Increase of Muscle Activities in Hemiplegic Lower Extremity During Driving a Cycling Wheelchair

Kazunori Seki,1 Motohiko Sato2 and Yasunobu Handa1

1Department of Restorative Neuromuscular Rehabilitation, Tohoku University Graduate School of Medicine, Sendai, Japan
2Department of Occupational Therapy, Sendai Institute of Health and Welfare, Sendai, Japan

For the patients with severe hemiplegia, long-time wheelchair sitting is unavoidable, which however increases a risk of secondary impairments due to non-use of the affected leg. A cycling wheelchair (C-W/C) has a possibility to activate paretic muscle through self-locomotion with bilateral pedaling. We therefore measured driving speed of C-W/C and electromyogram (EMG) in both legs during driving in the healthy adults and severe hemiplegic patients. Ten healthy volunteers (mean age 32.8, 26-45 years) and ten non-ambulatory post-stroke patients (mean age 69.0, 55-81 years) with complete or semi-complete hemiplegia participated in this study. EMG was recorded from the key muscles for cycling during isometric movement as baseline and during driving a C-W/C straightforward. All of the patients could drive a C-W/C with mean maximum driving speed of 46.6 (31.7-61.7) m/min, which was about half of that in the healthy subjects and within practical level. Root mean square of EMG (R-EMG) as a parameter reflecting muscle activity was compared between baseline and C-W/C driving. There was no increase in most of the values of R-EMG during driving in the healthy subjects and in the intact side of the hemiplegic patients. In contrast, significant increase was found during driving in several paretic muscles, despite that EMG of the paretic leg showed almost silent at baseline. These results suggest C-W/C can induce muscle activities of the paretic leg and provide a chance of practical locomotion even for the severe hemiplegics. Daily use of a C-W/C may contribute to restore paretic leg function.

Wheelchair; electromyogram; hemiplegia; pedaling; motor function.


Increase of elderly population raises the number of the patients with severe impairments in the field of medical rehabilitation. The rate of physically disabled over 70 years old has reached more than 50% in Japan (Ministry of Health Labour and Welfare in Japan 2008). Hemiplegia caused by stroke is the common reason of physical impairment especially in the elderly. Patients with severe hemiplegia essentially require longer time for functional recovery, including walking ability, and they sometimes cannot get back practical walking. In such cases, long-time sitting on a wheelchair is unavoidable.

Use of a wheelchair is a common way of locomotion for hemiplegic stroke patients in recovery stage (Garrison and Rolak 1998). However, since driving a wheelchair needs no use of the affected lower extremity, long-time sitting on it with the hip and knee flexed frequently makes joint contracture in the patients without practical walking ability (Davies 1985). Furthermore, patients with spastic hemiplegia occasionally show increase of spasticity in the paretic leg, resulting from excessive movement of the intact leg to propel a wheelchair (Currie et al. 1998). In the acute phase after a stroke onset, early intervention is very important for recovering motor function. Use of a wheelchair has less advantage to achieve early recovery because of immobility in the paretic lower extremity. Continuous movement of lower extremities during daily living including sitting on a wheelchair, therefore, would be a desirable condition in the aspect of both impairment prevention and early rehabilitation.

On the basis of these backgrounds, we developed a new type of cycling wheelchair (C-W/C). This is a wheelchair with a steering system to control a front wheel by one hand and with a pedaling system for self-locomotion and pedaling exercise (Seki et al. 2004a, 2004b). Pedaling movement with the lower extremities like bicycling is one of favorite exercise for early rehabilitation because it is safe, self-paced and performable even on a bed or a wheelchair (Brown and DeBacher 1987; Brown and Kautz 1998). Pedaling includes simultaneous and reciprocal movement of lower extremities and, in the patients with hemiplegia, voluntary movement of the healthy leg during pedaling realizes passive or active-assisted movement of the affected lower
limb (McIloy et al. 1992). A bicycling ergometer is a representative pedaling machine but riding on a bicycle is difficult for the patients with severe hemiplegia and its use is not a realistic way of exercise. Besides a bicycling ergometer, there are some machines developed for pedaling movement like a recumbent type ergometer (Fujiwara et al. 2003) and a portable type of pedaling machine (Imray et al. 2005). Comparing with these exercise machines, C-W/C has an advantage of realizing pedaling movement during daily locomotion.

