EMG normalization.

After familiarization, six experimental conditions (Table 1) were recorded in a semi-random order to answer the four questions mentioned in the introduction. The conditions were defined as follows. The first letter explains whether arm movements were synchronous (S) or asynchronous (A). The number represents the movement frequency. The final letter indicates whether the arm movements were mechanically coupled (C) or decoupled (D). In each condition, subjects were instructed to step at a comfortable pace and to focus on the rhythm of a metronome instead of on the isokinetic resistance. During each experimental condition, a series of 15 stepping cycles without arm movements (ARMS/H11002) was altered with a series of 15 cycles with arm movements (ARMS/H11001), such that there were five series with and six series without arm movements for each condition (Fig. 2). During the ARMS/H11002 cycles, the arms were resting on the separate handles for the decoupled conditions and held in front of the chest for the coupled conditions.

Table 1. Experimental conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>Frequency, RPM</th>
<th>Phasing of Arm Movements</th>
<th>Mechanical Coupling</th>
<th>Question Addressed</th>
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<tbody>
<tr>
<td>A50D</td>
<td>50</td>
<td>Asynchronous</td>
<td>Decoupled</td>
<td>Question 1</td>
</tr>
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<td>Question 4</td>
</tr>
<tr>
<td>A70D</td>
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<td>Decoupled</td>
<td>Question 3</td>
</tr>
<tr>
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<td>Questions 3 and 4</td>
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<td>Coupled</td>
<td>Question 2</td>
</tr>
<tr>
<td>A70C</td>
<td>70</td>
<td>Asynchronous</td>
<td>Coupled</td>
<td>Questions 2 and 3</td>
</tr>
</tbody>
</table>

Phasing (A, asynchronous; S, synchronous), frequency (in RPM), mechanical coupling (D, decoupled; C, coupled). The experimental conditions were carried out in a semi-random order. See introduction for definition of questions.

To answer question 1, ARMS+ cycles were compared with ARMS− cycles. For question 2, a condition with decoupled arms and legs (A50D) was compared with a similar condition with coupled arm and leg movements (A50C). To address question 3, all conditions were repeated at a frequency of 70 RPM (A70D, A70C). For question 4, the decoupled conditions were, in addition to the asynchronous arm movements, performed with synchronous arm movements (S50D, S70D).

Data analysis. EMG signals were first processed with a high-pass (cutoff frequency of 20 Hz), second-order Butterworth filter. Then a band-stop filter (second-order Butterworth) was used to attenuate the 50-Hz noise that was present in the signals. Goniometer data were 10-Hz, low-pass filtered. EMG signals were normalized with respect to the maximum value measured in the control condition (20 movement cycles on the lowest resistance level). This maximum value was determined for each subject and for each muscle separately by calculating a running average with a window of 30 ms.

Movement cycles were defined from the start of the extension phase to the beginning of the next extension phase using kinematic data of the left pedal of the Biostep. Since series of ARMS+ were alternated with series of ARMS− during each condition, cycles at the point of transition between these series were irregular and therefore left out of the analyses.

Further analyses were done for each individual cycle. The cycle was split into an extension and a flexion phase corresponding, respectively, to stance and swing phase in normal locomotion. Finally, an average of the filtered and rectified EMG was calculated for each cycle using kinematic data of the Biostep pedal to confirm that the required frequency was achieved. Outcome measures were averaged for each subject and for each condition.

Fig. 2. Protocol that was performed for each experimental condition. The elbow angle (middle) shows that −15 cycles with arm movements were altered with −15 cycles without arm movements, whereas the legs moved continuously (knee angle, bottom).
Statistical analysis. The effect of arm movements on leg muscle activity (ARMS + vs. ARMS −) was tested in a GLM (general linear model) for repeated measures with ARMS as a within-subjects factor (question 1). All experimental conditions were included in the model. To compare the effect of ARMS between the six different conditions, an interaction term ARMS*CONDITION was added to the model. In the model, the different conditions were compared by a contrast analysis with the A50D condition as a reference condition (questions 2, 3, and 4). The level of significance was set at $P < 0.05$ for the main effect of ARMS and Bonferroni corrected for the contrast analysis ($P < 0.01$).

