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Original Article

Knee joint movement and muscle activity changes in stroke hemiplegic patients on continuous use of knee-ankle-foot orthosis with adjustable knee joint

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Abstract. [Purpose] We aimed to evaluate knee joint movement and muscle activity ratio changes in stroke hemiplegic patients in recovery phase after using a knee-ankle-foot orthosis with an adjustable knee joint for 1 month; we also aimed to discuss the practical implications of our findings. [Participants and Methods] The participants were 8 hemiplegic patients in the recovery phase of stroke who were prescribed knee-ankle-foot orthosis with adjustable knee joint. We measured knee joint angles and electromyographic activity of the vastus medialis and biceps femoris during walking in two conditions: the knee-ankle-foot orthosis knee joint fixed in the extended position and the knee joint moved from 0° to 30° in the flexion direction. Measurements were taken 2 weeks after completion to account for habituation of the orthosis and repeated 1 month later. [Results] When the knee joint was moving from 0° to 30° in the flexion direction, the knee joint angle at initial contact and the minimum flexion angle of the gait cycle decreased significantly between the first and second measurements. When knee joint flexion was 30°, the muscle activity ratio of the vastus medialis increased significantly in the loading response and mid-stance compared to when it was fixed. [Conclusion] Setting the knee joint of a knee-ankle-foot orthosis in accordance with the knee joint movement may increase the muscle activity ratio of the vastus medialis from loading response to mid-stance.

Key words: Stroke, Electromyography, Knee-ankle-foot orthosis

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INTRODUCTION

Ankle-foot orthoses (AFOs) and knee-ankle-foot orthoses (KAFOs) are commonly used in recovery phase rehabilitation for stroke patients in Japan. KAFOs provide better support of the knee joint compared with AFOs and are therefore effective for standing and walking practice in stroke patients who have difficulty with weight bearing. Ota et al. reported that older stroke patients in the recovery phase who had lower Brunnstrom stage of the lower limb were more likely to be prescribed KAFOs than AFOs[1)]. Daryabor et al. conducted a systematic review of the effects of AFO use on gait in stroke patients and found an immediate effect of AFO use[2)]. However, Hesse et al. and Lairamore et al. reported that use of AFOs may lead to disuse atrophy of the tibialis anterior by limiting ankle joint movement[3, 4)]. Similarly, there is concern about disuse atrophy of the knee extensor muscles when using a highly fixed KAFO because it limits the motion of the knee joint. However, the effect of KAFOs on knee extensor muscle activity and joint motion in stroke patients during the recovery phase has not been reported. In addition, Murayama et al. showed that long-term use of AFOs providing plantarflexion resistance without limiting plantarflexion in loading response resulted in an increase in the activity ratio of the tibialis anterior in loading response[5)]. Therefore, using a KAFO with an adjustable knee joint that does not fix the knee joint during extension may increase the

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muscle activity ratio during the stance phase

The objective of this study was to evaluate the knee joint movement and muscle activity ratio changes in stroke hemiplegic patients in the recovery phase after using a KAFO with an adjustable knee joint for 1 month, and discuss the usefulness of KAFO.

PARTICIPANTS AND METHODS

This study involved 8 stroke hemiplegic patients (4 males, 4 females) admitted to Funabashi Municipal Rehabilitation Hospital. Average age was 61.6 ± 18.1 years; average height and weight were 163.4 ± 8.7 cm and 63.5 ± 16.0 kg, respectively. Inclusion criteria were first occurrence of stroke; in the recovery phase, within 60 days of onset of stroke; and prescribed a KAFO with an adjustable knee joint. Exclusion criteria were inability to practice walking with a KAFO with the assistance of a physical therapist and less than 6 weeks of walking practice with a KAFO.

This study was approved by the Ethics Committee of Funabashi Municipal Rehabilitation Hospital (Approval number K2019-22) and was conducted in accordance with the Helsinki Declaration. Participants received oral and written explanations of the aims and methods of the study, and informed consent was obtained from all participants included in the study.

The KAFO prescribed for the participants was equipped with an adjustable SPEX knee joint (Advanfit Co., Ltd., Kumamoto, Japan) and a double Klenzak ankle joint (Fig. 1). SPEX knee joints can be adjusted either by spring or by rod to change the range of motion of the knee joint flexion; in this study, we used the rod in all cases, and the ankle joint was set to resist on the plantar flexion side by using a spring and was set to allow free range of motion on the dorsiflexion side during walking practice. All participants underwent physical therapy, occupational therapy, and speech therapy 3 h a day, 7 days a week, and the physical therapy sessions ranged from 1 h to 1 h and 20 min a day, including at least 20 min of KAFO walking practice.

