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Achieving Personalized Wrist Training: Apply Human Factors in the Control Strategy of Rehabilitation Robot

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ABSTRACT

This paper focus on the control strategies design of wrist rehabilitation robot that meets the requirements of human factors according to the different rehabilitation mechanisms and needs of patients at each stage. We propose a collection of design techniques that can incorporate human factors into robot control schemes. The passive, assisted and resistant rehabilitation training modes are set for individuals in different stages of rehabilitation to realize personalized training. The proposed control strategy designed based on rehabilitation theory was realized in our developed NPU-Wrist rehabilitation robot. In addition, to evaluated the ergonomics design of control strategy of NPU-Wrist robot, the subjective scale was designed based on the Likert scale, and was set up in the order in which the interaction occurred. Subsequently, a questionnaire was administered on the non-probability sample. The statistical analysis of the data by one-way ANOVA found that the device was quite comfortable.

Keywords: Human factor, Wrist rehabilitation, Robot system design, Personalized training

INTRODUCTION

Stroke patients' quality of life is significantly reduced by carpal impairment or hemidisability and the rehabilitation process is very complex, nearly 1/3 of stroke patients still have serious upper limb dysfunction after half a year of rehabilitation treatment (Cakar E, 2016). The rehabilitation process based on individual patient normally be divided according to the recovery stage into multiple levels, and each stage requires different rehabilitation treatment methods. For example, according to the well-used Brunnstrom motor assessment method (Basteris A, 2014), the motor function is divided into six stages from I to VI, and the rehabilitation process of patients can be roughly divided into early, middle and late terms.

As the most frequently used joint of human upper limb, wrist can achieve fine and dexterous movements. If its motor function is damaged, it will seriously affect people's daily life. Rehabilitation training for stroke patients by wrist rehabilitation robot is of great significance for patients to recover their ability of daily life and improve their quality of life. Based on the comprehensive analysis of all kinds of wrist rehabilitation robots, considering the individual adaptability of different patients, the matching of wrist motion law and the patients capabilities in different rehabilitation stages, the existing rehabilitation robots still have limitations and are difficult to meet the patients' individual rehabilitation needs. Therefore, this paper introduces human factors in the design of control strategy of wrist rehabilitation robot, aiming at satisfying patients' requirement of different rehabilitation stages, realizing personalized rehabilitation.

RELATED WORK

A recent area of study combining rehabilitation theory with the rehabilitation robot control system design is a popular research direction. An upper limb exoskeleton neurorehabilitation robot called IntelliArm (Ren Y, 2012), specifically, for passive mode, is position-controlled by receiving the desired velocity generated from the intelligent stretching strategy (ISS). One research proposed a wrist rehabilitation robot with a novel actuation mechanism using an electromagnetic clutch, brake, and motor as well as a safe-related mechanism (Bae, 2019). Additionally, passive rehabilitation mode is a mode in which a robot moves without users' strength. It is measured that the excessive muscle signal is generated through the EMG sensor and is automatically released by the electromagnetic clutch control (free-running).

An impedance control scheme has been implemented for the IIT Genova wrist rehabilitation robot (V. Squeri, 2014), which is used in the assisted training mode. The haptic interaction between the robot and the patients is implemented by a combination of different torques. An assistive torque component helping the subject to carry out the tracking task. ParReEx-wrist abilities for the treatment of patients with upper limb disabilities (Gherman, 2021). The authors target an enhanced control system that is able to achieve an active and assistive control modality. A trajectory tracking control paradigm has been utilized for it in assisted training mode. A cable-driven 3-DOF (degree of freedom) wrist rehabilitation robot was developed to enhance human-robot interaction capabilities (Shi, 2020). Through the assisted training strategy, the patient is subjected to force-feedback and the robot used the impedance control paradigm measures the human-induced joint torque by using force sensors.