C-W/C is expected to be a practical implement for locomotion and have some effects to prevent muscle weakness and joint contracture through pedaling movement repetitively performed in daily living. It is also expected to have an effect inducing muscle activity of the paretic lower limb as same as the recumbent type ergometer. If C-W/C has such an effect, use of it might work in favor of functional recovery even in the patients with severe hemiplegia. However, it is unclear whether the patients with severe hemiplegia without walking ability can drive a C-W/C and what activity can be shown in the leg muscles during driving. In the present study, we investigated whether the patients with severe hemiplegia can drive a C-W/C by pedaling with bilateral legs. Furthermore, we studied what changes of muscle activity occur in the lower extremities during C-W/C driving comparing with voluntary movement.

Materials and Methods

Subjects

Ten healthy volunteers (8 males and 2 females) and ten non-ambulatory patients (8 males and 2 females) with sub-acute post-stroke hemiplegia participated in this study. The mean age was 32.8 (26-45) years for the healthy subjects and 69.0 (55-81) years for the patients. The healthy subjects had no signs or symptoms of neurological disease or orthopedic impairment in their lower limbs. Hemiplegic subjects were selected from the patients who were admitted to receive medical rehabilitation in three district hospitals based on the criteria as follows: (1) hemiplegia caused by initial onset of a stroke; (2) single, unilateral cerebro-vascular accident confirmed by CT or MRI; (3) hemiplegia with stage 1 or 2 evaluated by Brunnstrom’s test (Brunnstrom 1970) for the paretic lower limb; (4) no walking ability by the time the experiment was performed; (5) no remarkable joint contractures found in both legs; (6) no dementia and severe aphasia showing much difficulty to follow verbal instructions. Clinical status and characteristics of the subjects including time since the onset, type of a stroke and side of hemiplegia were summarized in Table 1. Although four patients with right hemiplegia showed motor aphasia and two patients with left hemiplegia showed mild left hemi-neglect, they could make appropriate performance following the verbal instructions. All of the patients showed hypotonus of the paretic lower limb and the scores of modified Ashworth scale (Bohannon and Smith 1987) in knee extension and flexion were all zero.

Informed consent was obtained from all of the subjects and their family prior to participation in the study. This study was conducted in accordance with the declaration of Helsinki and accepted by the institutional ethics committee in each district hospital.

Set-up of the cycling wheelchair

C-W/C used in this study is shown in Fig. 1. Details on its sub-systems are as below. A pedaling system is installed at the position corresponding to the footrest of a standard type wheelchair. Transmission of the rotation torque to the rear wheel is controllable by holding or releasing a clutch system fixed at the armrest. C-W/C can be moved with pedaling movement when the clutch is held, while only pedaling can be performed without driving during releasing the clutch. Brake lever for wheel lock is same as a standard type wheelchair and reverse pedaling causes slowdown and backward driving. There is a steering system combined to a front caster to control driving direction. Clockwise rotation of the steering brings about turning to the right, and vice versa. The position of the steering is changeable to each side to handle with the healthy arm of the hemiplegic patients.

When driving a C-W/C, both feet of the healthy subjects and the healthy foot of the patients were staying on the pedal without any fixation till the end of each trial, but the foot of the affected side was fixed on the pedal with belts to prevent slipping off during pedaling. Since the hip joint of the affected side externally rotated during sitting on the chair, some towels were put in between the armrest and the thigh to keep the paretic lower limb at neutral position. An electrical encoder to measure the rotation angle of a pedal was installed at the shaft of the right pedal and it generated 64 electrical pulses during a rotation of 360 degrees, namely, 5.625 degrees a pulse.

Fig. 1. Cycling wheelchair (C-W/C) used in the present study. Lateral view (left) and frontal view (right).
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Recording of EMG

Surface electromyogram (EMG) was recorded simultaneously from the gluteus maximus (GM), rectus femoris (RF), medial hamstring (Ham), tibialis anterior (TA) and soleus (Sol) muscles of both legs. Prior to attaching the electrodes, the skin was cleansed with alcohol. Silver-silver chloride disc electrodes with 1cm diameter (NF-50-K, Medicotest A/S, Copenhagen, Denmark) were positioned over the distal half of the muscle belly in longitudinal alignment with muscle fibers. Each pair of the electrodes was spaced with an inter-electrode distance of 2 cm.

