DBR-TILT: A Novel Direct Biomechanics Reflecting Therapist-in-the-Loop Telerehabilitation System

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Abstract*—Telerehabilitation robotic systems have the potential to enhance the efficiency and convenience of recovery training for poststroke patients. However, most state-of-the-art telerehabilitation systems rely on indirect teleassessment methods based on the patient's task tracking performance, which is hard to distinguish the actual biomechanical state of the patients, thereby limiting clinical applications. Remote biomechanical perception of the patient's recovery state remains a key challenge in the teleassessment and diagnosis of telerehabilitation. To this end, a novel Direct Biomechanics Reflecting Therapist-In-the-Loop Telerehabilitation (DBR-TILT) system is proposed in this article, which enables therapists to remotely perceive patients' active biomechanical states, enhancing teleassessment capabilities. To achieve transparent remote therapist-patient interaction, an improved wave compensation structure is presented to enhance the position/force tracking performance of the bilateral teleoperation. Moreover, a power-based time domain passivity controller with a pair of passivity observers and controllers was developed to ensure the passivity of the overall DBR-TILT system. A series of comparison experiments were conducted and validated that the proposed DBR-TILT system can provide high-fidelity performance of remote biomechanical perception for therapists. By leveraging the proposed DBR-TILT, the patients can benefit from effective telerehabilitation and teleassessment over long distances, potentially improving the actual clinical application of telerehabilitation.

***Index Terms*—Direct biomechanics reflecting, method, passivity control, teleassessment, therapist-in-the-loop telerehabilitation, transparency, wave compensation, wave-based teleoperation.**

Received 13 August 2024; revised 8 January 2025, 10 April 2025, and 24 June 2025; accepted 19 October 2025. Recommended by Technical Editor M. Boudaoud and Senior Editor C. Clevy This work was supported in part by SPS KAKENHI under Grant 15K2120 and in part by China Postdoctoral Science Foundation under Grant 2024M751091. *(Corresponding authors: Shuxiang Guo; Lei Ren; Zhihui Qian; Ruochen An.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board at the Faculty of Engineering, Kagawa University under Application No. 01-011, and performed in line with Helsinki Declaration.

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Color versions of one or more figures in this article are available at https://doi.org/10.1109/TMECH.2025.3627075.

Digital Object Identifier 10.1109/TMECH.2025.3627075

I. Introduction

ROBOTIC-AIDED rehabilitation system has been developed in recent years due to their capability to deliver precise and repetitive therapeutic motions for post-stroke patients [1]. In particular, home-based telerehabilitation robotic systems allow patients to perform predefined training tasks at home, enhancing training convenience and efficiency [2]. As interventional treatments from professional therapists are indispensable in real clinical scenarios to satisfy the individual-specific conditions of each patient, the therapist-in-the-loop telerehabilitation (TILT) systems have been developed by the leader-follower teleoperation frameworks, in which the remote therapist-patient interaction (RTPI) could be enabled [3]. However, the transmission of the position/force variables under the internet communication latency potentially leads to stability problems [4].

To address this issue, teleoperation technologies have been employed to maintain the stability of telerehabilitation systems under time-delay conditions, such as position-force (P-F) [5], or position/force-position/force (PF-PF) [6], among others. The notation A-B (A, B = P, F, PF) used here and throughout refers to A to the signal(s) of therapists sent from the leader to the follower side and vice versa. State-of-the-art TILT systems can be categorized into patient-guiding RTPI and patient-following RTPI methods based on the distinct teleoperation frameworks. In the patient-guiding method, patients perform predefined training tasks with assistance from the follower robot, while therapists provide support remotely via the leader robot. In contrast, the patient-following method enables patients to track the therapist's training movements using the follower robot, while therapists can feel and adjust the training in real time based on haptic force feedback from the patient's side [7]. Although both RTPI methods can achieve stable TILT training under communication delay, efficient teleassessments of therapists remain a significant challenge for TILT system.

In terms of remote perception and assessment by therapists, the haptic feedback methods in state-of-the-art TILT systems primarily include direct contact force-based feedback [8] and task performance-based feedback [9]. For the task performance-based feedback method (typically using the F-P or P-P framework), Atashzar et al. [10] considered the overall TILT system as a time-domain passivity network (TDPN) and proposed a modulated time-domain passivity control (M-TDPC) approach to provide direct therapeutic force to patients. In this system, therapists could perceive velocity-error-based impedance force feedback through a stabilizer. Moreover, a small-gain-theory-based control approach was developed for further dealing with the nonpassive behaviors of therapists and patients to improve the conservation of the stabilizer [11]. Paik et al. [12] presented a power-based velocity-domain variable structure passivity signature control in the F-P framework for the TILT system. This concept involved designing a nonlinear stabilizer to replicate therapist assistance while ensuring stable modification. These studies employed the F-P framework with a stabilizer to address unstable position/force transmission, enabling stable RTPI and kinesthetic impedance force feedback. Bauer et al. [13] developed an adaptive impedance control for an F-P framework bilateral rigid-exoskeleton TILT system to achieve compliant RTPI training. Sharifi et al. [14] proposed a nonlinear bilateral model reference adaptive control with bimodal interactive characteristics including "hands-over-hand" and "adjustable flexibility" modes, to achieve stable task performance-based force feedback. While the stability approaches are different among these task performance-based feedback methods, the position-error-based force (PEBF) feedback remains necessary for the therapist to perceive the patient's training task performance, simplifying the teleassessment. However, this is an indirect perception approach that lacks the details of the patient's actual biomechanical state and physical human-robot interaction (pHRI) conditions [15]. On the other hand, Zhang et al. [16] developed a shared model-based TILT system within the P-F framework, using a serial elastic actuator-driven robot on the patient side to enable compliant pHRI. The physical patient-robot interactive force was directly transmitted to therapists. Liu et al. [17] designed a velocity-domain stabilizer-based TILT system in the P-F framework, in which the patients could be assisted in tracking the task trajectory of the therapists by the variable stiffness actuators (VSA) integrated robot. Therapists could perceive complaint patient-robot interactive force feedback. The direct contact force feedback method renders the needed assistance level for the therapist to indirectly evaluate the patient's recovery progress. These studies have significantly advanced safe and stable TILT training under time delays for telerehabilitation. However,

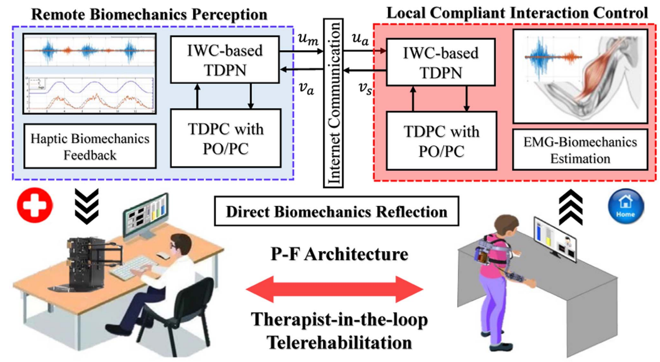


Fig. 1. Concept of the proposed DBR-TILT system.

therapists can only assess patient states based on task tracking performance or assistance levels without directly perceiving the states of the patient's impaired limb, making recovery effects difficult. In our recent study, we introduced state-switching remote therapist-patient interaction control (S^2-RTPIC) with a novel three-channel position–position/stiffness framework. This framework transmits the surface electromyography (sEMG) driven stiffness variables to adjust the impedance interaction model on the therapist side, enabling remote biomechanical perception of the patient's impaired limb [18]. However, the absolute stability criterion of S^2-RTPIC imposes a minimal damping force requirements for overall stability due to the position-based impedance model, potentially reducing biomechanical perception fidelity.

