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Change in the Mechanical Energy of the Body Center of Mass in Hemiplegic Gait after Continuous Use of a Plantar Flexion Resistive Ankle-foot Orthosis

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Abstract. [Purpose] The aim of this study was to investigate the changes in mechanical energy due to continuous use of a plantar flexion resistive ankle-foot orthosis (AFO) of subjects with chronic hemiplegia. [Subjects and Methods] The subjects were 5 hemiplegic patients using AFOs without a plantar flexion resistive function in their daily lives. We analyzed the gait of the subjects using a 3D motion capture system under three conditions: patients' use of their own AFOs; after being fitted with a plantar flexion resistive AFO; and after continuous use of the device. The gait efficiency was determined by calculating the mutual exchange of kinetic and potential energy of the center of mass. [Results] An increased exchange rate of the kinetic and potential energy was found for all subjects. A larger increase of energy exchange was shown on the non-paralyzed side, and after continuous use of the plantar flexion resistive AFO. [Conclusion] We found that continuous use of a plantar flexion resistive AFO increased the rate of mutual exchange between kinetic energy and potential energy. The change in the rate was closely related to the role of the non-paretic side, showing that the subjects needed a certain amount of time to adapt to the plantar flexion resistive AFO.

Key words: Hemiplegic gait, Plantar flexion resistive ankle-foot orthosis, Mechanical energy of the body center of mass

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INTRODUCTION

Walking is an action with an extremely low energy cost. From the perspective of energy conversion of the center of mass (COM), the trajectory of the COM in the sagittal plane is similar to the motion of a pendulum, and this movement in known as the inverted pendulum model[1, 2)]. In this model, kinetic energy in the direction of progress reaches its peak at the time of heel strike, and gradually decreases in the first half of the stance phase as kinetic energy is converted to potential energy of the COM. The potential energy shows its peak at the midpoint of the stance phase. During the latter half of the stance phase, when the COM goes down, potential energy gradually decreases, as it is converted into kinetic energy. In order to achieve an efficient gait, energy conversion through the efficient use of gravity is important. This has been shown by passive walking robots[3)] achieving ambulation with relatively low energy cost. Although the free gait speed of hemiplegic patients is less than half of that of healthy individuals, their oxygen consumption cost is about 25% larger[4)]. The cause of the increased energy cost of hemiplegic gait is closely related to the increase of external work by the muscles involved in moving the COM[5)]. Furthermore, it is thought that inefficiency in the energy conversion described above is one of the characteristics of hemiplegic gait[6)].

The rocker function proposed by Perry[7)] is said to play an important role in reproducing the inverted pendulum model and achieving efficient energy conversion. A plantar flexion resistive ankle-foot orthosis (PF-AFO) is an AFO which assists the rocker function[8–10)]. The PF-AFO directly assists the initial turnover period, and wearers also show an improvement in the second turnover period after continuous use of the PF-AFO[11, 12)]. The objective of this study was to investigate the change in mechanical energy of the COM in hemiplegic gait after continuous use of a PF-AFO.

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Table 1. Subject characteristics

	Case 1	Case 2	Case 3	Case 4	Case 5
Sex	Female	Male	Female	Male	Male
Age (years)	33	37	50	67	65
Diagnosis	Cerebral Infarction	Cerebral Hemorrhage	Cerebral Hemorrhage	Cerebral Infarction	Cerebral Infarction
Paretic Side	Left	Right	Left	Right	Right
Period from Onset (Months)	20	28	124	202	44
Lower Limb BRS	III	IV	III	III	III
Lower Limb FMA	9 (41%)	20 (91%)	15 (68%)	15 (68%)	17 (77%)
Ankle Joint MAS	2	1	2	1+	2
Independence	Supervision required	Independent	Independent	Independent	Independent
Subject's own Orthosis	AFO with metal uprights	Plastic Leaf Spring	Plastic Leaf Spring	Plastic Leaf Spring	Plastic Leaf Spring
Height (cm)	160	175	151	164	163
Weight (kg)	57	75	51	68	65

BRS: Brunnstrom recovery stage; FMA: Fugl-meyer assessment; MAS: Modified Ashworth scale

SUBJECTS AND METHODS

The subjects were 5 maintenance-phase hemiplegics who used AFOs without a plantar flexion-resistive function in their daily lives (Table 1). The participation criteria for the study were: cerebrovascular disease hemiplegia with unilateral pathology at onset; no rehabilitation treatment during the experimental period; no marked higher brain dysfunction or difficulty understanding commands; no marked limitation in joint mobility of the lower limbs or trunk; being able to walk unassisted; and being able to walk forward by means of a heel strike. The subjects received a thorough explanation about the study content and methods both orally and in writing, and their written consent to participation was received. The study content conformed to the principles of the Declaration of Helsinki and received approval from the Hokkaido Institute of Technology Graduate School Research Ethics Committee.