CR2-Haptic is a one-DOF rehabilitation robot based on the concept of modularity and reconfigurability has been developed at UTM (K. X. Khor, 2017). More specifically, in resistive mode, the controller generated the resistive force based on the end effector's current position. One research proposed a simple design of a two-DOF balanced and compliant wrist rehabilitation robotic device with serial kinematic configuration (Yellewa, 2022). It integrates impedance control and hybrid position and force control in resistive mode. A novel mechanical proposed in one research has been put out to accomplish a 5-DoF elbow-wrist exoskeleton (Wu, 2019). Additionally, the robot used impedance control in resistance mode, a control method that simultaneously controls force and position.

Human factors and rehabilitation engineering must be connected in the construction of a rehabilitation robot (Hussain, 2021; Zhang, 2020), and a crucial component of that connection is the evaluation of agreeableness. PLUTO - a single DOF robot (Nehrujee, 2020) used System Usability Scale (SUS) and User Experience Questionnaire (UEQ) to evaluate the system and the usability. A comparison between items of the SUS and UEQ questionnaires across groups was carried out through a two-way ANOVA.

However, the robot control strategy associated rehabilitation theory is seldom studied, which hardly realize personalized training with different stage. Aiming at the problems involved in above rehabilitation stages, there are corresponding comprehensive rehabilitation strategies, namely passive, assisted and resistance rehabilitation training. Thus, this paper focus on the control strategies design of wrist rehabilitation robot that meets the requirements of human factors according to the different rehabilitation mechanisms and needs of patients at each stage.

METHODS

The rehabilitation strategy of the robot can be broadly categorized into passive, assisted, and resistance rehabilitation training depending on the various stages of recovery. More specifically, (1) Patients in the first to second recovery stages should use the passive rehabilitation training mode. (2) Patients in the third to fourth recovery stages should use the assisted rehabilitation training mode. (3) Patients in the fifth to sixth recovery stages should use the resistance rehabilitation training mode. Patients who are at various phases of rehabilitation need to exercise using various rehabilitation strategies. Additionally, passive wrist joint rehabilitation exercises for stroke patients in stages I ~ II can enhance wrist blood flow, minimize joint degradation, and lessen wrist muscle spasm symptoms. The supported rehabilitation training of the wrist joint for stroke patients in stages III ~ IV can encourage patients' capacity to move on their own, improve their muscular strength, and restore nerve connections. Resistance rehabilitation training is necessary for stroke patients in stages V ~ VI since they still have inadequate muscle strength, endurance, and coordination compared to normal levels.

The human factors of patients at various rehabilitation stages (defined by Brunnstrom motor assessment method) are introduced into three training modes (illustrated in Figure 1).

Control Strategy Design of Different Training Mode

Hemiplegia Early-Term (Stage I to II)

Patients in the early stages of hemiplegia (stage I ~ II) often have delayed paralysis of the affected limb without any voluntary movement ability. Therefore, CPM training for patients in the early stages of hemiplegia can prevent joint degeneration and treat joint stiffness, prevent joint contracture and soft tissue disuse atrophy. The passive rehabilitation training mode of wrist joint rehabilitation robot mainly includes two forms, that is, passive rehabilitation training with SDOF (single degree of freedom) and passive rehabilitation training with MDOF (multiple degree of freedom) coupling.

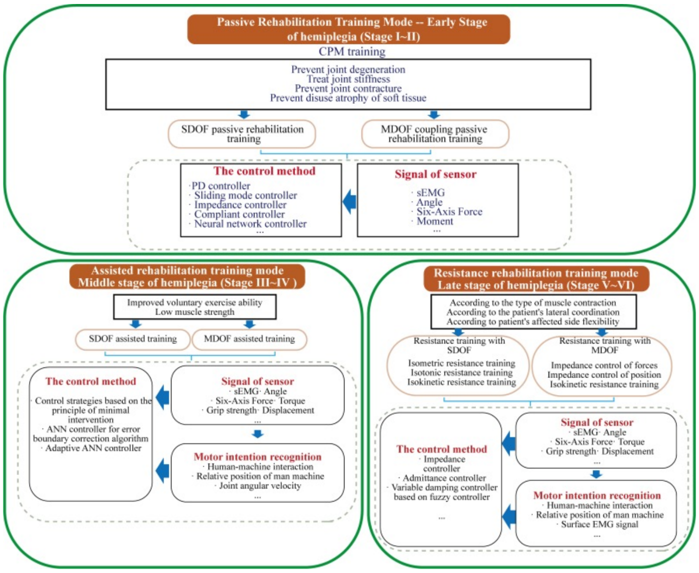

Figure 1: Training modes and related control methods for wrist rehabilitation robot.

