Reflex Response to Imposed Bilateral Hip Oscillations in Human Spinal Cord Injury

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INTRODUCTION

In human spinal cord injury (SCI), imposed unilateral movements of the hip produce multijoint reflexes of the ipsilateral leg that involve complex spinal networks (Schmit and Benz 2002; Steldt and Schmit 2004). It has been suggested that these spastic reflexes might be mediated by increased excitability of interneuronal circuits associated with spinal control of locomotion (Schmit and Benz 2002). Although other afferent systems, including load afferents of the foot and ankle (Wu and Schmit 2006) and knee proprioceptive afferents (Wu et al. 2005) can contribute to the response, hip afferents appear to be particularly strong triggers for inducing excitation of these neuronal networks. If the spastic reflex pathways activated by hip proprioceptors overlap with spinal circuits involved in locomotor control, the reflex responses produced by imposed hip movements would be expected to depend on sensory cues from the contralateral leg. The purpose of this study was to examine the effects of contralateral hip proprioceptive cues on spastic reflexes triggered by imposed hip movements in human SCI.

Hip proprioceptive stimuli have been shown clinically and experimentally to be a dominant trigger for spastic reflex activity. As early as the late 1940s, clinicians observed that extensor spasms could be consistently activated when patients were shifted from a sitting position to a supine position, with responses generally involving bilateral extension of the lower extremities (Little et al. 1989; Macht and Kuhn 1948). These responses have also been reproduced experimentally through a controlled extension movement of one leg about the hip in human SCI subjects (Schmit and Benz 2002). Coordinated activity, typically consisting of hip flexion, knee extension, and ankle extension, occurs with imposed movement of the leg into hip extension, which is consistent with the clinical descriptions. Moreover, imposed sinusoidal oscillations about the hip also produce coordinated muscle activity that entrains to the speed of the movement (Steldt and Schmit 2004). These observations suggest that extensor reflexes are mediated by polysynaptic pathways and are heavily modulated by hip afferents. However, thus far, extensor reflex activity has been examined experimentally only in response to unilateral leg movement. Anecdotal observations have suggested that a bilateral coupling may exist, in which the reflex activity elicited in the ipsilateral leg induces a reflex in the contralateral leg as well.

Hip proprioception is an important modulator of locomotion in spinalized animals and in people with SCI. For example, hip kinematics alters the patterns of muscle activation in people with SCI undergoing partial body-weight–supported treadmill walking. Specifically, the stepping limb exhibits swing enhancement when hip extension is augmented during the stance phase of gait (Dietz et al. 2002; Dobkin et al. 1995), which is similar to observations in human infant stepping (Pang and Yang 2000). It has also been recognized that hip afferents are important for initiating the transition from stance to swing in spinalized cats during walking (Grillner and Rossignol 1978; Hiebert et al. 1996; Lam and Pearson 2001).

In addition to sensory information received from the ipsilateral limb, afferent information from the contralateral limb can also influence locomotor activity. Interlimb interactions have been implicated in locomotor control during split-belt treadmill walking in humans (Dietz et al. 1994; Pang and Yang 2001; Reisman et al. 2005; Yang et al. 1998). For instance, the prevention of swing in one limb of human infants prolongs the stance phase in the contralateral limb (Yang et al. 1998). Further evidence for bilateral organization has also been shown...
in adult SCI. During unilateral stepping, rhythmic muscle activity can be induced in the nonmoving leg, with hip proprioceptive cues from the contralateral limb contributing to the locomotor-like patterns (Ferris et al. 2004).

The aim of this study was to identify the effects of contralateral hip proprioceptive feedback on spastic reflexes produced by imposed sinusoidal oscillation about the hips in human chronic SCI. Bilateral (alternating and synchronous) and unilateral (left leg stationary) hip oscillations were imposed in 11 SCI study participants. Reflex responses were characterized using hip, knee, and ankle joint torque measurements and electromyographic (EMG) recordings in eight muscles from both legs. We hypothesized that reflex behavior would be augmented during alternating hip movements compared with the other movement types due to the similarity of the hip sensory feedback during this movement to the hip proprioceptive feedback during locomotion.

**METHODS**

**Subject population**

Eleven chronic SCI subjects were recruited for this study. Participants (mean age: 43 yr; range: 23–70 yr) included three clinically complete [American Spinal Injury Association (ASIA) classification A] and eight clinically incomplete (ASIA B, C, or D) individuals with cervical (eight subjects) or thoracic (three subjects) level of lesion. The mean duration after injury was 15 yr (range: 3–25 yr) at the time of this study. Four subjects were prescribed antispastic medication to reduce the intensity and frequency of spasms. Specific subject information is summarized in Table 1. Additionally, five study participants (age range: 18–25 yr) with no reported neurological damage were recruited for this study as controls. Exclusion criteria included: significant complications due to skin breakdown, urinary tract infection, other secondary infections, respiratory failure, heterotopic calcification, or other concurrent illnesses limiting the capacity to conform to study requirements; significant osteoporosis; or the inability to give informed consent. Before study participation, informed consent was obtained from each participant and all procedures were conducted in accordance with the Helsinki Declaration of 1975 and approved by the Institutional Review Board of Marquette University.

**Test apparatus**

A novel system (Fig. 1, A and B) was constructed for measuring the reflex response to imposed bilateral oscillations of the hip in people with chronic SCI. This apparatus included custom-built knee–ankle braces with integrated torque transducers that aligned with the knee and ankle joint axes of rotation of each leg. The leg was supported in the brace by a strap around the thigh, a strap securing the heel, and a clamp over the dorsum of the foot, which secured the foot to a footplate at the end of the leg brace. Adjustable linkages permitted a variety of leg-segment lengths to fit within the brace. Each leg brace was fastened to a servomotor drive system (Kollmorgen, Northampton, MA). Multijoint torque responses were measured using hollow-flange reaction-torque transducers (S. Himmelstein, Hoffman Estates, IL) and hip position was recorded using optical encoders (US Digital, Vancouver, WA) that were coupled to each servomotor system drive shaft.

