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Pedaling Alters the Excitability and Modulation of Vastus Medialis H-Reflexes After Stroke

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Abstract

Objective

Individuals post-stroke display abnormal Group Ia reflex excitability. Pedaling has been shown to reduce Group Ia reflexes and to normalize the relationship between EMG and reflex amplitude in the paretic soleus (SO). The purpose of this study was to determine whether these changes extend to the paretic quadriceps.

Methods

H-reflexes were used to examine Group Ia reflex excitability of the vastus medialis (VM). H-reflexes were elicited in paretic (n = 13) and neurologically intact (n = 13) individuals at 11 positions in the pedaling cycle and during static knee extension at comparable limb positions and levels of VM EMG.

Results

VM H-reflexes were abnormally elevated in the paretic limb of stroke survivors. During static muscle activation, H-reflex amplitude did not change with the level of background VM activity. Pedaling reduced the amplitude of paretic VM H-reflexes and restored the normal relationship between VM EMG and H-reflex amplitude.

Conclusions

Pedaling-induced changes in Group Ia reflex excitability that have been reported for the paretic SO are evident in the paretic VM. Pedaling may have a generalized effect on lower extremity Group Ia reflexes post-stroke.

Significance

Pedaling may be therapeutic for reducing Group Ia reflexes after stroke.

Highlights

► Individuals post-stroke display abnormal Group Ia reflex excitability. ► Pedaling reduces Group Ia reflex excitability to the paretic soleus and vastus medialis. ► Pedaling may be therapeutic for reducing Group Ia reflexes after stroke.

Keywords

Locomotion, Spasticity, Rehabilitation, Cycling

1. Introduction

Individuals with chronic, post-stroke hemiparesis typically display hyperactive monosynaptic reflexes, and numerous pharmacological, surgical, and rehabilitation interventions are aimed at reducing reflex excitability in this population (Pandyan et al., 2009). Hence, our previously published observation that pedaling alters Group Ia reflex excitability of the paretic soleus (SO) may have clinical value (Schindler-Ivens et al., 2008). In a previous study, we examined SO H-reflexes during pedaling and matched static muscle contractions in people with and without stroke. During static contractions, SO H-reflexes in the paretic limb of stroke survivors were abnormally elevated, and the amplitude of the SO H-reflex failed to modulate with the level of SO muscle activity. Pedaling reduced the excitability of this reflex pathway and restored the normal, direct relationship between H-reflex amplitude and paretic SO muscle activity. While these observations suggest that pedaling may be useful for reducing abnormal Group Ia reflex behavior in stroke survivors, it remains unclear whether these pedaling-related reflex changes are unique to the SO or if they extend to other muscles of the lower limb. The purpose of the present study was to determine whether stroke-related and pedaling-induced changes in Group Ia reflex excitability extend to the paretic vastus medialis (VM).

The pedaling-related changes in SO H-reflex excitability that we reported previously in stroke survivors may not be representative of the VM H-reflex. Others have suggested that task-dependent reflex modulation, as described at the ankle, may not extend to other joints (Larsen and Voigt, 2006). It has been well established that SO H-reflex amplitude increases with increasing background muscle activity during static muscle activation, walking, and other locomotor-like tasks (Schindler-Ivens et al., 2008, Capaday and Stein, 1986, Capaday and Stein, 1987, Kernell and Hultborn, 1990, Butler et al., 1993, Larsen and Voigt, 2004, Edamura et al., 1991). Moreover, for a given level of background muscle activity, the SO H-reflex is smaller during walking and pedaling as compared to static muscle activation (Schindler-Ivens et al., 2008, Capaday and Stein, 1986, Brooke et al., 1992). In contrast to that which has been observed in the SO muscle, others have shown that quadriceps H- and tendon reflexes do not increase linearly with increasing background EMG and do not decrease in amplitude during locomotor-like movements as compared to static contractions. Dietz and colleagues (Dietz et al., 1990a, Dietz et al., 1990b) have shown that the excitability of quadriceps H- and tendon reflexes did not increase in parallel with increasing vastus lateralis and rectus femoris muscle output. Larson and Voigt (Larsen and Voigt, 2006) also showed that during pedaling the amplitude of H-reflexes recorded from the vastus lateralis and rectus femoris did not always change with increasing background muscle activity. Moreover, they showed that pedaling, as compared to static muscle activation, did not decrease the size of quadriceps H-reflexes at a given level of muscle activity.

