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Analysis of Muscle Activity Patterns between Two Different Walking Exercise Programs —Qualitative Analysis of Walking Exercise for the Amputee

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Abstract. While many studies have investigated muscle activity in amputated legs while walking, in physical therapy and other fields, few studies have examined muscle activity in the healthy legs of amputees. Furthermore, to the best of our knowledge, no previous investigations have examined the motor learning processes in leg amputees or efficient exercise programs for walking with a leg prosthesis. Our previous study clarified the function of the non-amputated legs of amputees while walking with a prosthetic leg by measuring muscle activity patterns using surface electromyography and ground reaction force plates. In the present study, healthy volunteers were asked to wear a pseudo-prosthetic leg and participate in either a basic or applied exercise program using clearly different exercises. Differences in muscle activity patterns between the programs were then analyzed. After 2 weeks of exercises, the exercise program allowing legs without a pseudo-prosthesis to function more like the non-amputated legs of amputees who were skilled at walking with their prosthesis was ascertained. Muscle activity patterns of volunteers on the applied exercise program tended to more closely resemble those of amputees.
Key words: Amputation, Walking exercise program, Surface electromyography

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INTRODUCTION

In our previous study on the function of the non-amputated legs of amputees[1)], muscle activity patterns of the non-amputated leg of amputees were assessed using surface electromyography and ground reaction force plates, and the results were compared with those from the legs of healthy individuals. Muscle activity patterns for the non-amputated legs of amputees were always efficient while walking. Therefore, in the present study, healthy volunteers were placed on one of 2 walking exercise programs with clearly different exercises, and the function of the leg without the pseudo-prosthesis while walking was analyzed by measuring muscle activity patterns. We then ascertained which program was able to more quickly make the leg without the pseudo-prosthesis function like the non-amputated legs of amputees who could skillfully walk with their leg prosthesis. Latash et al.[2)] stated that, regardless of the types of disease or disorder, no clear answer exists to the basic question, “What are normal movements?” In other words, the non-amputated legs of amputees should not function like those of healthy individuals, and therapists should not attempt to provide therapy aimed at making the non-amputated legs of amputees function like the legs of healthy individuals.

As far as motor learning is concerned, Cook et al.[8] investigated the system approach theory. That is, motor activity is generated as a result of multiple processes, involving: perception, recognition and motor action in the body; and interactions between the individual, the specific motor task and the environment. Furthermore, training conditions are very closely related to motor learning. In other words, the effectiveness and efficacy of motor learning differ depending on the contents (quality and quantity), length and methods of training. While this sounds reasonable, no previous studies appear to have investigated the effects of different training conditions on the non-amputated legs of amputees or the non-paralyzed legs of hemiplegics.

Saito[7] documented that the following variables are important for bringing about behavioral changes from the perspective of motor learning: feedback, training quantity and frequency, and difficulty. The present study investigated training quality and difficulty by designing 2 walking exercise programs: a basic walking exercise, and an applied walking exercise. In order to develop an efficient walking exercise program for leg amputees, we designed the present study as shown in Figure 1. The two programs were compared in terms of the following 6 parameters: EMG, %IEMG, ground reaction force, 10-m walking time, and stride.

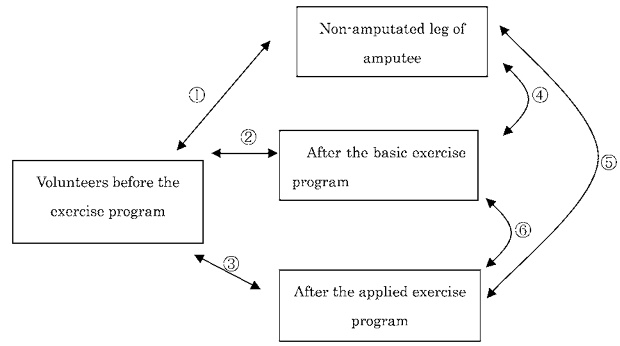

Fig. 1. Scheme of this study.
1) Comparison of muscular activities between the non-amputated leg of amputees and the leg without the pseudo-prosthesis of volunteers before the exercise program.
2) Comparison of muscular activities before and after the basic exercise program.
3) Comparison of muscular activities before and after the applied exercise program.
4) Comparison of muscular activities between the non-amputated leg of amputees and the leg without the pseudo-prosthesis of volunteers after the basic exercise program.
5) Comparison of muscular activities between the non-amputated leg of amputees and the leg without the pseudo-prosthesis of volunteers after the applied exercise program.
6) Comparison of muscular activities between the basic and applied exercise programs.