All signals were low-pass filtered (500 Hz) and sampled at 1,000 Hz using a data acquisition card (National Instruments, Austin, TX) and a PC. Custom-designed LabVIEW software (National Instruments) was used for acquiring data and producing the velocity command signal that controlled each servomotor drive system.

Surface electromyograms (EMGs) were recorded from the adductors (Add), vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), medial hamstrings (MH), medial head of the gastrocnemius (MG), soleus (Sol), and the tibialis anterior (TA) in both legs from all subjects. Disposable Ag/AgCl recording electrodes (Vermed Medical, Bellows Falls, VT) were applied to cleansed, lightly abraded skin over each respective muscle belly. EMG signals were amplified (×1,000–10,000) and band-pass filtered (10–1,000 Hz) (Bortec Medical AMT-16; Calgary, Alberta, Canada) before sampling.

**Experimental protocol**

Subjects were transferred to a trisection therapy table and lay supine with the legs supported in the aforementioned custom-built leg braces. The hip center of rotation (i.e., the femoral head, estimated from the location of the greater trochanter) of each leg was aligned with its respective servomotor axis of rotation. Proper alignment was verified by no observable leg translation within the brace during manual hip rotation. The knee and ankle anatomical centers of rotation were aligned with the torque transducers within the braces for both legs. The knees were held in a slightly flexed position while the ankles were held in moderate plantarflexion, as summarized in Table 2.

Imposed sinusoidal oscillations to the hips were applied by the servomotor drive systems. Each hip was moved through an approximately 50° range of motion (ROM), with the hip starting position set at 40° flexion and the end position set at 0–10° hip extension, depending on individual ROMs (refer to Table 2). Figure 1D illustrates the relative positioning of the hips at end ROM. To test the sensory effects from the contralateral hip, the experiments were

**TABLE 1. Subject clinical characteristics**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age, yr</th>
<th>Injury Level</th>
<th>ASIA Score</th>
<th>Postinjury Duration, yr</th>
<th>Medication(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>64</td>
<td>C8–T1</td>
<td>A</td>
<td>6</td>
<td>Baclofen</td>
</tr>
<tr>
<td>B</td>
<td>36</td>
<td>T5–T7</td>
<td>A</td>
<td>8</td>
<td>Baclofen, lorazepam, oxybutyn chloride, carbachamazine</td>
</tr>
<tr>
<td>C</td>
<td>48</td>
<td>C6–C7</td>
<td>A</td>
<td>24</td>
<td>None</td>
</tr>
<tr>
<td>D</td>
<td>70</td>
<td>T2</td>
<td>C</td>
<td>3</td>
<td>Baclofen, gabapentin, oxybutyn chloride, imipramine, tropsium chloride, botulinum toxin type A</td>
</tr>
<tr>
<td>E</td>
<td>26</td>
<td>C6</td>
<td>D</td>
<td>4</td>
<td>Oxybutyn chloride</td>
</tr>
<tr>
<td>F</td>
<td>41</td>
<td>C5–C6</td>
<td>C</td>
<td>25</td>
<td>None</td>
</tr>
<tr>
<td>G</td>
<td>40</td>
<td>C5–C6</td>
<td>C</td>
<td>23</td>
<td>None</td>
</tr>
<tr>
<td>H</td>
<td>42</td>
<td>C5</td>
<td>B</td>
<td>27</td>
<td>None</td>
</tr>
<tr>
<td>I</td>
<td>43</td>
<td>C5–C6</td>
<td>C</td>
<td>17</td>
<td>Baclofen, tolterodine tartrate, propoxyphene NAP/APAP</td>
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<tr>
<td>J</td>
<td>23</td>
<td>T8</td>
<td>B</td>
<td>6</td>
<td>Oxybutyn chloride</td>
</tr>
<tr>
<td>K</td>
<td>48</td>
<td>C6–C7</td>
<td>D</td>
<td>23</td>
<td>None</td>
</tr>
</tbody>
</table>

Neurological injury levels (column 3): C, cervical; T, thoracic. ASIA classification (column 4): A = sensorimotor complete; B = motor complete, sensory incomplete; C = sensorimotor incomplete with majority of key muscles having a motor score <3; D = sensorimotor incomplete with majority of key muscles having a motor score >3.
performed using the following four conditions: 1) bilateral synchronous movement (IN PHASE), 2) bilateral alternating movement (180° OUT OF PHASE), 3) unilateral leg movement with the contralateral leg held stationary in hip extension (UNILATERAL EXTENDED), and 4) unilateral leg movement with the contralateral leg held stationary in hip flexion (UNILATERAL FLEXED). The right leg was considered the test leg, oscillating for all test conditions, while the left leg was held stationary during the unilateral oscillation tests. For clarity, the right leg will be referred to as the ipsilateral leg and the left leg will be referred to as the contralateral leg. The unilateral tests were performed to determine whether there were differences in the reflexes of the ipsilateral leg in response to postural or dynamic afferent input from the contralateral leg. Figure 1C illustrates the relative hip trajectories during each of the four test conditions. During these tests the leg(s) were oscillated at the hip for ten cycles at two different frequencies (0.50 and 0.75 Hz) to test for velocity dependence of the reflexes. Between tests 2–5 min were allowed and each test was repeated three times for each movement frequency (total of 24 tests). The order of the tests was determined by a random-block design. Torque and EMG data were acquired throughout the entire movement.

At the completion of the entire experiment, a separate set of hip movements were performed to identify the effects of gravity, passive joint resistance, and the mass moment of inertia of the legs. Passive resistance and gravitational torque were approximated by moving the leg throughout the entire range of motion in increments of 2°/s, pausing for 5 s between movements. To account for any torques resulting from passive stretch of the hips in the different postures, the slow incremental movement was implemented for each test condition.