In the present study, we examined the excitability of VM H-reflexes during pedaling and matched static contractions in people with and without chronic post-stroke hemiparesis. The VM is a uniarticular knee extensor muscle. The paretic VM, like the paretic SO, displays extraneous muscle activity during the flexion phase of pedaling and the swing phase of walking (Knutsson and Richards, 1979, Kautz and Brown, 1998). These muscle phasing abnormalities are associated with elevated Group Ia reflex excitability, and they contribute to reduced mechanical work during pedaling and stiff-legged gait (Schindler-Ivens et al., 2008, Kautz and Brown, 1998, Yelnik et al., 1999). Hence, reducing the Group Ia reflex excitability of the VM and other quadriceps muscles may be therapeutic. We hypothesized that, if monosynaptic reflex excitability of the paretic VM was similar to the SO, then paretic VM H-reflex amplitude would be abnormally elevated and would not be modulated with the level of background EMG during static contractions. Moreover, pedaling would reduce the excitability of this pathway and induce a more normal relationship between paretic VM muscle activity and Group Ia reflex excitability. Portions of this work have been presented previously in abstract (Fuchs et al., 2008).

2. Methods

2.1. Subjects

Thirteen individuals with chronic post-stroke hemiparesis (paretic, 6 male, 7 female) and 13 neurologically intact individuals (8 male, 5 female) volunteered to participate. The mean (±standard deviation) age of paretic and neurologically intact subjects was 55.15 (±7.85) and 40.08 (±11.31) years, respectively. While effort was made to match the groups with respect to gender and age, the paretic group was older than the control group (independent *t*-test, $P = 0.0006$). Because of this disparity, we examined the data for age effects and found similar patterns of H-reflex amplitude modulation and suppression in older and younger subjects. Specifically, to determine whether age had an important effect on the results, we arranged all subjects' plots of crank position versus H-reflex amplitude in order according to age. We looked at each subject's responses and asked, "Is the effect of pedaling on H-reflex amplitude influenced by age in a systematic fashion?" We reasoned that, if responses were affected by age, we would see a change in the effect of condition (pedal versus static) and/or crank position with changing subject age. Visual inspection of data showed no systematic effect of age. In the neurologically intact group, some younger and older subjects showed dramatic pedaling-related suppression of the VM H-reflex. There were also young and old subjects with modest pedaling-related suppression. A similar trend was observed in the stroke group where pedaling-related suppression was observed in most subjects,

regardless of age. All subjects, regardless of age, displayed position-dependent H-reflex amplitude modulation. Paretic subjects had sustained a stroke at least 1 year earlier [average 8.77 (±7.83) years] with residual lower limb paresis, were able to follow the instructions associated with the task, and reported no contraindications to pedaling. There were 8 subjects with left and 5 with right hemiparesis. All paretic subjects used walking as their primary mode of ambulation and had lower extremity Fugl-Meyer scores (Fugl-Meyer et al., 1975) in the range of 65–96 [average score 81.9 (±9.0), maximum possible score = 96]. Neurologically intact individuals showed no sign of neurological disease and reported no significant past medical history for neurological disease or injury. Each subject could sit on a bicycle seat that was attached to a backboard for 2 h. All subjects participated voluntarily and gave informed consent according to the Declaration of Helsinki and as approved by the Institutional Review Board at Marquette University.

2.2. Instrumentation

Subjects were positioned on a bicycle ergometer that was equipped with a frictional flywheel (EFI Sports Medicine). A rigid backboard was connected to the pedaling mechanism to support the subject's pelvis, trunk, and head. The head and trunk were oriented 39° from horizontal. Subjects' feet were coupled to the pedals using toe and heel clips.

An optical encoder (BEI Model EX116-1024-2) was used to measure the angular position of the crank to an accuracy of 0.3°. Bipolar silver surface electrodes (DelSys, Inc. 10 mm length, 1 mm width, 1 cm inter-electrode distance) were used to record EMG from the VM. Signals from the SO, tibialis anterior (TA), rectus femoris (RF), and semimembranosus (SM) were also monitored. EMG signals were amplified 10X at the electrode site before remote differential amplification (common mode rejection ratio 92 dB, gain range 100–10,000 times, frequency response 20–450 Hz). The digital optical encoder signal was converted to analog with a digital to analog converter before sampling. Position and EMG data were sampled online at 2000 Hz via a 16-bit analog to digital converter (Cambridge Electronic Design).

VM H-reflexes and M-waves were elicited using a constant current stimulator and isolation unit (Digitimer DS7A) with current range of 50 μA–200 mA and total output capability of 400 V. Bipolar stimulating electrodes were placed over the femoral nerve in the inguinal crease approximately half way between the anterior superior iliac spine and pubis. The cathode was positioned proximal to the anode. Electrodes were placed to avoid inadvertently activating nearby muscles. Electrical stimulation was triggered by a digital pulse from a data acquisition board that received an input from the optical encoder signaling crank position. Pulses were delivered within ±3.0° of the desired crank position.

