Increased Workload Enhances Force Output During Pedaling Exercise in Persons With Poststroke Hemiplegia

D.A. Brown, PhD, PT; S.A. Kautz, PhD

Background and Purpose—A principle of poststroke rehabilitation is that effort should be avoided since it leads to increased spasticity and produces widespread associated abnormal reactions. Although weakness also contributes to movement dysfunction after a stroke, it has been feared that heightened activity levels during strength training will further exacerbate the abnormal tone imbalance present in spastic hemiplegia. The purpose of this study was to test this hypothesis by quantifying the effects of increased workload on motor performance during different speeds of pedaling exercise in persons with poststroke hemiplegia.

Methods—Twelve healthy elderly subjects and 15 subjects with poststroke hemiplegia of greater than 6 months since onset were tested. The experimental protocol consisted of having subjects pedal at 12 randomly ordered workload and cadence combinations (45-J, 90-J, 135-J, and 180-J workloads at 25, 40, and 55 rpm). Pedal reaction forces were measured and used to calculate work done by each leg, including net positive and negative components. An electromyogram was recorded from seven leg muscles.

Results—The main finding was that net mechanical work done by the plegic leg increased as workload increased in 75 of 81 instances without increasing the percentage of inappropriate muscle activity.

Conclusions—This study provides evidence that persons with hemiplegia increase force output by their plegic limb when pedaling against higher workloads without exacerbation of impaired motor control. Therefore, exertional pedaling exercise is a beneficial intervention for achieving gains in muscular force output without worsening motor control impairments. (Stroke. 1998;29:598-606.)

Key Words: exercise ■ hemiplegia ■ motor activity ■ muscle spasticity
positive (the limb assists crank propulsion), negative (the limb resists crank propulsion), or zero. Since the total work provides a net measure for a cyclic movement, and pedaling typically includes periods of assistance and resistance, it is useful to independently assess the assistance and resistance provided by the leg. The net positive work done by the plegic leg represents the component of the mechanical work that propels the crank against the load and is principally the result of muscular contributions in neurologically normal subjects. The net negative work done by the plegic leg represents the component of the mechanical work that resists crank propulsion. Negative work occurs in the upstroke for neurologically normal subjects and represents the combined effect of muscular activity and gravity and inertial forces.

The purpose of this study was to quantify the effects of increased workload on motor performance during different speeds of pedaling exercise in persons with poststroke hemiplegia. We compared the motor performances of a control population consisting of healthy, elderly subjects with those from persons with hemiplegia. It is generally believed that performance is degraded and muscle activity patterns do not respond appropriately to increased workload. Thus, if net mechanical work done by the plegic leg does decrease because of greater relative amounts of inappropriate muscle activity, then worsened performance is a consequence of exertion and exertion should be avoided. However, if net mechanical work by the plegic leg actually increases and performance improves, then strengthening exercises such as high workload pedaling would be recommended as a potentially effective training modality for reversing muscular weakness and possibly improving motor performance.

Subjects and Methods

Twelve healthy elderly subjects and 15 subjects with poststroke hemiplegia of greater than 6 months since onset were tested (Table). Subjects had sustained a single, unilateral cerebrovascular accident with residual lower limb plegia; had no severe perceptual, cognitive, or sensory deficits, no significant lower limb contractures, and no significant cardiovascular impairments contraindicative to pedaling; and could tolerate sitting on a bicycle seat for approximately 1 hour. All subjects gave informed consent as approved by the internal review board of the Stanford University School of Medicine. Patients underwent the lower limb portion of the Fugl-Meyer test for assessment of global motor function. The reliability and validity of this assessment have been documented for the poststroke hemiplegic population. The healthy elderly subjects showed no signs or symptoms of neurological disease or lower limb orthopedic impairment. The hemiplegic subjects in this study ranged in their walking ability from mildly impaired to nonambulatory. They also varied in their ability to perform movements outside of extensor/flexor synergy patterns (eg, Reference 25) as assessed clinically by a portion of the modified Fugl-Meyer assessment (see “Synergy Performance” in the