Based on the abovementioned discussion, we argue that the direct haptic feedback of the patient's impaired limb biomechanical states provides an intuitive solution for enhancing therapist perception and enabling efficient teleassessments. In this article, we propose a novel direct-biomechanics-reflecting therapist-in-the-loop telerehabilitation (DBR-TILT) system with a two-channel P-F architecture. The proposed DBR-TILT system directly transmits the patient's elbow biomechanical torques to the therapist's side, enabling remote perception and evaluation of the biomechanical states of the patient's affected limb, thereby facilitating teleassessment and telerehabilitation, as illustrated in Fig. 1.

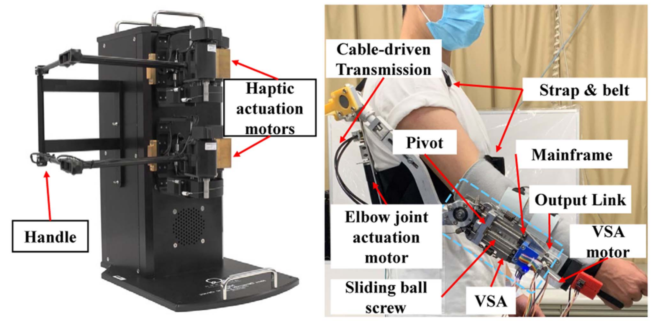
The rest of this article is organized as follows. The related two-channels P-F framework of the teleoperation systems will be reviewed to illustrate the technical contributions in Section II. The overall of the proposed DBR-TILT system was introduced in Section III. The improved wave compensation (IWC) based TDPC approach for remote biomechanics perception will be presented in Section IV. Experimental results and discussion were given in Sections V and VI. Finally, Section VII concludes this article.

II. Related Works of the P-F Framework Teleoperation System

Since the P-P architecture fails accurately reflect the real contact force between the follower robot and the patient, the P-F architecture provides an effective alternative by transmitting measured force from the follower to the leader side [19]. In P-F framework teleoperation system, the energy/power-based TDPC method has been developed, in which a pair of passivity observer (PO) and passivity controller (PC) are designed to monitor and modify the transmission variables to maintain passivity under the asymmetric time-delay [20]. Furthermore, the classical wave variable method was subsequently introduced to prevent energy mismatching by converting the power-conjugated variables into wave variables pairs [21]. However, the wave reflections of the transmitted wave signals at both leader and follower side caused oscillation and degraded transient response [22]. To address this limitation, the four-channel PF-PF architecture was developed to achieve transparent force/position tracking performance, and even fully transparent tracking under time delay conditions [23]. Considering that the zero time-delay condition is impossible in practical applications, Sun et al. [24] integrated TDPC with the four-channel PF-PF architecture to improve tracking transparency while keeping overall system stability. Due to limited internet bandwidth, minimal communication variables should be used for better robustness. Achieving transparent teleoperation with minimal communication port requirements is a reliable solution for robust practical application. For this purpose, Li et al. [25] presented a wave compensation (WC) structure for the P-F framework to improve the position/force tracking performance. However, since the power-conjuncted variables cannot be decoupled by the wave variables in the WC structure, a pair of overconservative energy reservoirs was designed, which is hard to modify the passivity of overall system precisely. Moreover, potential position drift issues caused by velocity-error accumulation may occur, affecting transparency performance.

Inspired by the aforementioned works, the P-F framework was selected to directly transmit the patient's biomechanical force to the therapist's side in the proposed DBR-TILT system. It should be noted that the P-F framework is used in this article, but the backward transmitted force variable is sEMG-driven biomechanical force of the patient's affected limb rather than the patient-robot contact force. The main challenges of the two-channel P-F framework-based DBR-TILT system can be summarized as follows: achieving precise position/force tracking performance of wave-variable-based teleoperation to enable high-fidelity remote biomechanical perception and facilitate teleassessment. To address this issue, we propose an IWC-based TDPC approach for DBR-TILT system. In the proposed IWC structure, the power-conjuncted variables can be derived from wave variables, allowing for the implementation of a pair of TDPN-based PO and PC to achieve precise position/force tracking maintaining the passivity of the overall system under time delays. The main technical contributions of this article are summarized as follows.

1) DBR-TILT is the first work to achieve high-fidelity remote biomechanical perception by directly transmitting the sEMG-driven biomechanical forces for teleassessment.
2) Leveraging the precise wave transformation performance of the proposed IWC structure, DBR-TILT system achieves high transparency in position tracking and force feedback under the minimal channel conditions of bilateral teleoperation.
3) The passivity of the overall DBR-TILT system with the proposed IWC-based TDPC approach is proven by both theoretical analysis and experimental results, further ensuring its stability and safety.



(a) (b)

Fig. 2. Leader and follower robots utilized in the DBR-TILT system. (a) Quanser HD^2 device as leader side robot. (d) PVSED as follower side robot.

III. Overall of the Proposed DBR-TILT System

A. Configuration of the DBR-TILT System

To implement the proposed DBR-TILT, the system adopts a leader-follower teleoperation framework. A six degree-of-freedoms (DOF) haptic-enabled manipulator (HD^2, Quanser Inc., Canada) is employed as the leader-side robot to record the real-time therapist kinematic data and render haptic feedback on the patient's biomechanical states. The HD^2 is a teleoperation platform that provides high-fidelity haptic interfaces, allowing manipulators to interact with remote environments via programmable haptic feedback [26]. It is equipped with six dc motors and high-resolution optical encoders, enabling precise and dexterous haptic interaction. On the follower side, the powered variable stiffness exoskeleton device (PVSED) described in [27] is employed, incorporating one active DOF at the elbow joint to provide compliant assistive interaction for patients. The PVSED independently actuates elbow flexion/extension and adjusts joint stiffness through its main joint actuation system and a VSA system. The main actuation system delivers joint torque via a cable-driven mechanism powered by a compact dc motor (Maxon RE-30 graphite brushes motor). The VSA system, integrated into the PVSED mainframe, utilizes antagonistic springs connected by a pulley and lever to modulate joint stiffness. This setup transfers torque from the mainframe to the output link, assisting patient movements, as illustrated in Fig. 2.

B. Dynamic Models of the Leader–Follower Robots

The dynamics of the leader robot can be described as the nonlinear dynamics of the n-DOF manipulator. On the follower side, the dynamics of the PVSED can also be simply described by a set of nonlinear dynamic equations to express both the robot dynamic and the independent VSA part dynamics based on our previous study [28]. Assuming the gravity has been compensated on both leader and follower robots, the gravity-compensated leader and follower dynamics are given as follows:

$$M_m\left(q_m\right)\ddot{q}_m + C_m\left(\dot{q}_m, q_m\right)\dot{q}_m = \tau_m + \tau_T \tag{1}$$

$$M_s\left(q_s\right)\ddot{q}_s + C_s\left(\dot{q}_s, q_s\right)\dot{q}_s = \tau_{VSA} + \tau_P \tag{2}$$

$$\tau_{\text{VSA}} = K_{\text{VSA}} \cdot \left(\theta_1 - q_s\right) \tag{3}$$

where $\ddot{q}_i \in \Re^n$ $\dot{q}_i \in \Re^n$ $q_i \in \Re^n$ (i = m, s stand for leader or follower) in (1) and (2) are the output joint acceleration, velocity, and position of the leader and follower robots. $M_i(q_i) \in \Re^{n\times n}$ is the inertial term, $C_i(\dot{q}_i, q_i) \in \Re^n$ is the Coriolis term. $\tau_T \in \Re^n$ and $\tau_P \in \Re^n$ are the therapist and patient torques. $\tau_m \in \Re^n$ is the torque control term of the leader robot, and $\tau_{\text{VSA}} \in \Re^n$ is the VSA torque control term of the follower robot. The VSA dynamics is described as (3) in which $\theta_1 \in \Re^n$ is the angle position of the mainframe of the VSA. In our previous study, a PID controller was implemented in the mainframe actuator system, which converted the torque control to the position control of the rotation angle θ_1 of the mainframe of the VSA [29].

