Changes in Brain Perfusion in Patients with Unilateral Lower-limb Paresis, before and after Training on a Pedaling Wheelchair: A Feasibility Study

Takaaki Sekiya,*, # Kazunori Seki, ** Yasunobu Handa***

Abstract Our aim was to evaluate the effects of a 4-week training program using a self-powered pedaling wheelchair on brain perfusion in patients presenting with lower limb hemiparesis due to stroke, brain injury, or spinal cord injury. Our cross-sectional observational study included seven patients with lower limb hemiparesis (five men, two women; mean age, 68.3 ± 17.5 years), due to the following causes: cerebral hemorrhage (n = 1), stroke (n = 4), brain contusion (n = 1), and spinal cord injury (n = 1). The control group consisted of eight healthy participants (3 men, 5 women; mean age 62 ± 8 years). The training program consisted of five bouts of 3-min continuous pedaling per day (total, 15 min/day). The outcome variable of interest was blood flow velocity in the middle cerebral artery (time average peak [TAP], cm/s) measured using Doppler. TAP was measured at rest and after a 3-min pedaling bout, before and after the training program. In the patient group, TAP was significantly greater after the 3-min bout than at rest, both before and after the training program (p < 0.05). There was no effect of pedaling identified in the control group. In the patient group, TAP increased significantly (p < 0.05) after training, both at rest (36.9 ± 16.9 to 47.6 ± 13.8 cm/s), and after the 3-min bout (43.3 ± 13.3 to 50.5 ± 15.1 cm/s). Our pedaling wheelchair provided a safe and effective intervention to improve brain perfusion in this patient population.

Keywords: wheelchair, pedaling, gait disturbance, brain perfusion.


1. Introduction

Hand-powered and electric wheelchairs are often used as a means of transportation by patients with lower limb paresis and gait impairment. Conventional wheelchairs do not engage the lower limbs for propulsion in a systematic manner. Moreover, prolonged sitting in a wheelchair increases the risk of developing flexion contractures at the hip and knee on both the paretic and the unaffected side. The recovery of functional movement and strength of the paretic lower limb is a fundamental goal of rehabilitation, and maximizing the use of the lower limb in activities of daily living is imperative to achieve this goal. Therefore, changing the passive nature of wheelchairs to engage the lower limbs in mobility would be desirable. To this end, we developed a pedal wheelchair that increases the functional demand on the paretic lower limb.

Pedaling is a highly efficient task to promote bilateral use of the lower limbs. For patients with hemiplegia, pedaling provides active-assisted exercise of the hemiparetic limb, with the unaffected lower limb providing assistance. In clinical practice, upright and recumbent ergometers are used in therapeutic pedaling exercise. Nevertheless, maintaining patient motivation is difficult because of the monotonous and repetitive nature of the exercise. Moreover, this equipment is not easy to integrate into daily life, limiting opportunities for training. However, as our pedaling wheelchair is self-powered, it increases the opportunities for exercise of the hemiparetic lower limb, as well as promotes self-mobility, both of which are meaningful to patients. In our previous study, we demonstrated that our pedaling wheelchair can be used with sufficient ease by patients having lower limb motor impairment of Brunnstrom Stage IV or lower, without severe limitation in range of motion (ROM). We also demonstrated the feasibility of using our pedaling wheelchair in patients presenting with lower limb paresis (and even quadriparesis) due to spinal cord injury.
the perspective of participation, the pedaling wheelchair allows patients to achieve mobility speeds that are equivalent to the fast-paced walking of healthy adults [1–4].

Our wheelchair design incorporates several features that facilitate its use for daily mobility. These include a small turn-radius for good maneuverability, the capacity for forward and backward mobility (depending on the direction of pedaling), and relatively light weight to decrease physical effort and maximize speed. Although the pedaling wheelchair could be used outdoors, we designed it as a therapeutic tool intended for indoor training to improve cognitive and/or physical functioning in patients with gait impairment. As an example, we demonstrated in a previous study that use of the pedaling wheelchair by elderly individuals residing in or visiting care facilities improved mobility within a greater area and led to increased interaction and communication with other people, thereby providing psychological benefits [5]. To date, however, the effects of long-term use of the pedaling wheelchair as a component of physical therapy program has not been evaluated. Moreover, various types of continuous exercise devices such as the ergometer have been shown to have various effects on the brain, either increasing or decreasing brain activity and perfusion depending on the type of exercise [6]. Therefore, the aim of this study was to evaluate the effects of a 4-week training program using our self-powered pedaling wheelchair on brain perfusion in patients presenting with lower limb hemiparesis due to stroke, brain injury, or spinal cord injury.