### Table 2. Subject test parameters indicating range of motion (ROM) and static knee and ankle angles

<table>
<thead>
<tr>
<th>Subject</th>
<th>Ankle Plantarflexion Angle, deg (L/R)</th>
<th>Knee Flexion Angle, deg (L/R)</th>
<th>Hip Flexion Angle, deg (L/R)</th>
<th>Hip Extension Angle, deg (L/R)</th>
<th>Hip ROM, deg (L/R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>13/13</td>
<td>37/37</td>
<td>40/40</td>
<td>0/0</td>
<td>40/40</td>
</tr>
<tr>
<td>B</td>
<td>13/13</td>
<td>22/22</td>
<td>40/40</td>
<td>-10/-10</td>
<td>50/50</td>
</tr>
<tr>
<td>C</td>
<td>13/13</td>
<td>22/22</td>
<td>40/40</td>
<td>-5/-5</td>
<td>45/45</td>
</tr>
<tr>
<td>D</td>
<td>13/13</td>
<td>22/22</td>
<td>40/40</td>
<td>-10/-10</td>
<td>50/50</td>
</tr>
<tr>
<td>E</td>
<td>13/13</td>
<td>22/22</td>
<td>40/40</td>
<td>-5/-5</td>
<td>45/45</td>
</tr>
<tr>
<td>F</td>
<td>13/13</td>
<td>22/22</td>
<td>40/40</td>
<td>-5/-5</td>
<td>45/45</td>
</tr>
<tr>
<td>G</td>
<td>13/13</td>
<td>22/22</td>
<td>40/40</td>
<td>-10/-10</td>
<td>50/50</td>
</tr>
<tr>
<td>H</td>
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<td>31/25</td>
<td>40/40</td>
<td>-5/-5</td>
<td>45/45</td>
</tr>
<tr>
<td>I</td>
<td>13/13</td>
<td>22/22</td>
<td>40/40</td>
<td>-10/-10</td>
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<tr>
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<td>13/13</td>
<td>22/22</td>
<td>40/40</td>
<td>-10/-10</td>
<td>50/50</td>
</tr>
</tbody>
</table>

L, left leg; R, right leg.
(IN PHASE, OUT OF PHASE, UNILATERAL EXTENDED, and UNILATERAL FLEXED). The inertial properties of the legs were determined by oscillating each leg about the hip at 9.42 rad/s (1.5 Hz) through a 15° range (25–10° hip flexion).

Data analysis

REFLEX TORQUE CALCULATIONS. The reflex torque was calculated using a method similar to that previously described by Steldt and Schmit (2004). Briefly, the reflex torque was identified by removing the gravitational torque, passive joint resistance, inertial torque, and a torque estimate of the mechanical artifact, from the recorded torque measurements. The reflex torque \( \tau_{\text{reflex}} \) (i.e., the torque due to active muscle contraction), was calculated for each trial using Eq. 1

\[ \tau_{\text{reflex}} = \tau_{\text{measured}} - \tau_{\text{passive/gravity}} - \tau_{\text{inertia}} - \tau_{\text{artifact}} \]  

The passive joint resistance and gravitational torque were approximated from the slow movement of the legs at 2°/s with a 5-s pause between each movement to allow any reflexive muscle activity to subside. The passive resistance and gravitational torque \( (\tau_{\text{passive/gravity}}) \) was estimated by fitting a third-order polynomial curve to the mean torque data (Eq. 2). The mean torque was calculated for each pause period. The polynomial coefficients \( (a_1, a_2, a_3, a_4) \) were then used to calculate the \( \tau_{\text{passive/gravity}} \) component of the measured torque for other movement types (i.e., IN PHASE, OUT OF PHASE, etc.) using measured hip position \( (\theta_{\text{hip}}) \)

\[ \tau_{\text{passive/gravity}} = a_1\dot{\theta}_{\text{hip}} + a_2\theta_{\text{hip}} + a_3\dot{\theta}_{\text{hip}} + a_4 \]  

The inertial properties of the legs were determined from the torque recorded during the high-frequency oscillation in which each leg was oscillated from 25° of hip flexion to 10° of hip flexion at 1.5 Hz, for ten cycles. Restricting the hip to the midrange minimized reflexive muscle activity during the movement. The inertial constant of the entire leg \( I_{\text{hip}} \) was found by first correcting for the passive resistance and gravitational torque \( (\tau_{\text{passive/gravity}}) \) using Eq. 2, and then calculating \( I_{\text{hip}} \) using Eq. 3 implemented in Matlab. Note that Matlab uses a linear regression to estimate \( I_{\text{hip}} \) in this calculation. The inertial torque was then calculated using Eq. 4, where \( \theta_{\text{hip,trial}} \) was the rotational acceleration of the leg about the hip during a test trial

\[ I_{\text{hip}} = \frac{(\tau_{\text{measured}} - \tau_{\text{passive/gravity}})}{\ddot{\theta}_{\text{hip}}} \]  

\[ \tau_{\text{inertia}} = I_{\text{hip}}\dot{\theta}_{\text{hip,trial}} \]  

An additional torque was calculated that represented a mechanical artifact within the system that could not be attributed to the biomechanical properties of the legs. To account for this artifact, the experiment was repeated in its entirety using the five neurologically intact (NI) individuals as controls. Because oscillation about the hips in NI individuals did not elicit reflexes, the corrected torques (using the procedure mentioned earlier) represented the remaining artifact.

An ensemble average of the torque at each joint and test condition across all NI controls was calculated. The average torque \( \tau_{\text{artifact}} \) was then subtracted from the SCI subject torque data. Figure 2B illustrates the hip, knee, and ankle torque from the right leg of one control subject demonstrating the relative amount of noise within the system.

The hip reflex torque (i.e., the torque produced by active hip muscle contraction) was calculated by subtracting the passive/gravitational torque, inertial torque, and artifact from the measured torque (refer to Fig. 2A). The passive/gravitational torque and inertial torques were first calculated using the coefficients \( a_1 \) and \( I_{\text{hip}} \) obtained from the previous analysis, along with \( \theta_{\text{hip}} \) from individual trials. Portions of the passive/gravity and inertia trials in which EMG was detected were removed from this analysis. The hip reflex torques were then calculated using Eq. 1 and were used for subsequent analyses. The reflex torques of the knee and ankle joints were calculated using the same procedures.