2.3. Protocol

After subjects were informed of the procedures and paretic individuals underwent the lower limb portion of the Fugl-Meyer test (Fugl-Meyer et al., 1975), the skin over each muscle was gently abraded and cleaned with an alcohol swab. Surface EMG electrodes were placed over the distal half of each muscle of the right leg of neurologically intact subjects and both legs of paretic subjects. A common reference electrode was placed over the distal tibia on the medial aspect of the leg. Electrodes were secured with adhesive tape.

VM H-reflexes were examined on the paretic limb of stroke survivors and the right leg of neurologically intact individuals. As shown in Fig. 1, H-reflexes were examined during forward pedaling at 11 different positions in the pedaling cycle (15, 45, 90, 113, 135, 158, 180, 225, 315, 330, and 345° past top-dead-center) and during static isometric knee extension contractions at comparable levels of VM EMG and similar positions in the pedaling cycle. These positions were selected because previous work indicated the presence of inappropriate extensor muscle activity at these crank positions in people with post-stroke hemiparesis (Kautz and Brown, 1998, Schindler-Ivens et al., 2004). The amplitude of VM H-reflexes was compared during pedaling and static

conditions in order to account for changes in H-reflex amplitude that are associated with changes in muscle activity and the excitability of the motor neuron pool.

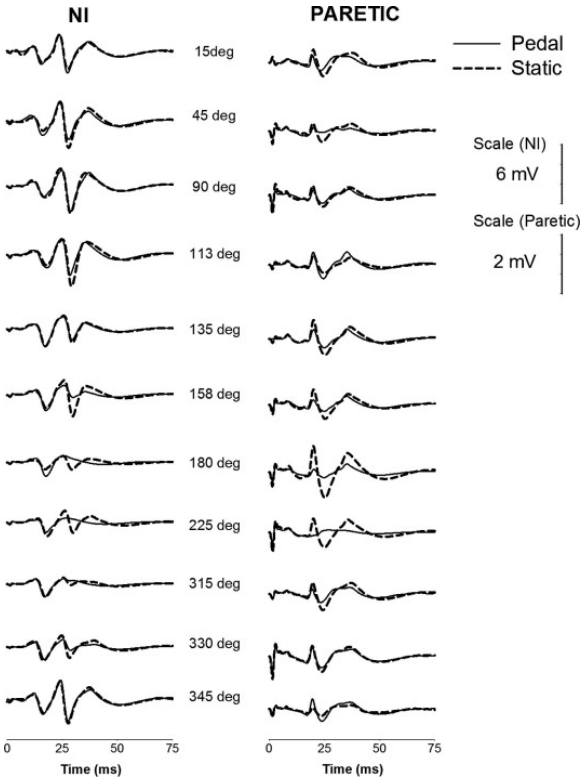

Fig. 1. Representative examples of vastus medialis (VM) H-reflexes recorded at 11 different positions in the pedaling cycle and during matched static contractions at comparable limb positions. NI = neurologically intact.

The tension on the ergometer was adjusted to approximately 50% of the subject's maximum pedaling load, defined as the highest tension against which subjects could complete 10 crank revolutions smoothly and continuously. To set this load, we asked subjects to complete 10 crank revolutions at 40 rotations per minute (RPM) at a negligible load. After successfully completing this task, we increased the load by 10–15% and asked the subject to complete another 10 revolutions at 40 RPM. This procedure was repeated until we reached a load at which the subject was unable to complete 10 revolutions while maintaining smooth and continuous pedaling at 40 RPM. We knew that we had reached the maximum load when subject would stop pedaling before 10 revolutions were complete or when they attempted to complete the task with a jerky, discontinuous pedaling pattern. After noting the maximum pedaling load, we adjusted the tension to 50% of this value for the experiment, and the subject rested for several minutes before proceeding. With the help of visual feedback, subjects were instructed to pedal forward at a rate of 40 rotations per minute using both legs. All of the individuals with stroke were capable of pedaling at the desired rate and load without physical assistance.

At each of the test positions, approximately 13 stimulation and 13 pass trials were recorded. Pass trials, in which data were sampled but no stimulation occurred, were used to identify the amount of VM EMG present at the points in the cycle where H-reflexes were elicited and to set EMG targets for the static task. A single test position was examined in each run of data collection. This approach allowed us to adjust the stimulation intensity at the start of the run and to maintain the preceding M-wave at a constant amplitude ($\leqslant$20% of M-max) across all conditions. Thus, at the start of every run, stimulation intensity was manually adjusted to maintain constant M-wave size during pedaling and static tasks and across all 11 test positions. Typically, the M-wave could be adjusted within the first 2–3 pulses. The first 2–3 pulses, which were typically outside the desired range of $\leqslant$20%

of M-max were discarded. Maintaining a constant M-wave size helped ensure that stimulation intensity was comparable across conditions and crank positions. H-reflex amplitude was not deliberately manipulated but was allowed to fluctuate based on the condition and crank position. The order in which test positions were introduced was randomized among subjects to avoid order effects. Pass trials were introduced randomly during each run. Subjects were offered rest breaks at least every 5 min.

