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Plantarflexor training affects propulsive force generation during gait in children with spastic hemiplegic cerebral palsy: a pilot study

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Abstract. [Purpose] The purpose of this preliminary study was to assess the trade-off relationship between the hip and ankle joints after plantarflexor training in children with spastic hemiplegic cerebral palsy (CP). [Subjects and Methods] Three boys aged 9, 10, and 13 years with spastic hemiplegic CP participated in the study. Gait analysis was performed using a three-dimensional motion analysis device and a floor reaction force detection device before and after plantarflexor training. Data on gait speed and stride length for both sides were collected. Peak hip and ankle powers in the sagittal plane and ankle-to-hip power ratio (A2/H3 ratio) were calculated. Plantarflexor training comprised heel raises and exercise band resistance at the participant's home (3 times/week for 12 weeks). [Results] The A2/H3 ratio increased significantly on both sides in two of three subjects after training. Peak A2 power increased significantly on both sides in subject 3 and on the affected side of subject 2. Peak H3 power decreased significantly on the non-affected side of subjects 1 and 2. [Conclusion] This study confirmed that two of three subjects demonstrated a trade-off relationship between the hip and ankle joints during gait after plantarflexor training.

Key words: Cerebral palsy, Trade-off relationship, Ankle joint

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INTRODUCTION

The ability to walk independently is one of the most important activities for social engagement, particularly for children with spastic cerebral palsy (CP)[1–4)]. However, even if children with spastic CP acquire this ability, they face the challenge of severely weakened lower limb muscles with decreased volume and strength. Since the decrease in selective motor function and lower limb muscle weakness are marked in the distal regions[1–3)], it is difficult for children with spastic CP to push-off from the mid-stance phase to the early swing phase during gait. Moreover, the kinetic and physiologic factors of gait into adolescence and adulthood increase the likelihood of secondary conditions, such as joint contracture, deformity, and pain. Consequently, many individuals with spastic CP experience functional deterioration, including loss of mobility[5)].

Generally, during the push-off phase of gait, there are two strategies based on propulsive force[6)]: (1) ankle plantarflexor strategy, wherein push-off using ankle plantarflexion contributes to propulsive force generation, and (2) hip flexor strategy, wherein propulsive force generation and lower limb swing mainly depend on the hip flexors. Propulsive force generation by the ankle and hip joints during gait is based on a complementary trade-off relationship[7, 8)]. In a simulation study using a musculoskeletal model, Komura et al.[9)] showed that a decrease in iliopsoas muscle power output during gait led to an increase in that of the gastrocnemius muscle, and vice versa. Similarly, in a clinical study by Lewis et al.[7)], when instructing healthy individuals to walk with increased push-off, peak flexion moment and hip power immediately decreased. If this trade-off relationship holds true for individuals with CP, plantarflexor training could not only prevent misuse and overuse of the hip joint but also maintain or improve walking ability.

Therefore, this preliminary study aimed to assess the trade-off relationship between the hip and ankle joints after plantarflexor training in children with spastic hemiplegic CP. The working hypothesis was that ankle plantarflexor training could affect propulsive force generation during gait in individuals with CP who depend on the hip flexor strategy.

SUBJECTS AND METHODS

Subjects were recruited from the Department of Rehabilitation at five hospitals in Kyoto, Japan. A convenience sample of three boys with spastic hemiplegic CP who regularly attended community schools was utilized for this

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Table 1. Characteristics of the subjects

		Subject 1	Subject 2	Subject 3
Age, y		9	10	13
Gender		Male	Male	Male
Affected side		Left	Right	Right
GMFCS level		II	I	II
Ankle ROM limitations, °	Right	-	Dorsiflexion −5°	Dorsiflexion −15°
	Left	Dorsiflexion −5°	-	-
Orthosis		-	-	Plastic AFO
History of surgery		-	-	Present*
MAS grade (ankle dorsiflexion)	Right	1	1+	2
	Left	1+	1	1+
Walking debut, mo		18	14	22
Conventional treatment frequency		1 time/mo	3 times/mo	3 times/mo

*Right Achilles tendon and hamstrings were lengthened 3 years previously.
AFO: ankle-foot orthosis; GMFCS: Gross Motor Function Classification System; MAS: Modified Ashworth Scale; ROM: range of motion

preliminary study. All subjects received conventional physiotherapy treatment more than once a month. The inclusion criteria were: (1) ability to walk independently for at least 10 meters; (2) Gross Motor Function Classification System (GMFCS) level I or II (walking without aids)[10)]; (3) age from 9 to 15 years; (4) no invasive surgery or Botox treatment within the past six months; (5) Modified Ashworth Scale (MAS) grade 1 or 2 for ankle dorsiflexion on the affected side[11)]; (6) absence of visual or auditory problems; and (7) ability to understand simple verbal commands and instructions. The characteristics of the subjects are shown in Table 1.

The children and their guardians were given oral and written explanations regarding the study objective after which informed consent was obtained. This study was conducted with approval from the Research Ethics Committee of the School of Comprehensive Rehabilitation at Osaka Prefecture University (2011P02).