2. Methods

2.1 Design and study group

Our cross-sectional observational study included 7 patients with lower limb hemiparesis (5 men, 2 women; mean age, 68.3 ± 17.5 years) who were hospitalized for an intensive course of rehabilitation in the Rehabilitation Department of Wakuyacho National Health Insurance Hospital in Miyagi prefecture. The causes of the hemiparesis were stroke (1 case of cerebral hemorrhage and 4 cases of cerebral infarction), brain contusion (1 case); and spinal cord injury (1 case). Among these patients, 4 presented with right-sided hemiparesis and 3 had left-sided hemiparesis. The relevant clinical and demographic data of participants in the patient group are summarized in Table 1. We also included a control group consisting of 8 healthy participants (3 men, 5 women; mean age 62 ± 8 years) with no history of lower limb impairment or respiratory and cardiovascular disease.

The experiment was conducted according to the ethical guidelines at Tohoku University School of Medicine. The study conforms to the Declaration of Helsinki and other ethical regulations. All participants received full explanation of the study’s objectives, safety and risks concerning the pedaling wheelchair, safety and risks concerning the items to be measured, and how risks would be managed. All participants provided informed consent.

2.2 Training using the pedaling wheelchair

The Sakigake model of the pedaling wheelchair (FES Co., Ltd. Sendai-city Miyagi) as shown in Fig. 1 was

![Fig. 1 The Sakigake model pedaling wheelchair.](image)

2.2 Training using the pedaling wheelchair

The Sakigake model of the pedaling wheelchair (FES Co., Ltd. Sendai-city Miyagi) as shown in Fig. 1 was

<table>
<thead>
<tr>
<th>Participant</th>
<th>Diagnosis impairment</th>
<th>Age (years)</th>
<th>TSO (days)</th>
<th>BS</th>
<th>Sex</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>Right hemiparesis</td>
<td>38</td>
<td>141</td>
<td>2 M</td>
</tr>
<tr>
<td>B</td>
<td>Cerebral infarction</td>
<td>Right hemiparesis</td>
<td>87</td>
<td>90</td>
<td>2 M</td>
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<tr>
<td>C</td>
<td>Cerebral infarction</td>
<td>Left hemiparesis</td>
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<td>38</td>
<td>4 M</td>
</tr>
<tr>
<td>D</td>
<td>Cerebral contusion</td>
<td>Left hemiparesis</td>
<td>66</td>
<td>111</td>
<td>2 M</td>
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<tr>
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<td>53</td>
<td>43</td>
<td>– F</td>
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<tr>
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<td>Right hemiparesis</td>
<td>83</td>
<td>132</td>
<td>2 M</td>
</tr>
<tr>
<td>G</td>
<td>Cerebral infarction</td>
<td>Right hemiparesis</td>
<td>74</td>
<td>15</td>
<td>2 F</td>
</tr>
</tbody>
</table>

BS, Brunnstrom stage; F, female; M, male; TSO, time since onset.
used in all measurements and training. Participants were instructed on how to use the pedaling wheelchair and were provided with opportunities to practice under supervision. Once comfortable with the use of the wheelchair, participants completed the experimental protocol.

For the patient group, training was performed on a 50-m track that was set up in the training center. Patients were asked to pedal around the track on their own under supervision by a physical therapist, with assistance provided as necessary. Patients completed 5 bouts of 3-min continuous cycling per day (a total of 15 min per day), 5 times per week, for 4 weeks. A 1-min rest was provided between each 3-min bout, as shown in Fig. 2. Simultaneously, the pedaling distance of each trial was measured. Training was conducted separately from the regular schedule of rehabilitation for each patient, with the rehabilitation program individualized based on the needs and goals for each patient. For the control group, a 50-m track was set up in a gymnasium and participants completed 3-min continuous cycling under supervision by a research assistant.

2.3 Measurement of brain perfusion
Blood flow measurements were obtained by transcranial Doppler using the Micro Maxx system (SonoSite Inc.), as shown in Fig. 3, with participants in a seated position. The low-frequency sector-scanning probe was placed against the temporal bone to record blood flow through the central cerebral artery by pulsed Doppler. The Doppler signal was analyzed offline using the SiteLink Image Manager software (version 3.3) to calculate the time average peak (TAP) that was used as a measure of blood flow velocity in the central cerebral artery.

