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Comfort degree of patients' rehabilitation training based on DSMT theory

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Abstract. This paper aims to solve the problem that most rehabilitation robots lack to integrate their physiological functions and psychological states into closed controlling loop in rehabilitation training of stroke patients. The application of fusion technology of multi-electromechanical sensor signal and DSMT signal is used to achieve patients' comfort judgement. Mean value and variance are used to extract physiological information such as heart rate, temperature and skin resistance. Sensor information of fusion technology of rehabilitation robot based on classical DSMT theory can realize on-line diagnosis of multi-comfort degree of patients' coupling.

1. Introduction

The disability rate of stroke is as high as 75%, and patients with stroke and limb disability are increasing day by day [1]. Rehabilitation robots have gradually come to the stage of history, but most of the robot control systems lack the ability to integrate the physiological function and psychological state of patients into controlling loop.

In order to solve the key problem of asymmetric one-way interaction between human and machine, Riener firstly proposed the concept of bio-coordinated control in 2009, and discussed the application of bio-coordinated control in rehabilitation robot in 2010[2]. Koenig studied the human-in-loop control of Locomat, which is a suspended rehabilitation robot considering the physiological and psychological factors of patients. The bio-coordinated control in gait rehabilitation training was summarized in detail [3]. The Hefei Institute of Intelligent Machinery has also introduced psychological factors into the study of suspended lower limb rehabilitation robots [4]. Munich introduced the bio-coordinated rehabilitation robot technology into adaptive assistant control [5]. Yang Jinjiang of Zhejiang University proposed a variable gain Kalman data fusion attitude algorithm based on the research platform of the lower extremity exoskeleton robot with the help of force. The algorithm is based on fuzzy theory and has the characteristics of high universality, high stability and high reliability [6].

Compared with traditional information fusion theory and method, DSMT (Dezert-Smarandache Theory) fusion theory has certain advantages in the measurement and combination of imperfect information [7]. The process of multi-sensor information fusion based on DSMT theory is to preprocess the data collected by sensors first, then it obtains basic probability assignment function of all sensor datas, and calculates the basic probability assignment function under all super-power sets



according to the rules. Finally it selects the maximum basis according to the set decision-making basis [8]. Probabilistic assignment function is the result of fusion. Because of the imperfection of the feedback of multiple electromechanical signals in the training process, the judgment of patients' comfort becomes the most difficult point [9]. In this paper, DSMT fusion theory is introduced into rehabilitation robot for the first time, and is combined with the feedback of patient's multiple electromechanical signals. Thus, the on-line detection of patient's coupling comfort during training is realized.

2. Identification of physiological information of patients

Physiological signals can be measured by physiological sensors. The feature extraction methods of physiological signals include average value, variance, mean square root of difference value, difference between first-order difference mean value and maximum/minimum value. For example, RR_i represents the time between two peaks of heart rate, and the mean square root HRV of the difference reflects the rate of variation in heart rate variability.

$$HRV = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n-1} (RR_{i+1} - RR_i)^2} \quad (2-1)$$

We can get the heart rate peak mean M

$$M = \frac{1}{n} \sum_{i=1}^n RR_i \quad (2-2)$$

The overall standard deviation $HPSD$ can also be used to reflect the overall variation of ECG variability.

$$HPSD = \sqrt{\frac{1}{n} \sum_{i=1}^n (RR_{i+1} - \overline{RR_i})^2} \quad (2-3)$$

We can get the variance expression of skin conductance signal σ_Y

$$\sigma_Y = \frac{1}{n} \sum_{i=1}^n (Y_n - MEAN)^2 \quad (2-4)$$

We can get the first order difference mean δ_Y of skin conductance sensing signal

$$\delta_Y = \frac{1}{n-1} \sum_{i=1}^{n-1} |X_{n+1} - X_n| \quad (2-5)$$

3. Sensor information fusion of rehabilitation robot based on DSMT theory

The membership function of each comfort model can be calculated by statistical method.

$$\mu_F(x) : U \rightarrow [0,1], x \in U \quad (3-1)$$

Firstly, the sensor data corresponding to various typical comfort patterns during rehabilitation training are collected by simulation or experiment. The arithmetic average value of the sensor data is M_k . k ($k = 1, 2, \dots$) represents group k data.

$$M_k = (x_{k,1} + x_{k,2} + \dots + x_{k,n})/n, 30 \leq n \leq 50 \quad (3-2)$$

$x_{k,1}, x_{k,2}, \dots, x_{k,n}$ are measured values of sensors respectively.

