A Feasibility Study of Robot-Assisted Ankle Training Triggered by Combination of SSVEP Recognition and Motion Characteristics

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Abstract—In order to inspire subjects exerting more energy and pay more attention to SSVEP-based ankle training, this study introduce motion intention detection both in the first half cycle of single trainings and at the beginning of the training. This study also propose a novel method to recognize motion intention of subjects through merging the motion characteristics of the ankle training into the identification of SSVEP signals. Five healthy subjects participate in the training, and all can accomplish the training with the success rate of more than 80%. The proposed hybrid method can increase success rate from 50% to 80% comparing with the identification of SSVEP signals.

Index Terms—SSVEP, motion characteristic, ankle robot, motion intention, virtual reality.

I. Introduction

Ankle joints are one of the most vulnerable parts of the human body, although it need to load the whole body [1]. In daily life, ankle joints are often injured by various reasons, such as the damage of the nervous system, which can reduce the ability of the brains to control the ankle joints, or even completely lose the control ability [2]. Therefore, research about how to improve ankle rehabilitation is of great practical significance. Traditional physical therapy of ankle joints is usually operated manually by therapists, which are conducted mostly in hospitals. Therefore, ankle rehabilitation has many limitations in professional manpower and operation site [3].

In order to address those limitations, various ankle robots have been developed to substitute partial functions of traditional therapy, and some robots have been in commercial stage [4]. There have two kinds of ankle robots, one of which is platform based robots, and the other is wearable devices [5]. Platform based robots is suitable to subjects with weak motion ability of ankle joints, while wearable ankle robots are designed to exercise those subjects, whose motion ability of ankle joints are strong enough to walk, but gait needs to be rebuilt [6]. There have two kinds of training applied in platform based ankle robots, passive training and active training. Passive training mainly are used to exercise ankle joints to retain its motion capacity, while active training are used to exercise ankle joints to improve its motion control ability [7].

Although there have many kinds of training strategies applied to active training, its basic function is to provide necessary assistance for subjects to accomplish the training targets within the predefined time, and its advanced function is to enhance the difficulty of the training to challenge the motion ability of ankle joints [5]. Assist-as-needed is a typical training strategy, which will provide necessary torque to assist subject to accomplish the training if they cannot touch the targets within the predefined time [5]. In other words, under the assist-as-needed strategy, subjects can accomplish the training successfully only if they can trigger the robot. Zeng et al., [8] proposed a SSVEP-based passive training on an ankle rehabilitation robot, advantage of which is enable subject without enough motion ability to conduct active training have opportunities to conduct ankle training based on his own motion ability, but the limitation of which is in that subjects only have one chance to display their motion intention in a single training. However when in active training, subjects need run several rounds of displaying motion intention to touch the targets. Therefore this study will refer this multi-interaction mode to enable subjects to have more opportunities to trigger the training in a single training.

Identification of SSVEP signals can be conducted through different algorithms, which include ICA, PCA, CCA and so on [9]. The basic idea of those algorithms come from below several points: 1）to remove noise signal from EEG signal to get SSVEP more easy to be distinguished; 2) correlation analysis to identify SSVEP signal through constructing a similar periodic signal, or extracting homologous signals from EEG signals from surrounding different electrodes; 3) to extract the principal component from EEG signals [10]. Although those algorithms can increase the success rate in identify the SSVEP signals, the excitation of SSVEP signals mainly depend on subjects themselves, some of whom cannot excite intensive SSVEP signals enough to be distinguished from noise signals. [11] improved the classification accuracy of SSVEP signals through applying a camera in front of subjects to judge their visual direction when they were exciting SSVEP signals. Being inspired from this idea, this study will merge the trajectory characteristic of ankle trainings into the identification of SSVEP signal as an auxiliary basement, and then increase the accurate rate.

In order to increase the degree of initiative intervention in the ankle rehabilitation training triggered by SSVEP signals, this study refer multi-interaction mode in the active training to enable subjects have more opportunities to realize their motion intention in the training. Meanwhile, in order to improve the identification accuracy of SSVEP signal, the motion

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characteristics of ankle rehabilitation training are proposed to be as one of the base for robot to judge the motion intention of subjects. Five healthy subjects are recruited to conduct the training to verify its feasibility.