The experimental schedule was as follows. On the first day, a 3D-motion analysis device was used to measure the gait of the patients' while wearing their own AFO, and their gait after the first fitting of the PF-AFO. After subjects had consented to continuous use of the PF-AFO, the same gait measurements were performed after 3–4 weeks of PF-AFO use. Each PF-AFO was manufactured from a cast of the foot of each subject.

At the first fitting, the plantar flexion movement of the ankle joint of the PF-AFO was confirmed in stance. After subjects had consented to use the PF-AFO, the amount of resistive moment and the initial ankle joint angle of the PF-AFO were adjusted for each subject's condition.

Subjects were orally instructed to "touch the ground with the heel of the side with paralysis first." In the measurement of PF-AFO gait on the first day, sufficient walking practice time was provided to familiarize subjects with the new orthosis. Then, 3D-motion analysis was performed on a flat walking pathway 7.5 m in length, and 6 one-way trial walks were performed under two conditions, with subjects' own AFOs and with the PF-AFO. Data after the fourth step from the start of ambulation was used in order to extract a steady state. The apparatus used for measurement was a 3D-motion analysis device (VICON-Nexus, Vicon Motion System Inc., Ltd., Oxford, United Kingdom). Six infrared cameras were placed around the walking pathway. Sixteen reflective markers were placed on the subjects: on the left and right sides of the acromion, one-third of the distance from the greater trochanter and the anterior superior iliac spine, the lateral center of the knee joint cleft, the external malleolus, the head of the fifth metatarsal, the calcaneal region, the anterior superior iliac spine, and the posterior superior iliac spine. The sampling frequency was 120 Hz. A seven-link segmental model was used to calculate the COM using the anthropometric data of typical Japanese men and women.

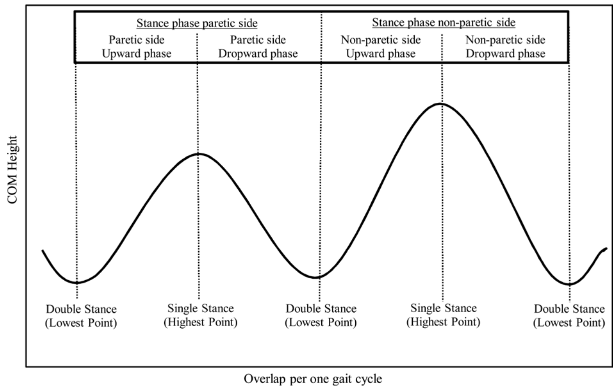

Fig. 1. Separate phases of the mechanical energy of COM

The conversion efficiency of COM potential energy to kinetic energy was calculated using the method of Cavana et al[13–23]. In the present study, the mechanical energy was calculated as described below based on the COM informa-

Table 2. Changes in gait speed

	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
				[m/sec]	Mean (SD)	
Case 1	0.39 (0.03)	0.41 (0.05)	0.50 (0.02)		*	**
Case 2	0.75 (0.03)	0.76 (0.02)	0.85 (0.04)		**	**
Case 3	0.62 (0.04)	0.55 (0.04)	0.69 (0.02)		**	**
Case 4	0.28 (0.02)	0.28 (0.01)	0.29 (0.02)			
Case 5	0.21 (0.01)	0.21 (0.02)	0.25 (0.02)		**	**

