Research on the Formulation of the Motion Angle of Human Lower Limb Joints

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Abstract. In order to make the exoskeleton recognize and predict human gait after walking for a period of time, the control system of the exoskeleton must establish the human gait database in real time. The traditional method is to collect the discrete point data of the angle of each lower limb joint changing over time and then store it in the database. There are two main disadvantages: first, the data volume is too big to store everyone's gait data which is unrealistic; second, it is slow to find the optimal matching of gait process one by one from the database, and it will affect the speed of the gait recognition and prediction, so the exoskeleton is slow to respond. Therefore, it is necessary to find a method dividing human gait data and fitting the function of each piece of data, namely, the formulation of joint motion angle. This paper presents a research on the formulation of the motion angle of human lower limb joints.

1. Theoretical Background
Due to the delay of the control system of the lower-limb assisted exoskeleton robot, it is difficult to achieve a good cooperative movement with the human body. Therefore, the human gait recognition and prediction function must be added to the control algorithm. To recognize and predict human gait, exoskeleton control system needs to establish human gait database. The traditional method is to store the time-varying discrete points of the angle values of the joints of the lower limbs collected by the sensor. This method has two main disadvantages: First, the data volume is too large, so it is unrealistic to store everyone's gait data. Second, it is slow to find the optimal gait matching from the database, and it needs to be compared one by one, which will inevitably affect the speed of gait recognition and prediction, so the exoskeleton response is slow, and the good human-machine cooperative movement cannot be achieved. Aiming at solving this problem, this paper proposes the formulation of human joint angle. Based on the law of human gait cycle, the human walking phase is divided into seven stages, respectively including the initial double stance, mid-single stance, terminal single stance, terminal double stance, initial swing, mid swing, terminal swing. Then the function expression of discrete point data in each stage is obtained by curve fitting, which helps us get the piecewise function of the change in joint angle. After achieving the basic function expressions of different gait stages, the expression parameters only need to be modified to adapt to different walking modes, so as to accelerate the process of gait matching and improve the speed of gait recognition and prediction.
2. CGA and Division of Human Gait

Gait characteristics of human body in a gait cycle are usually gained by gait analysis. There are many methods for gait analysis, such as complex step analysis method, joint angle kinematics analysis method, force table and plantar pressure analysis method, and EMG analysis method\[1\]. CGA is the Clinical Gait Analysis method for obtaining sagittal motion data of human lower limb joints.

Human walking is a cyclic process and can be divided into different stages. During the gait cycle, both feet are in contact with the ground, which is called the standing stage. When foot touches the ground and the other is suspended, it is called the swing phase. During the gait cycle, about 60 percent of the time is spent standing and 40 percent is spent swinging. It can also be divided into single-foot support and two-foot support according to the number of foot standing, as shown in Figure 1 [2]. Table 1 contains the time distribution and functions of different gait [3].

![Fig. 1. The Gait Cycle](image)

**Table 1. Gait Cycle(GC) with phase and corresponding function.**

| Phase   | Initial Double Stance | Single Stance | Terminal Double Stance | Swing |
|---------|-----------------------|---------------|------------------------|-------|
|         | 2% Heel strike | 6% Loading Response | 2% Toe off | 20% Mid stance | 20% Terminal stance | 2% Heel strike | 6% Loading Response | 2% Toe off | 13% Initial Swing | 13% Mid Swing | 13% Terminal Swing |

| Functional Objectives | Shock Absorption | Weight transfer | Forward Propulsion | Weight support | Base HAT CG | Over stance foot | Weight support | Advance Body past | Stance foot | Shock Absorption | Weight transfer | Forward Propulsion | Flexion Of knee to clear Ground and Acceleration Of swing leg | Advancement of swing leg | Preparation For heel-strike | Deceleration Of swing leg | Extension of knee |
|-----------------------|------------------|-----------------|-------------------|----------------|-------------|-----------------|----------------|------------------|-------------|------------------|-----------------|-------------------|----------------------------|--------------------------|-----------------------------|-----------------------|-------------------|