II. METHODS

A. Ankle Rehabilitation Robot and control Strategies

The ankle robot and its control strategies is the same as the one applied in [8], which are briefly described as below separately. The ankle robot have three ROM, through which subjects can realize ankle rehabilitation training along DF/PF, INV/EV, and adduction/abduction (AA). The robot is actuated in parallel by four FFMs, pressure control of which are regulated respectively by four proportional pressure regulators. Three magnetic rotary encoders are installed along each axis respectively to measure angular positions forming a three dimensional coordinate system of the footplate. Four single-axis load cells are installed to measure contraction forces generated respectively by FFMs. A six-axis load cell is installed below the footplate to measure interaction forces and torques between human feet and the footplate.

The control strategy applied in this study is to realize the position control of the moving platform in the robot through controlling individual FFM length. Firstly the desired individual FFM length is calculated by inverse kinematics based on the desired angular position of rotation axles. Meanwhile, the actual individual FFM length is calculated by inverse kinematics based on the actual angular position of rotation axles, which are real-time measured by three magnetic rotary encoders. With error compensation of pressure values provided by PID controller based on the error between the desired individual FFM length and the actual length, the position controller outputs four pressure values that directly go to four proportional pressure regulators for the actuation of the robot.

B. VR Game

VR game is set up as a game of whack-a-mole, cursor of which is a hammer and can move freely through a vertical rail and a horizontal rail with the cross-point in the center of VR circumstance, as described in Fig. 1. The vertical rail is projected to DF/PF trajectory, and the horizontal rail is corresponding to INV/EV trajectory. At the end of the vertical and horizontal rail, there have four hamsters as the targets corresponding to the extreme position of ankle stretching. As long as the hammer touch one of hamsters, a periodical target is accomplished, and then the hammer will return to the cross-point. Tent will appear only when subjects are requested to trigger the moving platform, and will disappear once robot begin to move. During a single ankle training, the tent will appear about 5s at the beginning of the training, and appear again 1s in the middle time from the cross-point to the hamster. Nearby every hamster, there have a circle with a diameter of 22 mm, with the flickering frequency of 10 Hz for the upper, 12 Hz for the bottom, 8.6 Hz for the left and 15 Hz for the right [12].

C. Recognition of Motion Intention of subjects

When conducting the combined training of DF/PF, and IV/EV, the moving platform move along a trajectory of sin curve, which is expressed as in (1), where A is the amplitude of trajectories, f is the frequency, t is the time variable.

$$x(t) = A \sin 2\pi f t \qquad (1)$$

For robot-assisted ankle rehabilitation training, its essence is to stretch ankle joints to its extreme position based on the assistance from robots. Under this kinds of continuous stretching, motion ability of ankle joints are remained and then the formation of foot drop are alleviated. In the view of motion trajectories, ankle training is a continuous process for ankle joints to achieve the extreme position. However, the extreme position of motion trajectories are different because it is set up according to specific ROM of subjects. When arrive at the vertex of motion trajectories, the muscles and ligaments of ankle joints are stretched to the maximum extent. Therefore, the significance of conducting passive training is to continuously guide ankle joins to reach its extreme position. As soon as reaches the apex of its motion trajectories, ankle joints will begin to return back to its natural position with the assistance of ankle joints based on two cause, one of which is to relax and restore the ankle joints, the other of which is to prepare for the subsequent stretching training to the opposite apex of motion trajectories. Both stretching are combined to an integrated movement, such as DF/PF motion synthesis. Therefore, when conducting a single passive training, its trajectory characteristics is in that, the purpose in the first half cycle of the movement is to exercise the ankle joints to reach its extreme position, and the one in the bottom half is to relax ankle joints for preparation of the next stretching. When conducting ankle training based on SSVEP signals, this kind of motion characteristics can be applied as a basement for the robots to identify correctly SSVEP signals.

Motion intentions of subjects are categorized to two kinds in this study, one of which is to judge what kinds of training applied in the beginning of a single training, the other of which is to judge what orientation applied in the middle of the first half of the single training. For the first kind of motion intention, its identification is the same as the one in [8], while for the second one, SSVEP signals and motion characteristics are combined together to recognize the motion intention of subjects.