Subject Population Characteristics

<table>
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<tr>
<th>Subject</th>
<th>Age, y</th>
<th>Sex</th>
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<th>Synergy Performance*</th>
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Plegic (n=15) | 65.3±5.8 | 12 M | 42.3±43.1 | 0–14, n=3 | 86.7±8.7 | 10 L |
|             | 3 F     | 15–18, n=6 | 5 R     | 19–22, n=6 |

Control (n=12) | 69.5±8.4 | 7 M | ... | ... | ... | ... |
|              | 5 F     | ... | ... | ... | ... | ... |

*Synergy performance reflects the ability to move within (0–14), to combine (15–18), or to move outside of (19–22) extensor/flexor synergy patterns as measured in a portion of the modified Fugl-Meyer assessment (maximum score=22).
Table). Subjects scoring 14 or less were only able to move within the synergy patterns (n=3), those scoring 15 to 18 were additionally able to combine elements of the synergy patterns (n=6), and the best-performing subjects (scoring >18) were able to at least partially perform a movement outside of the synergy patterns (n=6). Therefore, although the group did not contain any subjects with severe perceptual, cognitive, or sensory deficits, it was representative of a range of rehabilitation candidates with motor impairment after stroke.

A standard ergometer with a frictionally loaded flywheel was modified by including a backboard seating mechanism with shoulder and lap harnesses to stabilize the subject and remove the need to control balance. Further details concerning the apparatus are presented elsewhere. Reaction forces oriented normal and fore-and-aft to the pedal surfaces were measured by instrumented pedals. The feet were firmly attached to foot plates on the pedal surface, which allowed the subjects to create shear and vertical forces. Angular rotation of the crank and pedals was measured by optical encoders.

The experimental protocol, conducted in an hour, consisted of measurement of pedal forces, pedal and crank kinematics, and EMG during pedaling at 12 randomly ordered workload and cadence combinations (45-[very low], 90-[low], 135-[medium], and 180-[high] workloads at speeds of 25-[slow], 40-[medium], and 55-[fast] rpm). Crank angular velocity was displayed to the subjects, and they were instructed to maintain a steady cadence while pedaling. Once a steady cadence was achieved, 15 seconds of EMG, pedal force, and encoder data were collected (1200 samples per second).

Surface EMG was recorded from tibialis anterior (TA), soleus (SO), medial gastrocnemius (MG), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), and semimembranosus (SM) of the right leg in healthy subjects and of both legs in subjects with hemiplegia. EMG (Ag-AgCl) electrodes (Therapeutics Unlimited) were positioned over the distal half of the muscle belly such that contact surfaces were aligned longitudinally to the muscle fibers. Electrode sites were prepared by cleaning the skin with isopropyl alcohol and shaving the hair, when necessary, to ensure good contact. Electrodes (interelectrode distance≈22 mm, diameter≈8 mm) were attached with the use of adhesive pads and electrode gel. Electrodes provided preamplification with a gain of ×35. A common ground reference electrode was placed on the distal end of the right tibia. Amplifier gain was selectable from ×500 to ×10 000 with a bandwidth of 20 to 4000 Hz. The common mode rejection ratio was 87 dB at 60 Hz, and input impedance was greater than 15 MΩ at 100 Hz.

Data Processing and Analysis

The net mechanical work done by each limb was calculated from the kinematic and kinetic data and used as a measure of motor performance. First, a third-order Butterworth low-pass filter was used to filter pedal forces (20-Hz cutoff) and the crank and pedal angles (8-Hz cutoff). The pedal force components oriented radial and tangential with respect to the crank arm were calculated from the normal and shear forces. The tangential component of the pedal force created a torque about the crank center (referred to as the crank torque) that contributed to the angular acceleration or deceleration of the crank. The crank torque was plotted against crank angle, and the area under the resulting curve yielded the net mechanical work done by the leg. The positive and negative areas were also computed separately as measures of the positive (propulsive) and negative (retarding) work done by the limb.

