Research on rehabilitation assessment methods based on human gait and sEMG

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Abstract: Based on the study of human gait, the rehabilitation assessment indicators which can comprehensively reflect the motor function of lower limbs are summed up, including muscle force, range of motion, stride length and gait speed. Then the surface electromyography (sEMG) acquisition equipment and kinematics data acquisition equipment are used to collect the EMG data and kinematic data in real time during subjects' walking process, and the statistical analysis method is used to verify the rationality of the selected assessment indicators. By using analytic hierarchy process, the weight of each evaluation index is determined, and finally a relatively scientific, accurate and objective rehabilitation evaluation model is formed. The model can be used to assess the lower limb motor function of subjects through the quantitative index, overcoming the high subjectivity and low sensitivity of the clinical rehabilitation physician assessment.

Keywords: human gait; sEMG; analytic hierarchy process; rehabilitation assessment

1. Introduction
According to the functional assessment before and after the rehabilitation training in patients, rehabilitation physicians can have an objective analysis on patients' treatment status, and then develop suitable rehabilitation goals and training programs for patients, so that patients can get better

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PUBLIC INTEREST STATEMENT
Recently, gait analysis parameters are used by many researchers to assess the limb motor functions and rehabilitation status of patients. Gait analysis system is a method widely used in the evaluation of lower limb motor functions due to its objectivity, accuracy, quantification and convenient operation. In this paper, rehabilitation assessment indicators that can comprehensively reflect motor functions of lower limbs in human gaits are studied. Statistical analysis is employed to verify the rationality of selected assessment indicators. The weight of each index is determined by using analytic hierarchy process. Finally a model which can overcome the high subjectivity and low sensitivity of the clinical rehabilitation physician assessment is built. And a lot of experiment results are conducted to prove the feasibility of the model.
rehabilitation effect in a short period of time. Among the function evaluation, the evaluation of lower limb motor function is the most important part.

At present, there are mainly two methods for evaluation of lower limb motor function of stroke patients: one is evaluation through changes in muscle forces; another is evaluation through changes in overall motion patterns (Huang, Chen, Guo, & Liu, 2006). In recent years, due to the different understanding of the concept of lower limb motor function, the methods for evaluating lower limb motor function through changes in muscle force are less and less used. However, the methods for assessment through changes in overall motion patterns are more and more used, main of which are some kinds of international recognized clinical scales, including Ueda Min evaluation method, function evaluation of hemiplegic lower limb, walking ability evaluation and etc. (Xu & Li, 2002).

Recently, gait analysis parameters are used by more and more researchers to assess the limb motor function and rehabilitation status of patients. Gait analysis system is a method widely used in the evaluation of lower limb motor function. Due to its objectivity, accuracy, quantification and convenient operation, it has obtained more and more attention in the field of rehabilitation evaluation (Carmo, Kleiner, Costa, & Barros, 2012; Mao, Li, Chen, et al., 2012; Xu, Lan, Mao, et al., 2010). Liu, Tang, Qian, et al. (2012) mentioned the application of gait parameters in rehabilitation assessment. Yavuzer, Öken, Elhan, et al. (2008) evaluated the rehabilitation effects of stroke patients by using the time distance and gait kinematics parameters acquired with the gait acquisition system. Wan, Wu, Liu, et al. (2014) quantitatively measured the gait characteristics and joint kinematic parameters of lower limb of stroke patients with hemiplegia by a gait analysis system, through which the walking ability of hemiplegic patients was evaluated and the objective basis was provided for clinical treatment and rehabilitation assessment. Wang (2013) selected the carrying capacity of legs, joint rotation angle, stride length and gait speed as the parameters for lower limb rehabilitation evaluation, and then determined the weight of these parameters and built an assessment model. The model can score for the angle of knee gait or hip gait, the carrying capacity of thigh or calf, stride length and gait speed, and can also rate on the entire limb motor function.

Surface electromyography (sEMG) signals reflect limb motor status, so they are used more and more for limb rehabilitation and rehabilitation assessment. A review about applications of sEMG signals in rehabilitation medical field was conducted (Wu, Huang, Bao, & Yang, 2011). In this study, different from others, muscle force and some kinematic parameters are combined as the assessment indicators. And the weight of each indicator is determined through the analytic hierarchy process and then a rehabilitation assessment model is established. The model can be used to assess the lower limb motor function of patients through the quantitative index.