For the static task, approximately 13 H-reflexes were recorded while the bicycle crank was locked into each of the same 11 positions that were examined during pedaling. In each test position, subjects produced a static isometric knee extension contraction while the pedal and crank were held stationary in positions comparable to pedaling. Subjects were instructed to extend their knee and maintain VM muscle activity within a specified target zone displayed on a computer monitor. When EMG activity was within the target range for 200 ms, a pulse was delivered. H-reflexes were elicited every 5 s as long as the appropriate level of EMG (static trials) or crank position (pedaling trials) was achieved.

The VM M-max was elicited at each of the 11 static positions. Previous work has shown that M-max may change considerably with changes in muscle length associated with changing limb position (Gerilovsky et al., 1977). Therefore, it was necessary to record M-max at all 11 positions.

2.4. Data processing

The mean peak-to-peak (PP) amplitude of VM H-reflexes and M-waves was calculated at each crank position for pedaling and static trials. The level of background VM activity observed during pedaling was estimated by calculating the root mean square (RMS) of the EMG during pass trials using the same temporal window in which H-reflexes were observed during stimulation trials. VM background activity during static conditions was estimated by calculating the RMS of VM EMG during a 50 ms window preceding stimulation. The PP amplitude of H-reflexes and M-waves and the RMS of background EMG were normalized to respective values of M-max recorded at comparable positions in the crank cycle. Calculations were completed in Matlab (Mathworks, Inc.) and Spike 2 (Cambridge Electronic Design) software.

Previous work has demonstrated that the amplitude of quadriceps H-reflexes may be difficult to detect (Larsen and Voigt, 2006) because these muscles reside in close proximity to the spinal cord and their H-reflex latency is shorter than in distal leg muscles. Consequently, the VM H-reflex may not be well separated from the preceding M-wave. In order to obtain the best possible estimate of VM H-reflex PP amplitude we used a signal processing procedure first developed by Larsen and Voigt (Larsen and Voigt, 2006). See Fig. 2. In short, we used the M-max recordings, which were free of any H-reflex, to identify the portion of the preceding M-wave that may have extended into the H-reflex. This portion of the M-max signal was then subtracted from the VM H-reflex to remove potentially contaminating effects of the preceding M-wave. Specifically, the ensemble averages of the M-max and H-reflex recordings were calculated for each position and each condition (Fig. 2, top). The M-max signals were scaled so that they were the same size as the M-wave preceding the H-reflex (Fig. 2, middle). We then identified the portion of the M-max signal that coincided in time with the H-reflex (referred to as “hindmost flank” in Fig. 2, middle) and subtracted this portion of the scaled M-max from the H-reflex. This manipulation allowed us to use the M-max trace, which was free of an H-reflex, to see how the preceding M-wave affected the size of the H-reflex. In effect, we pretended that the M-max was the M-wave preceding the H-reflex. Because the M-max was adjusted to be the same size as the preceding M-wave, we could then subtract the hindmost flank of the M-max trace from the H-reflex trace to account for the effect of the preceding M-wave on the size of the H-reflex. The PP amplitude of H-reflexes was identified from the subtracted trace (Fig. 2, bottom). This signal processing procedure was completed for VM data at each of the 11 test positions for pedaling and static conditions.

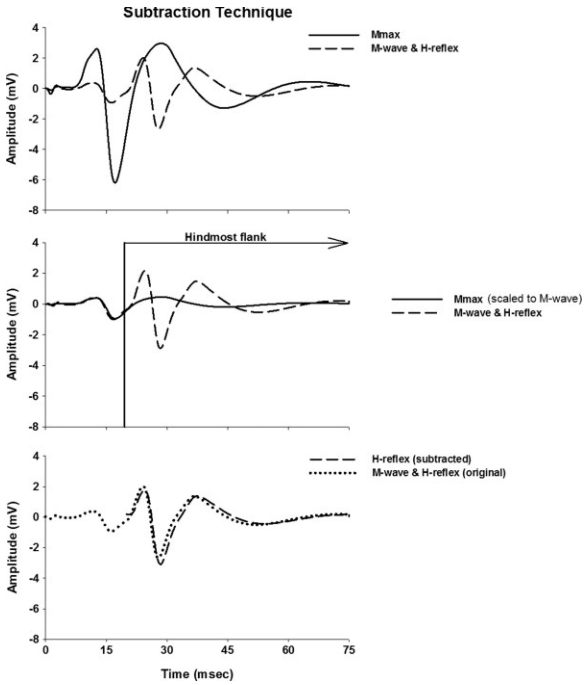

Fig. 2. Signal processing technique to remove potentially contaminating effects of the M-wave from the H-reflex. Top: Ensemble averages of M-max (solid line) and H-reflex (dashed line) recordings, shown on their original scale. Note the small M-wave preceding the H-reflex. Middle: Ensemble average of M-max and H-reflex recordings after the M-max had been scaled to the same size as the preceding M-wave. The hindmost flank is the portion of the M-max signal that coincided in time with the H-reflex. Bottom: The signal labeled "original" (dotted) is the same as the "M-wave & H-reflex" signal (dashed line) in the top panel. The signal labeled "subtracted" (dashed line) is the H-reflex recording after the hindmost flank of the M-max was subtracted. One can see the effect of the subtraction technique on H-reflex amplitude. The peak-to-peak (PP) amplitude of the "subtracted" signal (dashed line) was used in further analysis.