In order to realize the passive rehabilitation training mode, it is very important to select the appropriate sensor to transmit the correct sensor signal. The sensors such as torque sensors, six-dimensional force sensors, angle encoders and sEMG signal collectors are mainly used to collect real-time human-computer interaction data. However, in the choice of control method, because of the realization of passive rehabilitation training mode of rehabilitation robot, it is often necessary to control the position of rehabilitation robot, so as to drive the patients to move according to the predetermined trajectory. In the position control of rehabilitation robots, PD controller are frequently used to achieve passive rehabilitation training mode. In order to improve the preset trajectory tracking accuracy, adaptive PD controller, sliding mode controller and other control methods can be widely used. The flexibility of passive rehabilitation training has also attracted attention. For example, impedance controller or compliance controller is introduced, which reduces the accuracy of position control, but improves the comfort and safety of passive rehabilitation training. In order to enhance the participation and initiative of patients, the rehabilitation trajectory judgment method based on sEMG signal can be introduced into the control system, that is, the sEMG signal is used to predict the human intention trajectory, and then the position control is used to realize passive rehabilitation training.

Hemiplegia Medium-Term (III ∼ IV)

In patients with hemiplegia medium-term (stage III ∼ IV), after a series of early rehabilitation treatment, motor nerve system function gradually began to recover and has a certain capacity for independent movement, but the limb muscle strength is still weak, only can finish the small range of motion, is difficult to independently conduct a complete body movement. Therefore, for these patients, assisted rehabilitation training is essential.

In order to realize the assisted rehabilitation training mode, it is not only necessary to select the appropriate sensor to transmit the correct sensor signal, but also to recognize the motion intention of the human wrist joint. The torque sensor, force sensor and angular velocity sensor are adopted to collect the real-time interactive data. The sEMG is used to predict the intention of muscle contraction and contraction, nerve and muscle function. As for the selection of control methods, assist-as-needed control strategies have attracted more and more attention. For example, the ANN controller using Error Bound Modification Algorithm can make patients with strong autonomous movement ability move ahead of the preset trajectory, and the adaptive ANN controller can provide the required auxiliary force according to the recovery degree of different patients. Similar to the ANN control strategy, there is also a control strategy based on the minimal intervention principle to achieve the assisted training mode that does not interfere with patients' voluntary movements as much as possible. The wrist rehabilitation robot mainly judges the current movement intention through the human-machine interaction force or the relative position of the human-machine, so as to provide the minimum auxiliary force to the patient. This control strategy can improve the patient's participation in rehabilitation training and stimulate the patient to carry out voluntary movement.

Hemiplegia Last-Term (V ∼ VI)

In patients with hemiplegia last-term (stage V ∼ VI), after the prophase and metaphase stages rehabilitation training, the ability of patients' movement larger degree of recovery, and can carry on some simple voluntary movement. The resistance training, according to the type of muscle contraction can be divided into the isometric resistance training and constant resistance training. In addition, according to the coordination and flexibility of the patient's affected side, it is necessary to carry out resistance training coupled with degrees of freedom.

Resistance rehabilitation training is helpful to improve the muscle strength and the motor coordination ability of the affected limb. To make the wrist rehabilitation robot realize resistance training is an effective way to help patients recover their motor function to close to the normal level. We select torque sensor, sEMG sensor, angular velocity sensor and six-dimension force sensor to collect real-time human-computer interaction data. In the implementation of resistance rehabilitation training mode, impedance control is a commonly used compliance control strategy. By adjusting or omitting the parameters of impedance controller (inertia coefficient, damping coefficient and stiffness coefficient), resistance rehabilitation training with different control effects and different degrees of difficulty can be achieved. Moreover, according to the rehabilitation mechanism of isokinetic motion, the variable damping controller based on fuzzy controller is an effective method to realize the isokinetic resistance training mode.