TORQUE ANALYSIS: AMPLITUDE. Peak flexion and extension torque for the hip, knee, and ankle of both legs were calculated for each cycle of the movement to identify the effects contralateral hip position and phasing of bilateral hip movements have on the amplitude of the reflex response. The mean peak flexion and extension torques at the hip and knee were calculated for each test condition, across all three trials for each subject. Before identifying the peak ankle torque for each cycle, the data were first corrected for an underlying gradual plantarflexion or dorsiflexion (present in one subject) torque response that was concurrent with the oscillatory reflex response (Fig. 3). To correct for the underlying response, a curve (cubic spline) was fitted to the measured ankle torque data and then subtracted. This technique allowed for a clearer demarcation between cyclical plantarflexion and dorsiflexion torque responses, which were then identified for each cycle of movement using the same procedure used for the hip and knee torque data. A multifactor ANOVA was used to compare the effects of movement type and movement frequency on the mean peak torque response for each joint and direction (i.e., flexion or extension). Tukey’s post hoc test was used to identify the differences among the four experimental conditions. Significance was accepted at \( P < 0.05 \).

EMG ANALYSIS: AMPLITUDE. Overall muscle activity during each test condition was determined using surface EMG recordings. EMG data were first notch filtered (59–61 Hz) for line noise and band-pass filtered (20–300 Hz) to exclude motion artifact using fourth-order Butterworth filters (Matlab; The MathWorks, Natick, MA). For analysis, the root-mean square (RMS) of the filtered EMG was calculated using a 100-ms sliding-window. The area of the RMS EMG was calculated for each cycle, over the time the muscle was active during the movement cycle (one cycle of movement is illustrated in Fig. 1C). EMG recordings during the first cycle of each trial were excluded from analysis due to an inconsistency and incompleteness in the reflex response to the imposed movements during the initial cycle. The calculated EMG area per cycle was then normalized to the mean of each subject’s entire EMG data based on all four test conditions for
PHASE ANALYSIS. A phase analysis was performed using the reflex torques and RMS EMG data to determine the timing of reflex activity with the position of the hip during each cycle of movement. The EMG phase analysis was pursued only if the EMG data demonstrated sufficient muscle activity. Similarly, threshold values for the hip, knee, and ankle extension and flexion reflex torques were used as the criteria for including individual torque responses for the phase analysis. These threshold values were determined using NI data and were set so as not to include artifacts associated with hip movements. Furthermore, for SCI subject torque and EMG data, only the last seven cycles were used for the phase analysis because the reflex responses exhibited consistent suprathreshold activity during this time.

The phase analysis was performed using the circular statistics method described by Batschelet (1981). Using a polar coordinate system, the RMS EMG data were normalized from 0 to 360°, where 180° corresponded to full extension of the hip and 0° corresponded to full flexion. For each movement cycle, the rectangular coordinates \((x, y)\) of the resultant vector were calculated, respectively, as

\[
\bar{x} = \frac{1}{n} (\cos \phi_1 + \cos \phi_2 + \cdots + \cos \phi_n) \tag{5}
\]

\[
\bar{y} = \frac{1}{n} (\sin \phi_1 + \sin \phi_2 + \cdots + \sin \phi_n) \tag{6}
\]

From these rectangular coordinates, the phase angle was calculated using Eq. 7. The vector length \(r\) was then normalized to a unit vector size in a conversion back to rectangular coordinates. After normalization, the mean phase angles \(\bar{\phi}\) and vector lengths \(r\) were calculated (Eqs. 7 and 8, respectively) across all three trials for each subject. The mean phase

\[
\bar{\phi} = \arctan \left( \frac{\bar{y}}{\bar{x}} \right) \tag{7}
\]

\[
r = \sqrt{\bar{x}^2 + \bar{y}^2} \tag{8}
\]

angles and vector lengths were used to detect significant phasic muscle activity during the imposed oscillation. A similar analysis was done using the reflex torque signals. Torque signals were separated into flexion and extension and the mean flexion and extension torque was then identified per cycle for each subject. The mean phase angle of the resultant vector was found using the procedure described earlier. Rayleigh’s test for directedness was performed on the torque and EMG data to determine significant phasing (\(\alpha = 0.05\)).

A power spectral analysis was used to examine the spectral content of the Sol, MG, and TA EMG data to determine whether the responses in these muscles were phased to the movement frequency. Because the ankle produced a bimodal response to the imposed movement (described in RESULTS), Rayleigh’s test was not appropriate for detecting phasic activity. As a result, the power spectral density of the zero-mean filtered EMG signals was determined. A hamming window was used and all EMG data were zero-padded to a length of \(2^{15} (16,384)\) to increase frequency resolution. The maximum peaks that corresponded to the movement frequency (i.e., 0.75 or 0.50 Hz) were identified for all EMG signals and were then compared with the maximum spectral peaks from NI control data to determine whether phasic EMG signals could be detected. Additionally, a similar analysis was done using the corrected ankle torque data. Corrected ankle torques were first divided into plantarflexion and dorsiflexion, and then a power spectral analysis was performed on the each data set as described earlier.

RESULTS

In this study, EMG and torque measurements were used to demonstrate that hip sensory information from the contralateral leg has an effect on the reflex response in the ipsilateral leg during imposed hip movements in chronic SCI subjects. Torque and EMG measurements were made during imposed sinusoidal oscillations to the hips of 11 SCI study participants. A typical reflex response from the right leg of subject F is provided in Fig. 4 for each of the four experimental conditions. The response to the imposed hip movement typically consisted of hip extension and knee flexion torques occurring when the limb was moving into hip flexion, and hip flexion and knee extension torques occurring when the limb was moving into hip extension. Hip flexor (RF) and knee extensor (VM and VL) EMG responses were elicited during hip extension and hip extensor/knee flexor (MH) EMG responses were elicited during hip flexion, which were all consistent with the recorded torque responses.