To identify the first kind of motion intention, the algorithm is the same as the one in [8], which are described briefly as below. Firstly, to ascertain five adjacent frequencies centered on every flickering frequency, and then to compare the amplitude in those five adjacent frequencies, finally to designate the maximum amplitude to the flickering frequency, which is expressed as in (2), where X_{ij} is the amplitude of five adjacent frequencies centered on the flickering frequency, and j is the serial number of five adjacent frequencies, and i is the serial number of flickering circles.

$$A_i = \max(x_{ij}) \;\; (i = 1, \cdots, 4;\; j = 1, \cdots, 5) \quad (2)$$

After amplitudes of flickering frequencies are ascertained, the dominant frequency in the SSVEP signals will be identified as the flickering frequency with the maximum amplitude, in (3).

$$f_{\text{target}} = \arg\max(A_i) \qquad (i = 1, \cdots, 4) \qquad (3)$$

To identify the second kind of motion intention, besides applying the algorithm described above to ascertain the SSVEP signals, motion characteristics of ankle training are extracted as an auxiliary basement. Specifically, when being in the first half of training trajectories, normally ankle joints should be stretched to its extreme position, but if being in the second half, ankle joints should be stretched to its natural position. If being coincide with the motion characteristics of ankle training, the identification of motion intention from SSVEP signals would directly trigger the movement. If not being coincide with the motion characteristics of ankle training, it is necessary to conduct the second judgment of motion intention from SSVEP signals, result of which will trigger the movement, with trajectories described as below.

$$x_m(t) = A\sin 2\pi f(t+\varphi) \tag{4}$$

$$\varphi = \frac{1}{2f} - \frac{1}{\pi f}\cdot \sin^{-1}\frac{|x|}{A} \tag{5}$$

Where A is the amplitude of trajectories, f is the frequency, t is the time variable.

D. Training Protocol

Five healthy subjects with ages at 24±3years are recruited to participate in this study. Inclusion criteria are subjects with: (i) normal vision; (ii) corrected-to-normal vision; (iii) no history of clinical visual impairment. Subjects who can be easily distracted will be excluded. All subjects are right-handed. During the training, blinking is not prohibited but it is better to avoid it. The whole experiment was conducted in a laboratory with a floor space of approximately 43 square meter. It is quiet in the surrounding and light illumination is weak.

Each subject was requested to sit calmly 50 cm in front of LCD, looking straightly at the virtual reality circumstance, and put the right leg in the ankle rehabilitation robot, with the right foot fixed on the footplate. The electrode cap is placed on the head of subjects following up the regulation of international 10/20 system [13], and electrode gel is applied. Before the training, subjects are informed: (i) gazing at the upper flickering circle represent the motion intention for DF, the bottom for PF, the left for INV, and the right for EV; (ii) gazing at the intended flickering circle once the tent appear, and giving up the gazing when the tent disappear or ankle joints begin to rotate; (iii) during stretching of the robot, subjects need observe moving situation of the hammer, and imagine rotation situation of related ankle joints; (iv) if actual stretching of the robot is not consistent with their motion intention, subjects merely follow up the rotation without any resistance against the movement.

Subjects were requested to conduct two kinds of combined ankle movement tasks through focusing on one of four flicking sources to trigger the robot. One kind of task combines ankle DF training with PF training together, and no time interval exists between them. Total five tasks are set in the training. The other kind of task is the combination of INV and EV training, without time interval among them, and a total of five tasks are set. There are 1 minute for free between both tasks. Once the tent appears, subjects are requested to focus their attention on one of flashing source representing their motion intention to trigger the SSVEP signal. During a single ankle training, the tent will appear about 5s at the beginning of the training, and appear again 1s or 2s in the middle time from the cross-point to the hamster, which depend on whether the identification of motion intention from SSVEP signals is coincide with the motion characteristics of ankle training.

E. Evaluation Procedures

In this study, the performance of motion intention detection is evaluated by success rate and information transfer rate (ITR). Because there have two methods applied to detect motion intention of subjects, its evaluation will be conducted separately. The success rate is defined as the percentage of output that actual movements of the robot are consistent with motion intentions of subjects. Therefore the success rate is described as in (6), where A denotes the quantity of motion intentions which are correctly recognized, and B denotes the total quantity of motion intentions which are requested to identify.

$$success\ \ rate = \frac{A}{B}\times 100\% \tag{6}$$

The ITR [14] under the unit of bits/min is expressed as in (7), where N is the number of flickering circles, which is set to 4 in this study. P is the success rate, and T is the time during which SSVEP signals are extracted to determine the motion intention of a subject.

$$ITR = \left\{\begin{matrix}\log_2 N + P\log_2 P + \\ (1-P)\log_2\left[(1-P)/(N-1)\right]\end{matrix}\right\}\times\frac{60}{T} \tag{7}$$

III. RESULTS

When ankle joints are in neutral position, all five subjects could trigger the robot to rotate its moving platform following their motion intention, which all success rate is more than 80%, among them subject 1 achieved the highest success rate, about 95%, and subject 2&3 achieved the lowest success rate value of 80%, described as table I.