Arm muscle activity and elbow range of motion for ARMS+ cycles were compared with a GLM for repeated measures (contrast analysis). The A50D condition was set as the reference condition, and the level of significance was Bonferroni corrected ($P < 0.01$). Average movement frequencies for ARMS− and ARMS+ were compared with a paired samples $t$-test for each condition separately ($P < 0.008$ after Bonferroni correction).

RESULTS

Movement frequency was calculated for each cycle and then averaged for each subject and for each condition. Average movement frequencies for individual subjects ranged from 51.4 to 54.8 RPM during the 50 RPM conditions and from 70.2 to 74.3 RPM during the 70 RPM conditions. Movement frequencies were comparable for cycles with and without arm movements (no significant differences).

Muscle activity patterns during recumbent stepping. Group averaged EMG profiles and elbow angles from the A50D condition are shown in Fig. 3. The VL and SO muscles were predominantly active in the extension phase. The MG burst emerged later in the extension phase, and in the flexion phase the TA burst was present. Finally the BF was active in both phases. The EMG profiles demonstrate an increased muscle activity for ARMS+ cycles. Activity of the MG and BF was predominantly increased in the extension phase, whereas TA activity was enhanced during flexion of the leg. In the VL and SO, no clear facilitatory effect of arm movements was observed for this condition. Bursts of DA and DP activity were only present during ARMS+ cycles. Joint angle profiles, shown in the lower panels, indicate that reciprocal arm movements were well performed during the decoupled condition (ARMS+).

Effect of arm movements on leg muscle activity. For the extension phase, there was a significant main effect for ARMS at group level in all leg muscles except the left TA and VL (question 1; Table 2). For the flexion phase, there were significant main effects for the left TA and MG, and the right MG and SO (main effect arms, $P < 0.05$). For the right TA, the main effect of ARMS in the flexion phase was borderline significant ($P = 0.07$; Table 2).

These changes are further illustrated in Fig. 4. It can be seen that the main effects are due to an increase in leg muscle activity for ARMS+ cycles compared with ARMS−. For the right VL, however, muscle activity was decreased during ARMS+ cycles, particularly in the A50C condition.

To ascertain the observed facilitation was consistent among the subjects instead of being overestimated due to a few outliers, the results for the BF during the A50D condition were analyzed for individual subjects as well (Fig. 5).

From the figure, it can be concluded that the BF facilitation during the extension phase was significant for all except two subjects (paired samples $t$-test, $P < 0.05$), confirming that the results were reasonably consistent within the group. In contrast, facilitation during the flexion phase, which was not significant at the group level, was only found in half of the subjects.

Influence of mechanical coupling, phasing, and movement frequency on arm-leg coupling. Results of the repeated-measurements GLM are reported in Table 2. After Bonferroni correction, there was only one significant interaction effect for ARMS*CONDITION in the extension phase. For the left BF, the effect of ARMS was significantly larger in the A50D condition compared with the A50C condition (question 2). Although there were no significant interactions for other leg muscles, some trends can be observed. Similar to the BF, the facilitation of the left MG and SO muscles tended to be smaller in the A50C condition compared with the A50D condition ($P = 0.03$ and $P = 0.04$ for ARMS*CONDITION). For the left SO and VL muscles, there was a tendency for increased facilitation by arm movements in the S50D compared with the A50D condition, whereas facilitation of the right BF tended to be smaller. (question 4; $P = 0.03$ for ARMS*CONDITION).

Finally, TA facilitation in the extension phase tended to be

![Fig. 3. Group averaged leg muscle EMG (left) and arm EMG and joint angle profiles (right) during the A50D condition where the first letter explains whether arm movements were synchronous (S) or asynchronous (A), the number represents the movement frequency; and the final letter indicates whether the arm movements were mechanically coupled (C) or decoupled (D)]. The cycle started at the beginning of the extension phase. ARMS−, average trace of cycles without arm movements; ARMS+, average trace of cycles with arm movements; TA, tibialis anterior; MG, medial gastrocnemius; SO, soleus; VL, vastus lateralis; BF, biceps femoris; DA, deltoideus anterior; DP, deltoideus posterior; EL, elbow.
increased by movement frequency (question 3; P = 0.04 and 0.02 for A50D vs. A70D).