*p<0.05; **p<0.01

Table 3. Changes in Power-y

	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
				[W/kg]	Mean (SD)	
			Paretic side Elevation			
Case 1	1.4 (0.4)	−0.2 (1.6)	−1.8 (0.8)		*	
Case 2	−7.0 (3.3)	−6.5 (2.7)	−9.5 (2.9)			*
Case 3	−0.2 (1.6)	−2.2 (1.4)	−2.3 (0.7)	*	*	
Case 4	−0.4 (0.3)	−0.5 (0.3)	−0.5 (0.1)			
Case 5	0.4 (0.2)	0.2 (0.2)	−0.1 (0.2)		**	*
			Paretic side Drop			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	0.4 (0.9)	0.9 (0.5)	1.0 (0.6)			
Case 2	4.3 (1.0)	5.5 (1.6)	6.4 (2.4)			
Case 3	3.6 (2.7)	3.7 (1.2)	5.5 (1.5)			
Case 4	−0.3 (0.1)	0.8 (0.3)	0.8 (0.2)	**	**	
Case 5	1.1 (0.3)	1.6 (0.5)	1.5 (0.2)	*	**	
			Non-paretic side Elevation			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	−3.5 (0.6)	−3.2 (0.6)	−4.5 (0.6)			*
Case 2	−7.6 (1.5)	−9.3 (1.7)	−13.0 (5.6)		*	
Case 3	−7.7 (2.6)	−6.1 (1.2)	−8.3 (1.2)			*
Case 4	−1.1 (0.2)	−1.1 (0.2)	−1.5 (0.2)		*	*
Case 5	−2.0 (0.4)	−2.1 (0.5)	−2.1 (0.3)			
			Non-paretic side Drop			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	2.9 (0.3)	3.9 (1.2)	5.5 (0.8)		*	
Case 2	10.2 (1.6)	9.3 (1.9)	12.8 (2.1)		*	**
Case 3	6.2 (1.3)	5.5 (1.5)	8.1 (0.9)		**	**
Case 4	1.5 (0.1)	1.4 (0.2)	1.7 (0.1)		*	*
Case 5	0.4 (0.1)	0.4 (0.1)	0.7 (0.1)		**	**

*p<0.05; **p<0.01

tion measured and calculated from the 3D-motion analysis data.

In this study, mechanical energy was analyzed as four kinds. Thus, there were four kinds of power: the power used to accelerate in the travel direction of the COM (Power-y), the power for lifting the COM in the vertical direction COM (Power-z), the power generated by muscles (Power-ext), and the rate of exchange of kinetic energy to potential energy

Table 4. Changes in Power-z

				[W/kg]	Mean (SD)	
			Paretic side Elevation			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	12.4 (2.7)	14.1 (2.2)	16.9 (0.7)		*	*
Case 2	14.6 (1.8)	14.2 (1.7)	15.2 (3.9)			
Case 3	5.8 (0.8)	7.1 (1.5)	7.9 (1.7)		*	
Case 4	10.5 (1.5)	9.9 (1.6)	9.3 (0.8)			
Case 5	8.6 (2.8)	10.1 (1.9)	12.5 (1.3)		*	*
			Paretic side Drop			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	−5.6 (0.3)	−6.6 (1.3)	−6.9 (1.3)			
Case 2	−14.5 (1.6)	−15.8 (1.9)	−21.7 (4.8)		**	**
Case 3	−2.5 (1.1)	−4.7 (1.3)	−7.4 (1.0)	*	**	*
Case 4	−10.1 (2.5)	−12.6 (1.5)	−10.3 (1.1)			*
Case 5	−8.2 (1.5)	−8.7 (1.8)	−10.4 (1.1)		*	
			Non-paretic side Elevation			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	11.3 (1.6)	11.3 (1.3)	12.2 (0.8)			
Case 2	23.9 (0.8)	24.8 (2.3)	28.0 (4.0)		*	*
Case 3	27.3 (1.7)	25.4 (0.9)	21.5 (1.1)		**	**
Case 4	15.4 (2.1)	16.4 (1.1)	14.6 (0.8)			*
Case 5	19.3 (2.4)	17.1 (1.9)	14.7 (1.2)		**	*
			Non-paretic side Drop			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	−19.0 (2.3)	−18.9 (2.4)	−22.6 (1.2)			*
Case 2	−23.6 (2.2)	−22.2 (1.6)	−25.0 (3.1)			*
Case 3	−28.8 (1.5)	−29.3 (2.3)	−22.9 (1.6)		**	**
Case 4	−14.6 (0.7)	−15.5 (0.5)	−14.9 (1.4)			
Case 5	−18.2 (1.3)	−17.1 (1.3)	−17.3 (2.4)			

*p<0.05; **p<0.01

(% recovery).