IV. IWC-Based TDPC Approach for Remote Biomechanical Perception

A. sEMG-Based Muscle Contraction Dynamics Estimation

The sEMG signals reflect the muscle contraction level, the human joint angles [30], and torques [31]. The relationship between the sEMG signals and the patient's active torque of the elbow joint can be expressed by a set of nonlinear functions δ_r relating the muscle activation levels (A_e and A_f) of a pair of antagonistic muscles (biceps and triceps for the elbow joint) and the elbow angle θ_{elbow}, as follows:

$$\tau_{\text{EMG}}\left(t\right) = a_\tau \cdot \delta_r\left(A_e, A_f\right) \tag{4}$$

$$\delta_r\left(A_e, A_f\right) = \frac{a_\delta\left(1 - e^{-b_\delta\left(A_f - A_e\right)}\right)}{1 + e^{-b_\delta\left(A_f - A_e\right)}} \tag{5}$$

$$A_i\left(u_i\right) = \frac{e^{m\cdot u_i} - 1}{e^{u_i} - 1} \tag{6}$$

where a_τ, a_δ, and b_δ are the constants and δ_r is a nonlinear function given in (5). As the elbow joint angle and human body parameters are unnecessary, this model is simpler than the model in [32]. Benefiting from this simplified sEMG-driven active torque model (see Fig. 3), the overall model calibration is simplified, thereby avoiding a time-consuming parameter identification process. Using (4) and (5), the patient's active torque τ_{EMG} of the elbow joint can be estimated in real-time using the sEMG signals of the biceps and triceps, which will be utilized for remote biomechanical perception.

B. Improved Wave Compensation Method

As the proposed DBR-TILT system requires the transmission of the therapist's kinematic information and the patient's active

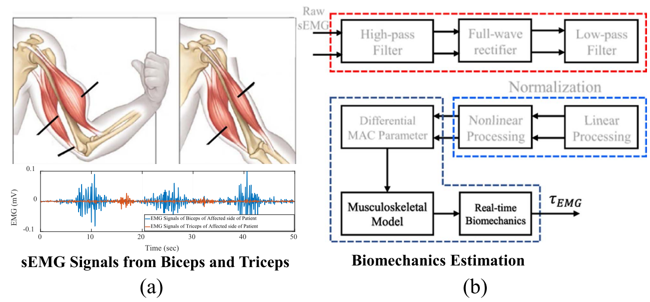


Fig. 3. sEMG-based musculoskeletal model. (a) Illustration of muscle contraction. (b) Calculation processing.

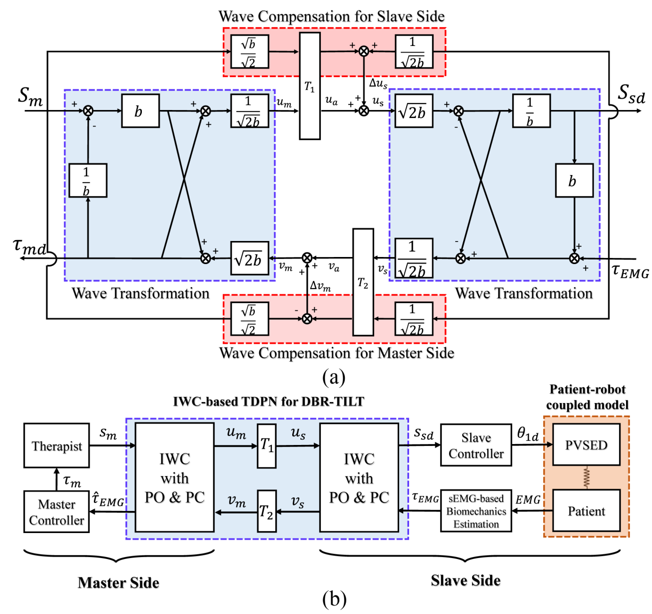


Fig. 4. TILT system architecture. (a) Proposed IWC structure. (b) Overall framework of DBR-TILT system.

force information, the wave compensation method with the P-F framework proposed in [25] was selected in this study. Considering the potential position drift issue of the original WC method due to velocity error accumulation, we improved the forward feed wave variable and follower control input to compensate for the position drift by a sliding variable of a weighted sums of the velocity and position. The sliding variables of both the leader and follower sides are defined as

$$s_m\left(t\right) = \dot{q}_m\left(t\right) + \lambda \cdot q_m\left(t\right) \tag{7}$$

$$s_s\left(t\right) = \dot{q}_s\left(t\right) + \lambda \cdot q_s\left(t\right) \tag{8}$$

where λ is a positive constant. A novel wave compensation structure was designed, as shown in Fig. 4. Therefore, the forward wave variable $u_s(t)$ and backward wave variable $v_m(t)$ are defined as follows:

$$u_s\left(t\right) = u_a\left(t\right) + \Delta u_s\left(t\right) = u_m\left(t - T_1\right) + \Delta u_s\left(t\right) \tag{9}$$

$$v_m\left(t\right) = v_a\left(t\right) + \Delta v_m\left(t\right) = v_s\left(t - T_2\right) + \Delta v_m\left(t\right) \tag{10}$$

where $u_a(t)$ and $v_a(t)$ are the T_1/T_2 delayed transfer wave variables. $\Delta u_s(t)$ and $\Delta v_m(t)$ are the wave compensation terms of forward and backward wave variables, respectively, given as follows:

$$\Delta u_s(t) = \sqrt{\frac{b}{2}}\, s_m(t-T_1) + \frac{1}{\sqrt{2b}}\tau_{\text{VSA}}(t) \tag{11}$$

$$\Delta v_m(t) = \frac{1}{\sqrt{2b}}\tau_{\text{VSA}}(t-T_2) - \sqrt{\frac{b}{2}} s_m(t) \tag{12}$$

where b is wave impedance, which balances the stability and transparency of the teleoperation system. To achieve a transparent therapist-patient remote interaction, b is set as 1 in this study. With the aid of the proposed IWC structure, the transmission of the forward and backward signals can be derived as

$$s_{sd}(t) = \hat{s}_m = s_m(t-T_1) \tag{13}$$

$$\tau_{md}(t) = \hat{\tau}_{\text{EMG}} = \tau_{\text{EMG}}(t-T_2). \tag{14}$$

Benefiting from the improved wave compensation structure, the sliding variable of the leader side and the patient's biomechanical torques are transferred to the therapist's side to eliminate the force/position drift issue, as derived in (13) and (14). If the communication latency T_1 and T_2 are equal to 0, the ideal transparency performance can be achieved.

