The Recognition of Motion Intention of Knee Joint Based on Piezoelectric Signals

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Abstract: Aiming at the human body exoskeleton motion intention recognition process, based on the pressure signals of muscle groups of control, building joint motion information acquisition system, the application of multi-sensor information fusion technique based on neural network, based on the piezoelectric signal muscle as input and output of the joint angle trajectory motion intention model, calculate the joint exercise intention and angle track. Finally, the knee flexion and extension movement as the main object of study, through calculation and practical test, the ideal results are obtained. It shows that the motion signals of the knee joint can be reflected by the piezoelectric signals collected during the motion of the knee joint.

1. Introduction

Exoskeleton [1] was first proposed in the 1960s, but because of its wide range of applications and high conditions, it has not made a relatively important technological breakthrough until recent years. Nowadays, research on the application of exoskeleton equipment in rehabilitation training, body support, and breaking the limits of physical fitness is widely concerned [2]. Wearable exoskeletons can protect operator-related activities as well as be controlled by the wearer to help wear many sports.

The key technology of exoskeleton equipment is sensing human motion intention, which can be divided into motion data collection and motion will discrimination. In order to solve the above problems, a knee joint motion information acquisition system is set up, which mainly controls the EMG and joint angle information in the process of joint motion. The motion intention model is established by combining multi-sensor data and neural network algorithm.

2. Establishment of motion intention model of knee joint

During the knee joint movement, the original muscle consists of the sartorius muscle, the semimembranous muscle, the gastrocnemius muscle, the semitendinosus muscle, the biceps femoris muscle, the fascius muscle and the extensor muscle. As a group of muscles that directly complete the
movement and do work, we should take the specific movement corresponding to the original muscle group as the object of piezoelectric signal collection, so as to better reflect the corresponding motion intention of the knee joint [3-6].

In order to reduce the interference factors, the experimenter lay sideways on the plane and his legs were supported by the plane. The femur, tibia and patella were regarded as rigid bodies, and the femur was fixed in sagittal plane. The center of the coordinate axis is defined at the origin of the rotation of the knee joint. The axis of rotation is set as the Y-axis, with the direction from the inner side of the leg to the outside and perpendicular to the horizontal plane; the Z axis is perpendicular to the Y-axis. Toward the center of the hip, the X axis faces the front from the back of the body, and the direction is perpendicular to the OXY plane. The sagittal plane of motion is the OXZ plane. Flexion and extension motion in sagittal plane, knee joint do on The rotation of the Y axis. In the sagittal plane, the angle from the origin to the center of the ankle and the angle of the Z axis are the knee joint angles [7]. As shown in figure 1:

![Figure 1. Knee motion coordinate system](image)

According to the principle of Dalembert, the equation is obtained:

\[
\sum_{i=1}^{n} M_o(F_i) + M_o(G) + M_o(R) - I_o \ddot{\theta} = 0 \quad (1)
\]

\[
\sum_{i=1}^{n} F_i + \vec{R} + \vec{G} - ma = 0 \quad (2)
\]

\( \vec{F}(i=1,2,\cdots,n) \) represents the muscle force of the primary muscle, \( \vec{G} \) represents gravity below the knee, \( \theta \) represents the angle of the knee joint, \( \vec{R} \) represents joint reaction force. When the knee joint moves slowly in the sagittal plane (generally lower than 0.25rad/s), the resulting acceleration can be ignored [8-10]. When the knee joint is active in sagittal plane, the horizontal plane is parallel to the sagittal plane, and gravity does not work. Therefore, the equation can be simplified as:

\[
\sum_{i=1}^{n} M_o(F_i) + M_o(R) = 0 \quad (3)
\]

\[
\sum_{i=1}^{n} F_i + \vec{R} = 0 \quad (4)
\]

As shown in figure 2, the biceps femoris start from the ischium and the end point is the fibula
head. Connecting the starting point and stopping point of biceps femoris, the straight line is the straight line of biceps femoris, the length of which intersects with Z axis in Anao is \( L_{11} \), and the point of intersection with origin pointing to the central line of ankle is \( L_{12} \).

![Biceps femoris position diagram](image)

**Figure 2. Biceps femoris position diagram**

The length of \( ML_1 \):

\[
ML_1 = \sqrt{L_{11}^2 + L_{12}^2 - 2L_{11}L_{12}\cos(\pi - \theta)}
\]  

(5)

The stress arm is:

\[
R = \frac{L_{11}L_{12}\sin\theta}{ML_1} - \frac{L_{11}L_{12}\sin\theta}{\sqrt{L_{11}^2 + L_{11}^2 - 2L_{11}L_{12}\cos(\pi - \theta)}}
\]  

(6)

According to the above relation, there is a nonlinear mapping relation between muscle force and knee joint angle. However, during knee joint movement, muscle force is difficult to be measured directly, and training samples can not be obtained to obtain mapping model. For this reason, a nonlinear mapping model is established based on the multi-sensor information fusion technique based on neural network, which takes the voltage signal generated by the original motor muscle as input and the angle of knee joint as the output. This reflects the motion intention of the knee joint.

3. **Application of BP Neural Network Technology**

As one of the most widely used neural networks, BP neural network is feedforward feedback, which can be divided into input layer, several hidden layers and output layer. Figure 3 shows its network structure.

![Neural network structure diagram](image)

**Figure 3. Neural network structure diagram**

The learning process of BP neural network is based on the functional relationship between input
data and output data. Get $E$ (total error). According to neural network rules (change of claim weight with negative gradient $-\frac{\partial E}{\partial W}$ azimuth of total error $E$). Duplicate modification of network data per node (potential factor $\alpha$, threshold $a_j$, $a_k$, learning factor $\eta$, weight value $w_{ji}$, $w_{kj}$). Make total error $E$ within range of error requirements. Total error formula: $-\frac{\partial E}{\partial W}$

$$E = \frac{1}{2m} \sum_{i=1}^{m} (d_k - O_k)^2$$  \hspace{1cm} (7)

$m$ is the sample number, $d_k$ is the expected output, and $O_k$ is the real output.