Ankle torque responses during imposed hip movements possessed greater variability among subjects than the reflex responses seen at the hip and knee. Six subjects (subjects D, E, G, J, K, and I) displayed responses at the ankle consisting of a gradual increase in plantarflexion torque that lasted throughout the remainder of the movement (Fig. 4), whereas one subject (subject A) demonstrated the opposite response at the ankle, which consisted of prolonged dorsiflexion throughout the hip movement. Three subjects (subjects B, C, and D) produced only small-amplitude responses, with no considerable net torque direction. Additionally, due to the variability in the ankle responses, the cubic spline fitted curves yielded no conclusive trends among the different movement conditions.

Although a greater variability was seen in the reflex torque response at the ankle, the imposed hip movements elicited a distinctive dual plantarflexion torque response. A bimodal plantarflexion pattern is evident in Fig. 5 for the right ankle torque response in subject K. A peak plantarflexion torque typically occurred twice during each cycle of movement, with each peak coinciding with the maximum hip flexion and
extension positions during the imposed movements (indicated by the arrows within the IN PHASE hip position vs. ankle torque plot in Fig. 5). In contrast, a peak dorsiflexion torque occurred only at a mid hip position during hip flexion in each cycle of movement.

Reflex response to bilateral hip movements

The magnitude of the reflex torque at the hip and knee was significantly greater for the OUT OF PHASE test compared with the IN PHASE test across the test group (ANOVA, \( P < 0.001 \)). The group means for peak torques are provided in Fig. 6A. In seven of eleven subjects, alternating (OUT OF PHASE) hip movement produced extension and flexion reflex torques at the hip and knee in both legs that were particularly pronounced, even exceeding the physiologic torque generated during normal walking (Perry 1992). In particular, two subjects (subjects F and K) produced peak hip and knee torques exceeding 100 and 40 Nm, respectively. Synchronous (IN PHASE) hip movement produced smaller reflex responses at the hip and knee, as demonstrated in ten of the eleven subjects, with no consistent response elicited from subject B in either movement condition. Figure 5 further illustrates the disparity in the hip and knee responses of the right leg between the IN PHASE and OUT OF PHASE.
test conditions for subject K and also presents the efficacy of alternating hip movements in eliciting the reflex responses.

The EMG results across the test group also indicated a higher response in the OUT OF PHASE test compared with the IN PHASE test (Fig. 6B). Even though the patterns of muscle activity were similar during both bilateral movement tests (i.e., in phase and out of phase), the magnitude of EMG activity was greater during out of phase hip movements compared with in phase hip movements in the Add, VM, VL, RF, and MH (ANOVA, \( P < 0.001 \), \( P < 0.01 \), \( P < 0.01 \), \( P < 0.001 \), respectively) of both legs. Both bilateral movement tests produced discernible rhythmic EMG activity in ten of eleven subjects for the RF and MH muscles, as well as in the VL (\( n = 5 \)) and VM (\( n = 4 \)).

In general, the out of phase and in phase tests produced varied patterns of muscle activity at the ankle. The plantarflexor (Sol and MG) muscle activity pattern was generally unaffected by the movement type, exhibiting continual contraction during both types of bilateral movement. However, out of phase hip movements manifested rhythmic bursting patterns in the TA EMG, lasting throughout the entire movement, in contrast to the response elicited during in phase movements, which displayed inconsistent bursting patterns (Fig. 4A).

Across the test group, the out of phase test produced significantly greater dorsiflexion torque responses than the in phase movement (ANOVA, \( P < 0.001 \)), whereas no significant differences were found for the normalized TA EMG (movement type: ANOVA, \( P > 0.05 \)). Interestingly, the in phase test produced significantly larger responses in the Sol muscle in both legs (ANOVA, \( P < 0.05 \)). No significant increases in MG EMG activity (ANOVA, \( P > 0.172 \)) or plantarflexion torque.
Effect of hip position during unilateral leg movements

During unilateral leg movements, the position of the contralateral (stationary) leg affected the ipsilateral reflex response in a manner consistent with the effects from the out of phase and in phase movements. Specifically, reflex responses in the right leg were larger when the hips were in opposite positions (Fig. 7A, with the left hip held in an extended posture (unilateral extended test), the ipsilateral hip extension and knee flexion responses in the right leg were larger during movement into hip flexion (i.e., when the hips are in the opposite position as illustrated in Fig. 7A), whereas hip flexion and knee extension reflex responses were smaller when the right leg moved into hip extension (i.e., when hips are in the same position as illustrated in Fig. 7B). Conversely, when the left hip was held in the flexed posture (unilateral flexed test), the opposite effect was observed in the right leg (i.e., increased right hip flexion and knee extension reflex responses (Fig. 7C) and diminished hip extension and knee flexion reflex responses (Fig. 7D)).

The position of the left hip did not greatly affect the overall response of the right ankle. In general, the response at the ankle followed a pattern similar to that observed during the bilateral hip movements, which consisted of the dual plantarflexion torque response. In subjects who demonstrated EMG activity in the MG (n = 6), Sol (n = 6), and TA (n = 4) muscles, similar patterns of activation were seen in response to both unilateral leg tests. In a few subjects, rhythmic EMG activity in the Sol (n = 4) and TA (n = 4) muscles was elicited in the moving leg during the unilateral test conditions, with the responses occurring during hip extension of the moving leg. Similar to bilateral movements, rhythmic EMG activity of the MG was not observed in any subject during either unilateral leg movement test. Rather, continual contraction of the muscle was exhibited, which generally lasted throughout the last eight cycles of movement for both unilateral test conditions.

Across the test group, hip postural changes in the contralateral leg contributed to the extensor reflex response in the ipsilateral leg, such that the reflex responses were enhanced at the time the hips were in opposite positions (Fig. 7, A and C) and were reduced at the time the hips were in the same position (Fig. 7, B and D). A summary of the group means (peak torques and normalized EMG) from the right leg for all four experimental conditions is provided in Fig. 8. The magnitude of hip extension and knee flexion responses, characterized by mean peak torques and normalized MH EMG activity, was consistently greater during the unilateral extended test condition compared with the unilateral flexed test (Tukey’s test, P < 0.01 for both joint torques; Tukey’s test P < 0.001 for MH EMG). In contrast, the mean peak hip flexion torque was consistently greater when the left leg was held stationary in hip flexion (unilateral flexed test), which approached significance (Tukey’s test, P = 0.081). No difference was found between the two unilateral movement types for knee extension torque (Tukey’s test, P = 0.982). Notably, right leg RF EMG activity (representative of the hip flexors/knee extensors) was significantly greater when the contralateral (left) leg was held in hip flexion than when it was positioned in hip extension (Tukey’s test, P < 0.05).

