Quantitative and Qualitative Evaluation of Exoskeleton Transparency Controllers for Upper-Limb Neurorehabilitation

Dalla Gasperina, Stefano; Ratschat, Alexandre L.; Marchal Crespo, Laura

DOI
10.1109/ICORR58425.2023.10304703

Publication date
2023

Document Version
Final published version

Published in
Proceedings of the 2023 International Conference on Rehabilitation Robotics (ICORR)

Quantitative and Qualitative Evaluation of Exoskeleton Transparency Controllers for Upper-limb Neurorehabilitation

Stefano Dalla Gasperina[1,†], Alexandre L. Ratschat[1,2] and Laura Marchal-Crespo[1,2]

Abstract— **High transparency is a fundamental requirement for upper-limb exoskeletons to promote active patient participation. Although various control strategies have been suggested to improve the transparency of these robots, there are still some limitations, such as the need for precise dynamic models and potential safety issues when external forces are applied to the robot. This study presents a novel hybrid controller designed to tackle these limitations by combining a traditional zero-torque controller with an interaction torque observer that compensates for residual undesired disturbances. The transparency of the proposed controller was evaluated using both quantitative—e.g., residual joint torques and movement smoothness—and qualitative measures—e.g., comfort, agency, and perceived resistance—in a pilot study with six healthy participants. The performance of the new controller was compared to that of two conventional controllers: a zero-torque closed-loop controller and a velocity-based disturbance observer. Our preliminary results show that the proposed hybrid controller may be a good alternative to state-of-the-art controllers as it allows participants to perform precise and smooth movements with low interaction joint torques. Importantly, participants rated the new controller higher in comfort and agency, and lower in perceived resistance. This study highlights the importance of incorporating both quantitative and qualitative assessments in evaluating control strategies developed to enhance the transparency of rehabilitation robots.**

I. Introduction

Despite the growing field of robot-assisted rehabilitation, the efficacy of rehabilitation robots is still questionable, especially for stroke survivors with mild to moderate motor impairments [1]. A suggested explanation is that most robotic devices mainly provide passive mobilization, i.e., the robot enforces repetitive movements without accounting for the patients' voluntary activity. However, rigid execution and repetition of the same pattern are not optimal for learning [2] and might lead to a reduction of the patients' effort [3], and therefore, limit the therapeutic efficacy of the training [4].

Therefore, promoting self-generated movements is crucial to enhancing motor learning in neurorehabilitation. This can only be achieved by enforcing the robot to behave transparently to human activity, intended as the capacity for the exoskeleton, to not apply any resistive forces in reaction to intentional movements of the user [5]. However, the complex mechanical structures of current rehabilitation exoskeletons limit their transparency, as they suffer from intrinsic bulkiness, friction, and inertia. This could be bypassed to some extent by control design.

Transparency through control design for upper-limb rehabilitation robots has been extensively investigated in the literature [6]. One conventional approach is the use of closed-loop zero-torque controllers. This approach employs PID or PI controllers to minimize the interaction forces between the robot and the human [7]–[9]. More recent approaches exploit Disturbance Observers (DOBs) to estimate and compensate for external disturbances [10], [11]. Our study focuses on a specific type of exoskeleton design, which employs force sensors at the cuffs but lacks joint-level torque measurements. While offering impressive transparency, this solution raises concerns about the system's ability to handle external forces and ensure user safety. For example, when a therapist applies forces to the exoskeleton's external links, the DOB counteracts them as if they were disturbances. Therefore, developing new controllers that maximize the robot's transparency while ensuring safety is essential.

Furthermore, despite current efforts to enhance the transparency of rehabilitation exoskeletons, there is a lack of clear guidelines for assessing transparency. One of the most commonly used methods is to measure the residual interaction forces/torques between the robot and the human [7], [10]. Another approach involves computing the output impedance, which is calculated for each joint as the ratio of the net interaction torque and the angle value during user-generated cyclic movements [8], [9]. As residual forces can cause artifacts in patients' self-generated movements, some studies have used deviations from "normal" movements as an alternative way for assessing transparency [12].

Remarkably, a recent study by Plooij et al. found that healthy participants preferred a small backward force when using a highly transparent device for optimal gait training conditions [13]. This highlights the importance of considering subjective perception and preferences in addition to quantitative data when assessing transparency in robotic rehabilitation devices.