SUBJECTS

Amputees

Amputee subjects comprised 3 men who had 1 leg amputated above the knee. Mean age, height and body weight of the 3 men were 33.0 ± 5.3 years, 178.8 ± 5.2 cm and 67.5 ± 5.2 kg, respectively. Table 1 shows the age, height, body weight, gender, amputated leg, time after amputation, cause of amputation, socket type, knee component type and foot prosthesis for each patient. Based on the duration since amputation, all 3 men were thought to be skillful in walking using a leg prosthesis. The cause of amputation was trauma (traffic accident) for all 3 subjects.

Healthy volunteers with a pseudo-prosthesis (pseudo-prosthesis group)

(1) Basic exercise program

Three healthy men without any past history of orthopedic or neurological disorder were enrolled. The mean age and body weight of these men were 20.7 ± 1.5 years and 71.7 ± 2.6 kg, respectively. A pseudo-prosthesis was attached to the right leg, and measurements were made on from the left leg.

(2) Applied exercise program

Another set of 3 healthy men without any past history of orthopedic or neurological disorder was enrolled. The mean age and body weight of these men were 24.3 ± 3.2 years and 69.7 ± 10.4 kg, respectively. A pseudo-prosthesis was attached to the right leg, and measurements were made on the left leg.

After clearly explaining the purposes of the present study, informed consent to participate in the present study was obtained from all subjects.

Table 1. Characteristics of leg amputees

Case.	Age (years)	Height (cm)	Body weight (kg)	Sex	Amputated leg	Stump length (cm)	Time after amputation (months)	Cause	Socket	Knee component	Foot prosthesis
1	37	181	71	M	Right	19	204	Trauma	Quadrilateral socket suction-type	Intelligent	1H38, single-axis joint
2	27	183	70	M	Right	26	96	Trauma	IRC	Single-axis hydraulic	Energy-storing foot
3	35	173	61.5	M	Left	28	180	Trauma	Quadrilateral socket suction-type	Single-axis hydraulic	Single-axis joint

Fig. 2. Lateral view of the pseudo-prosthesis. Explain: Pseudo-prosthesis comprised a plate for maintaining knee flexion, a belt for immobilizing the upper and lower legs, a plate for adjusting the anteroposterior direction, a quadrilateral socket, and a single-axis joint foot.

METHODS

Pseudo-prosthesis group (Fig. 2)

For both the basic and applied exercise groups, volunteers exercised 20 min/day, 3 times/week for 2 weeks, and both programs comprised the same amount of exercise (Table 2). In both groups, the first exercise was a balance exercise in which the volunteer stood while holding onto a parallel bar and tried to remain standing. In the basic exercise group, volunteers walked while holding onto a parallel bar for 5 min, walked with crutches for 5 min, and then walked on flat ground, such as a hallway, for 5 min. In the applied exercise group, volunteers climbed up and down stairs, indoors for 5 min, then walked on streets with an incline and steps for 10 min.

Measuring devices and methods

Surface electromyography was conducted using a Myo System 1200 (NORAXON, U.S.A), and 4 ground reaction force plates (Anima Force Plate, U.S.A; 1,200 mm × 600 mm) were used.

Muscle action potentials of the gluteus medius (GM), rectus femoris (RF), vastus lateralis (VL), adductors (AD), biceps femoris (BF), tibialis anterior (TA) and gastrocnemius (GC) were measured at a sampling frequency of 1,000 Hz while walking, and at 100% maximal voluntary contraction (MVC) using the bipolar electrode method. After thoroughly preparing the skin, surface electrodes (Blue Sensors; GE Marquette Medical System, U.S.A) were attached along the muscle fibers with an electrode interval of 3 cm at the mid-point between the motor point and distal tendon. In addition, a foot switch was placed on the sole at the base of the hallux and at the heel of the healthy leg (non-amputated leg for amputees, or leg without pseudo-prosthesis for volunteers).

