Foot Pronation Detection Based on Plantar Pressure Measurement

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Abstract. In the paper, we design a foot pronation detection system based on plantar pressure sensors. The system includes: collecting the pressure sensor signals by reasonably arranging the pressure sensors; collecting the plantar pressure signal value of the test object which has been walking for a period of time; taking the proportional calculation , determining the fuzzy sets , designing the membership function, the fuzzy processing was carried out and the fuzzy rules was established by the IF-THEN rules . Finally the gait phase was deduced according to the fuzzy output signal, and the system function was realized by pronation analysis algorithm. The experimental results show that the system has an important value for sports risk prediction.

1. Introduction

With the improvement of living standards, people are increasingly pay more and more attention to health problems. Exercise has become an indispensable part of people’s daily life[1]. For people who need more accurate monitor and analysis on sports health, such as athletes, irregular gait will have a serious impact on their health. If irregular gait is not corrected, it may cause serious damage to the knee. The distribution and magnitude of plantar pressure reflects the information of body lower limb movement function, and incorrect foot posture will affect the corresponding changes of plantar pressure. Pronation refers to the dorsiflexion, abduction and dorsal flexion of the foot .When pronation occurs, the heel bone is turned outward and the talus is retracted and wasted. In a gait cycle, pronation occurs from the initial contact (IC) to the middle stance (MS) to reduce the vibration from the ground. However, if the pronation exceeds 25% of the support phase, excessive anterior rotation will occur, which will affect the stress line of the tibia and knee joints, and further reduce the vibration from the ground. This will lead to overuse of related muscle and ligament damage, and eventually lead to chronic pain, such as foot pain and knee pain[2][3]. There are three commonly used instruments for measuring plantar pressure: force measuring table, force measuring plate and the force measuring insole system[4]. Although these three types of instruments have high precision, they are expensive, and the processing cycle is long, and they need to be completed in a specific field, which has certain limitations.

In this paper, the plantar pressure sensors are installed to collect the pressure signal of the foot and a set of plantar pressure measurement system is designed. According to the gait phase recognition rules, a gait phase detection algorithm is proposed to detect the posture of the foot. To provide reasonable advice and guidance to the user's running posture and potential foot problems.
2. Design of Plantar Force-measuring Insole

In order to collect sufficient signals from the sole of the foot, we designed the pressure insole, including the selection and layout of the pressure sensor. The sensor is ZNX-01 series, which is a piezoresistive sensor that can sense tiny pressure or tactile signals and has the characteristics of high sensitivity, bending resistance and repeatability. The technical parameters and performance indexes are shown in Table 1.

| Performance indexes | Value                  |
|---------------------|------------------------|
| Effective diameter  | 20mm                   |
| range               | Single point 10kg      |
| response point      | 400g                   |
| response time       | <1ms                   |
| Recovery time       | <15ms                  |

According to the relevant research of human body mechanics, if we want to analyze gait according to the plantar pressure, there must be at least 3 to 5 feature points of force in gait condition[5], and the sum of the forces at each feature is called the Ground Reaction Force (GRF). In order to fully collect the foot pressure signal and accurately analyze the gait, eight feature points are set on the pressure insole this paper. The pressure sensor layout is shown in Figure 1.

Figure 1. Pressure sensor layout.

As shown in Figure 1, eight pressure sensors (GRF1-GRF8) are used to collect the pressure in the heel area (GRF1, GRF2, GRF3), the first phalanges of the foot (GRF8), the first phalangeal joint (GRF7), the second phalangeal joint (GRF6) and the third and fifth metatarsals (GRF4, GRF5), i.e. there are total of eight pressure values. Experiment results show that, the plantar pressure signals collected in the diameter area of each circular sensor were valid. The pressure signal collected by the pressure sensor takes a digital value in the range of [0, 4096], which can be converted into analog voltage value by formula (1):

$$\text{Analog voltage values} = \frac{\text{Digital voltage value}}{4096} \times 3.3$$  \hspace{0.5cm} (1)

The converted voltage lies in the range of [0, 3.3V].

3. Experimental Data Acquisition of Plantar Force Measurement System

According to the biomedical standards, for a specific lower limb (e.g. right limb), the gait cycle is composed of stance and swing, where the stance period accounts for approximately 60% of the entire gait cycle and the swing period accounts for about 40% of the gait cycle. According to Perry's stage model[6], each gait cycle is divided into eight stages, as shown in Figure 2. Among them, five phases
belong to the stance, they are: Initial Contact (IC), Loading Response (LR), Mid Stance (MS), Terminal Stance (TS) and Pre-Swing (PS). In this paper, IC and LR are integrated into initial stance (IS), TS and PS are integrated and collectively referred to as Terminal Stance (TS).

