Paraplegic Using a Reciprocating Gait Orthosis（RGO） with Functional Electrical Stimulation

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Abstract— In this study, we used latest reciprocating gait orthosis (RGO) and combined the use of functional electrical stimulation (FES). The combination provides larger support range and applies features of mechanical structures in walking assistant. The coordination of FES especially helps to restore the walking abilities that paralyzed patients lost.

Keywords—spinal cord injury, long leg brace, reciprocating gait orthosis, functional electrical stimulation

I. Introduction

Many studies of nowadays related to the use of mobility aids in spinal cord injured patients have demonstrated that when taking comfort and abandonment rates into consideration, RGO is a better choice than other kinds of walking aids. [1, 2] At present, there is an ongoing trend in other countries to substitute traditional braces with RGO in paraplegic patients. On the other hand, among the mobility aids used by native paraplegic patients, traditional Long Leg Brace (LLB) still plays a dominant role. [3, 4]

Therefore the main purpose of this study was to develop a walking aid equipped with FES device. We hoped the FES device could give electrical stimulations on specific muscles (quadriceps muscle, hamstring muscle) in paraplegic patients.

II. Materials and Methods

Equipments

In this study, we developed a walking aid equipped with FES device. This walking aid can be used by paraplegic patients to help them rehabilitate or walk on their own. The composition of this newly developed walking aid is shown in Figure 1: (a) the principal structure of the walker; (b) a pair of control buttons on the walking aid; (c) the FES device and its control circuit. The principal structure of the walking aid consists of supporting poles made up of rigid frames, including braces, handles and protective bars. The walking aid is convenient to use in the sense its height can be adjusted through design to accommodate the heights of different users.

The FES device and its control circuit are located at an appropriate place on the walking aid. The system control circuit consists of a FES circuit, an input circuit and an output drive circuit. The FES device is actually a four-channel electrical stimulator developed by our laboratory in former studies. The stimulator has an output frequency f=10~1kHz and an output current I=0~140mA. The pulse width of the output ranges from 50μs to 500μs. Pressing down either one of the two buttons on the walking aid would trigger the FES device through the control circuit, and the drive circuit in the FES device would subsequently act to transmit stimulatory currents from the electrodes to specific muscles in the lower limbs of the patients. The left button is responsible to stimulate the quadriceps muscle in the left leg and the hamstring muscle in the right leg, while the right button is responsible to stimulate the quadriceps muscle in the right leg and the hamstring muscle in the left leg. The intensity of the stimulation can be determined by physical therapist on the basis of the assessment of the patient's illness so as to achieve an optimal function of the muscle.

Case report

After an initial assessment, our study included one patient as the subject. The subject was a 25-year-old female with a weight of 48kg and a height of 158cm. The subject was suffering a complete injury in the first section of the lumbar cord (L1) which had been diagnosed as the L1 Frankel C type. At the beginning of our study, the patient's spinal cord injury had lasted for 7 months. She received a walking training in our study for 5 weeks.

During the study, we have conducted measurements to collect basic data in relation to the patient's walking activities, such as time spent in a round of walk, the patient's steps, her heart rates and blood pressures before and after a walk, and volume of oxygen consumed (VO2) during the walking. Using these basic data, we then calculated a few useful parameters which include: walking velocity (cm/sec), step length, difference between heart rates before and after a walk (HRdifference), difference between blood pressures before and after a walk (MBPdifference), oxygen consumption in each minute (ml/min) and oxygen consumption in each minute for each kilogram (ml/min-kg).

Experiment Design

Grouping: After one patient was chosen as our subject, we divided the patient's activities into three sections on the basis of the rehabilitation therapies she received: the control section, the A section and the B section.

Control section: The walking training included traditional physical therapy, specifically speaking, the patient used

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Long Leg Brace for the rehabilitation therapy.
A section: The patient used Reciprocal Gait Orthosis for the rehabilitation therapy.
B section: The patient used Functional Electrical Stimulation along with Reciprocal Gait Orthosis for the rehabilitation therapy.

The spinal cord injured patient took different rehabilitation therapies at different hours of the day. First she would receive the specific training in control section, then the specific training in A section, at last the specific training in B section. She received the training on five days of the week; each day she has a two-hour training period both in the morning and in the afternoon. The whole training had lasted for about one month. At the end of the experiment, tests were conducted on the performances of the three sections respectively.

Statistical Analysis

After the patient had received the training in all three sections, a 10-meter walking test was conducted for each section. The test results could be divided into several categories of physiological parameter. Through individual statistical analysis on each category of data, we were able to understand the differential effects of the three walking aids on paraplegic patient.

We had employed a self-comparison method in this study and as a result the samples were not independent from each other. In addition, there were more than two normal state matrixes in the test results. We therefore conducted an ANOVA (Analysis of Variance) to test if any differences exist between three normal state matrixes, repeated measures ANOVA to investigate if the differences between the effects of the three walking aids on paraplegic patients are remarkable and a Newman-Keuls Multiple Test to explore the correlations between these three walking aids.

III. Results

Test Results of the Three Walking aids

On the basis of the above measurements and the data calculated, we were able to make comparisons between the effects of the three walking aids on the paraplegic patient.