C. Passivity Analysis and Power-Based TDPC Approach

To analyze the passivity of the P-F architecture with the proposed IWC method, the forward and backward wave compensation variables should be simplified by the modified form as follows:

$$\Delta u_s(t) = u_m(t-T_1) + v_s(t) \tag{15}$$

$$\Delta v_m(t) = v_s(t-T_2) - u_m(t). \tag{16}$$

Then, the wave variables of (14) and (15) can be expressed as

$$u_s(t) = 2u_m(t-T_1) + v_s(t) \tag{17}$$

$$v_m(t) = 2v_s(t-T_2) - u_m(t). \tag{18}$$

Thus, the input and output variables of the IWC-based TDPN can be expressed by the wave variables as

$$s_m(t) = \sqrt{\frac{2}{b}}\, u_m(t), \tau_{md}(t) = \sqrt{\frac{b}{2}}(v_m + u_m) \tag{19}$$

$$s_{sd}(t) = \frac{1}{\sqrt{2b}}(u_s - v_s), \tau_{\text{EMG}}(t) = \sqrt{2b}\, v_s. \tag{20}$$

Therefore, the total power flow $P(t)$ of the dissipated energy in the IWC-based TPDN is given as

$$\begin{aligned}
P(t) &= s_m(t)\,\tau_{md}(t) - s_{sd}(t)\,\tau_{\text{EMG}}(t)\\
&= \sqrt{\frac{2}{b}}\, u_m(t)\cdot\sqrt{\frac{b}{2}}(v_a - u_m) - \frac{1}{\sqrt{2b}}(u_a - v_s)\cdot\sqrt{2b}v_s\\
&= u_m(t)\cdot(v_a - u_m) - (u_a - v_s)\cdot v_s\\
&= \frac{1}{4}(u_m(t) + v_s(t-T_2))^2 + \frac{1}{2}u_m(t)^2 - \frac{1}{2}v_s(t-T_2)^2\\
&\quad + \frac{1}{2}(v_s(t) - u_m(t-T_1))^2 + \frac{1}{2}v_s(t)^2 - \frac{1}{2}u_{sm}(t-T_2)^2\\
&= \frac{1}{2}(u_m(t) + v_s(t-T_2))^2 - \dot{T}_2\, v_s(t-T_2)^2\\
&\quad + \frac{1}{2}(v_s(t) - u_m(t-T_1))^2 - \dot{T}_1\, u_m(t-T_1)^2\\
&\quad + \int_{t-T_1}^{t} u_m(\xi)^2 d\xi + \int_{t-T_2}^{t} v_s(\xi)^2 d\xi\\
&= P_{diss}^m(t) + P_{diss}^s(t) + \frac{dE(t)}{dt}
\end{aligned} \tag{21}$$

where $P_{diss}^m(t)$ and $P_{diss}^m(t)$ are the net power of the forward and backward wave transformation, respectively. According to (27), the net energy flow of the TDPN is always positive to satisfy the communication passivity. In practice, the initial energy is assumed as 0, so that the energy flow can be derived as follows:

$$\begin{aligned}
E_{\text{flow}}(t) &= \int_0^t P(\eta)\, d\eta = E(t) - E(0) + \int_0^t P_{diss}^m(\eta)\\
&\quad + P_{diss}^s(\eta)\, d\eta \geq \int_0^t P_{diss}^m(\eta) + P_{diss}^s(\eta)\, d\eta.
\end{aligned} \tag{22}$$

Hence, if the $\int_0^t P_{diss}^m(\eta) + P_{diss}^s(\eta) d\eta > 0$, the passivity of the IWC-based TDPN can be guaranteed. For this purpose, a power-based TDPA was realized. First, a PO was proposed for both the leader and follower sides as

$$P_{obs}^m(t) = \frac{1}{2}(u_m(t) + v_s(t-T_2))^2 - \varepsilon_1 \cdot v_s(t-T_2)^2 \tag{23}$$

$$P_{obs}^s(t) = \frac{1}{2}(v_s(t) - u_m(t-T_1))^2 - \varepsilon_2 \cdot u_m(t-T_1)^2 \tag{24}$$

$$\varepsilon_{1,2} = \begin{cases} \dot{T}_{1,2}, & \text{if } \dot{T}_{1,2} \leq 1\\ 1, & \text{if } \dot{T}_{1,2} > 1. \end{cases} \tag{25}$$

Based on the proposed passivity observers, the corresponding PC was designed on both the leader and follower side as

$$\hat{\tau}_{md}(t) = \tau_{md}(t) + \Phi_m(t)\cdot S_m(t) \tag{26}$$

$$\hat{s}_{sd}(t) = s_{sd}(t) + \Phi_s(t)\cdot \tau_{\text{EMG}}(t) \tag{27}$$

$$\Phi_m(t) = \begin{cases} 0, & \text{if } P_{obs}^m(t) > 0\\ \frac{P_{obs}^m(t)}{S_m(t)^2}, & \text{if } P_{obs}^m(t) \leq 0 \end{cases} \tag{28}$$

$$\Phi_s(t) = \begin{cases} 0, & \text{if } P_{obs}^s(t) > 0\\ -\frac{P_{obs}^s(t)}{\tau_{\text{EMG}}(t)^2}, & \text{if } P_{obs}^s(t) \leq 0. \end{cases} \tag{29}$$

By the PO and PC, the passivity of the IWC-based TDPN can be guaranteed as shown in the following theorem.

Theorem 1: The passivity of the communication channel of the DBR-TILT system using the proposed IWC-based method can be guaranteed through the designed power-based TDPC (26)–(29), *under the asymmetric time-varying delays.*

Proof: Using (21), the total power flow of the dissipated energy in the IWC-based TDPN under the designed TDPC (25)–(28) can be calculated as

$$\begin{aligned} P^*(t) &= s_m(t)\hat{\tau}_{md}(t) - \hat{s}_{sd}(t)\tau_{\text{EMG}}(t) \\ &= s_m(t)\tau_{md}(t) - s_{sd}(t)\tau_{\text{EMG}}(t) \\ &\quad + \Phi_m(t)\cdot s_m(t)^2 - \Phi_s(t)\cdot\tau_{\text{EMG}}(t)^2 \\ &= \left(P^m_{obs}(t) + \Phi_m(t)\cdot S_m(t)^2\right) \\ &\quad + \left(P^s_{obs}(t) - \Phi_s(t)\cdot\tau_{\text{EMG}}(t)^2\right) + \frac{dE(t)}{dt} \\ &= P^m_{diss}(t) + P^s_{diss}(t) + \frac{dE(t)}{dt} \geq 0. \end{aligned} \tag{30}$$

As shown in the abovementioned formula, the power P^* of the IWC-based TDPN under the control of the designed TDPC can be kept as non-negative. Therefore, the passivity of the communication channel of the DBR-TILT system under asymmetric time-varying delays can be ensured by the designed TDPC (26)–(29).

D. Controllers of the Leader and Follower Subsystem

Considering the sliding variable and torque are not a pair of power variables of the communication channel, the feedback passivity control (FPC) term should be included in both leader and follower control to satisfy the s-passivity requirement (also called r-passivity) [33]. Thus, the leader and follower controllers of the proposed P-F architecture DBR-TILT system based on IWC method are designed as follows:

$$\text{Leader side}: \tau_m = -K_m s_m + \hat{\tau}_{\text{EMG}} \tag{31}$$

$$\text{Follower side}: \theta_{1d} = q_s + K_{\text{VSA}}^{-1}\left(-K_s s_s + K_p\left(\hat{s}_m(t) - s_s(t)\right)\right) \tag{32}$$

where K_p stands follower control parameter and K_i (i = m, s) are the parameters of the FPC, which should be selected to satisfy the following condition:

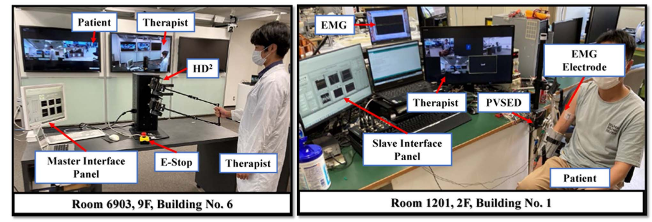
$$C_i + \lambda K_i > \lambda m_i, \lambda > 0 \text{ and } K_i > 0\,(\mathrm{i = m, s}). \tag{33}$$

Therefore, as the passivity of leader, follower, and the communication channel, the passivity of the overall DBR-TILT system could be guaranteed because the interconnection of passive systems is also passive. Moreover, the output stiffness of the PVSED could be regulated by therapists to achieve different training intensities according to the patient-specific clinical requirements. Benefiting from the proposed control input of the follower side (32), the patient-robot assistance control could be adaptive to different stiffness conditions.