The sampling frequency for the ground reaction force plates was set at 60 Hz.

Examined items

(1) EMG

Each subject was instructed to walk naturally, and while gait was stable, muscle discharges during the entire third step for the healthy leg (non-amputated leg for amputees, leg without pseudo-prosthesis for volunteers) were rectified to calculate peak integrated EMG (IEMG). To compare data,

Table 2. Walking exercise programs (20 min/day, 3 times/week for 2 weeks)

Basic exercise group	Applied exercise group
Balancing with a parallel bar (5 min)	Balancing with a parallel bar(5 min)
Walking with a parallel bar (5 min)	Climbing up and down stairs indoors (5 min)
Walking with crutches (5 min)	Walking outdoors on streets with an incline (10 min)
Walking on flat ground (5 min)	

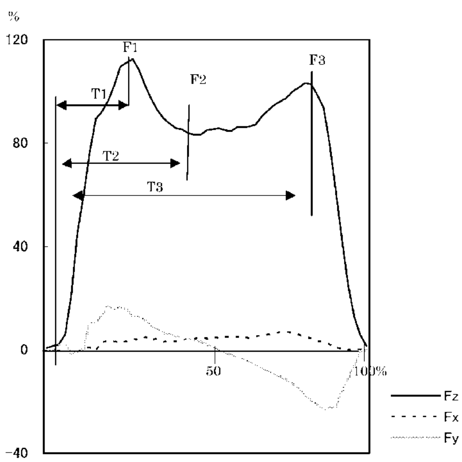

Fig. 3. Representative ground reaction force patterns of the healthy leg of an amputee while walking.

%IEMG was calculated in relation to 100% MVC.

(2) Ground reaction force (Fig. 3)

Peak values of the vertical component (Fz) were calculated, and percentage of total body weight including the prosthesis was calculated. Also, in relation to the entire walk cycle (100%), onset time of peaks was calculated as a percentage of peak time (%).

(3) Performance analysis

1) 10-m walk

While wearing the leg prosthesis, the time taken to walk 10 m was measured. This test was conducted 5 times for each amputee and volunteer before initiating and after finishing exercise programs. Mean values were calculated for each subject.

2) Stride

Stride was measured for the healthy leg (non-amputated leg for amputees, leg without pseudo-prosthesis for volunteers) while walking naturally with a leg prosthesis. This test was conducted 5 times in each amputee and volunteer before initiating and after finishing the exercise program. Mean values were calculated for each subject.

3) Normalized stride

As stride is dependent on height, stride was standardized by height. This parameter was calculated 5 times for each amputee and volunteer before initiating and after finishing the exercise program. Mean values were calculated for each subject.

RESULTS

EMG findings

(1) Comparison of typical muscle action patterns between non-amputated legs of amputees and legs of volunteers (Figs. 4 and 5)

In terms of integrated EMG patterns, no marked differences were noted among subjects in each of the groups. For the amputee group, amplitude peaks for each muscle were generally better defined, AD were active during the swing acceleration, early swing deceleration and late stance phases, and muscle action peaks of TA occurred during the swing acceleration and late stance phases.

(2) Comparison of muscle action patterns before and after exercise program (Figs. 6 and 7)

The action peak for AD was seen throughout the swing phase before the exercise program, matching the results for healthy individuals. After the exercise program, peaks were noted during the swing acceleration phase. In particular, after the applied exercise program, muscle action patterns of volunteers more closely resembled those of amputees. As for the muscle action patterns of GC, activity was seen during the swing phase before the exercise program, but only from the mid-to-late stance phase after the exercise program. Muscle action peaks of GM and RF were clearly expressed during the transition from the swing to stance

