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Human Factors in Interfaces for Rehabilitation-Assistive Exoskeletons: A Critical Review and Research Agenda

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Abstract. Exoskeletons are wearable robots designed to restore or augment human physical abilities and, indirectly, cognitive functions. These devices can be classified based on the sector of application, the body part they are intended to support or enhance, the degree of assistance, and the source which they gather power from. Regardless of such technical features, exoskeletons are usually equipped with Human-Machine Interfaces (HMIs), allowing users to interact with the system, both physically and cognitively. The current paper critically reviews the state of the art of HMIs, and discusses the future challenges concerning Human Factors issues associated with the experience of utilisation of HMIs for wearable assistive exoskeletons in neuromotor rehabilitation settings. An overview of extant types of rehabilitative exoskeletons' HMIs is provided, as well as a discussion on novel user experience research questions posed in light of the recent developments in the field.

Keywords: Exoskeletons · Wearable technologies · Rehabilitation · HMI

1 Introduction

Powered exoskeletons can be defined as robotic exosystems designed to restore or enhance user's physical performance.

These devices can be distinguished according to several descriptive criteria such as application sector (military, industrial, medical), part of the human body they are meant to support (full-body, upper-limbs, lower-limbs), degree of provided assistance (partial, complete), and source of power (motorised actuators, biomechanical energy through spring loads). Currently, the majority of market-ready exoskeletal products [1] are available in the medical field (e.g., HAL® by CYBERDYNE, Indego® by Parker

Hannifin Corp.), followed by industrial and military use-cases. There are very few consumer exoskeletons available for daily life use.

Besides the above technicalities, exoskeletons are usually equipped with Human-Machine Interfaces (HMIs). HMIs allow for user-exoskeleton interaction, both at the physical and at the cognitive level of analysis.

This paper aims to propose a Human Factors and Ergonomics (HFE) perspective on the current state of HMIs for assistive exoskeletons in neuromotor rehabilitation settings. In this context, both the medical operator and the patient must be considered as users of the exoskeleton. This is because the latter uses the exosystem to perform the rehabilitation training, while the former can monitor information regarding the patient and the task. Hence, interfaces enable four types of interactions, namely operator-exoskeleton, patient-exoskeleton, operator-patient, and operator-exoskeleton-patient.

In the next sections, the existing types of interfaces will be reviewed, along with some HFE issues they may be associated with. Furthermore, future challenges in terms of HMI analysis, design and evaluation, as well as research questions about user experience (UX) will be discussed in light of recent developments in the field.

2 Types of HMIs for Rehabilitation-Assistive Exoskeletons

The topic of HMIs for rehabilitative exoskeletons in literature dates back to 2011 [2]. Here, we propose a distinction between physical (pHMIs) and cognitive (cHMIs) human-machine interfaces.

2.1 Physical HMIs

We define pHMIs (e.g., shoulder straps, waist belt, thigh cuffs, shoe connections) as components that allow to transfer the mechanical power directly from the exoskeleton to the human body. Machine-user physical interfacing occurs through complex human-device dynamics depending on both biological tissues and interface materials properties [3]. Development of pHMIs has been mainly addressed in the field of Physical Ergonomics [4]. Wearing comfort has been especially assessed. This is because poorly designed pHMIs can add rigid constraints to the natural joint kinematics, thus becoming uncomfortable after prolonged use and resulting in pain to the user [5]. However, bottom-up approaches towards the analysis of rehabilitative exoskeletons' pHMIs are still lacking. Participatory UX research, entailing the adoption of both quantitative (questionnaires, surveys) and qualitative (interviews, focus groups) subjective methods, is needed. End-users are, indeed, the primary source of information concerning the experience of using the device. To this regard, tools like the well-accredited *Local Perceived Pressure Method* [6] may prove useful to identify whether discomfort originates from specific body regions which pHMIs are attached to.

2.2 Cognitive HMIs

Furthermore, we propose the distinction between three different types of cognitive HMIs based on their purpose, namely Control (C-HMIs), Feedback (F-HMIs), and

Training (T-HMIs). Table 1 shows an overview of different types of rehabilitative exoskeletons' interfaces.

Table 1. Taxonomy of cognitive HMIs for rehabilitative exoskeletons.