Yet, to our knowledge, the user's perception of arm exoskeleton transparency has hardly been investigated [10], [14]. Just et al. quantitatively compared the transparency of the ARMin IV+ upper-limb exoskeleton between a feedforward model-based controller and a disturbance observer [10]. Additionally, they asked participants questions regarding the perceived disturbance applied by the exoskeleton and the difficulty in performing precise movements and inquired about their preference between controllers. Sun et

*This work was partially funded by the Dutch Research Council (NWO, VIDI Grant Nr. 18934)

[1]Motor Learning and Neurorehabilitation Laboratory, Cognitive Robotics Department, Delft University of Technology, Delft, Netherlands. (email: s.dallagasperina@tudelft.nl).

[2]Department of Rehabilitation Medicine, Erasmus MC, University Medical Center, Rotterdam, Netherlands.

[†]S. Dalla Gasperina holds shares in AGADE srl, Milan, Italy.

2023 International Conference on Rehabilitation Robotics (ICORR) | 979-8-3503-4275-8/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICORR58425.2023.10304703

al. evaluated the transparency of the dual-arm exoskeleton EXO-UL8 by quantitatively assessing power exchange at the interaction points and actuation stress at each joint of the exoskeleton [14]. They also collected subjective data regarding the user's mental and physical workload, ease of control, and wearability. While these works assessed specific aspects of the users' perception of transparency, a more thorough analysis of the users' feelings–such as comfort, freedom of movement, and sense of agency–may lead to a more comprehensive understanding of perceived transparency. These subjective factors are particularly interesting in rehabilitation robotics, especially agency, as promoting self-generated movements requires users to feel in control of their own movements.

The scope of this work is twofold. First, we present the development of a novel controller to enhance the transparency of a six-degrees-of-freedom (DoF) exoskeleton. The new controller employs a conventional zero-torque controller enhanced with an interaction torque observer to compensate for the undesired parasitic interaction forces that the closed-loop controller cannot reject. Second, we present the qualitative and quantitative evaluation of the new controller and compare it to two state-of-the-art control strategies, namely, a zero-torque closed-loop controller and a velocity-based disturbance observer.

II. Methods

A. ARMin IV+ Exoskeleton

We employed an ARMin IV+ exoskeleton, a six-DoF robotic device designed for robot-assisted arm training of neurological patients (Fig. 1) [15]. The robot features three force/torque sensors (Mini45, ATI Industrial Automation, USA) placed at the human-robot interaction points at the upper arm and forearm cuffs and under the hand stick [11]. These sensors measure the interaction forces between the human and the robot.The control system of the exoskeleton is executed in real-time at 3 kHz in Simulink Realtime R2017b (MathWorks, USA).

B. Control Strategies for Enhanced Transparency

1) Conventional zero-torque controller (ZTC): One conventional approach to minimize the interaction forces between the robot and the human is the use of joint-space closed-loop zero-torque controllers [7]–[9]. This approach employs PID or PI controllers to enforce zero torque at each joint (Fig. 2a). In ARMin IV+, instead of measuring joint torque directly with torque sensors at the joints or series elastic actuators as done in other exoskeletons [8], [9], we record forces/torques from the three force/torque sensors located at the interaction points and convert these interaction wrenches into the joint space using the respective Jacobian matrices [10]. The vector of interaction torques projected from the force/torque sensors to the six joints is computed as:

$$\boldsymbol{\tau}_{int} = \sum_{i=1}^{N} \boldsymbol{\tau}_{S_i} = \sum_{i=1}^{N} \mathbf{J}_{S_i}^T \cdot \mathbf{w}_{S_i} \quad (1)$$

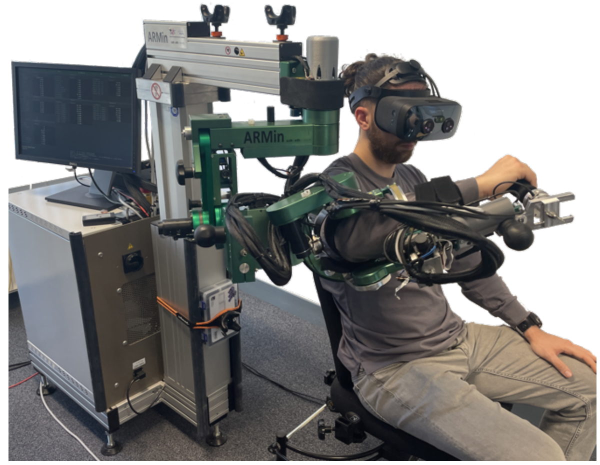


Fig. 1: The ARMin IV+ is a six-DoF exoskeleton for arm neurorehabilitation. It features three force/torque sensors placed at the interaction points between the human and the robot.