The validity of the subtraction technique was examined by visually inspecting the shape and size of the H-reflex after subtraction was completed. We reasoned that, if the M-wave bled into the H-reflex, it would inflate the amplitude of the first positive peak of the H-reflex. Hence, any technique that corrected for this problem would result in a smaller H-reflex positive peak. As expected, the bottom panel of Fig. 2 shows that the subtracted H-reflex positive peak is smaller than in the original trace. Also, the shape of H-reflexes was unchanged after subtraction suggesting that the subtraction technique did not distort the H-reflex in such a way as to result in erroneous measures.

2.5. Statistical analysis

Statistical analysis was performed on paretic and neurologically intact group data. Within each group, two-way repeated measures analysis of variance (ANOVA) was used to identify differences in mean normalized H-reflex and M-wave amplitude as well as background VM EMG across the pedaling cycle and between pedaling and static tasks. In the presence of significant condition (pedal versus static) by position interactions, simple effects analysis (paired *t*-tests) was used to identify the limb position at which these values were different. Two-way repeated measures ANOVA was also used to identify differences in mean normalized H-reflex amplitude between groups (neurologically intact versus paretic) across all crank positions examined. Non-linear regression analysis was used to examine the relationship between VM background EMG and mean normalized H-reflex PP amplitude in paretic and neurologically intact groups during pedaling and static tasks. Group mean values for H-reflex amplitude and background EMG were calculated at each crank position and used for the regression

analysis. Analyses were conducted in SPSS (SPSS, Inc.) or Sigmaplot (Systat Software, Inc.), and all differences were considered significant at $P < 0.05$.

3. Results

3.1. H-reflexes

As shown in Fig. 3, neurologically intact VM H-reflex amplitude was modulated across the pedaling cycle. The largest H-reflexes were observed during extension (~32.3% of M-max at 90°), and the smallest were seen during flexion (~1.1% of M-max at 225°). H-reflexes were smaller during the late extension and early flexion phases of the pedaling cycle as compared to matched static knee extension. Statistical analysis supported these observations as two-way repeated measures ANOVA showed a significant main effect of position ($P < 0.001$) and condition ($P = 0.006$) and a significant position by condition interaction ($P = 0.018$). Paired *t*-tests performed at each crank position showed that VM H-reflexes were significantly smaller during pedaling at 158°, 180°, 225°, and 315° ($P < 0.05$) but were not different at the other crank positions examined.

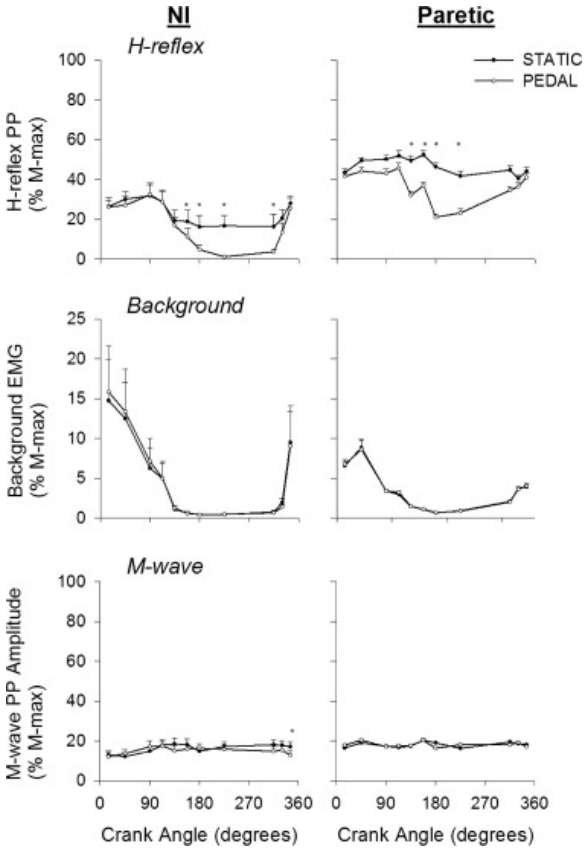

Fig. 3. Group mean (±SE) data during pedaling and static conditions at all 11 positions examined. Normalized H-reflex and M-wave peak-to-peak (PP) amplitudes and background EMG are shown. Asterisks indicate significant condition-dependent differences (pedaling versus static) at $P < 0.05$. Top: H-reflex PP amplitude.
Middle: Vastus medialis (VM) background EMG. Bottom: M-wave PP amplitude. All values are normalized to M-max.