2. Selection of rehabilitation assessment indicators
Walking is a very complex process of movement. Sometimes people have a limb injury caused by some diseases, resulting in muscle weakness, limited range of joint motion and abnormal coordinated movement in activities. These phenomena appear in the process of human gait, namely abnormal gait. For the stroke patients with lower limb hemiplegia, the kinematic parameters are different from normal people’s because of the abnormal gait. The gait abnormalities of patients with lower limb hemiplegia are mainly as follows: bad joint coordination, abnormal muscular tension, abnormal posture adjustment, abnormal motor coordination, discontinuous in space and time during walking and etc. (Levin, 1996). It can be seen from the above aspects that the patients with lower limb hemiplegia have the following characteristics compared with normal people: the time for a movement is too long and more time is needed to complete a gait cycle; the trajectory deviates from the ideal movement route, namely, due to the bad coordination of hemiplegic patients, the walking trajectory deviates from the ideal path; the movements are not continuous, namely, due to the influence of the affected side of hemiplegic patients, the walking process cannot be completed continuously (Fetters & Todd, 1987).
In this paper, we analyze and study the characteristics of human gait, and then select a number of quantitative indexes to assess the lower limb motor function.

2.1. Muscle force
Surface EMG signals can reflect the muscle activity patterns during walking, the beginning and ending of muscle activities, the role of muscle during walking, types of muscle contraction and level of muscle response related to body position. Besides, sEMG can also be used to analyze the activities of muscles related to walking. Human walking is a process of interaction between lower limbs and trunk muscles, and the muscles which can affect the motions of lower limb are quadriceps femoris, biceps femoris, triceps surae (gastrocnemius), and tibialis anterior. Muscle force is the force expressed from the muscle tension or contraction process. Studies have shown that the muscle force is in proportion to the root mean square (RMS) of sEMG. That is to say, RMS of sEMG can reflect the size of muscle force. So in this paper muscle force is selected as an effective rehabilitation evaluation index.

2.2. Range of motion
The angle of the joints rotation in different directions is called range of motion (ROM). Clinically, ROM is generally measured by a protractor.

2.3. Stride length
The distance between one side of foot landing and the other side of foot landing during walking is called stride length. Clinically, stride length is generally measured by a tape. Normal people’s stride length is generally between 50 and 80 cm, and there is a difference in the stride length of different individuals. The length of stride has a great relationship with the length of leg, and generally, the length of leg is longer, and the length of stride is longer.

Stride length can be calculated with the leg length and joint angle measured by gyroscopes. The lower limb of human body can be simplified as four link model, as shown in Figure 1. The model mainly consists of thighs and calves, feet, hip joint with two degrees of freedom and knee joint with a degree of freedom. The stride length can be obtained according to the length of thigh and calf and the two sides of angles between knee joint and hip joint. The stride length can be calculated as:

\[
L = L_1 (\sin \theta_1 + \sin \theta_2) + L_2 (\sin \theta_3 + \sin \theta_4)
\]  

(1)

2.4. Gait speed
The distance to move forward in unit time is called gait speed. The gait speed of normal people is generally about 65–95 m/min. It also can be measured with the time needed to walk for 10 meters. Clinically, gait speed can be measured and calculated by using a stopwatch and a tape. Gait speed is also the most basic and most sensitive evaluation index in gait analysis.
2.5. Stride frequency

The number of steps during walking in unit time (1 min) is called stride frequency. The stride frequency of normal people is about 95–125 steps/min.

Stride length, gait speed and stride frequency are the three parameters widely used in gait analysis, and stride length and gait speed are two important indexes to evaluate the walking ability (Rosano, Brach, Studenski, Longstreth, & Newman, 2007). Because the muscle force can reflect the state of muscle activities, the left and right side of the ROM can reflect the coordination of movements on both sides, and the length of stride is directly affected by the ROM. In addition, gait speed can synthetically evaluate the human walking ability. Therefore, considering from the angle of time and space, these four parameters—muscle force, ROM, stride length and gait speed—are selected as the evaluation indexes.