According to the error back propagation algorithm, the weights are more formal:

$$w_{kj} = w_{kj}(t) + \eta \delta_k O_k + \alpha[w_{kj}(t) - w_{kj}(t-1)] \hspace{1cm} (8)$$

$$w_{ji} = w_{ji}(t) + \eta \delta_j O_j + \alpha[w_{ji}(t) - w_{ji}(t-1)] \hspace{1cm} (9)$$

According to the number of key points of promotor muscle, 11 input and 1 output network models were selected for knee flexion and knee extension. According to the empirical formula $n_1 = \sqrt{n + m + a}$, 10 is chosen as the number of hidden nodes, in which $n_1$ represents the number of hidden nodes, $n$ represents the number of input nodes, and $m$ represents the number of output nodes. Because the continuous differentiability of Sigmoid function is convenient to introduce the least square learning algorithm, Sigmoid function $f(x) = \frac{1}{1 + e^x}$ is chosen as the transformation function of BP neural network node.

4. Experimental platform construction

**Design principle of PVDF Sensor**

PVDF piezoelectric film is chosen as the main material of the sensor. The silica gel base of the sensor is located at the bottom of the sensor, which protects the piezoelectric film. The second and fourth layers are conductive adhesives, which can lead to the conductor. The PVDF film is in the middle position and its thickness is 100 um. The corresponding cantilever beam, located at the top of the sensor, acts as a piezoelectric film.

**Angular transducer**

In order to collect the angle of knee joint in real time, the angle sensor adopts photoelectric encoder, and its minimum resolution is:

$$\theta = \frac{360^\circ}{n_a}$$  \hspace{1cm} (10)

$\theta$ — Minimum resolution of angle encode;  $n_a$ — Recorded pulse values.
When the recorded pulse value is 2000, it indicates that the photoelectric encoder has been rotated for exactly one week, the minimum resolution of 0.18 is calculated.

The motion intention model of knee joint is obtained by using neural network to fuse the data collected by the sensor. A set of test samples were input into the knee motion intention model, and the angle trajectory calculated by the model was compared with the actual angle trajectory recorded by the photoelectric encoder, as shown in figure 4 and figure 5:

![Figure 4. Flexion simulation contrast value](image)

![Figure 5. Knee extension simulation contrast value](image)

The correlation coefficient (similarity) between the angle trajectory curve calculated by the model and the actual angle trajectory curve is 0.99649 and 0.99405 respectively. It can be seen from the graph that the obtained piezoelectric signals of the knee joint muscles and the angle of the knee joint are fused by neural network, and the motion intention model can roughly reflect the actual angle trajectory of the knee joint motion. This gives feedback on the motion intention of the knee joint \(^{[11]}\).
5. Conclusions

In this paper, the motion intention of the knee joint is reflected by the electrocardiogram produced by the knee joint muscle group. Through BP neural network, the EMG signals collected by the sensor are fused to obtain the motion intention model, the angle trajectory of the knee joint is calculated, and the angle trajectory obtained by the model is compared with the actual angle trajectory. The results show that the EV generated by knee joint muscle group can reflect the true intention of knee joint motion. Compared with the conventional electromyography (EMG) signal extraction, the impedance of the PVDF piezoelectric film, the main material in the PVDF sensor, is similar to that of the human body, and it has small weight and extension. It has some advantages such as good expansibility, and it has certain generalizability.

References

[1] Liangwei Zhang . Intelligent shoe design and application of exoskeleton robot in lower extremity [D]. University of Electronic Science and Technology, 2016

[2] Zengguang Hou , XG Zhao , long Cheng , et al. Research Progress of Rehabilitation Robot and Intelligent Auxiliary system [J]. Journal of Automation, 2016,42 (12): 1765-1779

[3] Milosevic M, Yokoyama H, Grangeon M, et al. Muscle synergies reveal impaired trunk muscle coordination strategies in individuals with thoracic spinal cord injury.[J]. Journal of Electromyography & Kinesiology Official Journal of the International Society of Electrophysiological Kinesiology, 2017, 36:40.

[4] Hanjun Li . Model of muscle Force Distribution in knee Joint based on EMG signal [D]. Beijing physical Education University.

[5] Zane A C, Reiter D A, Shardell M, et al. Muscle strength mediates the relationship between mitochondrial energetics and walking performance[J]. Aging Cell, 2017, 16(3):461-468.

[6] Yi Long , Weidong Wang . Control and experiment of exoskeleton Robot based on Kalman Prediction of Human Motion intention [J]. Robot, 2015,37 (3): 304-309.

[7] Jing Xiong ,Zhizeng Luo . A method for measuring and calibrating knee joint angle [J]. Mechatronics, 2009,26 (12): 13-16.

[8] Peng Cheng , Lu Liu, et al. Study on the Stability of Center of Gravity and muscle Force in different steady State squat training [C] National Conference on Sports Biomechanics. 2013.

[9] Wang X, Zheng G T. Equivalent Dynamic Stiffness Mapping technique for identifying nonlinear structural elements from frequency response functions[J]. Mechanical Systems & Signal Processing, 2016, s 68–69:394-415.

[10] Zhenhui Zhang . Study on the modeling and prediction of muscle force in human upper limb [D]. Tianjin University, 2012.

[11] Jingming Zhang ,Jianguo Liu . Application of rough set and BP Neural Network in Transformer Fault diagnosis [J]. Transformer, 2009, 46 (4): 18-21.