Poster Abstract of Digital-twin-based Decision Support During Personalized Robotic Rehabilitation

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***Abstract*—Rehabilitation after a stroke requires personalized interventions, traditionally relying on physiotherapist expertise. Robotic rehabilitation systems, though promising, have not fully utilized expert systems for dynamic task tailoring. The introduced decision support system, based on digital twin technology, integrates a motor control model capturing patient perceptions. The dynamic digital twin continuously updates based on task performance, ensuring precise assessments and improved adaptation. It plans customized rehabilitation tasks, reducing uncertainty and improving patient's adaptation during rehabilitation. The digital twin framework and the task planning algorithms were validated using human subject and simulation experiments. Our findings affirm that adaptive task planning, steered by the patient's digital twin, offers superior efficiency and outcomes compared to static approaches. It showcases an intelligent healthcare environment for personalized and effective stroke rehabilitation.**

***Index Terms*—Digital twins, Rehabilitation robotics, Personalized medicine**

I. Problem Description

Cerebral stroke, a serious medical emergency, results in brain tissue damage due to disrupted blood flow. As the second leading global cause of death, stroke significantly contributes to disabilities.

Post-stroke patients commonly face motor impairment in the contralateral forearm,including weakness and spasticity of the affected muscles [1], hindering daily activities. Fortunately, physical rehabilitation training offers a promising avenue for restoring motor function. Patients engage in repetitive tasks aimed at specifically-designed targets [2], addressing movement errors through short-term improvements via neural *adaptation* [3]. This process induces neuroplasticity, leading to long-term enhancements in motor function [4]. Overall, the rehabilitation process enables healthy brain areas to take on functions previously performed by damaged regions, facilitating the recovery of motor capabilities.

Rehabilitation therapies currently rely on physiotherapist expertise, leading to outcome variations. Robotic rehabilitation, with its precise movements, aims to reduce dependency on human intervention for more efficient recovery [5]. Despite advancements, the manual design of rehabilitation tasks by physiotherapists remains time-consuming and subjective, prompting exploration of automatic task planning, which faces three key challenges.

Challenge 1: Patient Evaluation

Current patient evaluation methods using offline assessment scales struggle to track rapidly changing cognition states in real-time. Additionally, inferring motor control models from a patient's performance presents a complex, ill-posed problem. For a specific patient, his/her neural impairment S can be assessed such that:

$$S^* = \arg\min_{S} \|\tau_{max}^{[t_0,t_1]} - \bar{\tau}_{max}^{[t_0,t_1]}(S)\|_2^2 \tag{1}$$

where S^* is the optimal estimation of neural impairment and τ_{max} is the ground truth of maximum moment. It is assumed that τ_{max} is derived from the torque of the rehabilitation robot during patient interactions.

Challenge 2: Impairment Awareness

It is essential to track and monitor patients' perception of their own neural impairment and ”guide” them towards a more accurate understanding of their condition. The motor performance J, which is derived from the optimally estimated cognitive state $\bar{S}^*$, should align as closely as possible with that derived from the ground truth $\hat{S}$ across all tasks:

$$\bar{S}^* = \arg\min_{\bar{S}} \|J(\bar{S}) - J(\hat{S})\|_2^2 \tag{2}$$

Challenge 3: Compensation Prevention

It is important to prompt the achievement of short-term adaptation when the perceived neurological damage $\hat{S}$ matches the actual neurological damage S, while tracking accurately the patient's state $\hat{S}$,. Given a specific patient with neural impairment S and initial cognition State $\hat{S}^{(0)}$, find an optimal task sequence $Task = [task^{(0)}, ..., task^{(k)}]$ such that the estimated cognition state $\bar{S}$ can approach $\hat{S}$ as quickly as possible, on which basis $\hat{S}$ can then approach S as quickly as possible, i.e.

$$\begin{aligned} Task^* = \arg \quad & \min_{Task} |Task| \\ s.t. \quad & |\bar{S} - \hat{S}| < \epsilon_1, \\ & |\hat{S} - S| < \epsilon_2 \end{aligned} \tag{3}$$

where $|Task|$ is the number of tasks contained in the sequence and ϵ_1, ϵ_2 denote the allowable error.