V. Performance Evaluating Experiments

A. Experimental Setup

In the proposed telerehabilitation system, the leader robot was located in the No. 6903 room on the ninth floor of building No. 6 and the follower robot was placed in the No. 1201 room on the second floor of building No. 1. The communication between the leader and follower side is achieved by the User Data Protocol, with a maximum communication latency between the leader and follower PCs not exceeding 500 ms. Each side has a panel on the screen to display the task information, as shown in Fig. 5. In addition, the Zoom software was utilized to enable the visual and oral communications for achieving telepresence in real clinical scenarios. The overall DBR-TILT system was realized in LabVIEW at a 1 kHz control frequency.



(a) (b)

Fig. 5. Experimental setup of the proposed DBR-TILT system. (a) Leader side. (b) follower side.

B. Experimental Protocols

Ten participants (males, average age: 25.6 ± 3.7 years old; average weight: 69.4 ± 10.2 kg; average height: 178.1 ± 7.1 cm) with no neurological disability history were involved in the experiments after signing the informed consent. The ten subjects were divided into five pairs, each comprising a therapist and a patient. During the online TILT training experiments, the therapist subjects were instructed to perform the elbow extension/flexion task in the sagittal plane with three different motion velocities from low speed to high speed (V_1:3.3°/s, V_2:5.0°/s, and V_3:10.0°/s). Simultaneously, the patient subjects were asked to track the therapist's motion trajectory to their best ability in three different load conditions (L_1:0 kg, L_2:1.5 kg, and L_3:2.5 kg) and the sEMG signals of BB and TB were collected to calculate the biomechanics for DBR-TILT. The control parameters were set as follows: $K_m = K_s = 0.05$, λ = 0.5, b = 1. The experimental protocol has been approved by the institutional review board at the Faculty of Engineering, Kagawa University (*Protocol Number: 01–011*).

C. Experimental Results

1) Comparison Validation of the WC and IWC Method for DBR-TILT: The comparison experiment between the original WC and the proposed IWC method was conducted. A demonstration trial was selected to demonstrate the performance differences. For the position tracking results given in Fig. 6(a), the original WC method (yellow line) failed to accurately track the trajectory of the leader side (blue line) with obvious amplitude errors, and the overall tracking error of the original WC method was 12.45°. Notably, the tracking errors at the peak position were larger than in the valley position. Moreover, the position tracking errors of the original WC methods were increasing along with the increase in task speed, and a noticeable position drift issue was observed. This occurred because only the velocity variable was used in the original WC structure so that the tracking

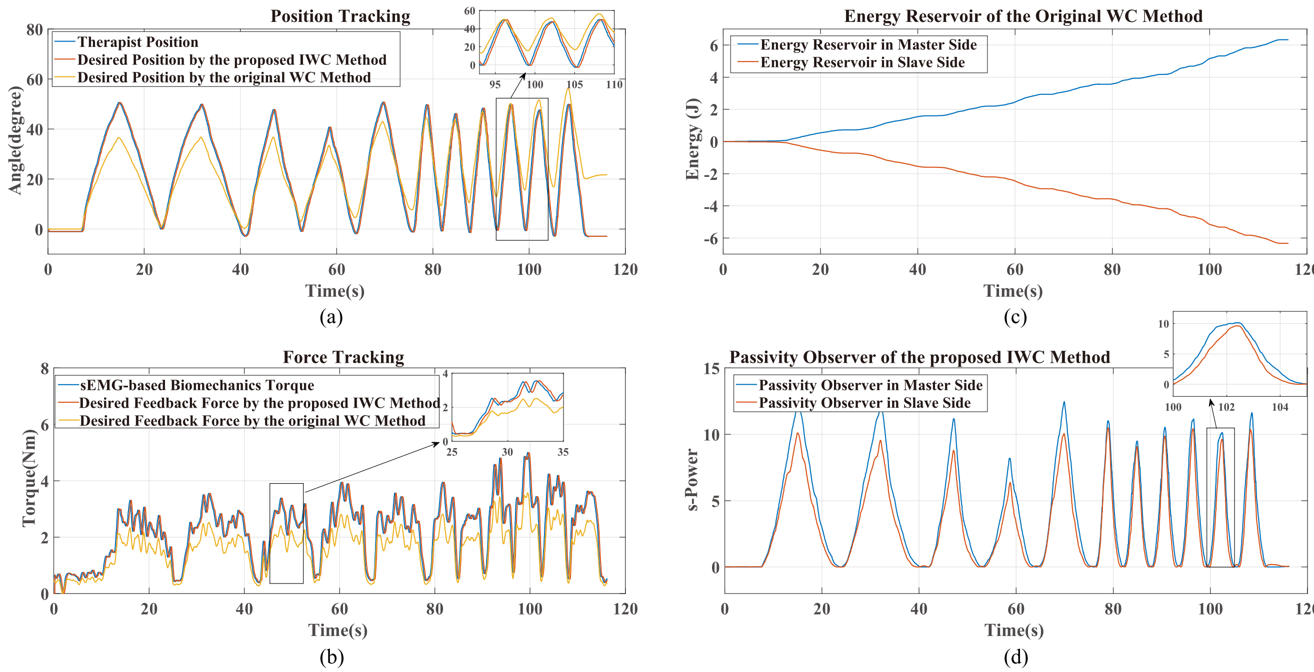


Fig. 6. Comparison results of the IWC and original WC method. (a) Position tracking performance. (b) Force tracking performance. (c) Performance of the energy reservoirs of original WC method. (d) Performance of the PO/PC of proposed IWC method.

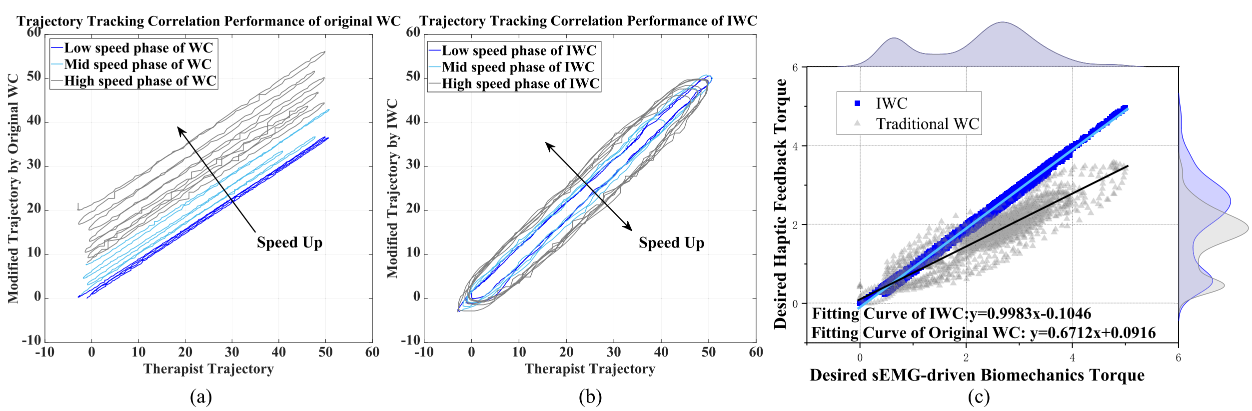


Fig. 7. Transparency performance results. (a) Trajectory correlation performance of the original WC method and the proposed IWC method. (b) Feedback force correlation performance of the original WC and IWC method. (c) Top marginal shade is the distribution of the desired sEMG-driven biomechanics torque and the right marginal shades are the distributions of the original WC method (gray area) and the proposed IWC method (purple aera).

error were amplified by the velocity error accumulation. For the haptic feedback fidelity performance shown in Fig. 6(b), significant amplitude errors were also observed along with the haptic biomechanical perception increased with an average force tracking error on the leader side was 0.85 Nm. In contrast, the IWC method achieved an average force tracking error of 0.28 Nm and a trajectory tracking error of 2.12° [orange line in Fig. 6(a) and (b)], which indicates the proposed IWC method has precise position/force tracking performance.