Methods Application on NPU-Wrist Rehabilitation Robot

We developed a wrist rehabilitation robot named NPU-Wrist, shown in Figure 2. The entire frame structure of the robot is made of an aluminum

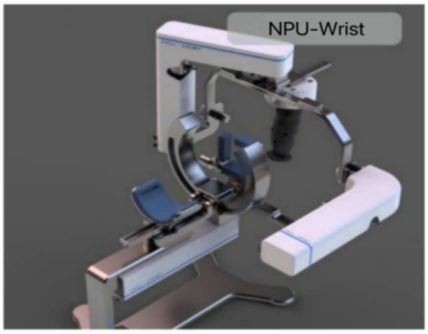

Figure 2: The structure of NPU-Wrist rehabilitation robot.

alloy material in order to make it reliable enough and to meet expectations for a light mechanical construction. The joint parts of the robot are made of stainless steel material, so that it has good fatigue resistance and high processing accuracy. In addition, the motion range of robot joints and the designed adjustable mechanism comply with human body dynamic and static measurement, and the overall mechanism does not appear dislocation and interference.

Based on the motion analysis of the human wrist, the NPU-Wrist rehabilitation robot has three active DOFs to perform flexion and extension, ulnar and radial deviation and pronation and supination. The three active DOFs can move independently as well as perform multi-degree coupling motion in order to satisfy the patients' needs for motor function. Besides, NPU-Wrist rehabilitation robot fitted with a range of sensors, such as angular velocity sensor, six-dimension force sensor to track the user's health throughout rehabilitation training, record the user's physiological data, and acheive various rehabilitation control strategies.

Apply Control Strategy in the NPU-Wrist Robot

1. The control method of passive rehabilitation training mode

Aiming at the passive rehabilitation training mode of wrist joint, firstly, the kinematics model of NPU-Wrist robot is established. Combined with the motion characteristics of human wrist joint, the space trajectory planning method is established based on the "dart thrower motion" law of wrist joint, and the trajectory tracking control is realized. The trajectory of the robot integrates the functional movement characteristics of wrist joint, which meets the requirements of passive rehabilitation and improves the comfort of patients. The Figure 3 is a control block diagram for one of the degrees of freedom. Where $\theta\ d\ (k)$ represents the expected trajectory of the k^{th} sampling point, $\theta\ a\ (k)$ signifies the actual joint angle, $\theta\ d\ (k)$ and $\theta\ a\ (k)$ are compared to get $e(k)$, and $\tau\ (k)$ indicates the output joint torque.

2. The control method of assisted rehabilitation training mode

Aiming at the wrist assisted rehabilitation training mode, a resistance control strategy based on motion intention recognition is established. Firstly,

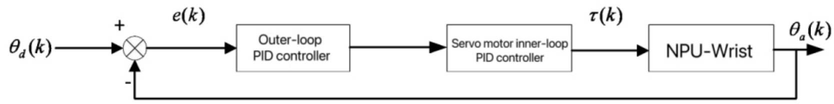

Figure 3: The block diagram use the outer-loop PID controller position control.

the surface electromyography (sEMG) signal is selected as the basis of wrist motion intention prediction. By using the sEMG signal, human-machine contact force and joint angle, the wrist output torque prediction algorithm based on neural network is established. The predicted torque is transformed into position compensation and introduced into the control loop. This control strategy improves the problem of power lag response in traditional control method.