Similar to the neurologically intact group, paretic VM H-reflexes were modulated with the phase of the pedaling cycle and with the condition (pedal versus matched static). H-reflexes were larger during the limb extension (~45.7% of M-max at 113°) as compared to the limb flexion (~21.8% of M-max at 180°) phase of pedaling and were smaller during the late extension and early flexion phases of the pedaling cycle as compared to the matched static condition. Statistical analysis revealed significant main effects of condition ($P = 0.001$) and

position (P = 0.022) and a significant condition by position interaction (P = 0.002). Paired t-tests at each crank position revealed that paretic VM H-reflexes were smaller during pedaling at 135°, 158°, 180°, and 225° but not at any of the other crank positions examined. Of note is the observation that, despite significant phase-dependent modulation and pedaling-related suppression, paretic VM H-reflex amplitude never fell below 21.8% (on average) of M-max. In contrast, the average minimum value of neurologically intact VM H-reflexes was 1.1% of M-max. This observation is further supported by statistical analysis indicating that, during pedaling, paretic H-reflexes were larger than neurologically intact H-reflexes at all crank positions examined (P = 0.014). There was no significant group by position interaction (P = 0.162) during pedaling, suggesting that the pattern of H-reflex modulation across the pedaling cycle was not different between groups.

3.2. Background muscle activity and M-waves

Within each group, background VM muscle activity was not significantly different during pedaling and matched static contractions at any position examined ($P \geqslant 0.343$, Fig. 3, middle). During the extension phase of pedaling, there was a tendency for VM background activity to be smaller in paretic as compared to neurologically intact limbs. However, this observation did not achieve statistical significance (P = 0.406). The average size of the M-wave was 15.7% (±8.6%) in the neurologically intact group and 18.1% (±7.0%) in the stroke group. These values were not significantly different (P = 0.378). In the neurologically intact group, paired t-tests revealed that the M-wave was significantly larger during the static as compared to the pedaling condition at 345°. At this position, mean values for the M-wave were 17.1% and 12.8% of M-max for static and pedaling conditions, respectively. There was no other group, condition, or position-dependent difference in M-wave amplitude that reached statistical significance. See Fig. 3, bottom.

3.3. Relationship between background EMG and H-reflex excitability

As shown in Fig. 4, the neurologically intact group displayed a significant relationship between VM EMG and H-reflex amplitude whereby H-reflex amplitude rose exponentially with increasing VM muscle activity until reaching maximum. This relationship was evident during static and pedaling conditions (static $P < 0.001$, $R^2 = 0.76$; pedal $P < 0.001$, $R^2 = 0.91$). In the paretic limb of people post-stroke, there was no significant relationship between VM EMG and H-reflex amplitude during the static condition ($P = 0.85$, $R^2 = 0.004$). However, during pedaling, the exponential relationship that was observed in the neurologically intact group became evident and reached statistical significance in the paretic group ($P < 0.001$, $R^2 = 0.77$). Regardless of the task, VM H-reflexes were larger in the paretic as compared to the neurologically intact group for a given level of VM EMG.

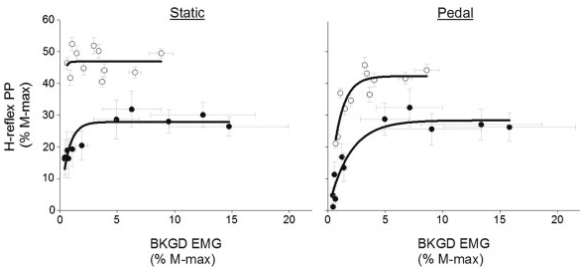

Fig. 4. Group data describing the relationship between background vastus medialis (VM) EMG and VM H-reflex peak-to-peak PP amplitude during pedaling and static conditions. Each point represents the group mean at a given crank position. Solid lines represent the best fit of the data. Error bars are standard error.

4. Discussion

The results of this study indicate that Group Ia reflex excitability of the VM is abnormally elevated in the paretic limb of people post-stroke and that, during static muscle activation, the excitability of this reflex pathway does

not change with the level of VM activity. Pedaling reduces Group Ia reflex excitability of the paretic VM and restores the normal relationship between EMG and reflex amplitude. These observations suggest that pedaling-induced changes in Group Ia reflex excitability that have been reported for the paretic SO are also evident in the paretic VM and that pedaling may have a generalized effect on lower extremity Group Ia reflex excitability after stroke.