EMG signals were recorded by using a telemetry system (NT11, NEC medical systems, Tokyo, Japan) with a sampling rate of 1,000 Hz and stored in a digital data recorder (LX10, TEAC, Tokyo, Japan) with a low cut filter of 30Hz and high cut with 200 Hz. All subjects wore a vest and shorts with Velcro sewed on the frontal half when the experiment was performed and cords from electrodes were tied up and fixed with Velcro tapes on the shorts to avoid disturbing pedaling movement. An EMG amplifier was put into a pocket of the vest and a transmitter connected to the amplifier was fixed at a hand–rail of the C-W/C. Electrical pulses from the encoder were also input to an external signal box of the transmitter.

Experimental procedures

After finishing recording setup, each subject performed a brief practice of pedaling and driving. First of all, an examiner orally instructed how to drive and control a C-W/C. Then the subjects made only pedaling with releasing a clutch. Finally, 5 m driving was practiced only one time.

Before driving, EMG of all target muscles was recorded simultaneously when making maximum effort to perform isometric total flexion and extension in unilateral leg alternately on a C-W/C. The hip, knee and ankle joint in the target leg were kept at 100 degrees, 90 degrees and 0 degree in flexion respectively during performing this task. When making total flexion, the subjects were instructed to lift up the unilateral leg against the resistance added by an examiner’s hand pushing down the distal part of the thigh. When making total extension the subjects were instructed to push down a pedal held by an examiner. In either case, the examiner added adequate resistance during 2 seconds to keep the same position of the pedal on which a subject’s foot was placed.

Then the subjects were moved to the start position of the driving course by assist of an examiner and the EMG activities were recorded during driving a C-W/C straightforward with maximum effort in 13 m distances. The driving course was on a straight line with more than 13 m distances and there were marks at the start position and the goal position. Before start of the driving session, the examiner instructed a subject to drive a C-W/C for 13 m as fast as possible and keep driving speed till passing the mark at the goal position. Total of 3 trials of driving in one session were performed in each subject. When starting driving, the foot of the healthy side was placed at the top position of a pedal in the patients and the left foot was also placed at the top position in the healthy subjects, i.e. the patients began to drive with intact leg and the healthy subjects did it with left leg. We confirmed no signals from the encoder at the top position of the starting pedal. The patients controlled the steering with the healthy arm and the healthy subjects controlled it with right hand. Actually the hand to control the steering was almost being kept at the same position because only straightforward driving was performed. EMG of the target muscles and rotation angles were recorded simultaneously in each trial.

Data analysis

Beginning of driving (0 second) was defined as the time first electrical pulse from the encoder had been generated by start of pedaling movement. Circumference of the rear wheel was 189cm and the rear wheel rotated two third of a circuit, 123 cm, associating with one rotation of the unilateral pedal. Consequently 10 rotations of the unilateral pedal propelled a C-W/C 12.3 m. Ten rotations of the unilateral pedal generated 640 electrical pulses form the encoder because 64 pulses corresponded to one rotation. Driving speed was calculated by the time for 10 rotations of a pedal (640 pulses) and the moving distances of 12.3 m. The maximum driving speed of each subject was determined as the fastest one in three trials of driving. We adopted the data recorded at the trial with the fastest speed for further analysis.

Fig. 2. Phases in one rotation of the left pedal. Rt, right; Lt, left; L/E, lower extremity. The pedal rotation cycle was divided into four phases in every 90 degrees. The basic point (0 degree) was defined as the top position of the left pedal.
Since there were some differences of pedaling movement between the beginning of driving for acceleration and the period after that to keep steady speed, EMG activities were analyzed for 8 rotations (9.84 m) except 2 rotations of the beginning (2.46 m). Pedaling movement was initiated by the left leg in the healthy subjects and the patients with right hemiplegia and by the right leg in left hemiplegics. The top position of the pedal to start driving was defined as 0 degree of the rotation angle of a pedal and one rotation cycle of a pedal was divided into 4 phases according to the movement of the pedal: from top to anterior-horizontal position (0-90 degrees; P1), from anterior-horizontal to bottom position (90-180 degrees; P2), from bottom to posterior-horizontal position (180-270 degrees; P3) and from posterior-horizontal to top position (270-360 degrees; P4) (Fig. 2). Ninety degrees (one phase) within one rotation of a pedal included 16 pulses from the encoder.