where $N = 3$ is the number of force/torque sensors, $\mathbf{J}_{S_i}^T$ represents the transpose Jacobian matrix of sensor S_i from the sensor frame to the robot joints, and $\mathbf{w}_{S_i}$ is the force/torque wrench measured at the sensor S_i frame. To further improve transparency, the gravity of the exoskeleton and the friction of the motor gears were modeled and used as dynamics compensation, represented with $\hat{\boldsymbol{\tau}}_{\boldsymbol{c}}$ (see Fig. 2a) [16]. The control signal $\boldsymbol{\tau}_u$ is then computed as:

$$\boldsymbol{\tau}_u = \mathbf{K}_p \boldsymbol{\tau}_e + \mathbf{K}_i \int \boldsymbol{\tau}_e + \hat{\boldsymbol{\tau}}_c \quad (2)$$

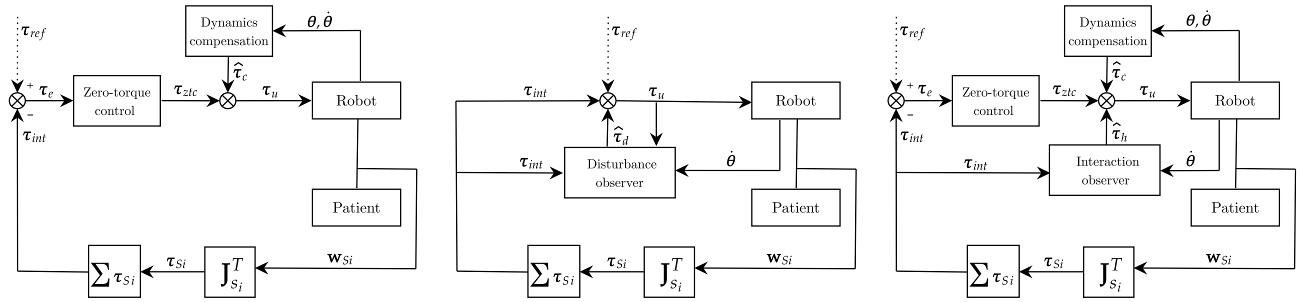
where $\mathbf{K}_p$ and $\mathbf{K}_i$ are the closed-loop gain matrices, empirically tuned to exhibit stable behavior and minimum interaction forces, and $\boldsymbol{\tau}_e = -\boldsymbol{\tau}_{int}$ is the torque error vector between the desired torque (i.e., zero-torque) and the joint interaction torques obtained in Eq. 1.

This approach makes the robot only compliant to forces applied by the user and is not affected by forces applied directly to the mechanical structure. Nevertheless, in order to achieve maximum performance, it requires an accurate dynamic exoskeleton model as well as meticulous manual tuning of the closed-loop gains.

2) Velocity-based disturbance observer (DOB): Disturbance observers are widely used in exoskeleton control systems to estimate and compensate for the disturbance torques acting on the joints in real-time. In previous work, Just et al. [10] proposed a velocity-based disturbance observer that uses the velocity of the joints, as well as the desired nominal inertia of the exoskeleton (see Fig. 2b). The observer estimates the joint disturbance torques $\hat{\boldsymbol{\tau}}_d$, for each joint, as follows:

$$\hat{\boldsymbol{\tau}}_d = \frac{\omega_g}{(s + \omega_g)} (\hat{\boldsymbol{\tau}}_d + \boldsymbol{\tau}_{ref} + \boldsymbol{\tau}_{int} + \dot{\boldsymbol{\theta}} \boldsymbol{a}_n \omega_g) - \dot{\boldsymbol{\theta}} \boldsymbol{a}_n \omega_g \quad (3)$$

where ω_g is the low-pass filter cut-off frequency, $\boldsymbol{\tau}_{ref}$ is the target torque ($\boldsymbol{\tau}_{ref} = 0$ for complete transparency), $\boldsymbol{\tau}_{int}$ is the interaction torques vector projected from the measured wrenches at the interaction points (see Eq. 1), $\boldsymbol{a}_n$ are the



(a) Zero-torque controller **(ZTC)** (b) Disturbance observer **(DOB)** (c) Hybrid controller **(HYB)**

Fig. 2: Control diagrams of the three control strategies.

nominal inertias, and $\dot{\boldsymbol{\theta}}$ are the joint velocities. ω_g and $\boldsymbol{a}_n$ are the design parameters that were manually tuned to achieve stable behavior in the human movement bandwidth. Finally, the control signal is computed as follows:

$$\boldsymbol{\tau}_u = \hat{\boldsymbol{\tau}}_d + \boldsymbol{\tau}_{ref} + \boldsymbol{\tau}_{int} \tag{4}$$

In this formulation, the gravity, friction, and inertia of the robot are considered disturbances and are rejected by the observer. However, if the exoskeleton encounters obstacles in the environment, e.g., a therapist or the patient touches the exoskeleton at a different part than the interaction points, the observer will generate forces that counteract the forces generated in this interaction since it views these interactions as disturbances as well. This might jeopardize the stability and safety of the system.