Measurements were taken first at 2 weeks after completion to account for habituation of the orthosis and again 1 month later. The participants wore a KAFO and walked about 10 m without a cane or handrails, and the physical therapists assisted them by hand from behind. One measurement was made after several trial walks with the KAFO knee joint fixed in the extended position (knee joint fixation), and the next measurement was made after several trial walks with the knee joint moving from 0° to 30° in the flexion direction (knee joint movement) (Fig. 2).

The setting of the ankle joint at the time of measurement was set to resist on the plantar flexion side by using a spring and was set to allow free range of motion on the dorsiflexion side.

The items of gait analysis were knee joint flexion angle (knee joint angle) and electromyography of the vastus medialis and biceps femoris. Knee joint angle and electromyographic measurements were performed at a sampling frequency of 1,000 Hz using the Gait Judge System (Pacific Supply Co., Ltd., Osaka, Japan). Electromyography sensor positions were

Fig. 1. Knee-ankle-foot orthosis used in this study.

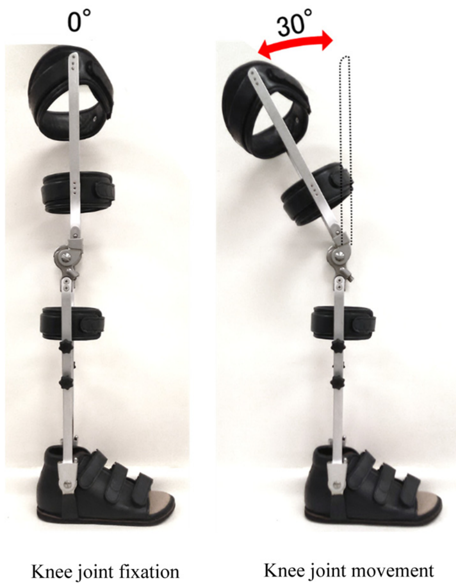

Fig. 2. Two conditions for the KAFO knee joint.

determined according to the SENIAM guidelines[6]. The continuous data for five gait cycles were divided into individual gait cycles by referring to the video recordings taken from the synchronized sagittal plane and the spike-like waveforms of vertical acceleration due to the impact of initial contact detected by an accelerometer attached to the lower leg portion of the KAFO. The five gait cycles were then averaged. The electromyographic measurements were smoothed by root mean square in the range of 50 ms and normalized by an average value of one gait cycle. Usually, the average in each phase of a single gait cycle in the electromyography data is normalized to 100% of the electromyographic measurement at maximum voluntary contraction. However, for stroke patients, maximum voluntary contraction cannot be performed due to problems such as spasticity and involuntary contractions, so we normalized the electromyography data by taking the average values for a single gait cycle as 100% (%EMG), as in a previous study[7]. Because actual electromyographic levels are easily affected by the positioning of the sensors, we used %EMG in this study, which can detect relative increases and decreases in muscle activity regardless of the actual level of muscle activity. Absolute comparisons could not be made when the mean value of a single gait cycle was set to 100% and the electromyography data were normalized; however, these were compared as a percentage in each phase of the gait cycle.

Data from the knee joint angles and electromyographic measurement of the vastus medialis and biceps femoris were divided for convenience into the following commonly reported phases: loading response (0% to 12%), mid-stance (12% to 31%), terminal stance (31% to 50%), pre-swing (50% to 62%), and swing (62% to 100%)[8]. The angle at initial contact and the displacement of the angle in each phase were calculated from the knee joint angles. For the vastus medialis and biceps femoris, the ratio in each phase of the gait cycle to the mean value of one gait cycle was calculated as %EMG. The measurements taken at 2 weeks after completion of the orthosis and again 1 month later were compared by the Wilcoxon signed-rank test (significance level $p<0.01$). In addition, each %EMG was compared between knee joint fixation and knee joint movement. All statistical analyses were performed using SPSS Statistics software version 25 (IBM Co., Ltd. Armonk, NY, USA).

RESULTS

Table 1 shows the basic characteristics of the 8 participants as well as their initial clinical evaluations and those 1 month later. Only Functional Independence Measure significantly increased 1 month later in the comparison between first measurement and 1 month later. There was no significant difference in other items, but there was a tendency for the number to increase 1 month later.