As the first processing, root mean square (RMS) of EMG (R-EMG) was calculated from the data obtained during making total flexion and extension and during driving a C-W/C. R-EMGs for total flexion and extension were divided by the time recorded (2 seconds each) and the maximum value of R-EMG/sec in four trials (right leg flexion, left leg flexion, right leg extension and left leg extension) of each target muscle was used as baseline. R-EMG in each rotation during driving was acquired for each phase in all of the target muscles. Since 8 rotations of a pedal provided 8 values of R-EMG for each phase in each muscle, total of 32 values of R-EMG could be obtained in one trial. To compare EMG activity during driving with baseline, each value of R-EMG during driving was divided by the driving time (sec) in each phase and the values of R-EMG/sec of 8 rotations were averaged on each phase. The mean R-EMG/sec in each phase was compared with the maximum value of R-EMG/sec as baseline.

Statistical analysis between R-EMG/sec of baseline and R-EMG/sec in each phase during driving was performed by Wilcoxon’s signed rank test. R-EMG/sec of baseline in each muscle between the left leg in the healthy subjects and the intact leg in the patients was compared by Man Whitney’s U test. The level of significance was determined to 5%.

Results

All of the patients could drive a C-W/C in a straight line with mean maximum driving speed of 46.6 (31.7-61.7) m/min (Table 1). The mean maximum driving speed in the healthy subjects was 84.4 (53.8-106.8) m/min. Driving speed of the patients was almost half of that in the healthy subjects, but was markedly faster compared with the speed observed when the patients drove a standard type wheelchair. Furthermore, C-W/C driving in these patients was quite smooth and natural with a constant speed and it was quite difficult to distinguish seemingly the pedaling movement of the paretic leg with that of healthy leg.

In every subject, the mean rotation time in a phase showed no significant difference among the four phases (P1-P4) except the first rotation. It was about 0.15 sec in the healthy subjects and 0.3-0.6 sec in the patients. This result means that all healthy subjects and patients performed pedaling movement with constant speed being independent of the pedaling phase. Therefore the values of R-EMG in each phase after the 2nd rotation reflect only the amount of muscle activities without influence of the time spent in each phase.

When making total flexion and extension of the lower extremities, all of the muscles examined showed apparent EMG activities during voluntary isometric movements as baseline in every healthy subject (Fig. 3-a). In the patients, however, EMG activities of the flexors and extensors in the paretic leg were almost silent during volitional effort for flexion and extension though some muscle activities were shown in their intact legs (Fig. 3-b). However, these patients showed some periodic muscle activities in the several leg muscles even in the affected side during C-W/C driving (Fig. 4). The mean values of R-EMG/sec in baseline and each rotation phase during driving were shown in Table 2 and Table 3. In the healthy subjects, R-EMG/sec of all target muscles except left TA and bilateral Sol during driving showed significant decrease compared with baseline in all or some phases. Increase was shown only in P4 of the right Sol (Table 2). In the patients, decrease of R-EMG/sec during driving was shown only in P2 of RF in the healthy side. In the paretic side, however, significant increase was found in all phases of TA and Sol and in P1 of RF (Table 3).

Table 1. Demographic and functional data and maximum speed of C-W/C driving in each patient.

<table>
<thead>
<tr>
<th>Patients (gender)</th>
<th>Age (years)</th>
<th>Type of stroke</th>
<th>Side of hemiplegia</th>
<th>Time since onset (days)</th>
<th>Br. Stage of lower extremity</th>
<th>Max. driving speed (m/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (M)</td>
<td>69</td>
<td>Hx</td>
<td>Rt</td>
<td>49</td>
<td>2</td>
<td>55.8</td>
</tr>
<tr>
<td>B (M)</td>
<td>69</td>
<td>Inf</td>
<td>Rt</td>
<td>43</td>
<td>1</td>
<td>48.7</td>
</tr>
<tr>
<td>C (M)</td>
<td>72</td>
<td>Inf</td>
<td>Rt</td>
<td>31</td>
<td>1</td>
<td>42.8</td>
</tr>
<tr>
<td>D (M)</td>
<td>70</td>
<td>Inf</td>
<td>Lt</td>
<td>44</td>
<td>1</td>
<td>49.3</td>
</tr>
<tr>
<td>E (M)</td>
<td>81</td>
<td>Inf</td>
<td>Lt</td>
<td>61</td>
<td>2</td>
<td>50.7</td>
</tr>
<tr>
<td>F (M)</td>
<td>62</td>
<td>Hx</td>
<td>Lt</td>
<td>105</td>
<td>2</td>
<td>38.3</td>
</tr>
<tr>
<td>G (F)</td>
<td>83</td>
<td>Inf</td>
<td>Rt</td>
<td>59</td>
<td>2</td>
<td>31.7</td>
</tr>
<tr>
<td>H (F)</td>
<td>69</td>
<td>Hx</td>
<td>Lt</td>
<td>134</td>
<td>2</td>
<td>36.7</td>
</tr>
<tr>
<td>I (M)</td>
<td>60</td>
<td>Hx</td>
<td>Lt</td>
<td>50</td>
<td>2</td>
<td>50.0</td>
</tr>
<tr>
<td>J (M)</td>
<td>55</td>
<td>Inf</td>
<td>Rt</td>
<td>111</td>
<td>2</td>
<td>61.7</td>
</tr>
</tbody>
</table>