In summary, sensory information from the contralateral hip influenced spastic reflex responses in the ipsilateral leg. Both the alternating bilateral movement (out of phase) and the hip position of the contralateral leg (unilateral flexed and unilateral extended tests) add to the reflex response as demonstrated in the hip and knee flexion and extension torques, as well as in the EMG responses of the hip and knee musculature (Fig. 8). In general, alternating (out of phase) hip movements enhanced the reflex response compared with synchronous (in phase) hip movements. Similarly, unilateral movement tests demonstrated reflex responses in the ipsilateral leg that were affected by postural changes of the contralateral leg in a manner consistent with responses observed during the out of phase and in phase tests.

Inconsistent ankle reflex activity was demonstrated in response to any of the movement types (i.e., in phase, out of phase, unilateral extended, or unilateral flexed). For instance, ankle plantarflexor (Sol and MG) EMG responses elicited during alternating (out of phase) hip movements were smaller than responses elicited during the unilateral extended
test (MG and Sol: Tukey’s test, \( P < 0.05 \)) as well as the UNILATERAL FLEXED test (Sol: Tukey’s test, \( P < 0.05 \)) (Fig. 8B). However, no significant results were found for the ankle plantarflexion torques.

**Reflex response in the nonmoving leg during unilateral leg movements**

The influence of contralateral leg movement on spastic reflex activity was further evidenced by torque and EMG responses in the stationary leg elicited during oscillation of the right leg in three subjects (incomplete injuries), as demonstrated by subject G in Fig. 9. The responses occurred primarily when the hips were in opposite positions, consistent with the difference in phasing and difference in position of the contralateral leg described earlier. For example, if the hip of the stationary leg was held in the flexed posture, the response in the hip extensors (represented by the MH) was elicited when the contralateral leg was moving into hip extension. Similarly, the response in the hip flexors (represented by the RF) of the stationary leg occurred when the contralateral leg was moving into hip flexion. Because the pelvis was not securely restrained during these tests, the MH and RF responses in the stationary leg could have been activated by the stretch of the muscle itself, elicited through excessive rocking of the pelvis during the movement. However, the vastus medialis (VM), a muscle that does not cross the hip, also showed rhythmic EMG activity in the stationary leg during the UNILATERAL EXTENDED test in three subjects. Therefore, it is assumed that the response induced in the stationary leg can be a result only of the movement of the contralateral limb.

**EMG phasing patterns during bilateral hip movements**

The phasing of the contralateral leg generally did not affect the timing of the reflex to imposed hip movement. The mean resultant vector for EMG recordings was used to ascertain the overall timing of muscle activity with respect to the right hip position during bilateral leg movement. Figure 10 illustrates right leg muscle phasing patterns during movement of the right hip for all subjects who demonstrated phasic muscle activity. Each mean resultant vector (signified by an arrow in Fig. 10) represents the response from one subject. A mean resultant vector with a phase angle of 180° corresponds to muscle activity IN PHASE with movement of the right leg into hip extension, and a phase angle of 0° corresponds to muscle activity IN PHASE with movement of the right leg into hip flexion.

EMG responses of the Add, RF, VL, and VM were commonly phased with hip extension (with the exception of two
subjects) and MH activity was largely phased with hip flexion (with the exception of one subject). For comparison, the timing of muscle activation relative to the position of the hip during normal locomotion is represented by the shaded areas in Fig. 10B (Perry 1992). Although the activity in most muscles was appropriately phased, activity in the VM and VL muscles was antiphased with the position of the hip corresponding to normal locomotion. Torque phasing patterns (not shown) followed the same trend, with hip flexion and knee extension torques (presumably produced by activity in RF, VM, and VL) coinciding mainly with the hip extended position and hip extension and knee flexion torques (which would be produced by MH activation) coinciding with the hip flexed position. These results are consistent with previously reported findings in unilateral leg movements (Steldt and Schmit 2004).

The phasing patterns seen in the ankle produced varied results. For subjects who exhibited sufficient ankle muscle activity, the Sol EMG phasing commonly occurred when the ipsilateral limb was moving into hip extension. MG and TA muscle activity did not show patterns that were consistent across subjects and, in fact, produced phasic responses in a fewer number of subjects compared with the other muscles. Moreover, MG activity displayed a weak directional dependence with timing of the hip movement, producing a strong response in only one subject for both bilateral movement phases and in another subject for in-phase oscillation only.

Although the overall muscle activity patterns were generally unaltered by the bilateral movement phasing, alternating (out-of-phase) movements appeared to produce significant phasing (Rayleigh’s test; $P < 0.05$) in a greater number of subjects for the Sol, TA, VM, Add, RF, and MH (the specific number of subjects is provided in Fig. 10 next to its respective muscle polar plot). The RF activity of the right leg was largely timed with the leg’s movement into hip extension, with activity typically leading the movement, whereas MH activity was primarily phased with the leg’s movement into hip flexion. Additionally, for most subjects, the RF and MH muscle pair was never jointly active during the bilateral movements, that is, one muscle was inactive during the time the other muscle was active.

![Reflex response from the stationary left leg of subject G (American Spinal Injury Association (ASIA) classification C) during a unilateral extended and unilateral flexed test condition. Left hip and knee torques, and left (L) leg and right (R) leg EMG responses are provided (note the scaling of the EMG plots for the right and left legs). Right hip trajectory is denoted by the dotted line and the left hip position is denoted by the solid line on the top plots. Muscle activity in the rectus femoris (RF), medial hamstrings (MH), and vastus medialis (VM) was elicited in the static leg while the right leg oscillated.](http://jn.physiology.org/)

![Phase relationship between hip position and muscle activity from the right leg.](http://jn.physiology.org/)
active. Phasic VM muscle activity was also elicited during bilateral alternating movements in nine of eleven subjects, with the muscle activity occurring when the right leg was moving into hip extension.