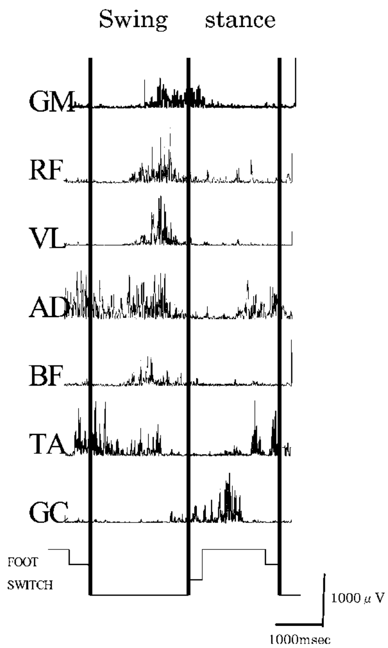

Fig. 4. Representative action potential waves of the non-amputated leg of an amputee while walking.

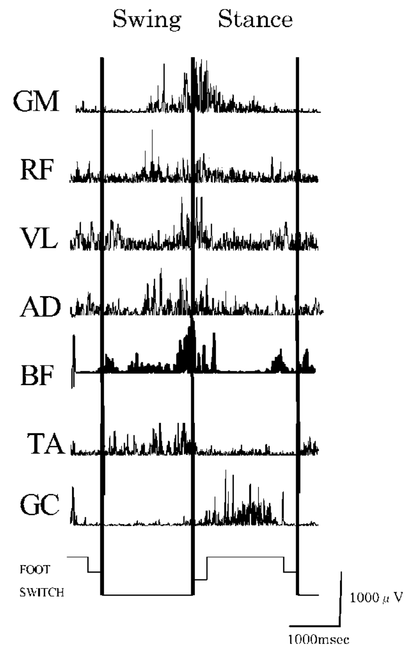

Fig. 5. Representative action potential waves of the leg of a healthy volunteer while walking.

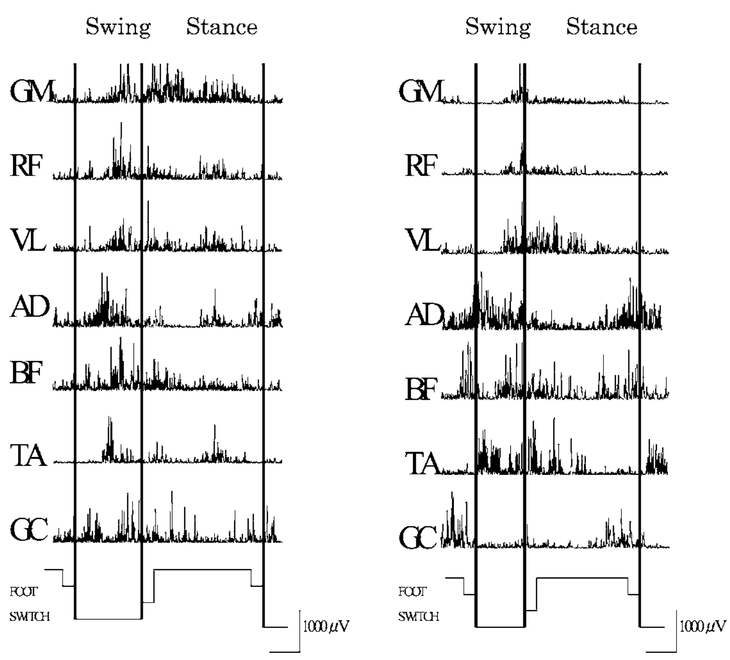

Fig. 6. Representative action potential waves of a leg in the basic exercise group. (left: pre-exercise; right: post-exercise)