On the basis of the changes of the motion angles of the hip, knee and ankle joints of ordinary people in a walking cycle, a series of angles were extracted and then the trend curve of the movement angles of each joint with time was depicted by taking the time as the horizontal axis (seconds) and the angle as the vertical axis (degrees). Through the analysis of the trend curve, the change law of the angle of each joint during walking and the maximum and minimum joint angle can be obtained. In the CGA analysis, the CGA data of the Hong Kong Polytechnic University [4-6] were used for reference. Figure 2, Figure 3 and Figure 4 respectively show the curve of the motion angle of the hip, knee and ankle joint on the sagittal plane over time at various walking speeds.
3. Data Extraction of Motion Angles of Lower Limb Joints

According to the analysis in the previous section, we know the curve of the motion angle of the human hip, knee and ankle joint on the sagittal plane with the change of time when the walking speed is not the same. To obtain discrete data of the joint angle at each moment, we need to extract data from each curve. Data extraction from curves on graphs or pictures is referred to as "matting" in data processing, which is very important in data processing, especially in transforming function graphs into curve data or digging out curves on pictures. We use data extraction and analysis software Origin 9.1 for data processing, and the process of data extraction is shown in Figure 5.

The discrete point data extracted from the curve is shown in Figure 6.
4. Curve Fitting of Motion Angles of Lower Limb Joints
We have got discrete data of the motion angles of each joint in last section, which will be fitted in the following part. The key steps of curve fitting are:

1. Select all the extracted data and draw the extracted data points into a discrete point graph.
2. Then adaptive least squares fitting is carried out for the discrete point graph.

CGA data shows the relationship between the angle of hip joint, knee joint and ankle joint over time. We want to fit this curve and find the relationship between the angular velocity of corresponding joint over time and the relationship between angular acceleration and time from the expression of each curve. The derivative of angle expression with respect to time gives the expression of angular velocity, and the derivative of angular velocity expression with respect to time gives the expression of angular acceleration, so the curve we fit is at least a second-order polynomial, as shown in Figure 7.

Fig. 7. The Completed Fitted Curve

![Fig. 7. The Completed Fitted Curve](image)

Fig. 8. Comparison of the Fitted Curve of Different Order Polynomials

It can be seen that when the curve is fitted by second-order polynomials, the sum of squares of residuals is 73.87109, and the correction determination coefficient is 0.99552. The curve is far from the discrete point near the inflexion point, and the fitting effect is poor and the sum of squares of residuals is large. Therefore, the second-order polynomials cannot meet the needs, and higher order polynomials should be used for fitting. Theoretically, the curve fitted with higher order is closer to the real distribution of discrete points, but the polynomial with higher order will bring too much calculation for the subsequent derivation process, so we need to find the order of compromise between the two. The third-order and fourth-order polynomials were used to fit the discrete points respectively, and the matching effects were compared, as shown in Figure 8, to find out the optimal regression equation.
The comparison results are shown in Table 2.

| Parameters          | Order | Residual Sum of Squares | Calibration Factor |
|---------------------|-------|-------------------------|-------------------|
|                     | 2     | 73.87109                | 0.99552           |
|                     | 3     | 7.6825                  | 0.99953           |
|                     | 4     | 6.9359                  | 0.99957           |

It can be seen from the table that the fitting effect of the 3rd-order polynomial is the same as that of the 4rd-order polynomial, with a difference of 0.7466 in the sum of squares of residues and a difference of 0.00004 in the correction determination coefficient. Therefore, the 3rd-order polynomial fitting can achieve the desired effect in this section of curve.