All subjects completed a proposed plantarflexion training program[12)]. Briefly, this training program consisted of approximately 50-minute exercises to be performed with rest intervals. Task 1: lean against a wall in a standing position for 5 to 10 minutes to warm up and stretch the lower limb muscles to increase muscle flexibility; Task 2: perform ankle plantarflexion resistance exercise using an elastic band (Thera-Band; Hygenic Corporation, Akron, OH, USA) for 5 sets of 20 repetitions on both sides (affected and non-affected sides); Task 3: crawl on hands and feet with arms and legs straight and perform lower limb extension exercise, involving ankle plantarflexion, for 5 sets of 20 repetitions, with adjusted loads on the lower limbs; and Task 4: perform heel-ups in a standing position for 5 sets of 20 repetitions, while touching a wall for support. At the end of each session, task 1 was repeated as a cool-down activity. Each subject performed this program three times a week. In consideration of both neurologic factors and those related to myopachynsis[13)], the training period was set at 12 weeks. A simple checklist, penned with input from each subject, was used to confirm appropriate implementation of the training.

Each subject was evaluated before and after the 12-week plantarflexor training program. All subjects underwent gait analysis using a motion capture system with 10 infrared cameras (200 Hz); data were reduced using Orthotrak (nac Image Technology Inc., Tokyo, Japan) and a Helen Hayes marker set[14)]. Kinetic data were collected using two 200-Hz force plates (OR6-7-2000; AMTI Japan Ltd. Kanagawa, Japan), which were placed in the center of a 10-meter walkway. Before evaluation, subjects sufficiently practiced walking on the force plates. Subjects were required to walk barefoot at a self-selected speed, and testing continued until a minimum of five trials with good force plate strikes were collected for both testing conditions (before and after training).

Using gait analysis software (Orthotrak), data on gait speed, stride length of both sides, and hip and ankle power as kinetic variables were collected. One gait cycle was normalized from initial contact (0%) to initial contact (100%) on the same side. Power (W) was normalized with body weight (kg). Then, peak hip and ankle powers in the sagittal plane were calculated. Power values were labelled according to the protocol of Eng et al.[15)]: H1 (hip extensor power generation during the early stance phase); H2 (hip joint power absorption); H3, (hip flexor power generation); A1, ankle plantarflexor power absorption; and A2 (ankle plantarflexor power generation). Furthermore, peak value of both joints and ankle-to-hip power ratio (A2/H3 ratio)[16)] were calculated. The A2/H3 ratio represents the proportions of ankle plantarflexion and hip flexion during the push-off phase, with a higher ratio indicates a higher proportion of ankle involvement compared with that he the hip.

Differences in spatiotemporal parameters and kinetic variables in five trials of each subject before and after training were tested with the Mann-Whitney U test (SPSS Statistics Standard Grad Pack 21.0; IBM, Tokyo, Japan)[17, 18)]. The level of statistical significance was set at $p< 0.05$.

RESULTS

All three subjects completed the plantarflexor training

Table 2. Gait speed and stride length before and after plantarflexor training

	Subject	Before training		After training	
Gait speed, cm/s	1	121.7	(3.2)	108.6	(17.1)
	2	131.4	(4.3)	139.7	(6.8)
	3	146.7	(11.6)	145.2	(9.7)
Stride length on affected side, cm	1	103.8	(3.4)	104.7	(3.7)
	2	117.2	(12.3)	121.8	(7.0)
	3	136.9	(13.6)	140.5	(5.3)
Stride length on non-affected side, cm	1	103.0	(4.6)	105.2	(5.4)
	2	113.6	(2.6)	128.5*	(3.9)
	3	139.3	(11.1)	143.5	(4.1)

All data are presented as mean (SD).
*p<0.01

Table 3. Peak ankle and hip power and A2/H3 ratio before and after plantarflexor training

			Subject	Before training		After training	
Peak power, W/kg	A2	Affected side	1	1.16	(0.24)	1.25	(0.70)
			2	1.74	(0.27)	4.60**	(2.29)
			3	0.29	(0.18)	0.54*	(0.16)
		Non-affected side	1	2.32	(0.11)	1.80	(0.70)
			2	2.78	(0.29)	2.92	(1.42)
			3	2.55	(0.22)	3.63**	(0.77)
	H3	Affected side	1	0.48	(0.16)	0.35	(0.14)
			2	1.06	(0.13)	1.44**	(0.18)
			3	1.73	(0.73)	1.59	(0.48)
		Non-affected side	1	0.55	(0.07)	0.38*	(0.11)
			2	1.11	(0.06)	0.71**	(0.26)
			3	0.81	(0.14)	0.77	(0.22)
A2/H3 Ratios		Affected side	1	2.57	(0.70)	3.42	(1.0)
			2	1.66	(0.22)	3.66*	(1.24)
			3	0.17	(0.09)	0.37*	(0.15)
		Non-affected side	1	4.31	(0.70)	4.67	(0.88)
			2	2.52	(0.32)	3.92*	(1.06)
			3	3.21	(0.60)	4.87*	(0.84)

All data are presented as mean (SD).
A2- ankle plantarflexor power generation; H3- hip flexor power generation; A2/H3 ratios − the proportions of ankle plantar-flexion and hip flexion during the push-off phase.
*p <0.05. **p <0.01

program, and no subject reported pain during any of the sessions. Data for spatiotemporal parameters, gait speed, and stride length on both sides before and after training are shown in Table 2. Gait speed and stride length on the affected side demonstrated no significant change between measurements in all subjects. However, stride length on the non-affected side increased significantly in subject 2 ($p < 0.05$).