Secondly, we calculate the standard deviation.

$$\sigma_k = \sqrt{\left((x_{k,1} - M_k)^2 + (x_{k,2} - M_k)^2 + \dots + (x_{k,n} - M_k)^2 \right) / n} \quad (3-3)$$

Then, according to M_k and σ_k , we calculate the membership function.

$$\mu_{F,k}(x_k) = \exp\left(-\frac{(x_k - M_k)^2}{2\sigma_k^2}\right) \quad (3-4)$$

Finally, the membership function of comfort model is obtained based on $\mu_{F,k}$.

$$\mu_F(x) = \begin{cases} \exp\left(-\frac{(x_k - M_a)^2}{2\sigma_a^2}\right), & x < M_a \\ 1, & M_a \leq x \leq M_b \\ \exp\left(-\frac{(x_k - M_b)^2}{2\sigma_b^2}\right), & x > M_b \end{cases} \quad (3-5)$$

x represents the measured value of sensor. $M_a = \min(M_k)$, $M_b = \max(M_k)$. σ_a and σ_b are the standard deviation corresponding to mean M_a and M_b respectively.

We should pay attention to the timeliness of the measured comfort model, and membership function of the measured comfort is also solved by the Gaussian membership function, which is defined :

$$\mu_o(x) : U \rightarrow [0,1] \quad (3-6)$$

$$\mu_o(x) = \exp\left(-\frac{(x - M_o)^2}{2\sigma_o^2}\right) \quad (3-7)$$

Suppose δ is a random number of given intervals and is uniformly distributed in the $[0,1]$ range.

$$\sum_F(\mu_F) = \{x \in U | \delta \leq \mu_F(x)\} \quad (3-8)$$

$\sum_F(\mu_F)$ is a set whose membership degree $\mu_F(x)$ is greater than or equal to δ . It changes due to randomness of δ . Measured comfort is defined:

$$\sum_\delta(\mu_o) = \{x \in U | \delta \leq \mu_o(x)\} \quad (3-9)$$

When the comfort characteristics $\sum_\delta(\mu_o)$ and $\sum_F(\mu_F)$ are consistent, the monitored comfort $\sum_\delta(\mu_o)$ is the same as the comfort characteristics F in the comfort library, indicating that there is no conflict between the two. It can be named as $\sum_\delta(\mu_o) \cap \sum_F(\mu_F) \neq \emptyset$. The comparison is a probability likelihood phenomenon. $\sum_\delta(\mu_o)$ and $\sum_F(\mu_F)$ are not constant. When they do not intersect with each other, they conflict, that is, the measured data can not prove the emergence of comfort template F ; when they intersect, it shows that they do not conflict, the measured data and comfort template F have similar characteristics. Therefore, if there is a constant matching between them, it is inferred that $\sum_\delta(\mu_o)$ should be generated by the comfort model F . The likelihood function of $\sum_\delta(\mu_o)$ is

$$\rho(\theta|F) = Pr(\sum_\delta(\mu_o) \cap \sum_F \neq \emptyset) = \rho(\delta \leq (\mu_F \wedge \mu_o)(x)) \quad (3-10)$$

Based on classical DSmt theory, the flow chart of multi comfort coupling judgement is shown in Figure 1.