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II. Conclusion

The poster introduces a digital-twin-based decision support framework for patient evaluation and adaptive task planning in robotic rehabilitation. It incorporates a motor control model to capture patient understanding and performance. Neural impairment, assessed through muscle spasticity and weakness (Response to Challenge 1), along with the patient's perception of impairment (Response to Challenge 2), is used to create a motor control digital twin. To ensure real-time performance in the framework computation, we endeavored to utilize neural networks to approximate the representation of complex musculoskeletal forward dynamics. The digital twin is then employed for planning customized rehabilitation tasks, aiming to reduce uncertainty, prevent compensation, and maximize adaptation efficiency (Response to Challenge 3). Our framework exemplifies an intelligent environment in health, offering personalized, efficient, and effective solutions for stroke rehabilitation.

We have verified the efficacy of our framework in capturing the forward dynamics of subjects' motor control through experiments. To closely replicate a stroke patient with forearm muscle spasms, we employed healthy subjects and applied electrical stimulation to the corresponding muscle groups. Subsequently, the task planning algorithm was validated on these approximated stroke patients. We conducted the experiment with the participation of 10 subjects, who performed a set of 50 tasks using three different task strategies:

1) **Adaptive Task Sequence:** This sequence is computed within our framework.
2) **Fixed Task Sequence ([20,-20]):** A fixed task sequence with tasks ranging from -20 to 20 was employed.
3) **Adaptive Task Sequence (Adaptation-only Ablation):** This sequence was specifically designed for optimizing adaptation efficiency without considering state tracking.

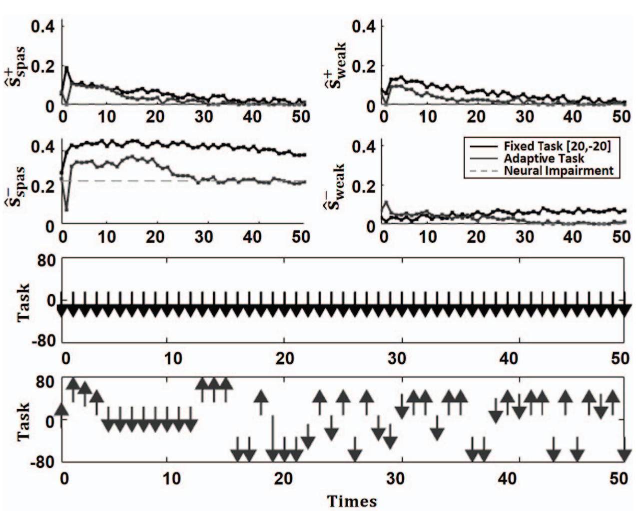

Fig. 1. Adaptive task planning can better identify gradient towards the neural impairment parameter.

Figure 1 visually compares adaptive and fixed tasks for subject, with biceps spasticity ($S^{-}_{spas} > 0$). In adaptive tasks (lighter line), the curves representing the ground truth $\hat{S}^{(t)}$ of the virtual patient converge towards the neural impairment state S (represented by the dashed line) after 50 tasks, while in fixed tasks (darker line), the lack of a discernible gradient indicates a deficiency in adaptability.

Adaptive task planning serves to prevent compensation behaviors, as depicted in Figure 2. In the [20, 60] task, patients performed similarly well. However, in the [-20, -60] task, patients who underwent fixed task training exhibited significantly poorer performance, indicating the presence of compensation behaviors. Conversely, patients undergoing adaptive task training consistently demonstrated excellent performance across all tasks, indicating highly effective adaptation.

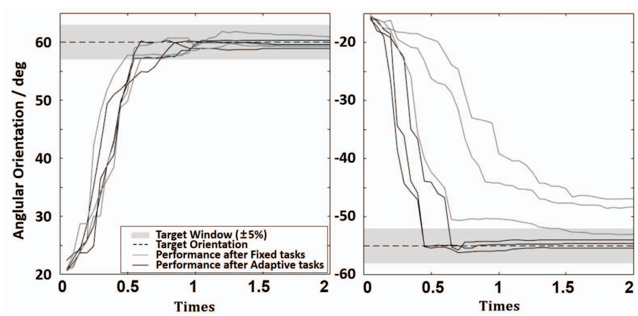

Fig. 2. Adaptive task planning avoids "local maximum" compared to fixed tasks.

Our experimental results show that adaptive task planning, guided by the patient's digital twin, outperforms fixed task planning in both efficiency and effectiveness in robotic stroke rehabilitation. This highlights the potential of our approach to enhance outcomes for stroke patients. Future enhancements include incorporating assistance/resistance forces for a nuanced rehabilitation approach and extending the framework to accommodate multiple degrees of freedom movements. These developments will be validated through clinical trials, aiming to continually improve the efficiency and effectiveness of robotic stroke rehabilitation for enhanced patient outcomes and quality of life.

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