Table 3 shows the peak hip and ankle powers on both sides. Peak A2 power increased significantly on both sides in subject 3 (affected side, $p < 0.05$; non-affected side, $p < 0.01$) and on the affected side in subject 2 ($p < 0.01$). In subject 2, peak H3 power decreased significantly on the non-affected side ($p < 0.01$), but increased significantly on the affected side ($p < 0.01$). Peak H3 power also decreased significantly on the non-affected side in subject 1 ($p < 0.05$).

The A2/H3 ratio increased significantly on both sides in subjects 2 and 3. The average A2/H3 ratio on the affected side increased significantly after training compared with the ratio before training (subject 2: 1.66 [SD, 0.22]–3.66 [SD, 1.24], $p < 0.05$; subject 3: 0.17 [SD, 0.09]–0.37 [SD, 0.15], $p < 0.05$). Moreover, the average A2/H3 ratio on the non-affected side also increased significantly after training (subject 2: 2.52 [SD, 0.32]–3.92 [SD 1.06], $p < 0.05$; subject 3: 3.21 [SD, 0.60]–4.87 [SD, 0.84], $p < 0.05$).

DISCUSSION

Propulsive force generation at push-off during gait in children with spastic CP is dependent on the hip joint rather than the ankle joint[16, 19]. In general, healthy individuals have a complementary relationship between the hip and ankle joints for propulsive force generation during gait[7, 8]. Furthermore, while walking, the plantarflexors provide much of the force required to support the body and propel the lower limbs, particularly in mid and late stances[20]. These findings led us to hypothesize that ankle plantarflexor training would improve propulsive force generation at push-off in individuals with CP who use the hip flexor strategy. Therefore, the aim of this preliminary study was to assess whether a trade-off relationship exists between the hip and ankle joints during gait in children with spastic hemiplegic CP after plantarflexor training. Although our findings are only preliminary due to the small sample size and incomplete research design, the results of this study support our hypothesis to a minor extent.

Generally, it is well known that function on the non-affected side in children with spastic hemiplegic CP tends to compensate for dysfunction on the affected side[21]. The trade-off relationship, which is similar to that seen in earlier studies[9, 15], was observed only on the non-affected side in subject 2 (Table 3). On the other hand, peak ankle power (A2) on the affected side increased significantly without decreasing peak hip power (H3) (Table 3), which led to a significant change in the A2/H3 ratio. From this point of view, our plantarflexor training caused two different trade-off relationship patterns in subject 2. Consequently, it can be assumed that the A2/H3 ratio on the affected side increased significantly after training because the plantarflexor on the affected side helped to push off more efficiently during gait. This explanation would support the significantly longer stride length on the non-affected side after training (Table 2). Conversely, the efficient push-off on the affected side also caused the A2/H3 ratio on the non-affected side to increase significantly after training by inhibiting excessive compensatory movement at the hip, which would reduce peak hip power (H3).

Although the A2/H3 ratio also increased significantly on both sides in subject 3 after training, this pattern was dependent on a significant increase in peak ankle power (A2). Thus, the hypothesis, that ankle plantarflexor training would lead to little reduction in compensatory movement of the hip, did not supported. The reasons for this result might be limited mobility of the ankle on the affected side and the grade of GMFCS.

In the present study, two of three subjects demonstrated a significant increase in A2/H3 ratio after training; the ratio did not change significantly in subject 1. Despite being at the same GMFCS level[10], the ankle dorsiflexion mobility of subject 1 was larger than that of subject 3. This phenomenon might have resulted from the frequency of physiotherapy for subject 1 (1 time/month) versus that for subject 3 (3 times/month) (Table 1).

There are several limitations of this preliminary study. The primary limitations are the lack of a control group and the small sample size. In addition, our findings might have been affected by the grade of severity of motor function and the frequency of physiotherapy intervention. Moreover, in this study, we cannot assess how ankle plantarflexor training would improve gait performance. Finally, this study focused on only short-term effects of plantarflexor training. Furture studies with a larger sample size that including children with spastic diplegia and an improved study design will be necessary to examine the long-term effects of plantarflexor training.

Although the A2/H3 ratio increased significantly on both sides in two of three children with spastic hemiplegic CP, our hypothesis that plantarflexor training can enable children with CP to decrease the force requirements of the hip during gait was only slightly supported. This information is invaluable for therapists planning therapeutic programs for children with spastic hemiplegic CP.

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