3. Rationality validation of rehabilitation assessment indicators

3.1. Experiment scheme

3.1.1. Experiment methods and procedures

Five healthy subjects and five lower limb hemiplegic subjects participated in the walking experiment, and all subjects were told about the purpose before the experiment and volunteered to participate in the walking experiments. There were three males and two females in the group with lower limb hemiplegia, 43.40 ± 17.37 years old; four males and one female in the control group, 24.80 ± 0.84 years old. All subjects participated in the experiment were all able to walk independently. Subjects walked for 8 meters along a straight line, and sEMG signals in their quadriceps femoris, biceps femoris, triceps surae and tibialis anterior were obtained by using an EMG acquisition instrument. Meanwhile, the kinematics data during subjects’ walking experiments were collected through a hardware device which was developed for lower limb kinematics data acquisition. Subjects needed to keep the level of their upper body as far as possible during walking. Figure 2 is a schematic drawing the position of EMG electrodes and sensors. Figure 3 shows the experiment process of data acquisition in subjects with hemiplegia.

3.1.2. Data processing

The frequency of EMG signals is mainly distributed between 20 and 500 Hz, and the acquired raw EMG signals contain many kinds of noises including the power line interference. As a result, the acquired original EMG signals are respectively passed through a 20–500 Hz band-pass filter, a 50 Hz notch filter and a 100 Hz notch filter, in which way the clutter signals and power line interference generated in acquisition can be removed. At the same time, the obtained angle signals are smoothed through the five point three smoothing algorithm.
3.1.3. Statistical analysis

The calculated EMG parameters and kinematics parameters are statistically analyzed using the statistical software SPSS 19.0. The calculated data are expressed as $\bar{x} \pm s$. Then the parameters of the unaffected side and affected side of hemiplegia group are given a $t$-test, so are the parameters of hemiplegia group and healthy group. And the significance test standard is set to $p < 0.05$.

3.2. Experimental results

The lower limb EMG signals and RMS values of a hemiplegic subject during walking are respectively shown in Figures 4 and 5. The original angle signals of lower limb and the angle signals after filtering are respectively shown in Figures 6 and 7.

It can be seen from the Figures 4 and 5 that: the amplitude and RMS of surface EMG signals in each muscle group of the affected side are significantly smaller than that of the unaffected side.
It can be seen from the Figures 6 and 7 that: the joint angles of lower limb in hemiplegic subject of the affected side are significantly smaller than that of the unaffected side.

The t-test results of the muscle force parameters and joint angle parameters of the affected and unaffected side in hemiplegia group are shown in Table 1. The t-test results of the kinematic parameters of the hemiplegia group and the control group are shown in Table 2.

It can be seen from the Table 1 that the average muscle forces of each muscle groups and the flexion and extension angles of hip joint and knee joint of the affected side are significantly smaller than that of the unaffected side (Mao et al., 2012). In addition, there are significant differences in the muscle force parameters and joint angle parameters between the affected side and the unaffected side of hemiplegic subjects. It can be seen from the Table 2 that: the stride length, gait speed and stride frequency of the hemiplegia group are significantly smaller than that of the control group. In addition, there are significant differences in the stride length and gait speed between the two groups.
It has been reported that: compared with normal people, subjects with lower limb hemiplegia have the lower stride length, gait speed and stride frequency, which is consistent with the results of this study (Mao et al., 2012). The contracture of joints and muscle weakness of the affected side of subjects are the main reasons which cause the limitation in knee and hip extension in the affected side of the subjects. And the asymmetry of movement between the affected and unaffected side of subjects will have an effect on the walking ability of subjects (Carmo et al., 2012). The results of this study show that: the muscle force and the flexion and extension angles of hip joint and knee joint of the affected side are significantly smaller than that of the unaffected side, and the stride length and gait speed of the subjects with lower limb hemiplegia are significantly smaller than that of normal people. Therefore, the four indexes selected in this paper all have a high sensitivity to assess the motor ability of subjects with lower limb hemiplegia.

Table 1. Comparison between muscle force and joint angle of the affected and unaffected side in hemiplegia group

|                      | Affected side | Unaffected side | p*   |
|----------------------|---------------|-----------------|------|
| Average muscle force (mV) | 0.0198 ± 0.0021 | 0.0347 ± 0.0036 | 0.001 |
| Hip joint angle (°)   | 21.6 ± 4.8    | 31.0 ± 4.6      | 0.001 |
| Knee joint angle (°)  | 26.2 ± 5.6    | 41.4 ± 5.0      | 0.004 |

*Level of significance.