3) New hybrid controller (HYB): Both the zero-torque and DOB controllers have disadvantages that we aim to reduce by proposing a new control strategy that employs a traditional zero-torque controller combined with an interaction torque observer. The control strategy combines a zero-torque controller with an interaction torque observer to ensure a safe and stable interaction between a robot and a human (Fig. 2c). This approach minimizes residual forces transmitted between the two entities while mitigating potential safety concerns related to external forces from unexpected interactions with external elements. Furthermore, the observer can compensate for residual disturbances due to imprecise dynamic models or sub-optimal closed-loop gain tuning.

The zero-torque controller minimizes the interaction forces between the robot and the human when the exoskeleton is unaffected by external torques or forces. The observer, on the other hand, is used to estimate residual disturbances that may be caused by the robot when the human applies forces to the interaction cuffs. The observer's formulation is similar to the velocity-based DOB presented by Just et al. [10], but with a difference: the input to the observer is the force applied by the human rather than the robot control torque. This is done to decouple the zero-torque controller from the action of the observer, allowing the two components to operate independently while being complementary.

The formulation of the observer is as follows:

$$\hat{\boldsymbol{\tau}}_h = \frac{\omega_g}{(s+\omega_g)}(\boldsymbol{\tau}_{int} + \dot{\boldsymbol{\theta}}\boldsymbol{a}_n\omega_g) - \dot{\boldsymbol{\theta}}\boldsymbol{a}_n\omega_g \tag{5}$$

(a) Frontal plane (b) Horizontal plane (c) Oblique plane

Fig. 3: First-person view of the virtual environment as experienced by the participants. Participants were instructed to move the end-effector blue ball (radius of 2 cm) along a circular path (radius of 12.5 cm) while maintaining contact with the semitransparent ball with a radius of 4 cm.

C. Experimental Protocol

We assessed and compared the transparency of the three controllers in a pilot study with six healthy young participants with a median age of 25.5. The study included four male and two female participants, five being right-handed and one left-handed. The study was approved by the TU Delft Human Research Ethics Committee (HREC)All participants provided written informed consent to participate in the pilot study.

In designing our experimental protocol, we drew inspiration from a previous study by Just and colleagues [17]. The task involved tracking trajectories in the three-dimensional space with the exoskeleton end-effector, which required coordinated arm movements across multiple joints. Given the kinematic redundancy of the robot, we chose to limit the motion of the sixth joint (wrist flexion/extension) to discourage compensatory movements at the wrist.

The desired trajectories were displayed to the participants in immersive virtual reality using a head-mounted display (Varjo XR-3, Varjo, Finland). Participants could see the virtual environment from a first-person perspective while seated and wearing the exoskeleton with their right arm (Fig. 1). A digital twin of the ARMin exoskeleton was also displayed with a virtual hand to facilitate the tracking task (Fig. 3).

The desired trajectories to track consisted of circular paths of radius $= 12.5$ cm and with the center placed in front of the participant's chest, at a distance of about 40 cm from the shoulder center of rotation and 90 cm above the floor of the VE. Participants were asked to track three distinct paths that were located in either the frontal, horizontal, or oblique (a combination of frontal, horizontal, and sagittal planes) planes, as illustrated in Figure 3. As movement speed might play a role in the perception of robot transparency [18], the tracking task was performed at two movement speeds, namely 1 rad/s and 2 rad/s, corresponding to 0.15 m/s and 0.3 m/s tangential velocity, respectively. To enforce the reference speed, a moving semitransparent ball of radius 4 cm was displayed, whose center followed the path at the required speed, and participants were requested to track this movement by trying to center a blue ball—located in the palm of the virtual hand—at the center of the moving semitransparent ball, with an error tolerance of about 4 cm.

Participants performed six repetitions for each controller, plane, and movement speed, for a total of eighteen tasks. To minimize the risk of memory bias, we used a Latin Square design to counterbalance the order of controller appearances. Furthermore, participants completed the questionnaire immediately after trying each controller and were not informed about the specific controller they were using.