Not all subjects produced alternating flexor and extensor muscle activity with imposed movement about the right hip. In subject D, MH activity was elicited early during movement into hip flexion with no considerable changes in the timing of RF activity. Also, subjects D and I showed VM activity when the hip was near full flexion within the movement during the synchronous and alternating movements with no substantial changes in the phasing of the MH.

**Discussion**

In summary, these results demonstrate that hip-triggered reflexes are considerably influenced by hip afferents from the contralateral leg. The extent of contralateral hip proprioceptive feedback on hip-triggered reflex activity was shown by significant reductions in reflex torque and EMG amplitude at the hips and knees during synchronous (IN PHASE) leg movements in comparison to alternating (OUT OF PHASE) leg movements. Furthermore, postural changes in the contralateral (stationary) hip also influenced the reflex responses in the ipsilateral leg in a manner consistent with the reflex response patterns during OUT OF PHASE and IN PHASE tests (Fig. 4). In general, reflex responses at the ankle were largely unaffected by afferent feedback from the contralateral hip and, as such, may require other afferent systems for reflex modulation.

Observations from this study suggest that contralateral hip afferent signals transmit information across the spinal cord and have the capacity to adjust reflex excitability in the ipsilateral leg. This implies that sensory information from one leg drives excitatory or inhibitory flexion or extension pathways that influence the motor output of the contralateral leg. For instance, if the contralateral (left) leg was in hip extension and the ipsilateral (right) leg was in hip flexion (see Fig. 7A), contralateral (left) hip afferent feedback triggered flexor excitatory pathways within the contralateral (left) leg and extensor excitatory pathways within the ipsilateral (right) leg. In this manner, ipsilateral (right) leg reflex excitability was enhanced by contralateral (left) hip afferent input. In contrast, if both legs were in hip extension (see Fig. 7B), transmission of contralateral (left) hip afferent feedback to ipsilateral (right) leg extensor muscles was ineffective, demonstrated by suppression of extensor muscle reflex activity when the leg was in hip extension with flexor muscle reflex activity generally dominating the response. Similarly, static positioning of the contralateral (left) limb at an extreme hip flexion (40°) or hip extension (10°) posture can enhance the reflex of the ipsilateral (right) leg by signals presumably originating from contralateral hip afferents.

**Role of interneuronal excitability in SCI spasticity**

The current results support the clinical assessment of hip-triggered reflexes as one component of the spastic motor syndrome. From a clinical perspective, spastic motor behaviors have traditionally been examined through single joint movements assuming they result from velocity-dependent stretch reflexes (Lance 1980). Because spastic reflexes involve multisegmental interneuronal pathways, conventional techniques do not distinguish among the various types and, furthermore, may require a more comprehensive assessment to measure multiple reflex behaviors (Benz et al. 2005; Priebe et al. 1996). The hip perturbations of the current study produced very large responses in some of the subjects (e.g., subjects F and K), emphasizing the importance of considering these types of reflex responses in the clinical assessment of spastic reflexes.

The findings from this study also emphasize the pervasive nature of extensor spasm activity in human SCI with implications in the management and clinical assessment of spastic motor behaviors. Extensor spasms are manifested more frequently, with prevalence in 82% of individuals with SCI (Little et al. 1989), and are more disabling than the other spastic motor behaviors, such that they have been known to force a patient out of a wheelchair and interfere with transfers (Barolat and Maiman 1987; Skóld et al. 1999). The results of this study suggest that attention should be given to the relative positioning of the hips during transfers or seating within a wheelchair to minimize the strength of extensor reflex activity.

**Do hip-triggered reflexes involve spinal centers for locomotion?**

**Significance of hip proprioceptive input.** Hip proprioceptive feedback is a primary contributor to the reflex generation and modulation of muscle activity in human SCI. In a recent study, multijoint reflexes triggered by unilateral hip oscillation were shown to entrain to the frequency of the imposed oscillation (Steldt and Schmit 2004), which correspondingly has been demonstrated in spinalized and decerebrate cats during fictive locomotion (Andersson and Grillner 1983; Kriellaars et al. 1994). The ability to modulate spastic reflex activity in an organized pattern similar to locomotion provides evidence that hip-triggered reflex activity involves similar pathways for the spinal control of walking in human SCI (Steldt and Schmit 2004). Several other studies have also shown that hip kinematics modulates muscle activity during locomotion in human SCI (Dietz et al. 2002; Ferris et al. 2004; Harkema et al. 1997; Kawashima et al. 2005). In particular, the importance of hip proprioceptive feedback in the regulation of gait is apparent by the absence of knee afferent feedback (hip-walking with knee-joint movements blocked) such that the modulation of muscle activity remains largely unaltered (Dietz et al. 2002; Kawashima et al. 2005). The muscle activity patterns produced by bilateral hip movements observed in the current study are generally consistent with these previous reports.

**Contralateral hip proprioceptive feedback**. The contralateral leg effects observed in the current study are consistent with an enhancement of locomotor reflexes by contralateral limb feedback observed in previous human SCI studies (Ferris et al. 2004; Kawashima et al. 2005). Through an approach similar to the one in the present work, Kawashima et al. (2005) demonstrated that imposed alternating (anaphase) hip oscillation, with knee and pelvis motion restrained, induces amplified locomotor-like EMG activity in the lower extremities compared with the induced muscle activity during synchronous (IN PHASE) leg movements. The enhanced activity was attributed to afferent input from the contralateral leg, such that the amplified activity occurred only when the contralateral leg was OUT OF PHASE with the ipsilateral leg during the imposed hip.
oscillation (Kawashima et al. 2005). Further, as shown in a clinically complete SCI subject, stepping movements imposed to one leg induce rhythmic muscle activity in the contralateral leg, with no movement or loading imposed to that limb (Ferris et al. 2004), which, to a similar degree, was observed in three subjects in the current study (Fig. 9).