A. HRdifference: Difference between heart rates measured before and after a walk. The HRdifferences of the three walking aids are shown in Table 1(A). The heart rate of the patient is easily influenced by various physiological or environmental factors, such as the mood and the habit of the patient or the air temperature. Therefore it is specified that the heart rate measured before a walk should be within a range of ±5 beats/min compared to that measured before a last walk. From the test results we know that the average HRdifference of LLB (38.6±4.4beats/min) is 10beats/min more than that of RGO (29±5.9beats/min), while the average HRdifference of RGO is 8beats/min more than that of RGO&FES (21±5.9beats/min). Using ANOVA we find the P-value is $0.006 < 0.05$, indicating the differences between the three walking aids are significant.
B. MBPdifference: The mean difference between blood pressures measured before and after the repeated walks. The MBPdifference of the three walking aids are shown in Table 1(B). From the test results we know that the difference between the MBPdifference of LLB and that of RGO is 5mmHg, and the MBPdifference of RGO&FES is 1.5mmHg more than that of RGO. Though the differences between the three walking aids seem not evident, using ANOVA we find the P-value is $0.001 < 0.05$, indicating the differences between the three walking aids are actually significant.
C. Steps: The total steps of the subject for a specific walking distance. The steps of the three walking aids are shown in Table 1(C). Rather than walking in an urgent manner, the patient was admitted to walk in a natural manner when the measurements were being taken since the visible walking performances could readily reflect the effects of different walking aids. Table 1(C) clearly shows the differences between the three walking aids. The average difference between LLB and RGO is 18 steps; while compared to RGO&FES, RGO has a surplus of 7 steps on average. Using ANOVA we find that significant differences do exist between the three walking aids.
D. Step Length: The average length of each step during a walk. The average step lengths of the three walking aids are shown in Table 1(D). The step length is calculated on the basis of the steps recorded for a given distance. It can serve to suggest if the walking aid is of any help for paraplegic patients during the walking. The test results clearly shows that the average step length of RGO&FES is bigger than that of RGO, while the average step length of RGO is bigger than that of LLB. The results also reflect significant differences between the three walking aids.
E. Velocity: The walking speed of the subject during a 10-meter walk. The velocities of the three walking aids are shown in Table 1(E). The velocity of LLB is evidently slower than those of other two walking aids. The average velocity of LLB is 3cm/sec slower than that of RGO, while the difference between RGO and RGO&FES is no more than 1cm/sec. Using ANOVA we find the P-value is < 0.05, indicating the differences between the three walking aids are still significant.
F. Volume of Oxygen Consumed (VO_2): The volume of oxygen consumed by the patient for a given walking distance. It can be converted to oxygen consumption in each minute for each kilogram (ml/min-kg). The VO_2 of the three walking aids are shown in Table 1(F). The labor cost of the patient during a walk can be judged by the volume of oxygen consumed through respiration, in other words, VO_2 can be used as an indicator to assess the energy consumption of the patient during a movement. The average difference of VO_2 between LLB and RGO is 2.4, and the average difference of VO_2 between RGO and RGO&FES is 3.1. Using ANOVA we find that significant differences do exist between the three walking aids.

Statistical Analysis on Test Results

After a preliminary statistical analysis, the categories of data do suggest some characteristics of the three walking aids, though such suggestion is far from our objectives. Further analysis is needed so as to get information out of these data as much as possible. In the six categories of parameter above, the ANOVA results are a unanimous $P < 0.05$, which means in a 95% confidence interval, significant differences exist between the three walking aids for each category of data. In order to get an in-depth understanding of the differences between the three walking aids, we also conducted a Newman-Keuls Multiple Test on each category of parameter:

a. HRdifference: We made the comparison on the basis of a critical q-value 0.05. The results of the statistical analysis are shown in Table 2(a), it serves to illustrate the comparison between the statistical results of the three walking aids. From Table 2(a) we can see that significant differences do exist between LLB, RGO and RGO&FES. As for the difference between RGO and RGO&FES, the calculated Q-value (2.90) is slightly smaller than critical q-value (3.26), indicating although the difference is small, it is statistically significant.
b. MBPdifference: The results of the statistical analysis are shown in Table 2(b) , it serves to illustrate the comparison between the statistical results of the three walking aids. From the comparison of Q-value and q-value in Table 2(b), we can see the differences between LLB and RGO/RGO&FES are evident. Meanwhile the difference between RGO and RGO&FES is not significant.
c. Steps: The results of the statistical analysis are shown in Table 2(c), it serves to illustrate the comparison between the statistical results of the three walking aids. In this category of data, the calculated Q-value is much bigger than critical q-value, meaning the differences between the three walking aids are significant.
d. Step Length: The results of the statistical analysis are shown in Table 2(d), it to illustrate the comparison between the statistical results of the three walking aids. From Table 2(d) we can see that the average step lengths of the three walking aids are in a descending order of RGO&FES, RGO and LLB. Significant differences exist between the three walking aids.
e. Velocity: The results of the statistical analysis are shown in Table 2(e), it serves to illustrate the comparison between the statistical results of the three walking aids. We can see the difference between RGO and RGO&FES is not evident, and from Table 2(e) we know the difference between these two is insignificant. Significant differences do exist between LLB and other two walking aids.
f. Unit Oxygen Consumption (VO_2/min-kg): The results of the statistical analysis are shown in Table 2(f), it serves to illustrate the comparison between the statistical results of the three walking aids. The statistical results of this energy consumption indicator show that significant differences exist between the three walking aids. RGO&FES has the best energy efficiency, and RGO comes next. Meanwhile LLB presents the highest energy consumption for the patient.