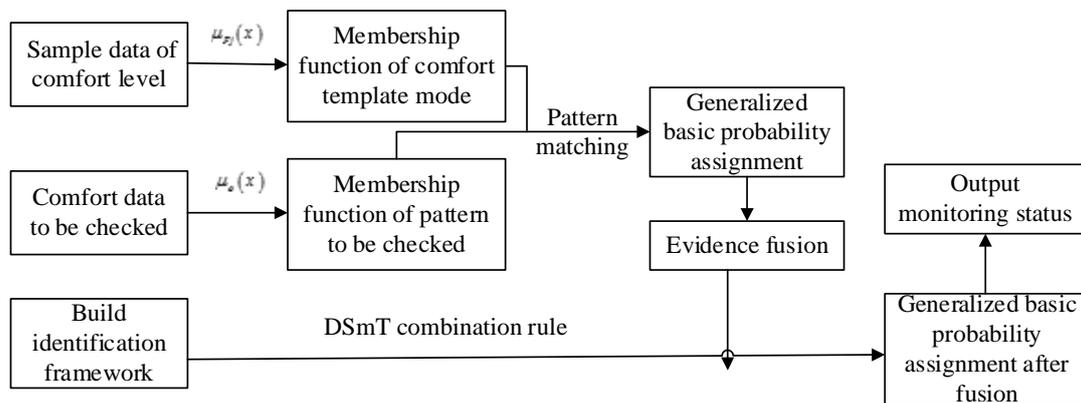


Figure 1. Judgement of patient comfort status based on DSmt theory.

The modified DSmt theory also needs to establish a judgement basis for the comfort state of the decision-making patients. Firstly, the basic probability assignment of maximum comfort degree should be greater than the threshold value T_1 , and the threshold value should be greater than $1/n$ (n is the type of comfort degree). Here is $T_1 = 0.45$. Secondly, the difference between the maximum generalized basic probability assignment and the probability assignment of other elements should be greater than the threshold T_2 . Here is $T_2 = 0.2$. The final uncertainty $m(\theta)$ should be less than the threshold value. Here is $T_3 = 0.25$.

4. Simulation experiment

In this paper, a simulation experiment is carried out to verify the validity of the classical DSMT theory in the diagnosis of multi-comfort coupled states. Patient comfort can be established through the patient's heart rate (variable x_1), body temperature (variable x_2), skin electrical response (variable x_3) and biomechanical sensors (variable x_4) mathematical relationship. Three possible comfort modes were set up in the simulation experiment, which were comfort 1 (weariness A_1), comfort 2 (fatigue A_2) and comfort 3 (excitement A_3).

(1) Simulation Experiment 1

Suppose that two sets of data to be obtained are shown in table 4-1. The identification framework $\theta = \{A_1, A_2, A_3\}$ and its corresponding superpower set D^θ are established. The evidence is fused by the combination rules of DSMT theory. The generalized basic probability assignment of all elements of the superpower set after fusion can be obtained. It is shown in table 4-2.

Table 1. Generalized basic probability assignment for the patient' comfort.

Variable / comfort level	x_1	x_2	x_3	x_4
$m(A_1)$	0.1	0.1	0	0.2
$m(A_2)$	0.7	0.5	0.6	0.2
$m(A_3)$	0.2	0.4	0.3	0.5

Data fusion, from Table 4-1, shows that the generalized basic probability of patients'comfort after a_7 fusion is 0.5396, greater than the threshold $T_1 = 0.45$. The difference between the generalized basic probability of comfort of patients after fusion with other elements is greater than the threshold $T_2 = 0.2$, and the GBPA of uncertainty a_{18} is less than the threshold $T_2 = 0.2$.

Table 2. After fusion of generalized basic probability assignment for the patient' comfort.