D. Outcome metrics

1) Quantitative outcome metrics: We quantitatively assessed the exoskeleton transparency by measuring the interaction torques and movement quality during the experimental tasks. We measured the human-robot interaction forces and torques through the F/T sensors installed at the arm cuffs and computed the mean and peak absolute joint residual torques following Eq. 1. Second, as the robot (lack of) transparency may affect natural arm movements [18], we assessed the movement quality by calculating: (a) the performance in the end-effector tracking using the root-mean-square error (RMSE) between the desired and actual positions, and (b) the movement smoothness through the SPectral ARC length (SPARC) [19].

2) Qualitative outcome metrics: The subjective perception of the transparency under the three different controllers was also collected through questionnaires. The full questionnaire can be found in Table I. We adapted the questionnaires from Just et al. [10] and Verdel et al. [20] to assess the perceived comfort (S1), the perceived resistance of the robot (S2), compliance of the robot (S3), tracking precision (S4), and stabilization of movements (S5). We evaluated the sense of agency, i.e., the feeling of control over own actions, with three statements (S6–S8) from the embodiment questionnaire by Piryankova et al. [21], adapted for our tracking task. Participants rated their agreement with each statement on a 7-point Likert scale ranging from strongly disagree (-3) to strongly agree (+3). The responses to statements S2 and S7 were reversed and the responses to the agency statements were averaged.

Finally, at the end of the experiment, we asked participants whether they preferred one controller in terms of comfort and ease of control.

S	Statement
S1	I felt comfortable during the movements.[a]
S2	I felt the robot was applying resistance during the movements.[b]
S3	The robot was following my movements.
S4	I could easily perform precise movements.[a,b]
S5	The robot was stabilizing my movements.
S6	It seemed like I was in control of the exoskeleton.[c]
S7	It seemed as if the exoskeleton was controlling me.[c]
S8	It seemed like I was causing the movements of the exoskeleton.[c]

[a] adapted from Verdel et al. [20], [b] adapted from Just et al. [10]
[c] adapted from Piryankova et al. [21]

TABLE I: List of statements of the customized questionnaire.

III. Results

A. Outcome metrics

1) Quantitative outcome metrics: The mean absolute and peak absolute residual torques for the five tested joints during task execution under the three different controllers and speeds are presented in Fig. 4. The zero-torque controller (ZTC) showed the highest mean and peak interaction torques in every joint, regardless of the speed of the task. The disturbance observer (DOB) achieved the lowest interaction torques in all joints regardless of the movement speed. Finally, the newly designed hybrid controller (HYB) resulted in an averaged behavior between the other two control strategies. Notably, we found higher interaction torques at higher speeds in all three controllers.

Regarding the tracking accuracy, the end-effector RMSE was, on average, consistently below 2 cm confirming that participants were able to track the reference trajectory within the 4 cm tolerance (see Fig. 5a). We did not observe large differences between controllers, just a slightly worst performance with the ZTC controller. However, we noted that the tracking accuracy decreased when performing at higher speeds for all controllers, in line with the speed/accuracy trade-off from Fitts' law [22].

The smoothness measures, shown in Fig. 5b, show slightly higher values in the SPARC, i.e., higher smoothness for the DOB controller and lowest values for the zero-torque controller. The smoothness of the hybrid controller was between the other two controllers. We found that all controllers achieved higher smoothness at higher speeds.

2) Qualitative outcome metrics: The results from the questionnaires are displayed in Fig. 6. The spider plot indicates that participants found the zero-torque controller to be less comfortable, more imprecise in tracking movements, and to apply higher resistance to movements than the DOB and HYB controllers. Conversely, the developed HYB controller received the highest ratings for comfort and sense of agency, while the perceived resistance was the lowest. Participants felt that they could achieve greater movement precision with the DOB controller compared to the ZTC, while the difference with the HYB was rather slight. Interestingly, the disturbance observer scored the lowest in the perceived sense of agency, at a similar level as the ZTC.

These results reflect the reported preferences of the participants. Four out of six participants chose the HYB as