For the flexion phase, there were no significant ARMS* CONDITION interactions after Bonferroni correction. Facilitation of TA activity by arm movements, however, tended to be increased at higher frequencies (question 3; left TA: P = 0.04 for S70D vs. A50D; right TA: P = 0.02 for A70D vs. A50D). The right SO tended to be facilitated more in the S70D compared with the A50D condition (P = 0.03).

Table 2. Repeated-measures analysis leg muscles

<table>
<thead>
<tr>
<th></th>
<th>TA</th>
<th>MG</th>
<th>SO</th>
<th>VL</th>
<th>BF</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>F</td>
<td>P</td>
<td>F</td>
<td>P</td>
<td>F</td>
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<tr>
<td>Extension</td>
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<td></td>
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<tr>
<td>Main Arms</td>
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<td>9.93</td>
<td>0.01*</td>
<td>23.52</td>
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<tr>
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<td>0.97</td>
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<td>0.90</td>
<td>7.00</td>
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<td>0.37</td>
<td>3.37</td>
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<td>Main Arms</td>
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<td>0.51</td>
<td>1.45</td>
<td>0.26</td>
<td>1.52</td>
</tr>
</tbody>
</table>

TA, tibialis anterior; MG, medial gastrocnemius; SO, soleus; VL, vastus lateralis; BF, biceps femoris. See Table 1 for definitions of experimental conditions.

*Significant difference for main effects (P < 0.05) and for contrast analysis (P < 0.01).
Arm muscle activity and elbow range of motion. To evaluate how far the effects on leg muscles depended on changes in arm movement, it was essential to assess the arm muscle activity and the arm movements. The results for muscle activity levels for the DA and DP muscles as well as maximum elbow (EL) flexion and extension angles are shown in Fig. 6 and Table 3. Ideally, the movements, in terms of maximum excursions, should be equal in the various conditions. Muscle activity should also be comparable for ASYNC and SYNC conditions but could be expected to differ as frequency was increased or as coupling mode changed.

The figure shows that DA and DP activity is usually higher in the extension than in the flexion phase. Synchronous activity was generally similar to asynchronous activity. However, there were some differences (Table 3) between the conditions. Differences in DP activity were most evident during the extension phase where muscle activity was increased as movement frequency or synchronization changed (left side, \( P < 0.01 \) for S70D vs. A50D; right side, \( P = 0.01 \) for A70D and \( P < 0.01 \) for S70D vs. A50D). Furthermore, during the extension phase, DP activity tended to be slightly smaller for coupled vs. decoupled arm movements, but only the A50C vs. A50D difference for the right DP remained significant after Bonferroni correction (\( P = 0.01 \)).

During the flexion phase, the DP activity was only different for the S70D vs. A50D condition (\( P = 0.01 \)). For the DA, there were only significant differences on the left side for S50D and S70D vs. A50D (\( P = 0.01 \) for both). DA activity during the flexion phase tended to be smaller for coupled vs. decoupled conditions, but these differences were not significant after Bonferroni correction.

Elbow range remained relatively constant among the conditions. The only significant differences were the flexion angles of the left and right elbow in the S70D and A70D vs. A50D condition, respectively. The absolute difference between these conditions was small (96.7° vs. 89.6° for left and 88.5° vs. 92.4° for right).

DISCUSSION

In the present study, it was demonstrated that leg muscle recruitment during submaximal recumbent stepping can be facilitated by active involvement of the arms. Significant facilitation of the TA, MG, SO, and BF muscles was observed at different movement frequencies and for two different types of arm movement. There was no clear advantage of different frequencies or movement types (SYNC or ASYNC). Leg muscle facilitation appeared to be somewhat phase-dependent with facilitation of extensors (MG, SO, BF) during the extension phase and of an ankle flexor (TA) during the flexion phase.