Furthermore, the trajectory tracking correlation performance of the original WC and proposed IWC is illustrated in Fig. 7(a) and (b), in which the low, mid, and high-speed phases are marked in blue, cyan, and gray, respectively. The results of the original WC behave as a rising parallel band as motion speed increases, proving that the trajectory drifting issue of the original WC method compromises the stability of the TILT system. In contrast, the result of the IWC shows a stable hysteresis loop shape, whose width expands as the motion speed increases. This symmetric hysteresis loop behavior indicates the stable and precise trajectory/force tracking performance of the IWC method. Moreover, the fidelity of the remote biomechanical perception was compared by the correlation analysis, as shown in Fig. 7(c). The distributions of the desired sEMG-driven biomechanical torque and the actual haptic feedback torque are intuitively shown in the top and right marginal shade. The original WC method and the proposed IWC method are shown in the gray

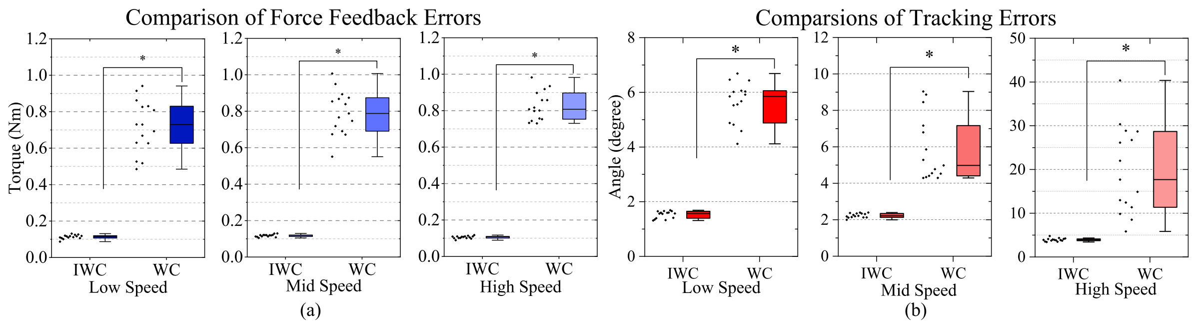


Fig. 8. T-test statistical analysis. (a) Comparison results of the tracking errors in low, mid, and high speed. (b) Comparison results of the force feedback errors in low, mid, and high speed.

and purple areas of the right marginal plot. Higher correlation is indicated by greater symmetry between the top and right shade patterns. The correlation coefficients of the original WC and IWC are 0.6712 and 0.9983, confirming the high fidelity of the remote biomechanical perception of the proposed IWC-based TDPC. The t-test statistical analysis between the original WC and the IWC was conducted, as shown in Fig. 8. There were significant statistical differences between the IWC and WC methods on both tracking and haptic feedback perception performance, demonstrating that the PO/PC of the proposed IWC method is less conservative compared to the original energy reservoir-based WC method. Therefore, the better transparency performance of the proposed IWC-based TDPC approach is verified for enabling remote biomechanical perception in the DBR-TILT system.

The reason why the IWC method outperforms the original WC method in terms of transparency is the effect of the TDPC. As the original WC structure could not derive the power-conjuncted variables by the wave variables, only the energy reservoir-based control could be utilized, which strictly equalizes energy between the leader and follower sides to ensure the nonenergy transmission on the internet communication channel, as shown in Fig. 6(c). This conservative control approach will modify the desired trajectory and feedback force to ensure the passivity of teleoperation while compromising teleoperation transparency. Conversely, the passivity observers of the proposed IWC method are positive [as shown in Fig. 6(d)] and the leader side's power consistently exceeds that of the follower side, which indicates the overall system will dissipate the energy. The overall system remained passive, preventing the passivity controller from activating. The precise position/force tracking performance was maintained across all speed conditions, as shown in Fig. 6. Therefore, the proposed IWC method has better transparency performance than the original WC method while ensuring teleoperation passivity to facilitate the therapist's teleassessments.

2) Comparison of the DBR Perception Performance Under Different Training Intensities: Training intensity not only affects the patient's biomechanical dynamics but also influences the remote biomechanics perception in the DBR-TILT system, as larger feedback torques can compromise the passivity of the communication channel. To this end, a comparison of the DBR perception performance was carried out under varying training intensities, including three load conditions (L_1:0 kg, L_2:1.5 kg, and L_3:2.5 kg). A demonstration trial is shown in Fig. 9. The good tracking performance of the IWC-based method on the patient side can be obviously confirmed in all load conditions. As training loads increase, increasing trends in sEMG-driven biomechanical torque of the subjects are clearly evident [see Fig. 9(b)], from 2.26 Nm in 0 kg load, to 3.43 Nm in 1.5 kg load, and 4.29 Nm in 2.5 kg load. Correspondingly, the total haptic feedback torque also increased, with average torques of 2.15 Nm in 0 kg load, 3.28 Nm in 1.5 kg load, and 3.11 Nm in the 2.5 kg load condition, respectively. It can be observed that the total haptic feedback torque is lower than the received sEMG-driven biomechanical torque due to the FPC component in the leader control law. Therefore, it is necessary to confirm the influence of the PFC on the remote biomechanical perception. From all trials of five subject-pairs, the average FPC was 0.558 Nm and the average sEMG-driven biomechanical feedback was 3.32 Nm resulting in an average ratio of sEMG-driven biomechanical feedback to total haptic feedback torque of 84.62%, as shown in Fig. 10(a). To further verify the effectiveness of the remote biomechanical perception in different task requirements, ANOVA was conducted. From the results in Fig. 10(c) and (d), there are significant differences between speed and load conditions, which shows that the proposed DBR-TILT system can effectively render the remote biomechanical perception across different task velocity and load conditions. Furthermore, the fidelity of the sEMG-based biomechanical perception was confirmed through the correlation coefficient between the actual haptic feedback and the original sEMG-driven biomechanical torques. The average R^2 results of the load and speed conditions were 0.9163 and 0.9213, respectively, demonstrating the high fidelity of remote biomechanical perception. Moreover, from the ANOVA results of the fidelity performance, there were not significant differences among load and speed conditions, indicating the proposed DBR-TILT system could realize high-fidelity performance of the remote biomechanical perception for different training task requirements.

VI. Discussion

Telerehabilitation aims to provide high-quality rehabilitation training and assessment services to patients remotely to improve convenience and efficiency. The immersive and precise perception of the patient's biomechanical state is a critical metric