M, male; F, female; Hx, cerebral hemorrhage; Inf, cerebral infarction; Rt, right; Lt, left; Br. Stage, Brunnstrom’s stage.
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Fig. 3. Representative raw data of EMG recorded during isometric total flexion and extension performed by each leg (a) in a healthy subject and (b) in a left hemiplegic patient. RE, extension of the right leg; RF, flexion of the right leg; LE, extension of the left leg; LF, flexion of the left leg; Rt, right; Lt, left; GM, gluteus maximus; RF, rectus femoris; Ham, medial hamstrings; TA, tibialis anterior; Sol, soleus. In a healthy subject, extensors and flexors on the moving leg were active in flexion and extension respectively. In a left hemiplegic patient, muscle activities were only shown on the right (intact) leg.
A left hemiplegic patient

![Raw EMG data for C-W/C driving](https://www.example.com/raw_data_images)

**Fig. 4.** Representative raw data of EMG recorded during C-W/C driving in a left hemiplegic patient. GM, gluteus maximus; RF, rectus femoris; Ham, medial hamstrings; TA, tibialis anterior; Sol, soleus. Muscle activities and some reciprocation were shown during driving even on the paretic side.

**Table 2.** Mean (SE) values of R-EMG/sec in the healthy subjects.

<table>
<thead>
<tr>
<th></th>
<th>baseline</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
</tr>
</thead>
<tbody>
<tr>
<td>left</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GM</td>
<td>26.32 (6.35)</td>
<td>12.75 (3.80) #</td>
<td>7.53 (1.17) ##</td>
<td>8.14 (1.91) ##</td>
<td>13.81 (3.86) ##</td>
</tr>
<tr>
<td>RF</td>
<td>70.84 (12.38)</td>
<td>14.41 (3.08) ##</td>
<td>14.64 (3.26) ##</td>
<td>20.86 (6.76) ##</td>
<td>13.70 (1.40) ##</td>
</tr>
<tr>
<td>Ham</td>
<td>38.13 (7.49)</td>
<td>25.01 (6.19)</td>
<td>16.44 (3.63)</td>
<td>15.91 (2.94)</td>
<td>12.55 (1.76) #</td>
</tr>
<tr>
<td>TA</td>
<td>33.97 (8.88)</td>
<td>21.24 (9.50)</td>
<td>15.93 (2.19)</td>
<td>31.27 (7.29)</td>
<td>26.83 (6.72)</td>
</tr>
<tr>
<td>Sol</td>
<td>16.08 (3.18)</td>
<td>21.40 (3.16)</td>
<td>17.51 (2.53)</td>
<td>12.20 (1.76)</td>
<td>12.82 (1.32)</td>
</tr>
<tr>
<td>right</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GM</td>
<td>16.91 (3.40)</td>
<td>12.38 (2.74)</td>
<td>21.53 (9.38)</td>
<td>17.79 (6.01)</td>
<td>9.92 (2.20) #</td>
</tr>
<tr>
<td>RF</td>
<td>81.28 (13.35)</td>
<td>20.04 (3.0) ##</td>
<td>15.10 (2.50) ##</td>
<td>15.13 (2.39) ##</td>
<td>13.95 (2.55) ##</td>
</tr>
<tr>
<td>Ham</td>
<td>25.74 (5.28)</td>
<td>31.53 (10.40)</td>
<td>15.17 (2.50)</td>
<td>30.28 (9.24)</td>
<td>20.66 (3.84)</td>
</tr>
<tr>
<td>TA</td>
<td>37.40 (9.55)</td>
<td>31.50 (8.07)</td>
<td>31.04 (8.18)</td>
<td>22.82 (6.81)</td>
<td>18.49 (4.92) #</td>
</tr>
<tr>
<td>Sol</td>
<td>17.77 (4.35)</td>
<td>19.39 (2.27)</td>
<td>17.45 (2.93)</td>
<td>26.08 (3.56)</td>
<td>23.06 (3.57) *</td>
</tr>
</tbody>
</table>