Table 2. Comparison between kinematic parameters of the hemiplegia group and the control group

|                      | Hemiplegia group | Control group | p*   |
|----------------------|------------------|---------------|------|
| Stride length (cm)   | 34.18 ± 3.71     | 57.6 ± 4.56   | 0.002 |
| Gait speed (m/s)     | 0.41 ± 0.04      | 1.00 ± 0.08   | 0.000 |
| Stride frequency (steps/min) | 72.8 ± 7.5    | 106.7 ± 13.7 | 0.016 |

*Level of significance.
4. Design of rehabilitation evaluation model

4.1. Determination of weight on rehabilitation assessment indicators

An appropriate weight of the four selected assessment indicators is needed to be determined to build the final rehabilitation assessment model for lower limb motor function.

Analytic hierarchy process (AHP) is a method widely used in practice. It can not only make the relatively complex problems hierarchical, but also can make the qualitative questions quantitative. With comprehensive consideration of people’s subjective judgment, AHP is an analysis method which combines the qualitative analysis with the quantitative analysis. The method has the following characteristics: there are many factors to be considered; importance and influence between factors are difficult to quantify; subjective choices of people (decision makers or experts) play a very important role. The results of the rehabilitation assessment in this study are affected by several evaluation indexes, however, the importance and influence of each evaluation index are difficult to quantify, and the subjective viewing of rehabilitation physician or experts plays a leading role, so the problem is very suitable for AHP to solve.

The 1–9 scale proposed by professor Saaty is introduced in this paper to determine the weight of each evaluation index (Saaty, 1990). Saaty’s scale of relative importance is shown in Table 3.

In the process of determining the weights, a questionnaire survey is firstly conducted to three experts in rehabilitation field. The comparative values of the experts on the weight of each index are shown in Table 4.

Data in Table 4 are given an average and normalization processing, and the processed data are shown in Table 5.

The greatest characteristic root can be calculated by column sum method:

\[
W_i = \frac{1}{n} \sum_{j=1}^{n} \left( \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \right)
\]  

The calculated weight is \((0.20, 0.15, 0.27, 0.38)\).

The rehabilitation evaluation model for lower limb motor function is finally built:

\[
R = 0.20 \times X1 + 0.15 \times X2 + 0.27 \times X3 + 0.38 \times X4
\]  

### Table 3. Saaty’s scale of relative importance

| Scale               | Numerical rating | Reciprocal |
|---------------------|-----------------|------------|
| Extremely preferred | 9               | 1/9        |
| Very strong to extremely | 8       | 1/8        |
| Very strongly preferred | 7        | 1/7        |
| Strongly to very strongly | 6       | 1/6        |
| Strongly preferred  | 5               | 1/5        |
| Moderately to strongly | 4        | 1/4        |
| Moderately preferred | 3        | 1/3        |
| Equally to moderately | 2        | 1/2        |
| Equally preferred   | 1               | 1          |
where \( R \) is the overall evaluation results of subjects; \( X_1 \) is the evaluation results of muscle force; \( X_2 \) is the evaluation results of ROM; \( X_3 \) is the evaluation results of stride length; \( X_4 \) is the evaluation results of gait speed.

### 4.2. Reference standard of rehabilitation assessment indicators

#### 4.2.1. Muscle force

Muscle force can reflect the state of muscle activities during subjects’ walking process, and it is a typical assessment parameter during walking. Different muscle groups of different people have greater differences in muscle force, so in this paper, the sum of muscle forces of different muscle groups between the left and right side of lower limb are compared to reflect the differences between the states of muscle activities on the two sides.

To assume that the left side of subjects with lower limb hemiplegia is the affected side, and the right side is the unaffected side. The evaluation result of muscle force is:

\[
X_1 = \frac{\sum_{i=1}^{4} L_{RMS_i}}{\sum_{i=1}^{4} R_{RMS_i}} \quad \text{when} \quad X_1 > 1, \quad X_1 = 1
\]  

(4)

where \( \sum_{i=1}^{4} RMS_i \) is the sum of muscle forces in quadriceps femoris, biceps femoris, triceps surae (gastrocnemius), and tibialis anterior of the affected side, and \( \sum_{i=1}^{4} R_{RMS_i} \) is the sum of muscle forces in these four muscles of the unaffected side.

#### 4.2.2. Range of motion

In walking process, there exists larger difference in the ROM between different individuals. Therefore, in this paper, the sum of ROM of different joints between the left and right side of lower limb are compared to reflect the coordination of movements on the two sides. The selected ROM includes the ROM of knee joint and hip joint. The evaluation result of ROM is:

\[
X_2 = \frac{L_{kneeangle} + L_{hipangle}}{R_{kneeangle} + R_{hipangle}} \quad \text{when} \quad X_2 > 1, \quad X_2 = 1
\]  

(5)

where \( L_{kneeangle} + L_{hipangle} \) is the sum of ROM of knee joint and hip joint on the affected side, and \( R_{kneeangle} + R_{hipangle} \) is the sum of ROM of knee joint and hip joint on the unaffected side.