According to human gait analysis, the curves of angles over time of each joint were divided into corresponding intervals, and the percentages of each interval were shown in Table 1. Due to the small proportion of each segment of the double-supported state, the curve fitting was carried out as a whole, that is, the initial double-supported state and the end stage of the double-supported state accounted for 10% respectively, and the rest phases were divided according to the percentage in the table, and then the curve of each stage was piecewise fitted. Table 1 shows that each joint is divided into 7 curves for fitting. In this paper, the curve of flat walking and walking speed of 1.1m/s in CGA images was selected for fitting, and a gait cycle was set at 1 second, for example, the middle stage of single support accounted for 20%, that is, 0.2 second.

The fitting curve of hip joint angle changing over time is shown in Figure 9.

![Graph](image)

Fig.9. Fitted Curve of Hip Angle at Various Speeds  Fig.10. Hip Angle Formula Curve at Various Speeds in MATLAB

After fitting each discrete point, it is found that the correction determination coefficient of each curve is above 0.999, which can be obtained from statistical knowledge. The value of the correction determination coefficient ranges from 0 to 1. The closer the value is to 1, the higher degree of curve regression is, and the better fitting effect is. After the curve fitting of each segment is completed, the polynomial fitting curve of the hip joint with integrity can be obtained (Figure 9). By comparing the CGA curve of hip joint angle over time (Figure 2), it is found that the change trend and range of the two is consistent, indicating that the fitting effect is very good. The functional relationship between hip joint angle (Y1) and time (t) is expressed as follows:
InitialDoubleStance

\[ Y_1 = 36.82278 + 20.40615t - 2145.59512t^2 + 25088.82608t^3 - 108362.09784t^4 \]

Mid – SingleStance

\[ Y_1 = 35.44312 + 54.66293t - 1249.1298t^2 + 3883.55797t^3 - 4375.29934t^4 \]

TerminalSingleStance

\[ Y_1 = 13.67252 + 198.04365t - 1224.58736t^2 + 2018.53776t^3 - 1078.31724t^4 \]

TerminalDoubleStance

\[ Y_1 = -12509.16704 + 91221.54963t - 248263.06524t^2 + 298572.62308t^3 - 133855.11714t^4 \]

InitialSwing

\[ Y_1 = 14962.65297 - 88320.41177t + 194187.39962t^2 - 188814.78359t^3 + 68667.70953t^4 \]

MidSwing

\[ Y_1 = -87046.01113 + 440315.93917t - 834735.7916t^2 + 702883.72009t^3 - 221733.95358t^4 \]

TerminalSwing

\[ Y_1 = 630366.50318 - 3.42938e4t + 7.45371e4t^2 - 8.08999e4t^3 + 4.38476e4t^4 - 949431.3692t^5 \]

The obtained formula was plotted in MATLAB, and the curve was shown in Figure 10. It can be seen that the piecewise function curve drawn is consistent with the hip joint angle change curve in the CGA data, thus indicating the correctness of the fitting formula.

The fitting curve of the knee angle with time in each stage is shown in Figure 11.

![Fig.11. Fitted Curve of Knee Angles at Various Speeds](image)

![Fig.12. Knee Angle Formula Curve at Various Speeds in MATLAB](image)

After fitting each discrete point, it is found that the correction determination coefficient of each curve is above 0.999, which can be obtained from statistical knowledge. The value of the correction determination coefficient ranges from 0 to 1. The closer the value is to 1, the higher degree of curve regression is, and the better fitting effect is. After the curve fitting of each segment is completed, the complete polynomial fitting curve of the knee joint can be obtained (Figure 11). By comparing the CGA curve of knee joint angle with time (Figure 3), it is found that the change trend of the two is consistent with the change range, indicating that the fitting effect is very good. The function expression of knee angle (Y2) and time (t) is shown as follows:
Initial Double Stance
\[ Y_2 = -8.6409 - 149.32675t + 3647.62036t^2 - 7353.31502t^3 + 396753.11721t^4 \]

Mid – Single Stance
\[ Y_2 = 14.45708 - 707.11995t + 4609.9185t^2 - 12126.25459t^3 + 12216.24081t^4 \]