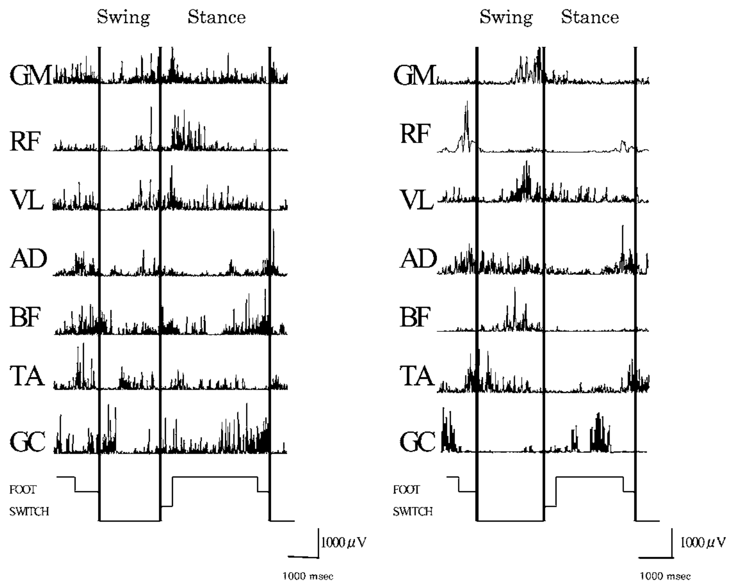

Fig. 7. Representative action potential waves of a leg in the applied exercise group. (left: pre-exercise; right: post-exercise)

phases in the basic exercise group. After the applied exercise program, marked activity was seen in GM during the transition from the swing to stance phases, thus resembling the muscle action of GM of amputees.

(3) %IEMG

1) Comparison before and after the basic exercise program

Before and after the basic exercise program, %IEMG values were 22.7% and 28.4% for GM; 18.0% and 12.0% for RF; 25.9% and 23.4% for VL; 23.4% and 26.3% for AD; 17.7% and 12.7% for BF; 34.8% and 29.6% for TA; and 70.5% and 52.3% for GC. For the basic exercise group, %IEMG decreased for all muscles after the program, except for GM and AD (Table 3).

2) Comparison before and after the applied exercise program

Before and after the applied exercise program, %IEMG was 22.5% and 37.7% for GM; 23.2% and 12.0% for RF; 22.3% and 17.5% for VL; 26.6% and 31.4% for AD; 20.6% and 12.3% for BF; 22.8% and 21.7% for TA; and 81.5 and 44.4% for GC, respectively (Table 3).

3) Comparison of amputees and volunteers after the exercise program

Compared to the basic exercise group, %IEMG each of the muscles after the exercise program in the applied exercise group was closer to the respective value in the amputee group.

Ground reaction force

Figures 3, 8 and 9 show typical floor reaction force patterns for the amputee, basic exercise and applied exercise groups, respectively. Table 4 shows peak value (%) and peak time (%) for the vertical component (Fz). No marked differences in peak value after the exercise program were noted between the basic and applied exercise groups.

Compared to the basic exercise group, onset time of T1 after the program for the applied exercise group was closer to the onset time of F1 for the amputee group.

10-m walk and stride

Table 5 shows the results for 10-m walk, stride and normalized stride for the amputee, basic walking and applied exercise groups. After applied exercise, 10-m walking time decreased and was closer to that for the amputee group when compared to the basic exercise group.

Table 3. Muscle activities while walking of the amputee and exercise groups

	GM	RF	VL	AD	BF	TA	GC
Amputee (n=3)	46.1 ± 43.6	10.6 ± 3.4	12.1 ± 5.6	35.4 ± 38.8	12.4 ± 6.0	16.9 ± 3.0	29.3 ± 10.1
Basic exercise group (n=3)							
Pre exercise	22.7 ± 11.2	18.0 ± 2.9	25.9 ± 2.7	23.4 ± 13.1	17.7 ± 6.1	34.8 ± 4.4	70.5 ± 8.6
Post exercise	28.4 ± 18.7	12.0 ± 3.1	23.4 ± 2.4	26.3 ± 12.3	12.7 ± 3.7	29.6 ± 4.1	52.3 ± 9.8
Applied exercise group (n=3)							
Pre exercise	22.5 ± 10.9	23.2 ± 18.4	22.3 ± 13.4	26.6 ± 27.1	20.6 ± 13.9	22.8 ± 9.4	81.5 ± 12.4
Post exercise	37.7 ± 8.2	12.0 ± 17.7	17.5 ± 13.9	31.4 ± 23.9	12.3 ± 12.4	21.7 ± 10.1	44.4 ± 21.4

mean ± SD(%)