The total IEMG was calculated over the entire crank cycle and was used to show any overall increases or decreases in total muscle activity during higher workloads. Also, we developed a quantitative measure of “inappropriate muscle activity” as a means for identifying increases or decreases at higher workloads. Since muscle excitation cannot be consistently characterized by a single set of on-off times in persons with hemiplegia, each EMG was quantified in terms of the relative percent excitation present during four equal quadrants (90°) in the pedaling cycle. The four quadrants were defined by axes parallel and perpendicular to the seat tube (Fig I). Quadrants I and II coincided with limb extension (foot moving away from pelvis), and quadrants III and IV coincided with limb flexion. Alternatively, contiguous quadrants IV and I (foot moving anteriorly with respect to the trunk/pelvis axis) or II and III (foot moving posteriorly) coincided with limb “transitions” (ie, the switch from limb flexion to extension or vice versa). For each quadrant, the excitation, quantified by integrating the rectified EMG (IEMG), was expressed as the percentage of IEMG over the entire cycle. The relative IEMG in a quadrant provided a measure to quantitatively test whether the plegic EMG was inappropriately timed (ie, excitation in a quadrant where excitation does not occur in control subjects). This technique has been reported elsewhere and has been used to identify one quadrant for each muscle group where inappropriate activity can occur (ie, SO3, MG1, VM3, RF3, BF1, SM1). Inappropriately timed activity occurs during periods in the pedaling cycle when muscles are lengthening and hence doing negative work.

We visually examined individual, nonaveraged crank kinematics, kinetics, and EMG activity for general trends. Then we calculated the total positive, total negative, and net mechanical work and percent IEMG in the “inappropriate” quadrant for each revolution and averaged to get the mean values for the plegic limb in each trial. Differences between the control subjects and the hemiplegic subjects were evaluated with a two-tailed Student’s t test (P<.05). The differences in net mechanical, positive, and negative work were calculated between each pair of contiguous workload conditions (eg, very low to low; low to medium; medium to high) within each actual speed. In the absence of a contiguous pair of workloads, the next highest workload was used for comparison. Because of the large intersubject variability among hemiplegic subjects, the individual subject data are also presented wherever possible to demonstrate the robustness of findings within the hemiplegic population.

Results

Success With Pedaling at Specified Workloads and Speeds

Although all subjects were able to pedal the ergometer at some speed-workload combination, problems related to completing the task occurred in almost all subjects with hemiplegia. In all, there were 180 speed-workload combinations possible for the 15 subjects with hemiplegia (12 combinations per subject times 15 subjects). Only 2 of 15 hemiplegic subjects were able to successfully pedal at all 12 speed and workload combinations. Of the 180 combinations, pedaling performance fell under the following four
categories: (1) successfully able to pedal at the specified workload and speed (108 combinations in all subjects); (2) unable to push the crank against the specified load (i.e., no cranking motion achieved) (48 combinations in 6 subjects); (3) pedaled slower than the target speed (16 combinations in 8 subjects); and (4) pedaled faster than the target speed (8 combinations in 7 subjects). Those combinations that were performed either faster or slower than the target speeds were recategorized at the level of actual speed if they fell within \( \pm 5 \) rpm of a specified target speed category measure (20 of 24 combinations were recategorized).

The following results contain analysis of those trials in which subjects successfully completed the task of pedaling (\( n = 128 \), or 180 total combinations minus 48 nonpedaling and 4 noncategorized speed combinations). Most subjects with hemiplegia were able to pedal against at least two workloads at the fastest target speed (55 rpm). Ten of 15 subjects with hemiplegia were able to pedal against at least two workloads at the highest workload level (135 J) and were able to hit the fastest target speed. In contrast, all control subjects were able to pedal at the highest workload and at the fastest target speed (although not all subjects when the highest speed and workload were combined). Of the healthy, elderly control subjects, 9 of 12 subjects were able to successfully pedal at all 12 conditions. Of the 3 remaining subjects, 2 were unable to push against some specified load, and all 3 pedaled slower than the fastest target speed at the highest workload.