IV. Discussion and Conclusion

This study provides us an insight into the utility of traditional Long Leg Brace and new Reciprocal Gait Orthosis. We also get some knowledge about the beneficial use of Functional Electrical Stimulation. For most of the native spinal cord injured patients, their walking aids are limited to Long Leg Brace and wheelchair. Wheelchair is most popular due to the fast speed and labor saving property it provides. On the other hand, the combined use of RGO&FES will not only serve as a walking aid, but also bring forward other advantages such as preventing osteoporosis and bedsore, improving cardiopulmonary function, kidney function and circulatory function, as well as improving body posture and daily-life habits. Such combined use is also conducive to patients' psychological construction. RGO has already become a prevailing walking aid in foreign countries, but it is hardly used by native patients. Perhaps it is because RGO is newly introduced into the country and its price is frightening high. In the future, improvements should be made in the bulky and complex auxiliary system near the hip joints, as well as in the hard back tubes and chest staffs. There is also a need to reduce the weight of the orthosis. In the meantime, further studies such as going on to explore the long-term effect of these walking aids are essential. Such studies may act to bring more convenient mobility aids to paraplegic patients, with an expectation the patients could become more independent and be able to integrate into society again.

Acknowledgements

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V. References

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Table 1. The ANOVA test results of the LLB, RGO 及 RGO&FES

	(A) HRdifference	(B) MBPdifference	(C) steps	(D) step length	(E) velocity	(F) VO2/min-kg
LLB	38.6±4.4	14.8±2.3	67.6±2.3	14.8±0.5	6.2±0.4	12.7±0.4
RGO	29.0±5.9	10.1±3.6	49.4±1.5	20.3±0.6	9.4±0.6	10.3±0.5
RGO&FES	21.0±5.9	8.6±2.4	42.6±1.9	23.5±1.1	10.1±1.4	7.2±0.3
ANOVA	0.006*	0.001*	0.008*	0.003*	0.002*	0.001*

*: $p<0.05$

Table 2. The Newman-Keuls Multiple test results of LLB, RGO and RGO&FES

	Mean Difference	P	Q	q（0.05）
(a) HRdifference				
LLB-RGO&FES	17.6	3	6.39	4.04*
LLB-RGO	9.6	2	3.49	3.26*
RGO-RGO&FES	8.0	2	2.90	3.26
(b) MBPdifference				
LLB-RGO&FES	6.2	3	8.20	4.04*
LLB-RGO	4.7	2	6.22	3.26*
RGO-RGO&FES	1.5	2	1.98	3.26
(c) steps				
LLB-RGO&FES	25.0	3	34.89	4.04*
LLB-RGO	18.2	2	25.40	3.26*
RGO-RGO&FES	6.8	2	9.49	3.26*
(d) step length				
LLB-RGO&FES	8.7	3	29.40	4.04*
LLB-RGO	3.3	2	10.99	3.26*
RGO-RGO&FES	5.5	2	18.40	3.26*
(e) velocity				
LLB-RGO&FES	3.9	3	10.37	4.04*
LLB-RGO	0.7	2	1.85	3.26
RGO-RGO&FES	3.2	2	8.52	3.26*
(f) VO2/min-kg				
LLB-RGO&FES	5.5	3	14.06	4.04*
LLB-RGO	2.3	2	5.96	3.26*
RGO-RGO&FES	3.2	2	8.10	3.26*

*：significant difference, Q value＞q value

LLB：long leg braces

RGO：reciprocating gait orthosis

RGO＆FES：reciprocating gait orthosis & functional electrical stimulation (FES)

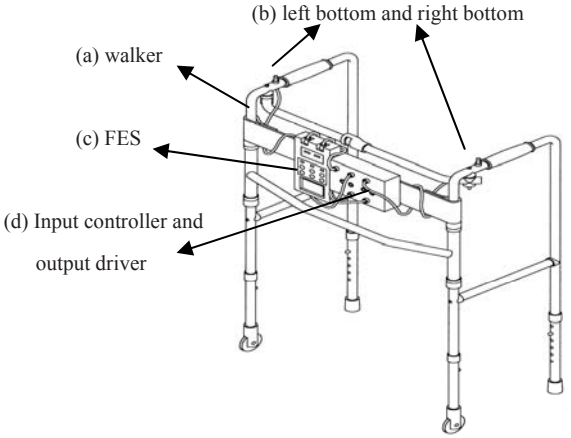

Figure 1 A novel walker (a) walker, (b) buttom, (c) FES , (d) Input controller and output driver