Biomechanical mechanisms. The increase of leg muscle activity induced by the arm movements could either be the result of biomechanical or neural coupling. For walking, it has...
been suggested that reciprocal arm movements improve mechanical efficiency (4, 9, 24). One possibility often cited is that arm movements are important for the control of angular momentum. For example, according to Bruijn et al. (3), arm movements are crucial for regulation of the total body angular momentum during walking, especially at higher velocities. Although angular momentum due to leg movements increased at higher velocities, total angular momentum around the vertical was maintained constant due to opposing momentum exerted by the arms. During recumbent stepping, however, such mechanisms are probably of minor importance, since the angular momentum produced by the legs will be much smaller when pelvic rotation relative to the shoulder girdle is restricted by the seat. In addition, effects of the SYNC and ASYNC arm movements appeared to be comparable. If arm movements were important for the regulation of the total body angular momentum during recumbent stepping, the results for SYNC and ASYNC movements would have been clearly different.

During walking, reduced postural stability can increase leg muscle activity. In a recent study by Stephenson et al. (22), the effect of arm movements on leg muscle activity during treadmill walking was investigated. Leg muscle activity during normal arm swing was larger compared with walking with arm support either stationary or on sliding bars that allowed reciprocal arm movements. The authors concluded that these differences may be explained by postural balance, which is most challenged during unsupported walking. Although a small contribution of the arms to postural stability during recumbent stepping cannot be ruled out, it is expected that this contribution is considerably smaller compared with walking, since subjects are in a seated position. Therefore, the leg muscle facilitation observed in the present study was probably for the most part the result of other factors, such as a neural coupling mechanism.

**Neural interlimb coupling mechanisms.** Neural interlimb coupling during locomotor tasks has been extensively documented in the literature, and it was argued that those interlimb connections are the remnants of quadrupedal locomotion (6–8, 28). Evidence from reflex studies suggests that such connections may be responsible for neural coupling between arms and legs during locomotor tasks, since interlimb reflexes, evoked by mechanical as well as electrical stimuli, are functionally modulated during gait, whereas they are absent during sitting (7, 11).

Several anatomical substrates have been suggested to be responsible for neural interlimb coupling during locomotor tasks. Propriospinal connections between the cervical and lumbar central pattern generators are often mentioned as one of the pathways for interlimb coordination (27). The fact that interlimb reflexes between upper and lower extremities can occur at latencies of ~60 ms supports this view (27). Disruption of propriospinal pathways by a complete thoracic SCI results in absence of arm leg coupling, whereas it is preserved after incomplete cervical SCI (18). In addition, there is evidence from animal studies indicating that the mesencephalic locomotor region (MLR) in the brain stem plays a role in interlimb coordination (2). Finally, results from MRI studies indicate that supraspinal centers (i.e., supplementary motor area, cingulate motor cortex, premotor cortex, primary sensorimotor cortex, and cerebellum) are involved in interlimb coordination (5). During combined cyclic movements of the wrist and ankle, activity of those areas is higher than the sum of activity during the two isolated limb movements, indicating that the coordination of combined arm and leg movements is at least partially under supraspinal control. Some of the observations from the present study support this contention. For example, it was clear that the task had a cognitive loading aspect since some of the subjects experienced difficulty in the performance of arm movements during the decoupled conditions. The ASYNC movements especially were initially experienced as difficult to perform the task as instructed.

Finally, it was hypothesized that arm movements, if mechanically coupled to leg movements, would not increase leg muscle activity due to reduced mechanical work for the legs. Overall, there tended to be less facilitation or even an attenuation of leg muscle activity when arm and leg muscles were mechanically coupled. These differences between coupled and decoupled arm and leg movements were, however, for the most part not significant after correction for multiple testing. Nevertheless, these results indicate that neural coupling mechanisms play a role during mechanically coupled arm and leg movements.

### Table 3. Arm muscle activity and elbow range of motion

<table>
<thead>
<tr>
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DA, deltoideus anterior; DP, deltoideus posterior; EL, elbow. See Table 1 for definitions of experimental conditions. *Significant difference for contrast analysis (P < 0.01).
movements, but facilitatory effects may be partially cancelled out by the smaller mechanical requirements for the legs. An alternative explanation for the smaller effects during the coupled conditions is that the arms were less actively involved during these conditions (as confirmed by lower EMG levels in arm muscles), resulting in a decreased facilitatory effect.