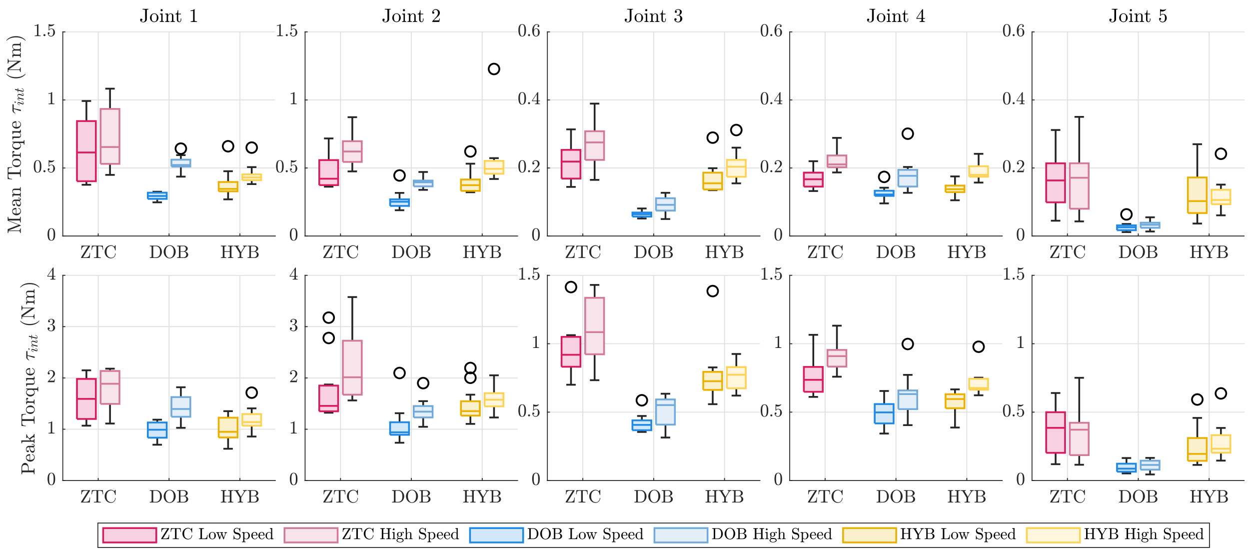


Fig. 4: Mean absolute and peak absolute residual interaction torques averaged across participants and tasks. Boxplots report median and interquartile range. ZTC = zero-torque controller, DOB = disturbance observer, and HYB = hybrid controller.

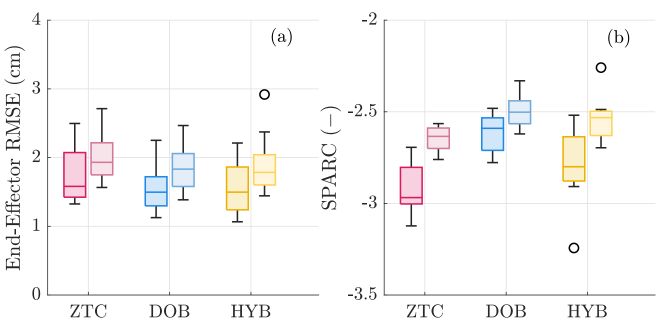


Fig. 5: Kinematic outcome measures averaged across participants and tasks. (a) End-effector RMSE, (b) movement smoothness computed as SPARC. Boxplots report median and interquartile ranges. Legend as in Fig. 4.

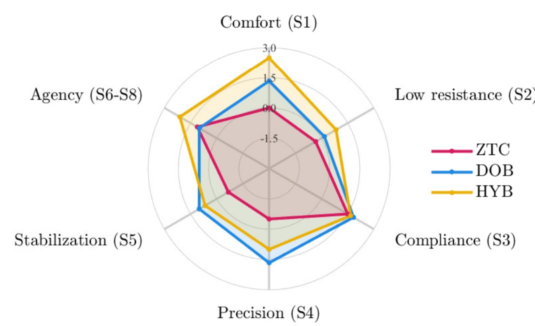


Fig. 6: Average ratings of the questionnaire subscales. Higher scores correspond to a higher agreement with the statements. Note: S2 and S7 scores are reversed.

the preferred controller, citing reasons such as comfort and ease of performing self-generated movements. The other two participants selected the DOB as their preferred controller, while none selected the ZTC controller.

IV. Discussion

In this study, we presented a novel hybrid controller that combines a closed-loop zero-torque controller with an interaction torque observer to enhance the transparency of arm exoskeletons while reducing potential safety concerns. We evaluated the performance of this new controller in a pilot experiment with six healthy participants, both quantitatively and qualitatively, and compared the results to those obtained with two conventional controllers: a zero-torque controller and a disturbance observer.

We found that the newly developed HYB controller achieved better performance in terms of mean and peak residual interaction torques and movement smoothness than the zero-torque controller, in line with the results reported in [10]. However, we could observe slightly lower interaction torques and greater smoothness with the DOB compared to the HYB controller.