Type	Sub-type	References
C-HMIs		
User Interfaces	*Patient HMI*	
	Smartphone app	[8]
	Wearable interface	[9]
	Touch screen display	[10]
	See-through display glasses	[9]
	Gaze analysis	[11]
	Operator HMI	
	Remote controller	[12]
	Graphical interface	[13]
Muscle-Machine Interface (MMI) Brain-Machine Interface (BMI)	*Electromyographic (EMG) pattern recognition*	[14]
	Electroencephalographic (EEG) pattern recognition	[15]
	Motor imagery	[16]
	Electro-oculography (EOG) pattern recognition	[17]
	Eye saccade	[18]
Hybrid Interface	*MMI-BMI*	
	EEG-EMG based	[19]
F-HMIs		
Therapy Status Visualisations		[7]
Patient Health Monitoring		[7]
T-HMIs		
Brain-Computer Interface		[20]
Virtual Reality-Based Game-Like Interface		[21]
Augmented Reality-Based Interface		[22]
Haptic Interface		[23]

Firstly, C-HMIs allow users to operate the exoskeleton and send commands to the machine so as to perform the tasks it is designed to accomplish. This is not necessarily done by the physician. For instance, lower-limb Ekso GT™ by Ekso Bionics has four buttons placed under the crutch's handle that patients can press to turn on, walk forward and backwards, and stop.

Secondly, F-HMIs [7] provide real-time information through auditory, visual or haptic signals, and allow the operator to monitor task-relevant factors during the rehabilitation training sessions, such as patient health status, system status and performance indicators. This type of HMIs is particularly useful for keeping track of improvements along the whole rehabilitation process.

Lastly, T-HMIs are meant to guide the patient during the rehabilitation training by placing the user in a stimulating environment.

3 Human Factors Issues

Some contributions to the rehabilitative exoskeletons' interfaces field refer to HFE concepts such as usability [8, 24–27], fatigue [24, 26], user engagement [28, 29], and workload [30, 31]. However, several issues have not been addressed yet.

The first challenge entails C-HMIs. From a user-centred design perspective, controllers for rehabilitative exoskeletons should be straightforward and intuitive in order to minimise perceptual, cognitive, and physical efforts associated with operating the system. An easily comprehensible control interface can improve users' mode awareness [32] and protect them from accidental actuation, misuse, or unintended behaviours. The implementation of a stop-switch is advised to ensure safety in case of system malfunction. Most importantly, C-HMIs should never fail to signal an exoskeleton malfunction, and ought to guarantee performance consistency and reliability, which are significant factors of trust in human-robot collaboration [33]. The failure of a technological device to signal the occurrence of a malfunction is a major concern, since mode awareness is not stimulated, and reactive behaviour is not prompted. Thus, the user will not be able to implement strategies to manage and fix the malfunction. To this regard, performance indicators such as number of error messages from the HMI, number of times safe mode is activated when not needed, and number of times safe mode is not activated when needed, can be valuable metrics to consider, for example, in an observational checklist.

Another issue concerns F-HMIs that can be used by both operator and patient at once. F-HMIs can support situational awareness and the development of a shared mental model concerning the definition of the situation. Hence, F-HMIs may have positive effects on plain communication and mutual understanding between operator and patient and may contribute to clinical compliance and therapy success. Future research should investigate practical solutions to keep optimal levels of shared situational awareness.

Finally, new developments have been recently made in the field of exoskeletons interfaces. Bioelectric signals and Brain-Computer Interfaces [34] stand as the most innovative evolutions of these products. It is essential to consider which research questions are posed by these trends in terms of HMI analysis, design, and UX assessment.

These developments may also redefine the distinction between passive and active exoskeletons. While the engineering perspective on exosystems distinguishes between active and passive exoskeletons based on the presence or absence of motors, the medical viewpoint is based on whether the patient is "the pilot" rather than "the passenger" of the device. A unified definition should be looked for in the future.

4 Conclusions

This paper provided an overview on extant types of HMIs for rehabilitative exoskeletons, as well as on current and future HFE issues they relate to.