4.1. Comparison with previous reports

Comparison of the present data with previous observations suggests that stroke affects Group Ia reflex excitability of the VM in the same way as the SO. In a previous study, we showed that paretic SO H-reflexes were abnormally elevated and not modulated in amplitude with background EMG (Schindler-Ivens et al., 2008). Pedaling decreased SO H-reflex amplitude and restored the normal, direct relationship between EMG and H-reflex excitability. Here, we report similar findings for the VM whereby paretic VM H-reflexes were abnormally elevated and did not change in amplitude with changing background VM activity during tonic muscle activation. During pedaling, paretic VM H-reflex amplitude was modulated normally with the level of background VM activity. Moreover, like neurologically intact individuals, paretic VM H-reflex amplitude decreased during pedaling at low levels of VM background activity that were coincident with the flexion and flexion-to-extension portions of the pedaling cycle, making pedaling-related VM H-reflex modulation comparable in neurologically intact and paretic individuals.

Further comparison between the present data and previous work suggests that differences in SO and VM H-reflexes are muscle-dependent, not stroke-related. In the paretic SO, pedaling decreased H-reflex amplitude at all positions examined (Schindler-Ivens et al., 2008); whereas, in the paretic VM, pedaling induced a significant decrease in H-reflex amplitude at only four positions (135°, 158°, 180°, and 225°). The same difference between the SO and VM was evident in the control group where pedaling decreased SO H-reflex amplitude at 10 out of 11 positions, but decreased VM H-reflex amplitude at only four positions (158°, 180°, 225°, 315°).

SO and VM responses also differed with respect to the relationship between Group Ia reflex excitability and background muscle activity. In the neurologically intact SO, the relationship between these variables was direct (Schindler-Ivens et al., 2008). In stroke survivors who did not display this direct relationship during static contractions, pedaling induced a positive, linear relationship between SO EMG and H-reflex excitability. In the paretic VM, pedaling induced a non-linear relationship between background muscle activity and H-reflex excitability that was well described by an exponential rise to maximum H-reflex amplitude with increasing VM background EMG. The same model provided a good fit of the control VM data, indicating that the non-linear relationship is not a pedaling- or stroke-related phenomenon, but rather, is a characteristic of the VM H-reflex.

One difference between SO and VM Group Ia excitability that cannot be attributed to the inherent behavior of each muscle is the frequency with which we observed impaired modulation between background EMG and H-reflex excitability in stroke survivors. In the paretic SO muscle, lack of H-reflex modulation with changing levels of EMG during the static condition was evident primarily in low functioning stroke survivors (Schindler-Ivens et al., 2008). In the paretic VM, lack of reflex modulation during static contractions was evident in all stroke subjects, regardless of impairment level. This observation suggests that abnormalities in Group Ia reflex excitability may be even more prevalent in the paretic VM as compared to the paretic SO. Consequently, any beneficial effects of pedaling on Group Ia reflexes may have a greater impact on VM as compared to SO.

4.2. Implications of experimental findings

Our results indicate that pedaling-related suppression of VM H-reflexes remains intact post-stroke as does the pattern of VM H-reflex modulation across the pedaling cycle. Similar observations in the SO have been attributed to presynaptic inhibition of Group Ia terminals (Brooke et al., 1992, Morin et al., 1982, McIlroy et al.,

1992, Pyndt and Nielsen, 2003, Petersen et al., 1999). If the same mechanisms are involved in VM H-reflex suppression, then a logical conclusion would be that presynaptic inhibition, as activated via pedaling, remains intact post-stroke. However, the mechanisms underlying pedaling-related suppression of quadriceps H-reflexes are unclear. To our knowledge, Larsen and Voigt (2006) are the only others who have examined quadriceps H-reflexes during pedaling. Contrary to our observations, they found no difference in H-reflex amplitude between pedaling and static muscle activation at comparable levels of background EMG. They suggested that condition-dependent (i.e. pedal versus static) reflex modulation, which has been studied mainly at the ankle, may not generalize to other joints. Discrepancies between the two studies may be due to different methodologies. In the present study, condition-dependent differences in H-reflex amplitude were observed in the neurologically intact group only at very low levels of VM muscle activity (<2.5% of M-max). This observation is displayed in Fig. 3 (middle left) where one can see very low levels of VM muscle activity at crank positions of approximately 135°–330°. Pedaling-related H-reflex suppression was evident only at these positions (Fig. 3, top left). The observation is also evident in Fig. 4 where one can see that neurologically intact VM H-reflexes were smaller during pedaling as compared to matched static contractions at very low levels of background EMG. The Larsen and Voigt paper (2006) did not examine condition-related (i.e. pedal versus static) H-reflex modulation at very low levels of background EMG. They examined H-reflex excitably only when the muscle showed substantial activity. In the pedal versus static portion of their analysis, they intentionally omitted crank positions between approximately 90° and 300° where EMG was very low. Therefore, it seems that they missed the condition-dependent H-reflex modulation of the quadriceps, which unlike the SO, appears to be evident only at very low levels of background muscle activity. More studies are needed to confirm this conclusion and to understand the mechanisms underlying condition-related (pedal versus static) VM H-reflex amplitude modulation. However, it is possible that the level of EMG, *per se*, is not responsible for the observed suppression. The positions with low levels of EMG are coincident with the flexion and the extension-to-flexion transition phases of the pedaling cycle. Hence, it may be the phase of the pedaling cycle that is responsible for VM H-reflex suppression. The VM is a knee extensor muscle that must decrease its activation during the extension-to-flexion transition and remain quiet during limb flexion to permit unopposed knee flexion. However, as the knee is flexing, the VM lengthens. This lengthening could induce a VM stretch reflex that results in knee extension and interferes with crank propulsion. Hence, it appears that inhibition of Group Ia reflexes to the VM during these portions of the pedaling cycle may be functionally important, helping the VM remain quiet at appropriate points in the pedaling cycle. Similar observations have been reported in the SO muscle where SO H-reflexes were inhibited by presynaptic inhibition during the flexion phase of pedaling, but not during the extension phase (Pyndt and Nielsen, 2003). Regardless of the mechanism, the VM H-reflex modulation across the pedaling cycle remains intact post-stroke.