Remarkably, although the DOB exhibited the lowest interaction torques compared to the other two controllers, the user questionnaires showed that participants, on average, scored the newly designed hybrid controller higher in terms of comfort, sense of agency, and lower perceived resistance. The lower scores in the qualitative evaluation of the DOB compared to the HYB controller, especially in the questions related to comfort and agency, might be due to the nature of the DOB itself, i.e., the robot might have responded to disturbances by causing the robotic arm to move unpredictably, e.g., moving against the user's intended movements. This is particularly relevant in rehabilitation robotics, as greater comfort and sense of agency during motor training may result in higher motivation and improved motor learning [23], [24]. Agency, in particular, is of great interest, as promoting self-generated movements in patients requires them to feel in control of their own movements.

Participants' ratings on stabilization and precision are very similar between the new controller and the DOB. In contrast, the zero-torque controller scored lower, which aligns with the tracking accuracy and smoothness results. While we did not observe large differences between the new controller and the DOB in these metrics, we observed that the movement smoothness was lower in the zero-torque controller compared to the other two. This lower smoothness could have been perceived as a lack of precision, as participants required more corrections to maintain the desired trajectory.

While this study primarily focuses on quantitatively and qualitatively evaluating the transparency of different control methods, future experiments are planned to investigate the behavior and safety concerns of the exoskeleton in real-world scenarios. Specifically, these experiments will explore how the robot performs when subjected to external forces applied by an operator or environmental elements.

Finally, it is essential to acknowledge that our study was limited by a small sample size of six healthy young participants and may not be generalizable to brain-injured patients. To enhance the reliability and applicability of our observations, it is crucial to conduct further research with a more extensive and diverse pool of participants.

V. Conclusion

Our preliminary findings suggest that the proposed hybrid controller may be a good alternative to DOBs as it allows participants to perform precise and accurate movements with low joint torques. The users' perception of the hybrid controller is also positive, with them preferring it in terms of comfort and ease of movement.

We also demonstrated that purely assessing joint interaction torques might not be sufficient to draw conclusions on users' perception of robot transparency and preferences. Thus, we suggest that future research should incorporate not only quantitative but also qualitative assessments, such as users' perception, cognitive and physical workload, and user satisfaction, to obtain a more holistic understanding of the effectiveness and ease of use of different control strategies developed to enhance the transparency of rehabilitation robots.

References

[1] J. M. Veerbeek, A. C. Langbroek-Amersfoort, E. E. Van Wegen, C. G. Meskers, and G. Kwakkel, "Effects of Robot-Assisted Therapy for the Upper Limb after Stroke," *Neurorehabilitation and Neural Repair*, vol. 31, pp. 107–121, 2 2017.

[2] E. Basalp, P. Wolf, and L. Marchal-Crespo, "Haptic Training: Which Types Facilitate (re)Learning of Which Motor Task and for Whom? Answers by a Review," *IEEE Transactions on Haptics*, vol. 14, no. 4, pp. 722–739, 2021.

[3] J. F. Israel, D. D. Campbell, J. H. Kahn, and T. G. Hornby, "Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury," *Physical Therapy*, vol. 86, no. 11, pp. 1466–1478, 2006.

[4] J. de Miguel-Fernández, J. Lobo-Prat, E. Prinsen, J. M. Font-Llagunes, and L. Marchal-Crespo, "Control strategies used in lower limb exoskeletons for gait rehabilitation after brain injury: a systematic review and analysis of clinical effectiveness," *Journal of NeuroEngineering and Rehabilitation 2023 20:1*, vol. 20, pp. 1–28, 2 2023.

[5] N. Jarrasse and G. Morel, "Connecting a Human Limb to an Exoskeleton," *IEEE Transactions on Robotics*, vol. 28, pp. 697–709, 6 2012.

[6] S. Dalla Gasperina, L. Roveda, A. Pedrocchi, F. Braghin, and M. Gandolla, "Review on Patient-Cooperative Control Strategies for Upper-Limb Rehabilitation Exoskeletons," *Frontiers in Robotics and AI*, vol. 8, pp. 1–24, 12 2021.

[7] B. Kim and A. D. Deshpande, "An upper-body rehabilitation exoskeleton Harmony with an anatomical shoulder mechanism: Design, modeling, control, and performance evaluation," *International Journal of Robotics Research*, vol. 36, no. 4, pp. 414–435, 2017.

[8] J. Pan, D. Astarita, A. Baldoni, F. Dell'Agnello, S. Crea, N. Vitiello, and E. Trigili, "NESM-γ : An Upper-Limb Exoskeleton With Compliant Actuators for Clinical Deployment," *IEEE Robotics and Automation Letters*, vol. 7, pp. 7708–7715, 7 2022.