**Kinetic Responses to Increased Workload**

Subjects with hemiplegia performed less net mechanical work with the plegic leg than control subjects with the nonpreferred leg (22.1 ± 21.8 J versus 68.3 ± 8.0 J at the 135-J workload level; \( P < 0.0001 \)) and produced a very large range of work values (−19.8 J to 54.3 J at the 135-J workload level). Compared with control subjects, single leg crank torque trajectory was characterized by less net positive (48.8 ± 13.3 J
versus 70.0±4.8 J; \( P<.0001 \) and more net negative work (−26.7±14.0 J versus −6.3±4.6 J at the 135-J workload level; \( P<.0001 \)) in the plegic leg. As a consequence, the nonplegic leg must necessarily generate compensatory forces to overcome the higher negative work (by increasing downstroke work) and lesser positive work (by generating positive work during the upstroke) generated by the plegic leg. The performance deficit in persons with hemiplegia can be characterized as reduced force output during the downstroke phase and increased resistive force output during the upstroke phase (Fig 2).

Control subjects demonstrated typical kinetic responses to increased workload (Fig 3). Subjects showed increased net mechanical work done by each leg as workload increased at all speeds (\( P<.0001 \)). This resulted from a combination of in-
increased net positive work ($P<.0001$) and decreased net negative work ($P<.0001$).

Subjects with hemiplegia appropriately increased the net mechanical work done by the plegic leg as workload increased at all speeds. This occurred even though the nonplegic leg is capable of generating all of the extra work output at higher workloads because the coupled cranks allow it to compensate for deficits in the plegic leg. Of those subjects with hemiplegia who were able to complete at least two levels of workload ($n=14$), there was rarely individual evidence for further impaired kinetic performance as a result of increased workload. With no exceptions, subjects showed increased net positive work done by the plegic leg. The net mechanical work done by the plegic leg, with only six exceptions of 81 workload pairs (subject 2 [medium and fast speeds, twice in each], subject 11 [fast speed], and subject 15 [medium speed]), always increased when the workload increased (Fig 4). The plegic leg contributed significantly less than 50% of the increase in workload ($P<.05$ for all 61 workload pairs). However, in 12 workload pairs (in subjects 1, 2, 3, 5, 8, and 12), the net mechanical work contributed by the plegic leg actually equaled or exceeded 50% of the mean contribution from the nonplegic leg.

**Muscle Activation Responses to Increased Workload and Speed**

Control subjects and subjects with hemiplegia showed increased IEMG by the plegic leg as workload increased at all speeds ($P<.05$ for all seven muscles and at all speeds). Nonplegic muscles, on average, also showed increased IEMG at higher workloads ($P<.001$), similar to control legs (Fig 5).

Plegic leg total IEMG increased without a disproportionate increase in the percentage of activity occurring during inappropriate quadrants of the pedaling cycle. In all inappropriate muscle activity quadrants (ie, SO3, MG1, VM3, RF3, BF1, SM1), the percent muscle activity occurring remained unchanged ($P>.05$ for all six muscles and at all speeds) (Fig 6). Although the plegic muscles showed greater percentages of muscle activity during these quadrants when compared with control subjects (at least $P<.05$ for all muscles except BF), this overactivity was not exacerbated by increased workload demands. In both the control muscles (Fig 6) and muscles of the nonplegic leg (not shown), inappropriate activity was low and therefore showed no significant increase with higher workloads.

Since three subjects (subjects 2, 11, and 15) showed a significant decrease in net mechanical work as a result of increased workload, we examined the change in inappropriate muscle activity for the major power muscles (ie, RF, VM, BF, and SM). These muscles would be expected to contribute significant inappropriate activity and hence do greater negative work at higher workloads. Fig 7 shows that for subject 2 at the medium-speed condition (when less mechanical work was done at the low versus very low workload), there is a large increase in RF3 activity (24% to 35%) and VM3 activity (19%
to 31%) in the plegic leg. In contrast, for the slow-speed condition (when net mechanical work actually increased), the percentage of both inappropriate plegic RF3 activity and plegic VM3 activity remained unchanged. The activity in these muscles is shown to proportionately increase during the appropriate as well as the inappropriate quadrants. Therefore, although both inappropriate activity and appropriate activity increase in absolute terms with increased workload, the majority of enhanced muscle activity occurs during the appropriate quadrants, leading to the increased net positive work done by muscles. This increase in appropriate activity offsets any increase in net negative work. As a result, increased net mechanical work is done at higher workloads.