Figure 3 shows the average values of knee joint angles and %EMG of each muscle in the 8 participants. At 1 month after the initial measurement, the knee joint flexion angle decreased from initial contact to mid-stance compared with the initial measurement. In knee joint movement, the %EMG of the vastus medialis tended to increase from loading response to mid-stance in both the initial measurement and at 1 month later compared with knee joint fixation. The %EMG of the biceps femoris did not show the characteristic trend in waveforms as the other measurements.

Table 2 shows the comparisons between the initial measurement and at 1 month later for each measurement item. The flexion angle of the knee joint in initial contact and the minimum flexion angle of one gait cycle were significantly reduced at 1 month later. However, the %EMG of each muscle did not change significantly between the two measurements.

Table 3 shows the comparisons of the %EMG of each muscle between knee joint fixation and knee joint movement. In the initial measurement, the %EMG of the vastus medialis was significantly increased in knee joint movement compared with

Table 1. Characteristics and clinical evaluation of the 8 participants

Item	Average (± SD) and number of participants
Age	61.6 (± 18.1) years old
Gender	Males 4 · Females 4
Paralyzed side	Right 2 · Left 6
Disease type	Hemorrhage 5 · Infarction 3
Stroke onset to delivery of KAFO	53.4 (± 11.9) days
[first measurement]	
Brunnstrom stage	II 4 · III 2 · IV 2
Functional Independence Measure	58.3 (± 22.0) ※Perfect score 126
Berg Balance Scale	8.6 (± 6.6) ※Perfect score 76
Stroke Impairment Assessment Set	30.9 (± 5.4) ※Perfect score 56
[1 month later]	
Brunnstrom stage	II 3 · III 2 · IV 3
Functional Independence Measure	70.4 (± 15.3) ※Perfect score 126
Berg Balance Scale	18.0 (± 13.4) ※Perfect score 76
Stroke Impairment Assessment Set	32.5 (± 5.2) ※Perfect score 56