One difference in the current results and previous investigations is that our results showed that rhythmic activity occurred primarily in muscles near the hip (RF, MH, VL, and VM), with no consistent rhythmic patterns evoked in muscles distal to the hip (MG and SOL), in contrast to the rhythmic ankle activity produced during upright leg locomotor movements (Ferris et al. 2004; Kawashima et al. 2005). In the study by Kawashima et al. (2005), subjects maintained an upright posture during imposed hip oscillation and, as such, load-related afferent feedback may have contributed to the differences in ankle EMG activity. Furthermore, it is important to note that the subjects recruited in the study conducted by Ferris et al. (2004) underwent extensive locomotor rehabilitation before study participation, whereas the subjects recruited for this study did not. The effects of locomotor training-induced plasticity may account for the differences observed in ankle activity patterns. Nonetheless, these observations provide evidence for an interneuronal mechanism for interlimb interactions during locomotor activity in the isolated human spinal cord that is manifested through contralateral hip afferents.

From the present findings, contralateral hip afferent feedback has the ability to enhance or suppress reflex activity in a coordinated manner, which suggests that extensor reflex pathways converge with locomotor spinal pathways, particularly for interlimb coordination. For some time it has been known that the cat spinal cord contains the neural pathways for interlimb coordination, such that a disturbance to one hindlimb causes the contralateral hindlimb to respond in a functional way (Conway et al. 1987; Duysens and Pearson 1980; Grillner and Zangger 1979; Hiebert et al. 1996). This suggests that sensory/motor feedback signals from one limb can influence the motor output of the opposite limb. Similarly, recent human infant studies have also shown that interlimb coordination is realized before independent walking, in which the stepping patterns of the infant accommodate bilateral locomotor coordination (Pang and Yang 2001; Yang et al. 2005). For instance, forcing one limb into the swing phase concurrently prolongs the stance phase in the opposite limb or quickly extends the limb for ground contact (Pang and Yang 2001). It has been suggested that in the human spinal cord an autonomous rhythm generator maintains bilateral coordination, such that alternating, out of phase motion of the legs is preserved during novel stepping patterns to maintain walking stability (Yang et al. 2005). As such, the enhanced reflexes observed during alternating leg movements in the present study may reflect the bilateral coordination for locomotion.

THE ROLE OF OTHER AFFERENTS FOR THE MODULATION OF LOCOMOTION. Load-related afferent feedback from the ankle and foot has been shown to be an essential sensory cue for modulating locomotor activity in human infants and people with SCI. In human infant studies, loading the limb while walking on a treadmill prolongs the stance phase and delays the swing phase of the gait cycle (Pang and Yang 2000; Yang et al. 1998). Load-related afferent feedback has also been shown to be a critical sensory cue for the generation of locomotor patterns in human SCI (Dietz et al. 2002; Harkema et al. 1997). Controlled stepping movements alone (100% body unloading), facilitated either by manual assistance (Ferris et al. 2004; Harkema et al. 1997) or with a robotic gait orthosis (Dietz et al. 2002), produce weak or absent leg muscle activation. Further, rhythmic limb loading of an extended leg while movement is imposed to the contralateral leg is not always sufficient for generating locomotor patterns in the extended leg (Dietz et al. 2002; Ferris et al. 2004; Kawashima et al. 2005). However, limb loading and limb kinematics in combination often provides ample sensory feedback for generating appropriate muscle activation for stepping. Observations such as these demonstrate that locomotor reflex activity requires a collection of sensory cues derived from multiple sites within the lower extremities for the proper execution of stepping in people with SCI (for review see Dietz and Harkema 2004). Thus the absence of ankle load-related afferents during imposed hip oscillations in the current study may provide an explanation for dissimilar reflex responses seen in distal and proximal muscles relative to the hip (Fig. 4).

Although stretch reflexes are recognized as a spinal mechanism for limb stabilization, they also contribute to muscle activity during walking and, in addition, have been shown to be phase dependent with the gait cycle. For instance, soleus stretch reflex excitability is greater during the stance phase of gait (Sinkjaer et al. 1996; Yang et al. 1991), and the biceps femoris tendon jerk is more active during late swing (Faist et al. 1999). However, in the current study, stretch-related afferent feedback during imposed hip movements was likely to have made only a small contribution to the reflex responses. Multijoint reflexes were observed in muscles spanning the knee and ankle joints, which were not stretched during hip oscillations. In most subjects, rhythmic muscle activity was observed in the vastus medialis (VM), lateralis (VL), and the tibialis anterior (TA), which do not cross the hip. In addition, the torque responses were not strongly dependent on the movement frequency, which would be expected from stretch reflex responses. Further, in a recent study examining extensor spasms triggered by knee extension, the vastus medialis was active during muscle shortening in spastic SCI subjects, suggesting a more complex neural control for muscle activation than a simple stretch reflex (Wu et al. 2005).

Intersubject variability

Imposed movements about the hip did not produce consistent reflex responses across all SCI subjects. Antispastic medication may have affected the magnitude of reflex responses for some subjects recruited for this study. At the time of the study, four of eleven subjects were prescribed baclofen to manage their spasms. Two subjects (B and D) taking baclofen had small responses and in the two other subjects (A and I) stronger reflex responses ensued from the hip movements. In addition, the level of injury has been suggested to affect EMG activity, in which higher (cervical) lesion levels produce EMG activity more closely resembling normal locomotor EMG patterns (Dietz et al. 1999). No conclusive results could be made regarding antispastic medications, injury level, injury completeness (ASIA score), or time since injury in the current study due to the limited sample size.
In conclusion, results from this study demonstrate that contralateral hip afferent feedback regulates spastic reflex excitability during oscillation about the hips in human SCI. Because the reflex response amplitude was dependent on hip proprioceptive cues from the contralateral leg, we concluded that spastic reflex pathways activated by hip proprioceptors might overlap with spinal circuits involved in locomotor control. Although amplitude modulation was observed in muscles proximal to the hip joint, additional afferent cues, such as limb load or proprioceptive input from ankle muscles, may be required for appropriate responses in distal muscles.

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