Clinical implications. Neural interlimb coupling, as reported in the present study, may be beneficial for rehabilitation of SCI patients. Currently, arm movements are often not integrated in locomotor rehabilitation therapy. During BWSTT, the arms are often needed for external support or for postural balance. Furthermore, driven gait orthoses (DGO), which are commonly used for gait rehabilitation, generally do not allow arm movements, although both the effectiveness of BWSTT and training in a DGO might improve by integration of arm movements. One possible method to integrate arm movements in treadmill training (BWSTT or DGO), introduced by Stephenson et al. (22), is the use of sliding bars that provide external support. With this method, arm movements during gait training are even possible for more severely affected patients.

It should be mentioned that the increased leg muscle recruitment does not necessarily result in improved training effects. Furthermore, it is not yet known whether the facilitatory effect of arm movements during submaximal exercise is present in SCI patients. If supraspinal commands are essential for this facilitation, the effect will be smaller in SCI patients where the supraspinal descending pathways are only partially intact. On the other hand, there is evidence that the interlimb interactions can be attributed largely to spinal mechanisms. In the case of stroke, for example, it was shown that stimulation of the tibial nerve during the mid-stance phase is followed by electromyography responses in the proximal arm muscles of both sides (19). Hence, it is possible that the same mechanism of an involvement of arm movements during rehabilitation can also be applied to stroke subjects. In addition, it was shown that the interactions are task-dependent. For example, it was shown by Dietz et al. (7) that interlimb reflexes (between arms and legs) can be strongly enhanced under conditions of walking (compared with sitting or standing). Hence, it is conceivable that interactions, such as shown in the present paper, are even more prominent when subjects are not sitting (as in the present study) but walking.

Limitations

Even though leg muscle recruitment increased by active arm movements, it remains unknown whether this resulted in increased work rate. Higher muscle activity without increased work rate would point to a less efficient activation pattern, which is not functional. However, the facilitation of leg muscles was somewhat phase dependent, with predominant facilitation of extensors in the extension phase and of flexors in the flexion phase. It can therefore be concluded that leg muscle activity was functionally modulated by active arm movements.

Another limitation of the study is that the “comfortable pace” that was instructed to the subjects may be interpreted differently among subjects. In fact, it was observed that some subjects stepped on a relatively high work rate compared with others. As shown in Fig. 5, leg muscle facilitation was present consistently among the subjects, indicating that the differences in work rate between subjects did not interfere with the facilitatory effects of arm movements.

There were no clear differences between different movement frequencies or between SYNC and ASYNC movements. However, a few trends were observed in the ARMS*CONDITION interactions. The lack of significance for these comparisons may be caused by the relatively small sample size (type II error). Furthermore, the frequencies tested (50 and 70 RPM) may not have been different enough to detect any frequency dependence in muscle activity, since another study did indeed report differences between movement frequencies (17). In the present study, however, we chose only to compare frequencies that would be clinically relevant for rehabilitation, and frequencies of >70 RPM were not considered feasible for patients. Frequencies of <50 RPM were not tested, since the isokinetic resistance mode was not available for these frequencies.

Finally, no significant facilitatory effect was found for the VL muscle, which is of major importance for the stepping movement. In general, this muscle had a relatively high EMG amplitude, indicating that VL activity was closer to its maximum. The absence of VL facilitation might therefore have been the result of a ceiling effect, which is in line with the observation of Huang and Ferris (14), who found facilitation in passively moved legs but not in maximally active legs.

In conclusion, from the results of this study, it can be concluded that active arm movements increase leg muscle recruitment, probably resulting from neural interlimb coupling mechanisms. Gait rehabilitation might therefore benefit from integration of arm movements. Since the results were obtained in healthy subjects, additional research is necessary to determine the effect in SCI patients.

GRANTS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: D.d.K., H.R., T.M., B.N., V.D., and J.D. conception and design of research; D.d.K., H.R., and T.M. performed experiments; D.d.K. and T.M. analyzed data; D.d.K., H.R., T.M., B.N., V.D., and J.D. interpreted results of experiments; D.d.K. prepared figures; D.d.K. drafted manuscript; D.d.K., H.R., T.M., B.N., V.D., and J.D. approved final version of manuscript.

REFERENCES