![Gait phase division](image)

Figure 2. Gait phase division.

In order to divide the phase of the gait accurately, the plantar pressure data collection was carried out. In the process of the experiment, a test object with weight of 70kg and shoe size of 42 was selected, and force was measured on the sole of the insole. Test subjects performed a 10-minute gait walking experiment on a flat ground and maintained a relatively constant gait speed during walking.

4. Gait Analysis Algorithm

4.1. Fuzzy Rule-based Gait Phase Division

In order to analyze the situation of pronation in a gait cycle, it is necessary to divide the gait phase of each gait cycle. Gait identification is the division of the human gait phase, the accurate division analysis has important research significance [7][8][9]. Experiments by force measuring plates and dynamic capture systems are expensive and cumbersome, and traditional gait phase division algorithms have low accuracy. In order to improve these shortcomings, this paper proposes a gait phase division algorithm based on fuzzy rules.

Firstly, the value of 8 pressure sensors of each foot are calculated proportionally, that is, the value of 8 pressure sensors are summed, then the proportion of each sensor signal is calculated [10][11]. As Figure 1 shows, for example, set the value of the 8 pressure sensors as $F_{GRF1}, F_{GRF2}, \ldots, F_{GRFS}$; $F_i$ represent the proportion of the pressure value of each sensor to the total signal. The calculation formula is as follows:

$$F_i = \frac{F_{GRFi}}{F_{GRF1} + F_{GRF2} + F_{GRF3} + \ldots + F_{GRFS}}$$  (2)

The proportional calculation constrains the value of $F_i \in [0,1]$, effectively avoiding external factors. The results of the calculation are substituted into the membership function, and the results are fuzzified. By designing fuzzy rules, the results of gait phase division are obtained. The framework of gait phase division algorithm is shown in Figure 3.
Before fuzzification, it is necessary to divide fuzzy sets and design membership functions. Due to the interval of the proportional value is in $[0,1]$, the fuzzy set is divided into two fuzzy states: large (L) and small (S). Fuzzy membership function and anti membership function are designed as follows:

$$f(F_i) = \frac{1}{1 + e^{-(F_i - F_k)}} \in [0,1]$$ (3)

$$h(F_i) = 1 - f(F_i) \in [0,1]$$ (4)

Where: $F_k$ is the threshold coefficient, taking 0.5. When the proportional value $F_i$ is greater than the threshold coefficient $F_k$, $f(F_i)$ tends to 1, $h(F_i)$ tends to 0, and the fuzzy set is large (L); when the proportional value $F_i$ is less than the threshold coefficient $F_k$, $f(F_i)$ tends to 0, $h(F_i)$ tends to 1, and the fuzzy set is small(S). Through the above proportional calculation and membership function fuzzification, the design of fuzzy rules is carried out. The design of fuzzy rules is shown in Table 2.

In the table, FS, MS, TS and SW represent the four gait phases, and / indicates that the value can be L or S.

**Table 2. Fuzzy rule table.**

| Rules | GRF1 | GRF2 | GRF3 | GRF4 | GRF5 | GRF6 | GRF7 | GRF8 | Phase |
|-------|------|------|------|------|------|------|------|------|-------|
| 1     | L    | /    | /    | S    | S    | S    | S    | S    | IS    |
| 2     | /    | L    | /    | S    | S    | S    | S    | S    | IS    |
| 3     | /    | /    | L    | S    | S    | S    | S    | S    | IS    |
| 4     | L    | L    | L    | L    | /    | S    | S    | S    | IS    |
| 5     | L    | L    | L    | /    | L    | S    | S    | S    | IS    |
| 6     | L    | L    | L    | L    | L    | /    | /    | /    | MS    |
| 7     | L    | L    | L    | L    | L    | /    | L    | /    | MS    |
| 8     | S    | /    | /    | L    | L    | L    | L    | /    | MS    |
| 9     | S    | S    | S    | S    | S    | S    | S    | L    | TS    |
| 10    | S    | S    | S    | S    | S    | S    | S    | S    | SW    |

In this paper, the fuzzy rules was established by the IF-THEN rule. For example, rule 9 takes the form of:
If (GRF1 is S) And (GRF2 is S) And (GRF3 is S) And (GRF4 is S) And (GRF5 is S) And (GRF6 is S) And (GRF7 is S) And (GRF2 is L) Then gait phase is TS.  \( (5) \)