The corresponding control block diagram used in NPU-Wrist was shown in Figure 4, in which *EF* represents the difference between expected auxiliary force *Fd* and the actual man-machine contact force *Fr*. *KP*,*KI* and *KD* represents the proportional, integral and differential gain of the PID controller respectively, while *dθ E* denotes the robot joint corner increment obtained by the PID controller. The robot joint actual angle *θ r* is input into established joint torque prediction model based on sEMG signal, which calculates the prepredicted wrist output torque *TsEMG*. *T* indicates the sum of *TsEMG* and expected auxiliary torque *TF*,which is calculated by hand length *L* and expect auxiliary force *Fd*. *KsEMG* indicates the proportional coefficient related to the human inertia and the sampling time, while *dθsEMG* denotes the feedforward increment of position control. Δ*θ* is the expected rehabilitation robot joint corner increment, which is generated by the sum of joint corner increment *dθE* obtained by the PID controller and *dθsEMG* predicted by sEMG.

3. The control method of resistance rehabilitation training mode

According to the resistance rehabilitation training mode of wrist joint, the control methods of isotonic, isometric and isokinetic rehabilitation training are established respectively. The isometric strength resistance training of wrist joint is realized by using the position control of single joint under different angles. Secondly, the isotonic muscular force resistance training is realized by using the force control method. The isokinetic resistance training of

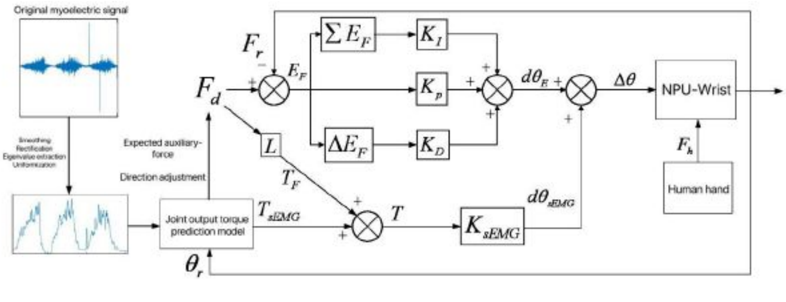

Figure 4: The control block diagram of the assisted rehabilitation training mode.

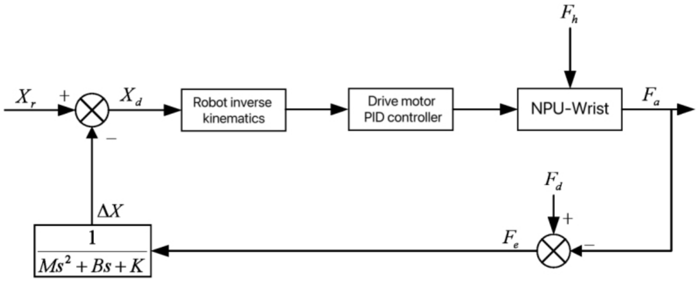

Figure 5: The block diagram of the position-based resistance control.

wrist joint is realized based on the torque angle coupling relationship model. Through the design and implementation of the controller under different rehabilitation training methods, the personalized rehabilitation requirements of different patients are met. Moreover, to realize the multi DOFs coupling wrist resistance training, a position-based resistance control method is applied on the NPU-Wrist robot (shown in Figure 5).

In Figure 5, *Fa* indicates the measured man-robot contact force after human put force *Fh* on robot. *Fe* is the force error between the expected contact force *Fd* and actual contact force *Fa*, which is the input of out-loop impedance controller to obtain the update position increment ΔX. For the impedance controller, *M, B, K* represents the inertia matrix, the damping matrix, and the stiffness matrix, respectively. The final end-effector desired position *Xd* is calculated by initial expected position *Xr* and update position increment ΔX.

RESULT

Evaluation Scale Design

The subjective evaluation scale based on a five-point Likert scale was designed for the system ergonomics assessment of our NPU-Wrist rehabilitation robot, which is focus on the control system performance. The five levels of questionnaire options are: “very dissatisfied”, “relatively dissatisfied”, “average”, “relatively satisfied “and “very satisfied”. The scale consists of 8 questions, and the order of these questions is oriented to the sequence of the interaction. The overall sample size for this study was 9 participants, with 3 participants in each group. The groups were divided according to the rehabilitation process of the patients mentioned above.