The absence of any relationship between background EMG and H-reflex amplitude during static contractions of the paretic VM suggests that there is an abnormal distribution of motor neuron recruitment thresholds for this muscle, at least within the range of motor neuron excitability examined. Others have reported EMG/H-reflex relationships in able-bodied individuals that were similar to those observed in our control group; whereby, H-reflex amplitude increased linearly with increasing background EMG and then reached a plateau (Capaday and Stein, 1987, Butler et al., 1993). The linear portion of this relationship has been explained as follows (Capaday and Stein, 1987): With increasing background EMG, there is an increase in the number of motor neurons on the subliminal fringe of activation (i.e. inactive motor neurons that are recruited reflexively) such that a given Ia input to the motor neuron pool will excite more motor neurons at higher as compared to lower levels of background EMG. With increasing background EMG, as the proportion of active motor neurons continues to increase, there are a smaller number of subliminally active motor neurons available for recruitment when the Ia barrage arrives in the spinal cord, resulting in a plateau in the EMG/H-reflex relationship. This explanation is predicated on the assumption that there is a range of motor neuron recruitment thresholds and that motor neurons are recruited in an orderly fashion according to the size principle. The absence of any EMG/H-reflex

relationship in the paretic VM during static contractions suggests a compression in the range of VM motor neuron recruitment thresholds such that even at low levels of background muscle activity there are a sufficient number of motor neurons subliminally active and capable of being activated in response to Ia input. These conclusions, however, are limited to the small range (~1–10% of M-max) of motor neuron excitability levels examined.

The distribution of excitability among motor neurons in a pool is a function of the intrinsic excitability of motor neurons and synaptic influences acting on the pool (Kernell and Hultborn, 1990). Evidence is lacking in support of altered intrinsic excitability of motor neurons post-stroke (Katz and Rymer, 1989). However, the compressed VM H-reflex recruitment range could be attributed to an unevenly distributed excitatory bias to higher threshold motor neurons or to reduced presynaptic inhibition of Ia afferent terminals (Kernell and Hultborn, 1990). Pedaling may restore a more gradual recruitment of motor neurons by redistributing the excitatory drive to motor neurons and/or by inducing movement-related presynaptic inhibition of Group Ia afferents.

Our observations also suggest that pedaling may be a useful therapeutic approach for reducing Group Ia reflex excitability in the paretic lower extremity of people post-stroke. It is estimated that approximately 35% of stroke survivors have spasticity (Sommerfeld et al., 2004). Pharmacological, surgical, and rehabilitation interventions are prescribed to reduce hyperactive reflexes that are characteristic of this impairment (Pandyan et al., 2009). Pedaling could enhance or replace other interventions, as it appears that this form of physical activity reduces Group Ia reflex excitability in proximal and distal extensor muscles. Barzi and Zehr (2008) also suggested that cyclic movements may be useful for reducing exaggerated reflexes in people post-stroke. This group showed that arm pedaling suppressed the amplitude of SO H-reflexes in people with hyperreflexia caused by stroke. Arm pedaling had a generalized effect on SO H-reflexes, reducing H-reflex amplitude in the paretic and non-paretic SO. Similarly, we report a generalized effect of lower limb pedaling on lower extremity H-reflexes that exerts its effects on the paretic SO and VM. However, further study is needed to determine whether the observed changes in Group Ia reflex excitability result in improved mobility and whether these changes last beyond the period of active pedaling.

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