The concrete expression of fuzzy rules is complicated. In the experiment, we used fuzzy reasoning rule matrix to replace it. For example rule 9, the corresponding rule matrix is \([2 2 2 2 2 2 2 1 3 1 1]\). Fuzzy reasoning rule matrix should follow the principles: if the system has \(M\) inputs and \(N\) outputs, the first \(M\) vector elements in the matrix correspond to the number of inputs, and the subsequent \(N\) columns correspond to the number of outputs. The first column element is the membership function related to the first input (L corresponds to 1, S corresponds to 2, / corresponds to 0), the element of column \(M + 1\) corresponds to the membership function of output (1 corresponds to FS, 2 corresponds to MS, 3 corresponds to TS, 4 corresponds to SW), and so on; the \(M + N + 1\) column is the weight value related to the rule, and the value in this paper is 1; the \(M + N + 2\) column specifies the rule connection mode, 1 represents the “AND” relationship, 2 represents “OR” Relationship. The number of rows in the matrix is equal to the number of rules to be added.

4.2. Foot Pronation Detection
In a gait cycle, foot pronation occurs from IS to BS. Based on the start time of IS, the end time of the MS and the end time of TS, the proportion of the foot pronation time in the stance is determined, the calculation formula is as follows:

\[
R = \frac{T_2 - T_1}{T_3 - T_1} \quad (6)
\]

Where \(R\) is the pronation ratio, \(T_1\) is the beginning time of IS, \(T_2\) is the end time of MS, and \(T_3\) is the end time of Stance. When \(R > 0.25\), excessive pronation occurs in the gait cycle; when \(R < 0.25\), the gait cycle is normal.

5. Experimental Results
The data of the left foot of the test object is selected for the experiment, and the collected plantar pressure data is converted into analog. After calculation, the pressure signals of each sensor are shown in Figure 4.

![Figure 4. Pressure signal.](image)

When in SW stage, the left foot is suspended, and the signal values of the eight pressure sensors are zero; when in IS stage, the pressure sensors GRF1, GRF2, GRF3 are stressed, the other signal values are zero; when in MS stage, the signal values of GRF1, GRF2, GRF3 increase rapidly and reach the peak value, GRF4 to GRF8 begin to be stressed successively. At the end of TS stage, the signal values of GRF1, GRF2, GRF3 gradually decreased to zero, while the signal values of GRF4 to GRF8
increased to the peak value first and then decreased to zero before the end of stance. The signal change of each pressure sensor in the figure is consistent with the actual situation and gait phase change.

According to the fuzzy rule table, the change of gait phase with the sampling points is shown in Figure 5.

![Figure 5. The result of gait phase division algorithm.](image)

In Figure 5, IS, MS, TS and SW are connected with each other to form a complete gait cycle. IS, MS and TS constitute the stance phase, which accounts for about 60% of each gait cycle, and the swing phase accounts for about 40% of each gait cycle. The change of gait phase in each cycle was consistent with the plantar pressure signal curve and the actual situation of gait walking.

The verification results of the corresponding relationship between the four gait stages are shown in Figure 6.

![Figure 6. Gait phase correspondence.](image)

In a gait cycle, the signs of IS, MS, TS and SW of each phase appear in sequence. The starting and ending points of each phase are closely connected, the time of each phase can be calculated accurately.

According to the plantar pressure data of the subjects walking for 10 minutes, the results of foot pronation analysis are shown in Table.3.

| Minutes | 0-2min | 2-4min | 4-6min | 6-8min | 8-10min |
|---------|--------|--------|--------|--------|--------|
| Number of gait cycles | 106    | 111    | 109    | 110    | 97     |
| Number of excessive pronation cycles | 3      | 5      | 5      | 4      | 2      |
In the experiment, the 10 minute data were evenly divided into five segments, the number of gait cycles and the number of excessive pronation cycles were counted. According to the results in Table 3, the algorithm can detect the gait cycle of excessive pronation during walking.

6. Conclusion
In order to deal with the risk of injury caused by excessive pronation, a plantar force measurement system based on ZNX-01 pressure insole was designed, including the selection and layout of pressure sensors. The data acquisition experiment was carried out to collect the plantar pressure signal of the test object walking on the ground; The plantar pressure signal was calculated proportionally, the fuzzy set was determined, the membership function was designed, and the gait phase was deduced according to the set fuzzy rules. Finally, we realized the foot pronation detection. This paper has a certain guiding role in the research of multimodal fusion system and gait analysis, which is suitable for sports training and rehabilitation analysis.

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