* *, significant increase vs. baseline (*; p < 0.05, **; p < 0.01)
# #, significant decrease vs. baseline (#; p < 0.05, ##; p < 0.01)

GM, gluteus maximus; RF, rectus femoris; Ham, medial hamstrings; TA, tibialis anterior; Sol, soleus.

Bold letters in the table show the combinations of a muscle and a phase with significant change.
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Table 3. Mean (SE) values of R-EMG/sec in the hemiplegics.

<table>
<thead>
<tr>
<th></th>
<th>baseline</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
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<tr>
<td>healthy side</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GM</td>
<td>11.70 (3.60)</td>
<td>11.01 (1.64)</td>
<td>7.81 (1.17)</td>
<td>9.3 (1.45)</td>
<td>9.35 (1.75)</td>
</tr>
<tr>
<td>RF</td>
<td>28.78 (7.78)</td>
<td>16.14 (4.08)</td>
<td>10.20 (2.12) *</td>
<td>17.64 (3.92)</td>
<td>18.44 (5.88)</td>
</tr>
<tr>
<td>Ham</td>
<td>26.67 (4.71)</td>
<td>29.87 (5.69)</td>
<td>21.82 (3.74)</td>
<td>24.69 (5.09)</td>
<td>18.99 (4.86)</td>
</tr>
<tr>
<td>TA</td>
<td>28.07 (7.47)</td>
<td>21.23 (2.97)</td>
<td>19.96 (4.24)</td>
<td>35.32 (5.56)</td>
<td>27.08 (5.36)</td>
</tr>
<tr>
<td>Sol</td>
<td>23.0 (3.54)</td>
<td>28.93 (5.65)</td>
<td>28.13 (6.26)</td>
<td>18.93 (3.71)</td>
<td>16.41 (2.98)</td>
</tr>
</tbody>
</table>

| paretic side |          |            |            |            |            |
| GM     | 7.97 (1.96)  | 8.25 (1.61)  | 6.24 (0.83)  | 7.51 (1.49)  | 5.59 (0.54)  |
| RF     | 5.83 (1.32)  | 14.82 (3.54) * | 10.19 (3.21) | 15.86 (4.91) | 7.89 (1.35)  |
| Ham    | 6.85 (1.89)  | 16.91 (8.07) | 18.03 (9.69) | 13.46 (4.25) | 11.24 (4.58) |
| TA     | 4.57 (1.06)  | 19.35 (4.89) * | 17.23 (3.91) ** | 18.17 (3.27) * | 15.10 (3.36) * |
| Sol    | 4.88 (0.67)  | 15.0 (3.73) ** | 13.89 (4.16) * | 16.85 (5.30) ** | 12.89 (3.24) * |

*, significant increase vs. baseline (*: p < 0.05, **: p < 0.01)
#, significant decrease vs. baseline (#: p < 0.05, ##: p < 0.01)
GM, gluteus maximus; RF, rectus femoris; Ham, medial hamstrings; TA, tibialis anterior; Sol, soleus.

R-EMG/sec of baseline in the left GM and RF of the healthy subjects was higher than that of the intact GM and RF in the patients respectively (p < 0.05), however no significant differences were shown in other muscles. There were no significant differences of R-EMG/sec in each muscle during driving a C-W/C (P1-P4) between the left leg of the healthy subjects and the intact leg of the patients. These results indicate feature of muscle activities was not remarkably different between the healthy subjects and the patients at least during driving though the two subject groups in the present study were not age-matched. Therefore, it is valid to compare the change of muscle activities between the two groups.

Fig. 5 showed the change of mean R-EMG/sec of RF, TA and Sol represented by percentage for baseline in the healthy subjects (left and right) and the patients (healthy side and paretic side). In the paretic side, relative activity of those three muscles during driving prominently exceeded baseline. In the healthy subjects, position of the relative peak activity in the four phases showed some specific pattern in each muscle. RF and TA showed the relative peak at P1 in the right leg and at P3 in the left leg, while Sol showed reverse pattern. In the patients, the pattern of the relative peak of TA and Sol in the healthy side was very similar to that of the left leg in the healthy subjects though RF in the healthy side was not. On the other hand, there were two peaks observed at P1 and P3 of the paretic RF. In the paretic TA and Sol, a peak of relative muscle activity was found at P1 and P3 respectively. Such a pattern of the relative peak during driving was similar to that of the right leg in the healthy subjects.