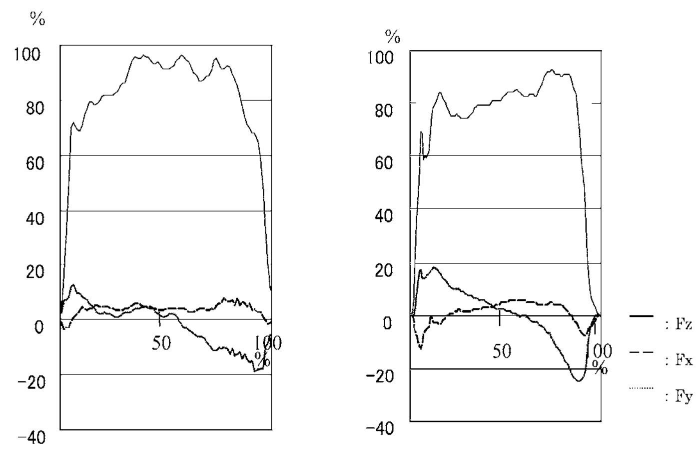

Fig. 8. Representative ground reaction force patterns of the basic exercise group. (left: pre-exercise; right: post-exercise)

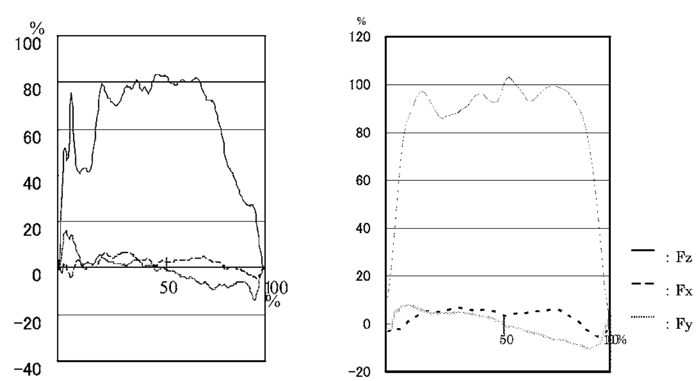

Fig. 9. Representative ground reaction force patterns of the applied exercise group. (left: pre-exercise; right: post-exercise)

DISCUSSION

Subjects

Latash et al.[2] stated that, regardless of the types of diseases and disorders, there is no clear answer to the question, “What are normal movements?” As the function of the non-amputated leg of amputees is not the same as that of healthy individuals, they

Table 4. Peak value and peak time of the vertical component of ground reaction force of the amputee and exercise groups (left, peak value; right, peak time)

	F1	F2	F3	T1	T2	T3
Amputee (n=3)	112.1 ± 1.2	82.2 ± 4.7	110.0 ± 14.3	25.0 ± 2.0	45.6 ± 8.0	82.0 ± 1.8
Basic exercise group (n=3)						
Pre exercise	99.7 ± 31.1	78.6 ± 2.3	87.1 ± 4.5	7.3 ± 1.2	49.7 ± 15.9	71.7 ± 6.9
Post exercise	92.8 ± 23.3	89.1 ± 9.9	90.8 ± 3.8	7.4 ± 1.0	50.2 ± 1.3	79.5 ± 4.6
Applied exercise group (n=3)						
Pre exercise	85.4 ± 13.9	70.6 ± 7.8	70.1 ± 16.9	5.0 ± 2.0	42.6 ± 0.7	67.5 ± 0.9
Post exercise	87.4 ± 10.2	87.0 ± 8.7	92.1 ± 16.8	18.2 ± 2.9	48.3 ± 4.4	72.1 ± 5.9

mean ± SD(%)

Table 5. Results of 10-m walk for amputees and volunteers

	Walking time (s)		Stride (m)		Stride/Height*	
Amputee group (n=3)	8.3 ± 0.4		1.2 ± 0.1		0.7 ± 0.1	
	Pre	Post	Pre	Post	Pre	Post
Basic exercise group (n=3)	23.4 ± 2.5	20 ± 3.6	0.7 ± 0.1	0.8 ± 0.2	0.4 ± 0.1	0.5 ± 0.1
Applied exercise group (n=3)	24.6 ± 1.4	16.7 ± 2.3	0.7 ± 0.1	0.9 ± 0.1	0.4 ± 0.1	0.5 ± 0.1

*Stride values normalized by height, since stride is proportional to height

concluded that the aim of therapy should not be to make the non-amputated legs of amputees function like the legs of normal individuals.