TABLE I
RESULT OF CONDUCTING COMBINED ANKLE MOVEMENT TASKS IN NATURAL POSITION OF ANKLE JOINTS

Item \ Subject	S1	S2	S3	S4	S5
Number of Accordant task	19	16	16	18	18
Success rate	95%	80%	80%	90%	90%
ITR(bits/min)	19.6	11.5	11.5	16.5	16.5

Note: Two kinds of tasks, one for combined DF and PF training, and the other for combined INV and EV training. Total number of motion intentions requested to identify for every subject is 20. Duration for robot to judge the motion intention of subjects is 5s. Number of flickering circles representing the motion intention of subjects was 4.

When ankle joints are in tension, subjects can trigger the robot within 1s with success rate of more than 50%, among which subject 1 achieved the highest success rate of 70%, and subject 3 achieved the lowest success rate of 50%. When the first identification of SSVEP signals cannot trigger the robot, all five subjects can trigger the robot to rotate the moving platform following up their motion intention with the success rate from 50% to 66.7%. In general, the total success rate increase to more than 80% within 2s, described as table Ⅱ.

IV. DISCUSSION

When ankle joints are in neutral position, all five subjects can successfully trigger the robot to rotate its moving platform according to their motion intention with success rate of more than 80%. When the ankle are in tension, five subjects were also successfully triggered a robot motion, success rate of which are more than 50% within 1s, and then increase to more than 80% within 2s. This section will be discussed from below two aspect: identification of motion intention of subjects, and feasibility.

TABLE Ⅱ
RESULT OF DIRECTION JUDGMENT TASK OF ANKLE MOVEMENT IN THE MIDDLE CYCLE

Terms \ Subject		S1	S2	S3	S4	S5
#1 SR	Number of Accordant	14	11	10	12	11
	Success rate	70%	55%	50%	60%	55%
	ITR (bits/min)	7.1	0.43	0	1.7	0.43
#2 SR	Number of Accordant	4	5	6	4	5
	Success rate	67%	56%	60%	50%	56%
	ITR (bits/min)	4.9	0.54	1.74	0	0.54
Total SR	Number of Accordant	18	16	16	16	16
	Success rate	90%	80%	80%	80%	80%
	ITR (bits/min)	15.9	8.34	8.34	8.34	8.34

Note: Two kinds of moving direction, one toward extreme position of ankle joints, the other toward neutral position of ankle joints. SR: SSVEP Recognition. Total number of motion intentions requested to identify for every subject is 20. Time length for robot to judge the motion intention of subjects is 1s. Number of flickering circles is 2.

A. Identification of motion intention of subjects

Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as IEEE, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or heads unless they are unavoidable.

In this study, Fast Fourier Transform (FFT) is used to identify the SSVEP signals from the EEG [15]. When ankle joints are in neutral position, subjects are requested to focus their attention on one of flickering sources representing their motion intention within 5s. And then the robot actuate its moving platform to conduct the training based on its judgment of motion intention of subjects through analyze EEG signals formed in those 5s. In this study, the success rate of judging motion intention of subjects is more than 80%.

In the middle of the first half cycle of the single training, subjects are requested to focus their attention to one of flickering sources representing their motion intention within 1s, and then the robot will judge the motion intention of subjects based on the EEG signals formed in those 1s. If the judgment of motion intention is coincide with the motion characteristics of ankle training, robot would directly actuate its moving platform following its judgment. If both are not coincide, the robot will still keep static, and judge again motion intention of subjects based on the EEG signals formed in the next 1s. This time robot will actuate its moving platform based on its judgment. The success rate of identification of motion intention is similar in both 1s and are from 50% to 70%, but the combined success rate in those 2s increase and are from 80% to 90%.