Discussion

Practical usefulness of C-W/C for hemiplegics

All of the patients subjected to the present study were in the recovery stage within 2 months after a stroke onset. They had severe hemiplegia without prominent spasticity but had no remarkable joint contractures in their paretic lower extremity. They had never experienced driving a C-W/C but they could drive it with an excellent manner. Makino et al. (2005) reported hemiplegic stroke patients could drive another type of C-W/C (EZchair®, Premier Designs, CA, USA), however participants were able to walk with some braces and their activity of daily living was almost independent level. The patients participated in the present study could not walk independently even with a brace and needed much assistance in daily living. Their level of paresis in the lower extremity was stage 1 or 2 evaluated by Brunnstrom’s test. Stage 1 means complete paralysis and no voluntary movement (Brunnstrom 1970), but three patients with this level of hemiplegia also could drive a C-W/C in the present study. This result was surprising and beyond our expectation.

Usually wheelchair driving by using unilateral upper and lower extremities is not efficient for locomotion and acquiring how to drive is often difficult for the patients with some cognitive problems (Kirby et al. 1999, 2005). In the present study, although three patients with right hemiplegia showed aphasia and a patient with left hemiplegia showed hemi-spatial neglect in the left side, all of the patients could follow the instruction of the examiner to teach them how to drive a C-W/C. Driving a standard type wheelchair was not impossible for them but it was difficult to keep a straight line during driving. In comparison, driving a C-W/C was much easier because all of them could keep propelling it...
Fig. 5. Changes of mean percentage of R-EMG/sec in RF, TA and Sol for baseline. RF, rectus femoris; TA, tibialis anterior; Sol, soleus. Dotted line and solid line show the change in the healthy subjects and the patients respectively. Open mark shows left side in the healthy subjects or healthy side in the patients. Closed mark shows right side in the healthy subjects or paretic side in the patients. There were two peaks observed at P1 and P3 of the paretic RF. A peak was shown at P1 in the right TA of the healthy subjects and paretic TA, and at P3 in the left TA of the healthy subjects and intact TA. A peak was shown at P3 in the right Sol of the healthy subjects and paretic Sol, and at P1 in the left Sol of the healthy subjects and intact Sol.
straightly for 13m distances without any assistance and discontinuance to control the direction. While some efforts were necessary at the beginning of driving, their pedaling movement seemed smooth during driving. Since the mean driving speed of them was more than the level of practical speed for indoor walking in hemiplegics (Nakamura et al. 1988), C-W/C can provide a chance of practical locomotion for the hemiplegic patients without walking ability at least when moving on a straight line.

Change of the muscle activities during driving

The leg muscles, especially GM and RF, during driving in the healthy subjects showed lower value of R-EMG/sec than baseline. This result suggests that for healthy adults driving a C-W/C is a work without heavy load to the leg muscles. Compared with the healthy subjects, most of the muscles in the intact leg of the patients did not show decrease of R-EMG/sec during driving. In other words, for driving a C-W/C, the proximal muscles in the intact leg of the patients needed contraction as same as that of isometric total flexion and extension with maximum effort. One of the valid reasons for this will be compensation for lack of driving force in the paretic side. The other reason might be muscle weakness of the proximal part of the intact leg caused by disuse and/or aging because R-EMG/sec as baseline of GM and RF in the intact leg of the patients showed significantly lower value than the left leg of the healthy subjects.

Most of the EMG signals as baseline in the paretic leg muscles showed very small amplitude and, particularly in the patients with severe hemiplegia evaluated as Brunnstrom’s stage 1, those were totally silent in all of the target muscles. Because of the severity of hemiplegia, voluntary effort of the patients for isometric total flexion and extension was insufficient to induce apparent EMG signals in the paretic muscles. During driving a C-W/C, however, some periodic EMG signals in the paretic side were found even in the patients with stage 1 level hemiplegia.