To calculate the COM energy changes during ambulation, it is necessary to have information about the peak value of the vertical COM position (COM-Z). The motion of COM-Z is described by a sinusoidal curve (Fig. 1). In order to know the rise and fall of the inverted pendulum on both the paretic and non-paretic sides, it is necessary to know the highest and lowest points of COM-Z during gait. Therefore, knowledge of the range between the peak values of COM-Z on the paretic side and non-paretic side is necessary. To find this, gait data of more than one gait cycle was extracted, from the heel contact of the paralyzed limb to the foot contact of the ipsilateral limb, to have information about the highest and lowest positions of the COM. To calulate the kinetic energy and potential energy during ambulation, the kinetic energy (Ek.y) in the direction of progress of the body COM was calculated using Formula 1, the kinetic energy (Ek.z) in the vertical direction by Formula 2, the potential energy (Ep) by Formula 3, the total kinetic energy (Ek) by Formula 4, and the total energy (Etot) by Formula 5.

$$Ek.y = 1/2mVy^2 \quad (1)$$

$$Ek.z = 1/2mVz^2 \quad (2)$$

$$Ep = mgz \quad (3)$$

$$Ek = Ek.y + Ek.z \quad (4)$$

$$Etot = Ek + Ep \quad (5)$$

Were, m is the body mass, g is the acceleration due to gravity (9.8 m/s^2), Vz is the vertical velocity of COM, and Vy is the velocity in the direction of COM progress.

The external work for accelerating the COM in the direction of progress was calculated using Formula 6, the

Table 5. Changes in Power-ext

				[W/kg]	Mean (SD)	
		Paretic side Elevation				
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	13.9 (3.1)	13.9 (3.8)	15.1 (1.0)			
Case 2	7.6 (2.9)	7.7 (3.5)	5.8 (3.5)			
Case 3	5.5 (1.0)	4.9 (1.9)	5.6 (2.2)			
Case 4	10.1 (1.6)	9.4 (1.3)	8.8 (0.7)			
Case 5	9.0 (2.8)	10.3 (1.9)	12.4 (1.3)		*	*
		Paretic side Drop				
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	–5.3 (0.8)	–5.7 (1.6)	–5.8 (1.6)			
Case 2	–10.3 (2.0)	–10.4 (1.2)	–15.3 (3.0)		**	**
Case 3	1.1 (14.9)	–1.0 (1.2)	–1.9 (1.4)			
Case 4	–10.5 (2.5)	–11.9 (1.6)	–9.6 (1.0)			*
Case 5	–7.1 (1.4)	–7.1 (1.3)	–8.9 (1.1)		*	*
		Non-paretic side Elevation				
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	7.8 (1.9)	8.0 (1.1)	7.7 (0.7)			
Case 2	16.3 (1.2)	15.5 (2.5)	15.0 (2.9)			
Case 3	19.6 (1.4)	19.3 (1.6)	13.2 (1.1)		**	**
Case 4	14.3 (1.9)	15.3 (1.1)	13.1 (0.8)			*
Case 5	17.4 (2.2)	15.0 (1.9)	12.6 (1.2)		**	*
		Non-paretic side Drop				
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	–16.2 (2.6)	–14.9 (2.2)	–17.1 (1.4)			
Case 2	–11.8 (1.8)	–13.0 (1.2)	–12.2 (4.0)			
Case 3	–21.9 (1.4)	–23.8 (2.4)	–14.8 (0.9)		**	**
Case 4	–13.0 (0.7)	–14.2 (0.5)	–13.2 (1.3)	*		
Case 5	–17.8 (1.2)	–16.7 (1.2)	–16.6 (2.3)			

*p<0.05; **p<0.01

external work of raising the COM in the vertical direction against gravity by Formula 7, and the external work generated by the muscles to move the COM was calculated using Formula 8.

$$Wy=\Sigma\Delta Ek.y \quad (6)$$

$$Wz=\Sigma\Delta\ (Ek.z+Ep) \quad (7)$$

$$Wext=\Sigma\Delta Etot \quad (8)$$

Were, Δ is the amount of energy increase or decrease and ∑ is the summation of the data of Δ.

By dividing the external work by time, it was possible to determine the external power (Power-y) use to accelerate the COM in the direction of progress, the external power (Power-z) for raising the COM, and the external power (Power-ext) generated by the muscles. External power was calculated for the four phases shown in Fig. 1.

Conversion efficiency (%recovery[16]) was calculated using Formula 9.

$$\%recovery=(|Wy|+|Wz|-Wext)/(|Wy|+|Wz|)\times 100 \quad (9)$$

%recovery is the rate of mutual exchange of the kinetic energy and potential energy of the COM in walking. Meaning the value of %recovery in walking with efficient use of gravity is high. The %recovery value was calculated for each phase shown in Fig. 1, and the averages of one whole gait cycle, and the stance phases of the paretic and the non-paretic sides were calculated. The data of gait speed, Power-y, Power-z, Power-ext of each phase, and %recovery, were compared among the three conditions of: gait with patients' own AFOs, with the PF-AFO at the first fitting, with the PF-AFO after continuous use. R 2.8.1 software was used for statistical analysis, and the Steel-Dwass method was applied. The level of significance was chosen as less than 5%.