In hemiplegic stroke patients, the importance of the function, and muscle strength in particular, of the healthy side for walking has been recognized for some time[3–5]. For example, Bohannon[3] reported that muscle strength of the non-paralyzed leg represented one of the important factors for walking speed, and Miya et al.[4] documented that strength of the extensors of the non-paralyzed knee was a factor in determining the maximum walking speed of hemiplegics. As far as muscle strength of the non-paralyzed side is concerned, Ohmiya et al.[8] reported that the strength of the quadriceps femoris and hamstrings were 73% and 68% of that of healthy individuals, respectively. However, reduced muscle strength in hemiplegics could be due to disuse muscle atrophy, central muscle atrophy of non-crossed fibers in the pyramidal tract, or reduced cerebral blood flow in the undamaged hemisphere[10].

As the cause of reduced muscle strength varies greatly in hemiplegic stroke patients, this parameter is unsuited to ascertaining the effects of exercise programs. The present study therefore examined the non-amputated legs of amputees.

Leg muscle action during walking

Our previous study[1] clarified muscle activity patterns for the non-amputated legs of amputees while walking and ascertained differences in action patterns compared to the legs of healthy individuals. Muscle activity patterns differed between amputees and volunteers: compared to volunteers, amplitude peaks for each muscle in the non-amputated legs of amputees were more defined and efficient. The goal of walking exercise as part of early-stage physical therapy should, therefore, not be to make the non-amputated leg of the amputee function like the leg of a healthy individual.

In the present study, two walking exercise programs with clearly different exercises were designed to ascertain differences in muscle activity patterns. After completing the exercise programs, muscle activity and amplitudes for most muscles decreased, and this difference was greater for the applied exercise group. The differences were attributed to the efficacy of exercises between the two programs. In the applied exercise group, muscle activities of RF, BF and GC tended to decrease and become closer to those of amputees. Cook et al.[8] listed training conditions as elements contributing to motor learning, and Saito[7] also reported that training quantity, frequency and difficulty represented important variables for behavioral changes from the perspective of motor learning. We believe that the differences between the results of the basic and applied exercise programs are attributable to these factors.

Ground reaction force of healthy legs after the basic or applied exercise program

The peak vertical component of ground reaction force after the basic or applied exercise program became closer to that of the amputees. However, peak T1 time was relatively short after basic exercise, but was long after applied exercise, more closely resembling the results for amputees. Since no marked differences in T3 were noted after the program between the basic and applied exercise groups, upward movement of the center of gravity was considered rapid and load shift to the forefoot of the healthy side took time before the program, but after the applied exercise program, load shift to the forefoot of the healthy side was performed more quickly and smoothly. This also suggests that volunteers learned to swing the pseudo-prosthesis more efficiently by minimizing shifts in the center of gravity in the left-right direction, particularly in the medial direction.

Overall discussion from the perspective of motor learning

Based on the above results for %IEMG, ground reaction force and performance, the applied exercise program allowed volunteers to more quickly adapt to walking with a prosthesis than the basic exercise program. In terms of motor learning, various exercises facilitate learning adaptability and better handling of new motor tasks[8]. Also, transfer of motor learning is reportedly better if training environments resemble actual environments and if motor tasks resemble actual living situations. As the applied exercise program incorporated various exercise and living situations, volunteers were able to become accustomed to walking with a leg prosthesis faster due to better adaptability and transfer. Thus, the present study also objectively clarified that in addition to training quantity and frequency, training quality (difficulty) is important in achieving behavioral changes.

Study limitations

The present study had a few limitations. Subjects in the two exercise programs were healthy volunteers who were asked to wear a pseudo-prosthesis, not amputees who had just undergone amputation. Thus, the lower thigh remained in the two exercise program groups. Volunteers exercised and the necessary measurements were taken while knees were flexed. Also, compared to exercise programs in most studies, the lengths of the exercise programs in the present study were much shorter. However, significant differences were seen even using these short, 2-week exercise programs.

ACKNOWLEDGEMENTS

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