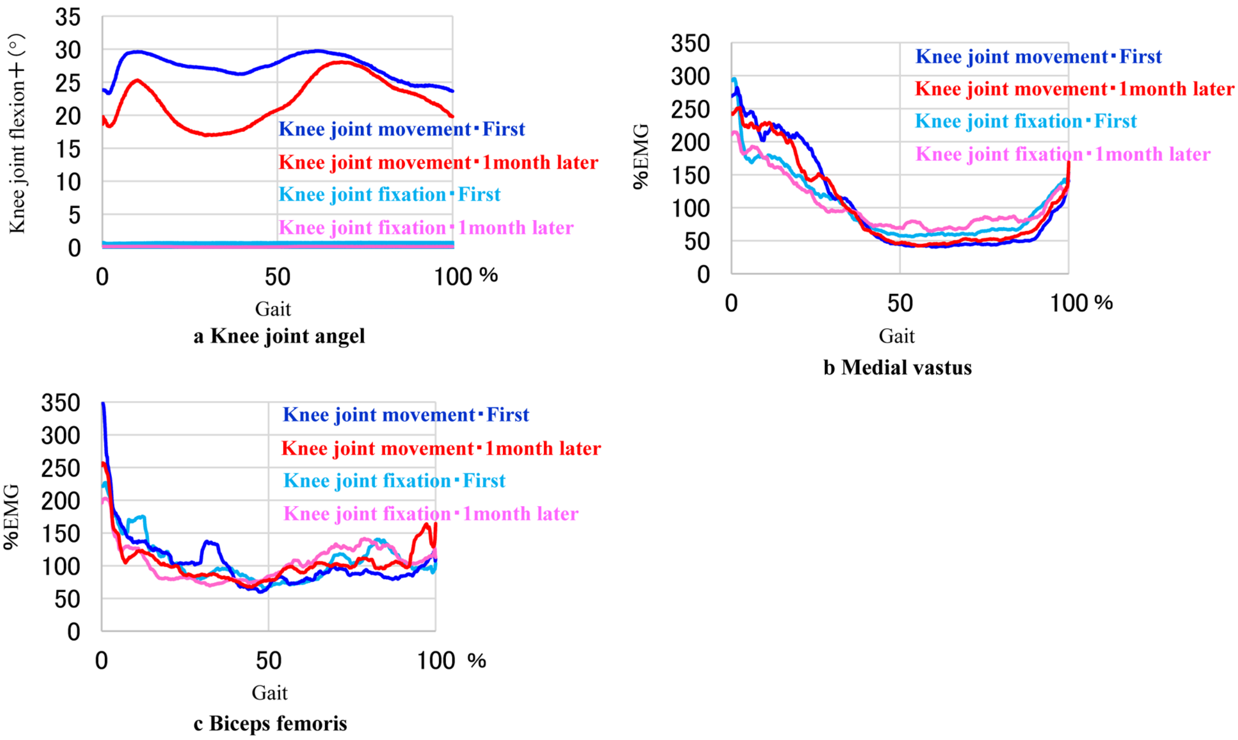

Fig. 3. Average values of knee joint angles and %EMG of each muscle in the 8 participants.
%EMG: Normalize was average values for a single gait cycle as 100%.

Table 2. Comparison of initial measurement and 1 month later for each measurement item

Item	Range	Period	Median	Interquartile range	p-value
Knee joint angle (Flexion direction is +)	Initial Contact	First	24.7	3.9	*
		1 month later	18.6	5.9	
Minimum flexion of knee joint angle (Flexion direction is +)	1 gait cycle	First	19.0	6.4	*
		1 month later	12.4	10.0	
Knee joint angle amount of displacement (Flexion direction is +)	1 gait cycle	First	11.4	6.4	
		1 month later	17.6	10.1	
	Loading response	First	5.0	5.0	
		1 month later	3.6	9.0	
	Mid-Stance	First	0.1	0.9	
		1 month later	−1.4	13.5	
	Terminal stance	First	0.0	0.4	
		1 month later	0.0	2.5	
	Pre-Swing	First	0.0	1.3	
		1 month later	0.3	6.0	
	Swing	First	−5.5	4.8	
		1 month later	−8.2	8.2	

knee joint fixation in mid-stance and significantly decreased in swing. At 1 month later, the %EMG of the vastus medialis was significantly increased in knee joint movement compared with knee joint fixation in loading response and mid-stance and significantly decreased in pre-swing. In contrast, there was no significant change between the two measurements in the biceps femoris.

Table 2. Continued

Item	Range	Period	Median	Interquartile range	p-value
Knee joint fixation vastus medialis muscle average of each phase (%EMG)	Loading response	First	191.1	27.1	
		1 month later	187.2	60.0	
	Mid-Stance	First	129.6	75.4	
		1 month later	120.1	41.6	
	Terminal stance	First	79.5	14.1	
		1 month later	80.3	13.1	
	Pre-Swing	First	62.4	13.2	
		1 month later	68.0	26.0	
	Swing	First	78.9	24.2	
		1 month later	98.4	28.1	
Knee joint movement vastus medialis muscle average of each phase (%EMG)	Loading response	First	240.7	94.9	
		1 month later	241.8	57.0	
	Mid-Stance	First	171.5	79.0	
		1 month later	164.2	83.5	
	Terminal stance	First	66.2	18.5	
		1 month later	68.1	33.7	
	Pre-Swing	First	43.4	35.0	
		1 month later	45.7	17.5	
	Swing	First	58.1	41.1	
		1 month later	72.4	28.8	
Knee joint fixation biceps femoris muscle average of each phase (%EMG)	Loading response	First	162.1	44.3	
		1 month later	157.0	54.7	
	Mid-Stance	First	108.7	32.4	
		1 month later	80.2	52.4	
	Terminal stance	First	78.2	27.0	
		1 month later	75.3	16.0	
	Pre-Swing	First	74.9	28.6	
		1 month later	100.4	37.7	
	Swing	First	96.6	34.8	
		1 month later	116.5	33.5	
Knee joint movement biceps femoris muscle average of each phase (%EMG)	Loading response	First	182.8	37.4	
		1 month later	145.9	46.5	
	Mid-Stance	First	112.3	48.4	
		1 month later	103.4	14.5	
	Terminal stance	First	84.7	28.8	
		1 month later	76.2	19.0	
	Pre-Swing	First	76.3	33.3	
		1 month later	85.8	44.2	
	Swing	First	80.9	46.7	
		1 month later	107.5	22.2	

%EMG: Normalize was average values for a single gait cycle as 100%.
*Significant difference according to Wilcoxon signed-rank sum test ($p<0.01$).