Terminal Single Stance
\[ Y_2 = 193.25931 - 2280.63016t + 8860.52767t^2 - 14103.30485t^3 + 7784.74173t^4 \]

Terminal Double Stance
\[ Y_2 = 3898.32287 - 248276.52996t + 680219.13984t^2 - 825813.20502t^3 + 374461.56205t^4 \]

Initial Swing
\[ Y_2 = -17808.38635 + 107820.62331t - 241999.11356t^2 + 238411.50719t^3 - 87161.13099t^4 \]

Mid Swing
\[ Y_2 = 107859.59318 - 545809.66485t + 1.03424E6t^2 - 870477.89563t^3 + 274665.00764t^4 \]

Terminal Swing
\[ Y_2 = -22107.24217 + 102850.24433t - 181458.42817t^2 + 42281.8342t^3 - 42281.8342t^4 \]

The obtained formula was plotted in MATLAB, and the curve was shown in Figure 12. It can be seen from the figure that the piecewise function curve drawn is consistent with the knee angle change curve in the CGA data, thus indicating the correctness of the fitting formula.

The fitting curve of ankle angle with time variation in each stage is shown in Figure 13.

Fig.13. Fitted Curve of Ankle Angle at Various Speeds

Fig.14. Ankle Angle Formula Curve at Various Speeds in MATLAB

After fitting each discrete point, it is found that the correction determination coefficient of each curve is above 0.995, which can be obtained from statistical knowledge. The value of the correction determination coefficient ranges from 0 to 1. The closer the value is to 1, the higher degree of curve regression is, and the better fitting effect is. After fitting all curves, a polynomial fitting curve of the ankle joint can be obtained (Figure 13). By comparing the CGA curve of ankle angle with time (Figure 4), it was found that the change trend and range of ankle angle were consistent, indicating that the fitting effect was good. The functional expression of ankle angle (Y3) and time (t) is shown as follows:
InitialDoubleStance
\[ Y_3 = -1.83524 - 62.22323t - 3904.29246t^2 + 69961.52283t^3 - 295124.02826t^4 \]

Mid – SingleStance
\[ Y_3 = -21.24073 + 161.04555t - 61.62979t^2 - 1387.80242t^3 + 2545.42174t^4 \]

TerminalSingleStance
\[ Y_3 = -195.14449 + 2088.82201t - 8305.30911t^2 + 14822.9312t^3 - 9831.13993t^4 \]

TerminalDoubleStance
\[ Y_3 = 26434.91283 - 193179.93737t + 527995.58643t^2 - 639020.77375t^3 + 288726.44172t^4 \]

InitialSwing
\[ Y_3 = -40695.75648 + 252439.42549t - 583811.62487t^2 + 596627.33795t^3 - 227401.42286t^4 \]

MidSwing
\[ Y_3 = 31293.37205 - 160609.34583t + 307678t^2 - 260859.24845t^3 + 82613.4442t^4 \]

TerminalSwing
\[ Y_3 = -27622.30211 + 122680.70419t - 203660.67621t^2 + 149760.2605t^3 - 41159.12104t^4 \]

The obtained formula was plotted in MATLAB, and the curve was shown in Figure 14. It can be seen from the figure that the piecewise function curve drawn is consistent with the ankle angle change curve in CGA data, which indicates the correctness of the fitting formula.

5. Conclusion
In order to solve the problem of storing discrete point data of joint angle change into human gait database, this paper proposes a formulation of human lower limb joint movement angle. Firstly, data of the curve of each joint angle changing over time were extracted from the data analysis and extraction software Origin, and then the segmented data were fitted into the corresponding functional expression. In order to verify the correctness of each function expression, the curve of each joint function was drawn in MATLAB and compared with the corresponding joint curve in CGA data. It was found that the change range and trend of the curve were consistent, indicating that the curve fitting effect was good. After achieving the basic function expressions of different gait stages, the expression parameters can be modified to adapt to different walking modes, thus accelerating the process of gait matching and improving the speed of gait recognition.

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