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**Table 4. Comparative values of the experts on the weight of each index**

|                      | Muscle force (RMS) | ROM       | Stride length | Gait speed |
|----------------------|--------------------|-----------|---------------|------------|
| Muscle force (RMS)   | (1, 1, 1)          | (2, 1, 2) | (1, 1/2, 1/2) | (1/2, 1/2, 1/2) |
| ROM                  | (1/2, 1, 1/2)      | (1, 1)    | (1/2, 1/2)    | (1/2, 1/2, 1/3) |
| Stride length        | (1, 2, 2)          | (2, 1, 2) | (1, 1)        | (1/2, 1, 1/2) |
| Gait speed           | (2, 2, 2)          | (2, 2, 3) | (2, 1, 2)     | (1, 1, 1)     |

**Table 5. The processed data**

|                      | Muscle force (RMS) | ROM       | Stride length | Gait speed |
|----------------------|--------------------|-----------|---------------|------------|
| Muscle force (RMS)   | 1                  | 1.67      | 0.67          | 0.5        |
| ROM                  | 0.67               | 1         | 0.67          | 0.44       |
| Stride length        | 1.67               | 1.67      | 1             | 0.67       |
| Gait speed           | 2                  | 2.33      | 1.67          | 1          |
4.2.3. Stride length and gait speed

There exist larger differences in stride length and gait speed between healthy people and subjects with lower limb hemiplegia. So in this paper, the stride length and gait speed between healthy people and subjects with lower limb hemiplegia are compared to reflect walking ability. The general stride length of healthy people is about 50–80 cm, and the general gait speed is about 1.08–1.67 m/s. Therefore, the reference standard is selected as 50 cm in stride length and 1 m/s in gait speed.

The evaluation result of stride length is:

The evaluation result of gait speed is:

It can be seen form Table 6 that: the evaluation results of hemiplegia group are between 0.51 and 0.61, and the evaluation results of control group are between 0.90 and 0.98, so the difference is obvious. The evaluation results in Table 6 are statistically analyzed, and the analytical results are shown in Table 7.

It can be seen from Table 7 that: there exist significant differences in the evaluation results between hemiplegia group and control group. By comparing the evaluation results of hemiplegic subjects and healthy people, the effectiveness of the proposed rehabilitation assessment model for lower limb motor function has been preliminarily verified.

5. Conclusion

In this paper, we have mainly conducted a study on the rehabilitation evaluation method based on human gait. Based on the study of human gait, some rehabilitation evaluation indexes which can comprehensively reflect the lower limb motor function are summed up, including muscle force, ROM, stride length and gait speed. Then the EMG acquisition equipment and kinematics data acquisition equipment are used to collect the EMG data and kinematic data in real time during subject’s walking process, and the rationality of the selected evaluation indexes is verified. The experiment results show that the selected evaluation indexes are highly sensitive to evaluate the motor ability of subjects with lower limb hemiplegia. Then by using analytic hierarchy process, the weight of each evaluation index is determined, and finally a relatively scientific, accurate and objective rehabilitation evaluation model is formed. The model can be used to assess the lower limb motor function of subjects through the quantitative index, overcoming the high subjectivity and low sensitivity of the clinical rehabilitation physician assessment.

Table 6. Evaluation results by the calculation of the assessment model

| Number of hemiplegia group | 1    | 2    | 3    | 4    | 5    |
|----------------------------|------|------|------|------|------|
| Evaluation result R        | 0.51 | 0.55 | 0.61 | 0.56 | 0.56 |
| Number of control group    | 1    | 2    | 3    | 4    | 5    |
| Evaluation result R        | 0.95 | 0.90 | 0.97 | 0.98 | 0.98 |

Table 7. Comparison of statistical analysis results between hemiplegia group and control group

| Evaluation result R of hemiplegia group | Evaluation result R of control group | p* |
|----------------------------------------|--------------------------------------|----|
| 0.558 ± 0.036                          | 0.956 ± 0.034                       | 0.000 |

*XLevel of significance.
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Statement
Written informed consent was obtained from all subjects participating in the experiments.

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