This study first propose to combine motion characteristics of ankle training and identification of flickering source to judge motion intention of subjects. Although there have many kinds of methods applied to identify SSVEP signals, the basic idea of those algorithms originate from below several points: 1）to remove noise signal from EEG signal to get SSVEP more easy to be distinguished; 2) correlation analysis to identify SSVEP signal through constructing a similar periodic signal, or extracting homologous signals from EEG signals from surrounding different electrodes; 3) to extract the principal component from EEG signals [10]. Correlation analysis method is widely applied to through below processes: firstly to construct a set of sine and cosine signals with frequency and Harmonic frequency of flickering sources; secondly to construct a multi-dimension reference signal by fitting those sine and cosine signals; thirdly to conduct correlation analysis between the EEG signals and the reference signal to ascertain the flickering source with the biggest correlation coefficient [10]. Principal component analysis method is also applied to identify SSVEP signals based on a prerequisite that it is independent between EEG signals and Pseudo signals, therefore firstly to realize feature separation of original signals through projecting EEG signals to several independent feature space; secondly to identify and remove the false signal; thirdly to recover reversely the remaining signals [10]. Although those algorithms can increase the success rate in identify the SSVEP signals, the excitation of SSVEP signals mainly depend on subjects themselves, some of whom cannot excite intensive SSVEP signals enough to be distinguished from noise signals. [11] improved the classification accuracy of SSVEP signals through applying a camera in front of subjects to judge their visual direction when they were exciting SSVEP signals. Being inspired from this idea, this study merge the motion characteristics of ankle trainings into the identification of SSVEP signal as an auxiliary basement, and then increase the accurate rate. In the view of motion trajectories, the essence of conducting ankle training is a continuous process for ankle joints to achieve its vertex. Therefore, the motion intention of subjects can be assumed to move towards the vertex in this study. If the identification of SSVEP signals are applied for the robot to guide ankle joints to move toward its extreme position of ROM, the judgment result will be ascertained to be coincide with the motion characteristics of ankle training, therefore the robot will be triggered to move. Otherwise, the robot need analyze the source of SSVEP signals again to ascertain the next movement direction. In other words, there have two opportunities for the robot to identify the motion intention of subjects through this kinds of recognition mode, which can increase largely the success rate. Furthermore, the basement of this recognition mode is the algorithm applied to identify the flickering source of SSVEP signals. In this study, the algorithm applied to identify SSVEP signals is the FFT, which can produce the success rate is more than 80%, therefore it is reasonable to believe that the advanced algorithm can achieve higher success rate.

B. Feasibility Analysis

The training protocol applied in this study is the similar with the one applied in [8], which include ten tasks of five combined DF/PF training and five combined INV/EV training triggered through recognition of SSVEP signals. But the training protocol applied in this study provide one opportunity for subjects to decide what orientation the robot should conduct in the next training. In the middle of the first half of the single training, the movement of the robot will be suspending 1s or 2s, during which the robot will recognize the motion intention of subjects through analyzing the SSVEP signals evoked by subjects paying their attention on one of flickering sources representing their movement demand. Although the same algorithm are applied in both phase to identify the SSVEP signals, there have some difference in both phase as below. Firstly the time length of applied EEG signals is different, which it is 5s in the initial stage, but 1s or 2s in the middle stage. Secondly the algorithm of identifying SSVEP signals are integrated with the motion characteristics of ankle training to recognize the motion intention of subjects.

The identification result of SSVEP signals is the similar with the one applied in [8], success rate of which is more than 80% in both stage. Therefore there still have less than 20% opportunities that the real moving of ankle joints is not coincide with motion intention of subjects. But subjects are informed about this difference in advance and advised not consciously to impede the movement. In general, all subjects have conducted the ankle training smoothly.

Comparing with the one in [8], the whole time of a single training is increased by 1s or 2s, which is shorter than the whole training time, therefore it is not affected on the whole training efficiency. But the active participation of subjects in the first half of the single training will be enhanced to increase their confidence and efficiency because in the middle they are requested to pay their attention to one of flickering sources to display their motion intention to the robot. In the middle mode, if the identification of SSVEP signals robot cannot be coincide with motion characteristics of ankle training, the next movement will be reversed to the neutral position of ankle joints to finish this single stretching training. Although conducting this single training cannot achieve the expected therapeutic effect, this loss can be made up easily if this failure rate can be considered when the training protocol are schemed.

C. Limitations

While preliminary experiments support the feasibility and the identification method of motion intention of subjects on an ankle rehabilitation robot, this study still has some limitations. Firstly, algorithm applied to recognize EEG signals is FFT which can support the identification only when noise signals is weak. More advanced algorithm should be introduced to improve the reliability. Secondly, although the combination of SSVEP signals recognition and motion characteristic of ankle training is proved to be feasible in this study, much more training protocols should be schemed to verify its feasibility from various aspects.

V. Conclusion

This study inspire subjects exerting more energy and pay more attention to the ankle training through introducing motion intention detection in the first half cycle of the single trainings and at the beginning of the training. This study largely increase the success rate of recognize motion intention of subjects through combining the identification of SSVEP signals and the motion characteristics of the ankle training together.

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