For patients with a brain lesion (stroke or injury), measurements were obtained from the middle cerebral artery on the unaffected side of the brain. For the patient with left hemiparesis due to a spinal cord injury and for participants in the control group, Doppler measurements were obtained from the right middle cerebral artery.

Blood flow velocity was measured at two time points: before the training and after the final training session. At both time points, Doppler signals were recorded first at rest and again after a 3-min bout of pedaling (Fig. 2).

2.4 Statistical analysis
The within-group change in TAP from baseline to the endpoint of training was evaluated using paired test. Wilcoxon’s signed rank test was used to test the difference between two paired groups. Mann–Whitney U test was used to test the difference between two unpaired groups. A significance level of 5% was used in all tests. All analyses were performed on MS Excel, using the Statcel3 (OMS Publishing Inc.) add-on program.
3. Results

3.1 Training completion

All participants were successful in using the pedaling wheelchair, including one patient who was unable to walk. Although all participants completed the 4-week training program, sessions were occasionally missed for health reasons. No incidence of adverse respiratory or circulatory events was noted.

In the patient group, the mean delay from onset of injury to start of training (or time since onset, TSO) was 81.4 ± 49.7 days. The distance travelled in the first and second 3-min bouts were comparable during week 1, with a mean of 101.4 m for bout 1 and 106.4 m for bout 2. Therefore, we did not consider the physical burden to be excessive, otherwise the distance would have decreased significantly from bout 1 to 2. None of the patients reported symptoms of muscle and overall fatigue.

3.2 Between-group differences

The mean distance travelled within 3 min was significantly greater in the control group (143 ± 31.1 m) than in the patient group (101.4 ± 30.7 m). There were no differences between the patient and control groups with respect to the number of beats per minute at the middle cerebral artery and changes in beat after pedaling for 3 min. Because the number of beats per minute is considered to correspond to the heart rate [7], no noticeable differences in exercise load for 3 min were observed between the groups.

Regarding TAP in the control group, blood velocity at rest (42.0 ± 14.3 cm/s) was comparable to the velocity after 3-min bout of pedaling (38.4 ± 5.9 cm/s) when measured prior to the training program. In the patient group, however, TAP increased from rest (36.9 ± 16.9 cm/s) to after 3-min bout of pedaling (43.3 ± 13.3 cm/s) prior to the training program (p = 0.024). After the 4-week training program, TAP in the patient group also increased from rest (47.6 ± 13.8 cm/s) to after 3-min bout of pedaling (50.5 ± 15.1 cm/s). In this group, there was a significant (p = 0.014) increase in resting TAP from 36.9 ± 16.9 cm/s prior to the training program to 47.6 ± 13.8 cm/s after the 4-week training program (Fig. 4).

Of note is the increase in TAP at rest in all patients after the 4-week training program.

4. Discussion

Studies have demonstrated various effects of exercises on cerebral blood flow, and the effects were largely dependent on the type of exercise. For example, while high-intensity anaerobic exercises such as maximal weight lifting decrease cerebral blood flow [6], walking in healthy adults increases perfusion to the motor areas of the brain and to the cerebellum [8]. There is also evidence that exercise influences brain function following a cerebrovascular accident. For example, abnormal distribution of alpha-band brainwaves was reported after a cerebrovascular accident [9]. Implementation of an early program of walking in these patients has been shown to be beneficial in increasing the power of alpha-band waves while lowering the power of slow waves [10]. On the contrary, Seki et al. [1] reported a decrease in the power of alpha-band waves with a concomitant increase in beta-band power after a walking program among patients with hemiplegic stroke. Although the specific effects of exercise on brain perfusion and activity are somewhat conflicting, there is good evidence overall that low-intensity aerobic exercise improves brain function following a cerebrovascular accident.

The intensity of exercise appears to determine perfusion. Imray et al. [12] investigated changes in brain perfusion during high-altitude training by measuring blood flow velocity in the middle cerebral artery using ultrasound Doppler, in healthy individuals while pedaling on a supine ergometer. At an exercise intensity between 30%–70% of the maximal oxygen consumption (VO2 max), cerebral blood flow increased by 15% compared to the resting state; however, it subsequently decreased as exercise intensity was increased to the VO2 max threshold. These effects of exercise intensity on cerebral blood flow have been corroborated by several studies [12–14]. In our present study, a 3-min bout of pedaling was associated with a mean 17% increase in TAP in our patient group, an increase that is comparable to previously reported values [11–14]. By comparison, in the control group, TAP increased in some individuals but had no effects in others. This may indicate that the intensity of the pedaling exercise may have been too low to induce an effect on cerebral blood flow. This could not be verified within the context of our study as we did not measure

![Fig. 4](image-url) Change in resting blood flow velocity (cm/s) in the middle cerebral artery from before to after the 4-week training.
exercise intensity, either directly by measuring VO\textsubscript{2} max or subjectively using a self-report exertion scale. It will be important to define the threshold of exercise intensity for positive effects of wheelchair pedaling on brain perfusion.