DISCUSSION

The flexion angle of the knee joint in normal gait is about 5° at initial contact, about 20° flexion in loading response, and about 5° extension in the terminal stance[8]. The results of this study show that the first initial contact is 24.7 ± 3.9° flexion, which is about 20° hyperflexion compared with normal gait. The minimum flexion angle is also about 14° hyperflexion compared with normal gait. At 1 month later, both the flexion angle of the joint and the minimum flexion angle of one gait cycle were significantly reduced, which was an improvement. Although not statistically significant, there was a trend toward

Table 3. Comparison of knee joint fixation and knee joint movement for the %EMG of each muscle

Item	Range	Knee joint	Median	Interquartile range	p-value
First measurement vastus medialis muscle average of each phase (%EMG)	Loading response	Fixation	191.1	27.1	
		Movement	240.7	94.9	
	Mid-Stance	Fixation	129.6	75.4	*
		Movement	171.5	79.0	
	Terminal stance	Fixation	79.5	14.1	
		Movement	66.2	18.5	
	Pre-Swing	Fixation	62.4	13.2	
		Movement	43.4	35.0	
	Swing	Fixation	78.9	24.2	*
		Movement	58.1	41.1	
1 month later measurement vastus medialis muscle average of each phase (%EMG)	Loading response	Fixation	187.2	60.0	*
		Movement	241.8	57.0	
	Mid-Stance	Fixation	120.1	41.6	*
		Movement	164.2	83.5	
	Terminal stance	Fixation	80.3	13.1	
		Movement	68.1	33.7	
	Pre-Swing	Fixation	68.0	26.0	*
		Movement	45.7	17.5	
	Swing	Fixation	98.4	28.1	
		Movement	72.4	28.8	
First measurement biceps femoris muscle average of each phase (%EMG)	Loading response	Fixation	162.1	44.3	
		Movement	182.8	37.4	
	Mid-Stance	Fixation	108.7	32.4	
		Movement	112.3	48.4	
	Terminal stance	Fixation	78.2	27.0	
		Movement	84.7	28.8	
	Pre-Swing	Fixation	74.9	28.6	
		Movement	76.3	33.3	
	Swing	Fixation	96.6	34.8	
		Movement	80.9	46.7	
1 month later measurement biceps femoris muscle average of each phase (%EMG)	Loading response	Fixation	157.0	54.7	
		Movement	145.9	46.5	
	Mid-Stance	Fixation	80.2	52.4	
		Movement	103.4	14.5	
	Terminal stance	Fixation	75.3	16.0	
		Movement	76.2	19.0	
	Pre-Swing	Fixation	100.4	37.7	
		Movement	85.8	44.2	
	Swing	Fixation	116.5	107.5	
		Movement	33.5	22.2	

%EMG: Normalize was average values for a single gait cycle as 100%.
*Significant difference according to Wilcoxon signed-rank sum test ($p<0.01$).

improvement in the motor paralysis and balance functions (Table 1). Lee et al. reported that stroke recovery was relatively rapid during the first 4 weeks after onset and then slowed between 3 and 6 months[9]. Also, Branco et al. demonstrated functional recovery up to at least 24 weeks after acute stroke[10]. In this study, gait was measured continuously after stroke onset until approximately 2 to 3 months later and included the recovery phase of gait ability, as in Lee et al. and Branco et al.

In contrast, there was no significant change in the %EMG of each muscle. Murayama et al. showed that using an AFO that provided plantarflexion resistance without limiting plantarflexion in loading response for 2 months resulted in an increase in the activity ratio of tibialis anterior in loading response[5]. In the present study, no change was observed after 1 month of use, so a longer period of time may be required to realize a change in muscle activity. In knee joint movement, the %EMG of the vastus medialis at 1 month later was significantly increased in loading response compared with knee joint fixation. Furthermore, the flexion angle of the knee joint at initial contact was significantly reduced, which may facilitate activity of the vastus medialis in loading response.

There are some limitations to this study. The analysis items in this study were activity of the vastus medialis and biceps femoris activity as well knee joint angle, which are less objective compared with three-dimensional motion data. In addition, this study had only 8 participants, which is not sufficient to ensure the generalizability of the results.

Setting the knee joint of KAFOs in accordance with the knee joint movement may increase the muscle activity ratio of vastus medialis from loading response to mid-stance. The results suggest that knee joint movement may be useful in preventing disuse atrophy of the knee extensor muscles.

Conflict of interest

The authors declare no conflict of interest. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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