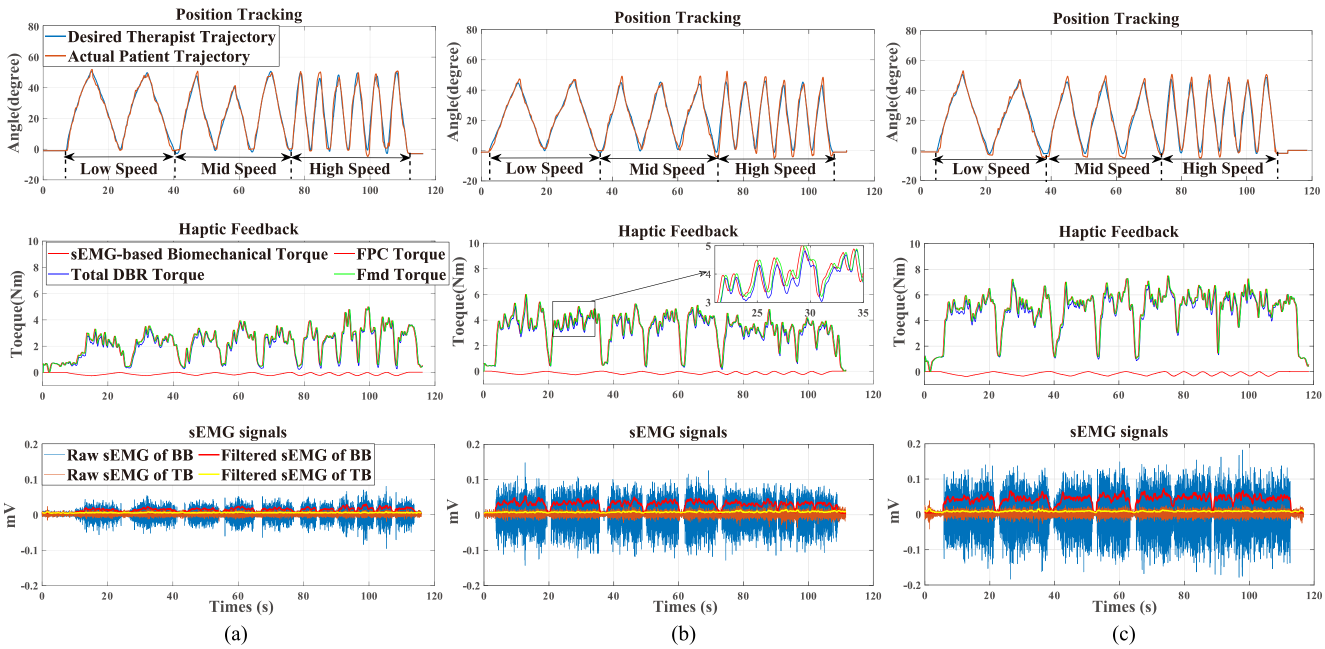


Fig. 9. Comparison results in three different velocity/load conditions. (a) 0 kg load. (b) 1.5 kg load. (c) 2.5 kg load.

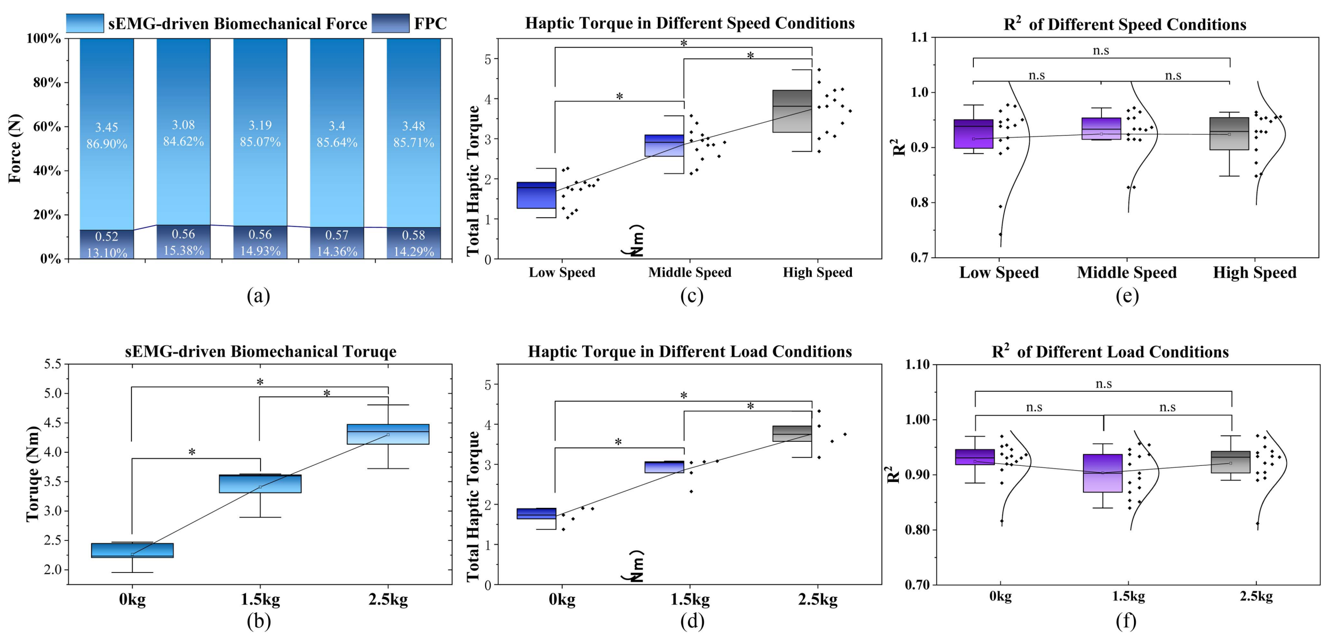


Fig. 10. Statistical analysis results in three different velocity/load conditions. (a) Comparison of haptic feedback torque components. (b) Comparison of the sEMG amplification in different load conditions. (c) Comparison of haptic feedback torque in different speed conditions. (d) Comparison of haptic feedback torque in different load conditions. (e) Comparison of the haptic force feedback correlation performance in different load conditions. (f) Comparison of the haptic force feedback correlation performance in different load conditions.

for therapists in making clinical diagnoses. Therefore, a novel concept of DBR-TILT system has been proposed in this study. Patients are expected to track the therapy motions of the therapists with assistance from the exoskeleton rehabilitation robot. Meanwhile, the sEMG signals of the patients are collected to estimate biomechanical torques using a musculoskeletal model, which is simultaneously fed back to the therapist side for haptic perception. To achieve the high-transparent and precise remote biomechanics perception under communication delays, an IWC method was proposed for the DBR-TILT system based on the P-F architecture teleoperation. A power-based TDPC method with a pair of PO/PC was designed to guarantee the passivity of the communication channel. Finally, the passivity of the proposed DBR-TILT system was analyzed and proven.

From the perspective of teleoperation technology, the transmission of velocity and force information with Internet communication latency may compromise the passivity of the communication port. Although this problem has been widely solved by wave-based teleoperation methods such as the WC method, transmitting only velocity information may lead to position drift due to the lack of position information. Furthermore, the original WC method relies on the energy reservoir controller because the power-conjuncted variables cannot be derived by wave variables. The proposed IWC method utilizes the sliding variables that incorporate both position and velocity information to improve the tracking performance. Moreover, the less conservative, power-based TDPC can realize high-fidelity performance with fewer modification effects. The comparison results in Fig. 8(a) and (b) show that there are significant statistical differences between the IWC and WC methods on both tracking and haptic feedback perception performance, which evidenced that the PO/PC of the proposed IWC method is less conservative compared to the original energy reservoir-based WC method, resulting in more precise trajectory and force tracking performance than the original WC method to achieve better transparency. Considering that the fidelity of the remote biomechanical perception is influenced by the FPC torque, a comparison of different training intensities was conducted. The comparison results indicate that the performance of trajectory tracking and DBR perception could be achieved in all load conditions, as shown in Fig. 9. It should be noted that the FPC torque could not be canceled due to the s-passivity requirement, but the high-fidelity performance of remote biomechanical perception can be enhanced by selecting the minimal control parameter Km that satisfied the s-passivity requirement. Furthermore, the selection of λ also influences the performance of the DBR-TILT system. The larger λ may lead to larger control efforts of trajectory tracking on the follower side to achieve better tracking performance, but may result in significant FPC torque, impacting the fidelity performance of the remote biomechanical perception on the therapist side. Thus, a tradeoff between tracking accuracy and perception performance should be considered based on real scenarios.