Although the intensity of exercise was self-determined, the volume was equivalent among all patients; that is, 15 min/day, 5 days/week for 4 weeks. This protocol was based on the study of Imray et al. [11] who reported an increase in cerebral blood at a VO\textsubscript{2} max threshold of 30%. We estimate that each 3-min bout of pedaling was equivalent to approximately 3 metabolic equivalents (METs), with no decrease in cerebral blood flow identified in any patient. Therefore, patients with lower limb impairments due to a central nervous system lesion can safely perform 3-min bouts of continuous pedaling at a self-determined pace without experiencing a decrease in brain perfusion.

Of note is the increase in TAP at rest in all patients after the 4-week training program. As we obtained all measurements from the unaffected hemisphere, this increase in TAP is not likely to reflect improvement in edema or other aspects of natural recovery. We noted that the greatest effect of exercise on TAP was exhibited in an 87-year-old man who presented with hemiparesis due to brain infarction sustained 90 days prior to start of the intervention. His resting TAP increased from 21.7 cm/s at the end of intervention. His resting TAP increased from 21.7 cm/s to 32.4 cm/s at the end of the training program to 47.9 cm/s at the end of the training, a TAP value exceeding the mean of the control group (42.0 cm/s). Considering the TSO of 90 days, we propose that this increase in TAP largely reflects the effects of exercise and not of natural recovery.

5. Conclusion

The present study did not include enough cases to draw clear conclusions. Using a pedaling wheelchair as part of a physical therapy program for the rehabilitation of patients with lower limb hemiparesis may provide several advantages, including improving brain perfusion, as we have described in this study, as well as increasing mobility and facilitating reintegration and participation. We clearly demonstrated the feasibility of our program of physical training using the pedaling wheelchair, serving as the basis for larger randomized or case-controlled trials to confirm the benefits of exercise on brain perfusion, to determine the optimal threshold for therapeutic effectiveness, and to investigate underlying mechanisms of the identified improvements.

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References


Takaaki Sekiya

He received Ph.D. degree from Tohoku University School of Medicine in 2009. He is currently a professor at Sendai University, Japan. His research interests include Rehabilitation Medicine and development of a pedaling wheelchair. He is member of the Japanese Society for Medical and Biological Engineering, the Japanese Society of Biomechanics.
**Yasunobu Handa**

Yasunobu Handa is a professor emeritus Tohoku University. He received Ph.D. degree in 1959 from Tohoku University. He served as an associate professor of Department of Anatomy in Shinshu University from 1960 to 1971. From 1971, he served as professor of Department of Anatomy, Graduate School of Medicine, Tohoku University. From 1977, he served as professor of Division of Restorative Neuromuscular Surgery and Rehabilitation, Tohoku University Graduate School of Medicine. Since 2009, he has been a professor emeritus, Tohoku University. His research activities are focused on rehabilitation engineering including functional electrical stimulation and development of a cycling wheelchair. He has been a member of the Japanese Association of Rehabilitation Medicine, the Japanese Society for Medical and Biological Engineering, the International Neuromodulation Society, International FES Society.

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**Kazunori Seki**

Graduated from Tohoku University School of Medicine in 1983. Working at Tohoku University as Instructor of the Institute of Rehabilitation Medicine from 1988 to 1994, Assistant Professor of Rehabilitation Division at Tohoku University Hospital from 1995 to 2000, Associate Professor in the Department of Restorative Neuromuscular Rehabilitation, Tohoku University Graduate School of Medicine from 2000 to 2010. Present Affiliation and Title: Sendai Clover Clinic in Wakokai Medical Corporation, Board Chairman of Wakokai Medical Corporation, MD, PhD. Research Field; Rehabilitation Medicine, Restorative Neurology, Clinical Kinesiology. Academic Society; International FES Society, International Neuromodulation Society, Japanese Association of Rehabilitation Medicine, Japanese Society of Neurology, Japanese Society for Medical and Biological Engineering.