R-EMG/sec in the paretic side during driving showed significantly higher value at P1 of RF and at all phases of TA and Sol compared with baseline. Nevertheless lower values of RF in the healthy subjects, the pattern of relative peak of RF activity indicates that RF chiefly acts as a hip flexor during driving because both P1 for right leg and P3 for left leg are upside phase with hip flexion. P1 is also an upside phase for the paretic side. Significant activity of the paretic RF in P1, therefore, suggests C-W/C driving induced the function of the paretic RF as a hip flexor. Activity of the paretic RF in P3 was not significant but showed tendency ($p = 0.0593$) of increase. Since P3 is a down-stroke phase for the paretic leg, C-W/C driving may also have a possibility to induce another function of the paretic RF for knee extension. On the other hand, the increase of EMG activities during driving in the paretic TA and Sol was not phase-dependent. Most of the patients with severe hemiplegia usually show distal dominant paresis.

Lack of EMG signals as baseline in the paretic leg of the patients was remarkable in the distal part, though isometric total flexion and extension did not necessarily induce maximum voluntary contraction of the paretic muscles. Therefore, driving a C-W/C also has a possibility to induce muscle activity in the distal part of the paretic side through all of the rotation phases.

Background mechanism of appearance of muscle activities

The results in the present study suggest C-W/C driving can induce some activities in the affected leg muscles, especially in the distal part and partially in the proximal part, even in the patients with severe hemiplegia with Brunnstrom’s stage 1 and 2. Fujiwara et al reported EMG signals of the paretic lower limb in the non-ambulatory hemiplegic stroke patients could be augmented during pedaling movement on a recumbent type ergometer (Fujiwara et al. 2003). C-W/C driving also provided activation of the paretic muscles as same as pedaling on a recumbent type ergometer. In this point of view, the present study supports their results and it is suggested that C-W/C driving has a training advantage for hemiplegic stroke patients similar to pedaling exercise on a recumbent type ergometer. Kautz et al reported that the net external mechanical work during pedaling on a standard ergometer was smaller in hemiplegic patients than that in the healthy subjects (Kautz and Brown 1998). They also indicated such reduction of work production in the hemiplegics was caused by depressed crank torque due to a combination of reduced down-stroke propulsion and increased upstroke resistance. Synergic movement in the paretic limb with spasticity usually produces upstroke resistance. The patients participated in the present study, however, did not show spasticity as mentioned already. Furthermore, the pattern of peak appearance of relative muscle activity during driving observed in RF, TA and Sol of the paretic side suggests manifestation of some reciprocation. The peak appearance of paretic RF in P1 can reduce upstroke resistance and help the intact leg in propelling C-W/C. The relative peak of paretic TA and Sol appeared at the phase opposite to that with peak in the intact leg as same as the homonymous muscles of the healthy subjects. The activity of paretic TA in P1 can reduce upstroke resistance together with paretic RF and the activity of paretic Sol in P3 can play a role to produce some crank torque in down-stroke phase. C-W/C, therefore, has another advantage to realize efficient locomotion without excessive muscle contraction of the intact side for the patients with hypotonic hemiplegia.

Physiological background on appearance of muscle activities during C-W/C driving or pedaling movement is still unclear. There are some studies on neurophysiological changes during pedaling movement in healthy subjects (Collins et al. 1993; Pyndt and Nielsen 2003). These studies indicate presynaptic inhibition reduces H reflex during pedaling via activation of an inhibiting interneuron in the
spinal cord. Transcranial magnetic stimulation during pedaling, on the other hand, facilitates motor evoked potential (MEP) according to the rotation cycle (Pyndt and Nielsen 2003). It suggests that transmission in the fast monosynaptic corticospinal pathway selectively increases during pedaling. We have experienced some spastic hemiplegics who showed MEP increase of TA and Sol in the affected leg without phase dependency during pedaling by the intact leg, and they showed no change of H reflex (unpublished). It is suspected that presynaptic inhibition arising alternately between both legs during pedaling plays a great role to maintain a rhythmic movement in healthy human. In hemiplegics, however, synergic mechanism or association movement as one of facilitation caused by excitation of cortical motor neurons may become more prominent during pedaling, especially in the area of the distal part of the leg according to the results in the present study.

**Conclusion**

The results of the present study indicate C-W/C can induce muscle activities of the paretic leg and provide a chance of practical locomotion even for the severe hemiplegics. Though further study is necessary to reveal training effect, daily use of a C-W/C might play a role of physical exercise to facilitate paretic leg function.

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**References**