[9] S. Dalla Gasperina, M. Gandolla, V. Longatelli, M. Panzenbeck, B. Luciani, F. Braghin, and A. Pedrocchi, "AGREE: A compliant-controlled upper-limb exoskeleton for physical rehabilitation of neurological patients," *IEEE Transactions on Medical Robotics and Bionics*, pp. 1–1, 2023.

[10] F. Just, O. Özen, P. Bösch, H. Bobrovsky, V. Klamroth-Marganska, R. Riener, and G. Rauter, "Exoskeleton transparency: Feed-forward compensation vs. disturbance observer," *At-Automatisierungstechnik*, vol. 66, no. 12, pp. 1014–1026, 2018.

[11] O. Özen, K. A. Buetler, and L. Marchal-Crespo, "Towards functional robotic training: motor learning of dynamic tasks is enhanced by haptic rendering but hampered by arm weight support," *Journal of NeuroEngineering and Rehabilitation*, vol. 19, pp. 1–18, 12 2022.

[12] D. Zanotto, T. Lenzi, P. Stegall, and S. K. Agrawal, "Improving transparency of powered exoskeletons using force/torque sensors on the supporting cuffs," *IEEE ... International Conference on Rehabilitation Robotics : [proceedings]*, vol. 2013, 2013.

[13] M. Plooij, S. Apte, U. Keller, P. Baines, B. Sterke, L. Asboth, G. Courtine, J. von Zitzewitz, and H. Vallery, "Neglected physical human-robot interaction may explain variable outcomes in gait neurorehabilitation research," *Science Robotics*, vol. 6, 9 2021.

[14] J. Sun, Y. Shen, and J. Rosen, "Sensor reduction, estimation, and control of an upper-limb exoskeleton," *IEEE Robotics and Automation Letters*, vol. 6, pp. 1012–1019, 4 2021.

[15] L. Marchal-Crespo, N. Rappo, and R. Riener, "The effectiveness of robotic training depends on motor task characteristics," *Experimental Brain Research*, vol. 235, pp. 3799–3816, 12 2017.

[16] F. Just, K. Baur, R. Riener, V. Klamroth-Marganska, and G. Rauter, "Online adaptive compensation of the ARMin Rehabilitation Robot," *Proceedings of the IEEE RAS and EMBS International Conference on Biomedical Robotics and Biomechatronics*, vol. 2016-July, pp. 747–752, 2016.

[17] F. Just, O. Özen, S. Tortora, V. Klamroth-Marganska, R. Riener, and G. Rauter, "Human arm weight compensation in rehabilitation robotics: Efficacy of three distinct methods," *Journal of NeuroEngineering and Rehabilitation*, vol. 17, no. 1, pp. 1–17, 2020.

[18] S. Bastide, N. Vignais, F. Geffard, and B. Berret, "Interacting with a "Transparent" Upper-Limb Exoskeleton: A Human Motor Control Approach," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 4661–4666, IEEE, 10 2018.

[19] S. Balasubramanian, A. Melendez-Calderon, A. Roby-Brami, and E. Burdet, "On the analysis of movement smoothness," *Journal of NeuroEngineering and Rehabilitation*, vol. 12, no. 1, pp. 1–11, 2015.

[20] D. Verdel, G. Sahm, S. Bastide, O. Bruneau, B. Berret, and N. Vignais, "Influence of the Physical Interface on the Quality of Human–Exoskeleton Interaction," *IEEE Transactions on Human-Machine Systems*, vol. 53, pp. 44–53, 2 2023.

[21] I. V. Piryankova, H. Y. Wong, S. A. Linkenauger, C. Stinson, M. R. Longo, H. H. Bülthoff, and B. J. Mohler, "Owning an Overweight or Underweight Body: Distinguishing the Physical, Experienced and Virtual Body," *PLoS ONE*, vol. 9, p. e103428, 8 2014.

[22] P. M. Fitts, "The information capacity of the human motor system in controlling the amplitude of movement.," *Journal of Experimental Psychology: General*, vol. 121, no. 3, pp. 262–269, 1992.

[23] N. Rohrbach, E. Chicklis, and D. E. Levac, "What is the impact of user affect on motor learning in virtual environments after stroke? A scoping review," *Journal of NeuroEngineering and Rehabilitation*, vol. 16, p. 79, 12 2019.

[24] O. Özen, K. A. Buetler, and L. Marchal-Crespo, "Promoting Motor Variability During Robotic Assistance Enhances Motor Learning of Dynamic Tasks," *Frontiers in Neuroscience*, vol. 14, p. 600059, 2 2021.