Table 6. Changes in %recovery

				[%]	Mean (SD)	
			Average of the one cycle gait			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	22.3 (5.7)	28.1 (7.1)	34.8 (2.5)		*	
Case 2	55.1 (6.9)	56.0 (4.9)	62.3 (3.9)		*	*
Case 3	43.8 (14.5)	49.5 (5.4)	59.5 (6.9)		*	*
Case 4	10.2 (0.3)	12.5 (1.1)	15.5 (1.1)	*	**	**
Case 5	11.6 (1.3)	14.2 (2.3)	15.0 (1.3)		**	
			Average of the paretic stance phase			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	7.7 (9.5)	17.1 (15.8)	22.6 (7.5)			
Case 2	53.2 (14.6)	55.8 (9.9)	60.4 (7.4)			
Case 3	43.2 (21.9)	64.1 (12.0)	65.1 (13.6)			
Case 4	3.6 (2.2)	10.5 (2.3)	12.0 (1.5)	**	**	
Case 5	11.5 (2.2)	15.5 (1.8)	13.8 (1.6)	**		
			Average of the non-paretic stance phase			
	(1)Subject's own Orthosis	(2)Before continuous use of PF-AFO	(3)After continuous use of PF-AFO	(1)vs.(2)	(1)vs.(3)	(2)vs.(3)
Case 1	37.0 (5.8)	39.1 (4.2)	46.5 (4.5)			
Case 2	57.0 (3.0)	56.3 (3.3)	64.2 (6.3)		**	**
Case 3	44.4 (11.3)	35.0 (3.0)	54.0 (2.5)			**
Case 4	16.9 (1.1)	14.5 (1.7)	19.1 (1.3)		*	**
Case 5	11.6 (1.4)	12.9 (3.0)	16.2 (1.8)		**	*

*$p<0.05$; **$p<0.01$

RESULTS

No significant changes were noted in gait speed for gait with the PF-AFO on the first day in all cases, but a significant increase was seen in four cases after continuous use of the PF-AFO (Table 2). An increase was also seen in Power-y in all cases in the non-paretic side downward phase after continuous use of the PF-AFO (Table 3). Power-z showed a significant change in all phases of both the paretic and non-paretic sides after continuous use of the PF-AFO in 3 cases (Table 4). The results of Power-ext showed some changes, but no clear trend was noted (Table 5). The average %recovery for one gait cycle after the continuous use of the PF-AFO increased in all cases. The comparison of the averages of the non-paretic and paretic stance phases, revealed increases in %recovery in the non-paretic stance phases of four cases, and in the paretic stance phases of two cases (Table 6).

DISCUSSION

The most interesting result of this study was the increase of %recovery in one gait cycle gait after the continuous use of the PF-AFO. Since the PF-AFO was worn only on the paretic side, it had no direct effect on the non-paretic side. However, comparing the averages of the non-paretic stance and paretic stance, four out of five subjects showed large increases in the stance phase of the non-paretic side. Furthermore, only small changes were found just after PF-AFO adaptation, but many changes were found after its continuous use.

The present results happened because loading on the paralyzed limb became smooth due to the use of the PF-AFO, eliminating the need for excessive control of the non-paretic side[24]. The increase of Power-y in the downward phase on the non-paretic side of all cases, indicates that subjects made steps without decreasing the speed of the COM in the late stance phase of the non-paretic side. Furthermore, the results suggest that the immediate effects at the time of first use of the PF-AFO were few, but many changes were found after its continuous use, indicating that time was necessary to learn to control the non-paretic side in order to adapt to the PF-AFO[11, 12, 24].

Taken together, the use of the PF-AFO increased COM energy conversion efficiency. This change was seen not only on the paretic side with the AFO, but also on the non-paretic side, and a certain amount of time was needed to adapt the PF-AFO.

A limitation of this study was that the time series of mechanical energy was not investigated in detail. Also, some parameters increased after 3–4 weeks use of the PF-AFO, but of the exact timing of these changes was not investigated. A detailed study of the time series of the adaptation to the PF-AFO, and the development of an exercise program to facilitate early adaptation of the PF-AFO will be necessary in a future study.

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