No subject reported any negative or positive effects on gait quality from the exercise resulting from participating in the 2-hour session of this study. Subjects did report a significant amount of fatigue after the experimental session ended, but all ambulatory subjects were able to leave the facility under their own volition. In addition, upper extremity postural tone typically increased as a result of extra effort during the experiment. In all cases, any increased postural tone returned to its usual state before the subject left the premises (within one half hour of the session end).

**Discussion**

The main finding from this study was that force output by the plegic leg, although impaired, was enhanced at higher pedaling workloads without exacerbating inappropriate muscle activity. This contradicts the principle of worsened motor performance and exacerbated spastic muscle activity at higher exertional levels. If this principle were supported, we would have observed that a disproportionately larger amount of inappropriate muscle activity would have occurred at higher workloads and lesser amounts of mechanical work would have been generated by the plegic leg. Although this did occur in rare cases (6 of 81 workload pairs), the majority of cases showed increased appropriate and inappropriate activity resulting in increased mechanical work output.

This study provides evidence that persons with hemiplegia can increase the positive work done by their hemiplegic limb during pedaling when working against higher workloads. Our results showed that when subjects with hemiplegia pedal...
against a low workload, they generate relatively low levels of muscular force. When higher workloads are encountered, the level of the muscular output is heightened so that greater positive work can be produced. These results are consistent with a previous study by Benecke et al., who also used ergometer pedaling to evaluate spastic movement dysfunction. One part of their study calculated the net mechanical work asymmetry between limbs as the workload increased from 1 to 5 kilopond-m (kpm) in nine subjects with hemiplegia pedaling at 40 rpm. It was found that the percentage of work done by the nonplegic limb increased from approximately 60% to 68% as the workload increased from 1 to 3 kpm and then remained essentially constant at 68% as the workload increased from 3 to 5 kpm. For the percentage to stay constant as the workload increased from 3 to 5 kpm, the net mechanical work done by the plegic limb had to increase with increased workload. We found in this study and in other studies related to pedaling in persons with hemiplegia that the nonplegic leg performs the majority of net mechanical work, working to overcome the increased negative work produced by the plegic limb. Therefore, increases in pedaling workload will consequently place greater demands on nonplegic leg muscles. Our work has shown that the nonplegic leg is usually capable of responding to the increased demands because the timing of muscle activity patterns is similar to that of control leg muscles and does not change with increased workload. However, one unintended consequence of this type of exercise may be a further asymmetry in muscle strength between the two legs. However, persons with hemiplegia often attempt to perform tasks that require strong compensation by the nonplegic limb to accomplish the task, and therefore the increased force capabilities of the nonplegic leg may be useful in functional tasks.

It is important to recognize the several unique aspects of pedaling exercise before attempting to generalize these results to all exertional leg exercise modalities. First, pedaling is a bilateral task that allows the nonplegic leg to compensate for functional impairments of the plegic leg (through coupling of the cranks). Second, pedaling allows stabilization of abnormal trunk postures so that, although abnormal trunk and upper extremity postural responses were observed, the functional output of the leg muscles could still increase. Third, the trajectory of the feet is constrained to move in a circle, which reduces sudden changes in direction of movement and allows relatively smooth phase tran-
sitions. As a consequence, the transition periods, usually a difficult portion of any reciprocal movement, are rendered less consequential. Finally, loading occurs at the pedal/crank interface, which differs from upper extremity tasks that usually involve increased manipulative skills in order to deal with heavier workloads. In contrast to pedaling, arm exercises in which grip is essential or when limbs are weighted, the added control demands can significantly reduce the person’s capability to respond to the load.

Studies have shown the physiological benefits of aerobic ergometer exercise.12 Dairaghi for technical assistance and Drs Felix E. Zajac and Kevin Mcgiil for their editorial contributions to this article.

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References

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