Coupling comfort super power set D^θ	m	Coupling comfort super power set D^θ	m
$a_1 = A_1$	0.0003	$a_{10} = A_2 \cup A_3$	0
$a_2 = A_1 \cap A_2$	0.0942	$a_{11} = A_1 \cap (A_2 \cup A_3)$	0
$a_3 = A_1 \cap A_3$	0.0285	$a_{12} = A_2 \cap (A_1 \cup A_3)$	0
$a_4 = A_1 \cap A_2 \cap A_3$	0.229	$a_{13} = A_3 \cap (A_1 \cup A_2)$	0
$a_5 = A_2$	0.0735	$a_{14} = A_1 \cup (A_2 \cap A_3)$	0
$a_6 = A_3$	0.0192	$a_{15} = A_2 \cup (A_1 \cap A_3)$	0
$a_7 = A_2 \cap A_3$	0.5553	$a_{16} = A_3 \cup (A_1 \cap A_2)$	0
$a_8 = A_1 \cup A_2$	0	$a_{17} = (A_1 \cap A_2) \cup (A_1 \cap A_3) \cup (A_2 \cap A_3)$	0
$a_9 = A_1 \cup A_3$	0	$a_{18} = A_1 \cup A_2 \cup A_3$	0

(2) Simulation Experiment 2

Assuming two groups of data are obtained as shown in Table 4-3 below, it is difficult to visually judge the changes of patients' training comfort through Table 4-3. Therefore, information fusion can be carried out by improved evidence fusion theory. The identification framework $\theta = \{A_1, A_2, A_3\}$ and its corresponding superpower set D^θ are established, and the evidence is fused by the combination rule of DSMT theory. The generalized basic probability assignment of all elements of the superpower set can be obtained as shown in Table 4-4.

Table 3. Generalized basic probability assignment for the patient' comfort.

Variable / comfort level	x_1	x_2	x_3	x_4
$m(A_1)$	0.1	0.1	0	0.1
$m(A_2)$	0.7	0.8	0.8	0.9
$m(A_3)$	0.1	0	0.2	0
$m(A_1 \cap A_2)$	0.1	0	0	0
$m(A_1 \cup A_2 \cup A_3)$	0	0.1	0	0

Table 4. After fusion of generalized basic probability assignment for the patient' comfort.

Coupling comfort super power set D^θ	m	Coupling comfort super power set D^θ	m
$a_1 = A_1$	0	$a_{10} = A_2 \cup A_3$	0
$a_2 = A_1 \cap A_2$	0.2016	$a_{11} = A_1 \cap (A_2 \cup A_3)$	0
$a_3 = A_1 \cap A_3$	0.0010	$a_{12} = A_2 \cap (A_1 \cup A_3)$	0
$a_4 = A_1 \cap A_2 \cap A_3$	0.0682	$a_{13} = A_3 \cap (A_1 \cup A_2)$	0.002
$a_5 = A_2$	0.5184	$a_{14} = A_1 \cup (A_2 \cap A_3)$	0
$a_6 = A_3$	0	$a_{15} = A_2 \cup (A_1 \cap A_3)$	0
$a_7 = A_2 \cap A_3$	0.2088	$a_{16} = A_3 \cup (A_1 \cap A_2)$	0
$a_8 = A_1 \cup A_2$	0	$a_{17} = (A_1 \cap A_2) \cup (A_1 \cap A_3) \cup (A_2 \cap A_3)$	0
$a_9 = A_1 \cup A_3$	0	$a_{18} = A_1 \cup A_2 \cup A_3$	0

By fusing the data, it can be seen from Table 4-4 that the generalized basic probability of comfort degree of patients after a_5 fusion is 0.5184, which is greater than the threshold value. The difference between the generalized basic probability of patient comfort and other elements is greater than the threshold $T_2=0.2$. The GBPA of uncertainty a_{18} is less than $T_2=0.2$ of threshold value. Therefore, according to the decision rules, the comfort degree of this group of data to be detected is comfortable.

5. Conclusion

Based on the classical DSMT theory of rehabilitation robot sensor information fusion technology, this paper has achieved coupled multi-comfort diagnosis. To calculate comfort model membership function, a single comfort and coupled comfort identification framework is constructed through the comfort template data. And the classical DSMT theory is applied through the comfort membership function. Based on combined fusion rules, decision rules are formulated according to actual experience, and the diagnosis results of multiple comfort degrees are obtained. The on-line detection method of rehabilitation robot's physiological status is proposed. Aiming at the difficult problem of on-line diagnosis of patients'physiological state during rehabilitation training, the coupling comfort judgment of patients is realized through fusion technology of multi-sensor signals and DSMT signals.

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