Statistical Analysis

The boxplot in Figure 6 shows the median of the collected data, which represents the average level of the sample data. The width of the box reflects the fluctuation of the data. It can be noticed that the box is not present in question 2. The reason is that there are too many identical numbers in the data and the overall average is close to the same number. The evaluation results between the three groups were compared using one-way ANOVA. Before conducting ANOVA, all data in this study were tested for normality and

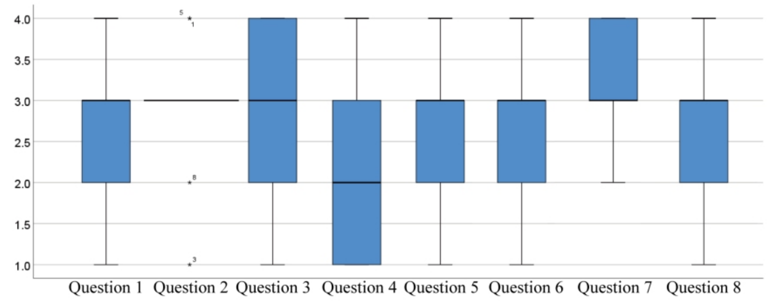

Figure 6: Boxplot for all data.

homogeneity of variance. More precisely, the former used the Shapiro-Wilk test, and the latter used Levene's test. The above operations were based on the software SPSS.

In S-W test, if the result shows $P > 0.05$, the data will be normal. On the contrary, it indicates that the data is not normal. In this test, P is 0.102, 0.068, 0.172, 0.122, 0.132, 0.248, 0.055, and 0.132 respectively, which are all greater than 0.05. It can be seen that the data obeyed normal distribution. Then, the homogeneity of variance test was performed. This test is based on the median because the data obtained by testing based on the median is relatively more stable. If $P < 0.05$, the level of significance is considered to be reached in Levene's test, which is uneven variance. In the test, P is 0.579, 0.492, 0.702, 0.746, 0.850, 0.824, 0.729, and 0.850,

which are all greater than 0.05. So, the variance is homogeneous. Finally, one-way ANOVA is performed. The significance among all groups is greater than 0.05 (see Table 1), so it can be concluded that the system usability assessment is not significantly affected by the groups.

The Results of the Ergonomics Assessment

A total of 9 stroke patients were recruited, 4 males and 5 females. For their recovery process, three patients were in the early term (stage I~II), three patients were in the middle term (stage II~V), and three were in the late term (stage V~VI). The distribution of responses from patients in the three terms is shown in Figure 7, where scores from 0 to 4 are indicated by different colors, with red presents 0 and green corresponding to 4, deeper green indicates a higher positive evaluation of the problem (ARAVIND NEHRUJEE, 2021). It can be seen that everyone involved in the experiment was relatively satisfied with the NPU-Wrist robot's performance.

Table 1. One-way ANOVA.

Question	F	P	Question	F	P
1	1.091	0.394	5	0.375	0.702
2	0.444	0.661	6	0.538	0.609
3	0.583	0.587	7	1.4	0.317
4	0.176	0.842	8	0.375	0.702

Figure 7: The distribution of attitudes towards the same question among the three groups.

CONCLUSION

This paper constructed the methodological framework diagram and applied ergonomics to the control strategy of wrist rehabilitation robot. Apart from that, passive, assisted and resistant rehabilitation training modes are set for individuals in different stages of rehabilitation to realize personalized rehabilitation training. Different patient rehabilitation stage features were introduced into the control strategy installation. Additionally, we applied our design concept in the control strategy of NPU-Wrist rehabilitation robot. Finally, to evaluate the robot's ergonomics design, the subjective scale was designed based on the Likert scale. Statistical analysis of the data by one-way ANOVA found that the device was quite comfortable. Our developed NPU-Wrist involves human factors throughout the control strategy design process provides a valuable approach for subsequent rehabilitation robots. In subsequent studies, we will gather more samples in order to do ergonomics evaluation more thoroughly and objectively.

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