Towards the real telerehabilitation clinic application, training intensity and assistance level should be regulated by the therapists to adapt to patient-specific requirements. Furthermore, the assistance characteristics are supposed to be compliant for safe physical patient-robot interaction. In this study, a VSA-integrated robot PVSED was utilized as the follower robot to render compliance assistance to patients. To evaluate assistive interaction performance across different stiffness conditions, a demonstration trial was conducted, in which the patient subject was instructed to track the therapy motion while the output stiffness of the PVSED could be remotely regulated from minimal stiffness 16.95 Nm/rad, to middle stiffness 60 Nm/rad, and maximal stiffness 119.5 Nm/rad by the therapist subject gradually. The experimental results show that consistent tracking performance could be realized across all stiffness conditions [see Fig. 11(a) and (c)]. This phenomenon is likely due to the follower control law (31) as it has considered the output

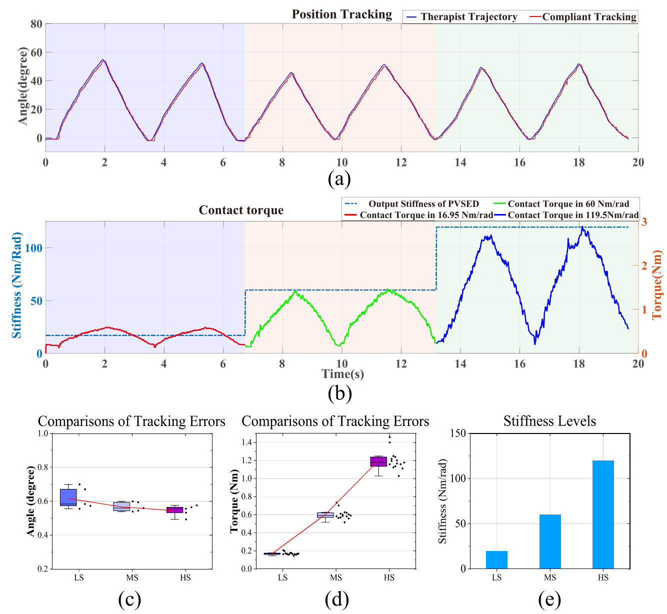


Fig. 11. Demonstration trial of comparison on three output stiffness conditions, including minimal stiffness 16.95 Nm/rad, to middle stiffness 60 Nm/rad, and maximal stiffness 119.5 Nm/rad. (a) Position tracking performance. (b) Contact torque between the patient and PVSED. (c) Comparison of the tracking errors in three stiffness condition. (d) Comparison of the contact force in three stiffness conditions. (e) Stiffness levels.

stiffness of the PVSED for tracking under different stiffness conditions. Moreover, from Fig. 11(b) and (d), the contact torque between the patient and PVSED was increased from 0.5 Nm (minimal stiffness), to 1.4 Nm (middle stiffness), and 3 Nm (maximal stiffness), which indicates that the compliant physical patient-robot interaction characteristics and assistance levels can be regulated by adjusting the output stiffness of the PVSED to suit patient-specific needs in real clinical scenarios.

Compared to the state-of-the-art TILT systems (shown in Table I), most existing TILT systems employ a patient-leading RTPI strategy, which requires the predefined training task so that the therapist cannot adjust the training task trajectory lacking the flexibility and adaptability to patient-specific injuries. Conversely, the patient-following strategy used in this study instructs patients to follow the therapist's free training motions without a predefined training task. Furthermore, the state-of-the-art TILT systems mainly render the tracking error-based haptic feedback torque to the therapists to provide perceptions of task performance, allowing therapists to assess the patient's motion abilities and estimate the patient biomechanical state. This indirect assessment method lacks direct biomechanical metrics. The proposed DBR-TILT system not only could realize the TILT training but also focus on the high fidelity and transparency of remote biomechanics perceptions for facilitating the teleassessments of the therapists. By directly feeding back the sEMG-based biomechanics of the patients to the therapist during the TILT training, the intuitive remote perception of the patient's biomechanical states can be achieved in the proposed

TABLE I
COMPARISON WITH THE STATE-OF-ART TELEREHABILITATION SYSTEM

	RTPI Strategy	System Architecture	Stability Approach	Feedback Force for Therapist	Remote Biomechanical Perception?	Position-independent Perception?	Force Sensor?
Bauer et al. [16]	Patient Guide	F-P	Adaptive Impedance Control	Kinesthetic Impedance Force	No	No	Therapist and patient side
Atashzar et al. [14]	Patient Guide	F-P	Energy-based TDPC	Kinesthetic Impedance PEBF	No	No	Therapist side
Atashzar et al. [15]	Patient Guide	F-P	Small-Gain Theorem	Kinesthetic Impedance PEBF	No	No	Therapist side
Paik et. al. [15]	Patient Guide	F-P	Power-based TDPC	Kinesthetic Impedance PEBF	No	No	Therapist side
Shafiri et al. [17]	Patient Following	PF-F	Bilateral Impedance Control	Kinesthetic Impedance Force	No	No	Therapist and patient side
Zhang et al. [5]	Patient Following	P-F	Shared model control	Kinesthetic PEBF	No	No	Therapist and patient side
Liu et al. [6]	Patient Following	P-F	Power-based Stabilizer	Contact Force	No	No	Patient side
	Patient Guide	/-F	None	Biomechanical Force	Yes	No	No
S^2-RTPIC	Patient Following	P-PK	Absolute Stability	sEMG-driven Biomechanical Impedance	Yes	No	No
DBR-TILT	**Patient Following**	**P-F**	IWC-based TDPC	**sEMG-driven Biomechanical Force**	**Yes**	**Yes**	**No**

DBR-TILT system without the requirement of force sensor, reducing cost and control noise. Considering the patient-specific injury conditions, the therapists can regulate the output stiffness of the follower side exoskeleton to adjust the compliance of patient-robot interaction to ensure appropriate assistance levels. Compared with our previous work [18], the issue that the position-based haptic force feedback model affects the fidelity of the remote biomechanical perception, has been addressed by the proposed DBR-TILT. To our best knowledge, this is the first work of the TILT systems that achieves the high-transparency direct biomechanical perception of patients under time delays to facilitate the teleassessments.

Although the significant advantages of the proposed DBR-TILT system have been proven, there are still some limitations. First, this study presents a general TILT system architecture to validate the feasibility and effectiveness of the remote biomechanical perception. The intelligent assist control strategies, such as assist-as-needed control, could be integrated into the follower control law to cater to the individual-specific and task-oriented requirements for further unlocking the potential of the clinical applications. Finally, only ten healthy subjects were involved in the experiment. In the future, it is anticipated that real clinical trials utilizing the proposed IWC-based DBR-TILT system will be conducted to provide conclusive assessments of its clinical effectiveness.

VII. Conclusion

This article presents a novel DBR-TILT system, which directly reflects the patient's biomechanical state to achieve high-fidelity teleassessments. The overall system architecture employs the minimal channel P-F teleoperation framework transmitting the therapist's position, as well as the sEMG-driven biomechanical torque of the patient's impaired limb. To guarantee the passivity of the DBR-TILT in the presence of time delays, an IWC method is designed with a power-based TDPC. Theoretical passivity analysis of the proposed DBR-TILT system demonstrates that stable and precise trajectory tracking and haptic feedback perception can be achieved for safe and transparent TILT training. Comparison experiments between the IWC and original WC methods were conducted, validating that the IWC method can realize more precise position/force tracking yielding enhanced transparency while maintaining passivity. Moreover, a comparison experiment was performed across various load/velocity conditions, demonstrating the ability of the proposed DBR-TILT system to achieve high-fidelity remote biomechanical perception across a wide range of training tasks. Therefore, the proposed system framework can provide high-fidelity remote biomechanical perception to therapists across diverse patients and task requirements, facilitating teleassessments of clinical applications. In the future works, intelligent assistive control can be integrated for better training effectiveness and more precise biomechanical model or learning-based biomechanical estimation method may benefit for teleassessment. Finally, clinical trials are expected to be conducted to verify the rehabilitation effectiveness.

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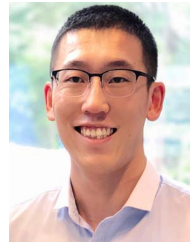

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