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References

1. Exoskeleton Report. https://exoskeletonreport.com
2. De Rossi, S.M.M., Vitiello, N., Lenzi, T., Ronsse, R., Koopman, B., Persichetti, A., Vecchi, F., Ijspeert, A.J., Van der Kooij, H., Carrozza, M.C.: Sensing pressure distribution on a lower-limb exoskeleton physical human-machine interface. Sensors **11**(1), 207–227 (2011)
3. Yandell, M.B., Quinlivan, B.T., Popov, D., Walsh, C., Zelik, K.E.: Physical interface dynamics alter how robotic exosuits augment human movement: implications for optimizing wearable assistive devices. J. Neuroeng. Rehabil. **14**(40), 1–11 (2017)
4. Levesque, L., Pardoel, S., Lovrenovic, Z., Doumit, M.: Experimental comfort assessment of an active exoskeleton interface. In: 5th IEEE International Symposium on Robotics and Intelligent Sensors, pp. 38–43. IEEE Press, New York (2017)
5. Cappello, L., Binh, D.K., Yen, S.-C., Masia, L.: Design and preliminary characterization of a soft wearable exoskeleton for upper limb. In: 6th International Conference on Biomedical Robotics and Biomechatronics, pp. 623–630. IEEE Press, New York (2016)
6. Van der Grinten, M.P., Smitt, P.: Development of a practical method for measuring body part discomfort. Adv. Ind. Ergon. Saf. **4**, 311–318 (1992)
7. Amirabdollahian, F., Ates, S., Basteris, A., Cesario, A., Buurke, J., Hermens, H., Hofs, D., Johansson, E., Mountain, G., Nasr, N., Nijenhuis, S.: Design, development and deployment of a hand/wrist exoskeleton for home-based rehabilitation after stroke - SCRIPT project. Robotica **32**, 1331–1346 (2014)
8. Chen, B., Ma, H., Qin, L.-Y., Guan, X., Chan, K.-M., Law, S.W., Qin, L., Liao, W.H.: Design of a lower extremity exoskeleton for motion assistance in paralyzed individuals. In: 8th Conference on Robotics and Biomimetics, pp. 144–149. IEEE Press, New York (2015)
9. Choi, H., Na, B., Lee, J., Kong, K.: A user interface system with see-through display for WalkON suit: a powered exoskeleton for complete paraplegics. Appl. Sci. **8**, 2287 (2018)
10. Walia, A.S., Kumar, N.: Powered lower limb exoskeleton featuring intuitive graphical user interface with analysis for physical rehabilitation progress. J. Sci. Ind. Res. **77**, 342–344 (2018)
11. Baklouti, M., Monacelli, E., Guitteny, V., Couvet, S.: Intelligent assistive exoskeleton with vision based interface. In: International Conference on Smart Homes and Health Telematics, pp. 123–135. Springer, Berlin (2008)
12. Airò Farulla, G., Pianu, D., Cempini, M., Cortese, M., Russo, L.O., Indaco, M., Nerino, R., Chimienti, A., Oddo, C.M., Vitiello, N.: Vision-based pose estimation for robot-mediated hand telerehabilitation. Sensors **16**, 208 (2016)
13. Ianosi, A., Dimitrova, A., Noveanu, S., Tatar, O.M., Mândru, D.S.: Shoulder-elbow exoskeleton as rehabilitation exerciser. In: 7th International Conference on Advanced Concepts in Mechanical Engineering, vol. 147 (2016)

14. Lu, Z., Tong, K., Zhang, X.: Myoelectric pattern recognition for controlling a robotic hand: a feasibility study in stroke. IEEE Trans. Biomed. Eng. **66**(2), 365–372 (2019)
15. Al-Quraishi, M.S., Elamvazuthi, I., Daud, S.A., Parasuraman, S., Borboni, A.: EEG-based control for upper and lower limb exoskeletons and prostheses: a systematic review. Sensors **18**, 3342 (2018)
16. Frolov, A.A., Mokienko, O., Lyukmanov, R., Biryukova, E., Kotov, S., Turbina, L., Nadareyshvily, G., Bushkova, Y.: Post-stroke rehabilitation training with a motor-imagery-based Brain-Computer Interface (BCI)-controlled hand exoskeleton: a randomized controlled multicenter trial. Front. Neurosci. **11**, 400 (2017)
17. Crea, S., Nann, M., Trigili, E., Cordella, F., Baldoni, A., Turbina, L., Nadareyshvily, G., Bushkova, Y.: Feasibility and safety of shared EEG/EOG and vision-guided autonomous whole-arm exoskeleton control to perform activities of daily living. Sci. Rep. **8**, 10823 (2018)
18. Wang, K.-J., You, K., Chen, F., Huang, Z., Mao, Z.-H.: Human-machine interface using eye saccade and facial expression physiological signals to improve the maneuverability of wearable robots. In: International Symposium on Wearable & Rehabilitation Robotics. IEEE Press, New York (2017)
19. Kawase, T., Sakurada, T., Koike, Y., Kansaku, K.: A hybrid BMI-based exoskeleton for paresis: EMG control for assisting arm movements. J. Neural Eng. **14**, 016015 (2017)
20. Jochumsen, M., Cremoux, S., Robinault, L., Lauber, J., Arceo, J.C., Navid, M.S., Nedergaard, R.W., Rashid, U., Haavik, H., Niazi, I.K.: Investigation of optimal afferent feedback modality for inducing neural plasticity with a self-paced brain-computer interface. Sensors **18**, 3761 (2018)
21. Bouteraa, Y., Abdallah, I.B., Elmogy, A.M.: Training of hand rehabilitation using low cost exoskeleton and vision-based game interface. J. Intell. Robot. Syst. **96**, 31–47 (2019)
22. Hidayah, R., Chamarthy, S., Shah, A., Fitzgerald-Maguire, M., Agrawal, S.K.: Walking with augmented reality: a preliminary assessment of visual feedback with a cable-driven active leg exoskeleton (C-ALEX). IEEE Robot. Autom. Lett. **4**(4), 3948–3954 (2019)
23. Hu, J., Hou, Z.-G., Chen, Y., Peng, L., Peng, L.: Task-oriented active training based on adaptive impedance control with iLeg–A horizontal exoskeleton for lower limb rehabilitation. In: International Conference on Robotics and Biomimetics, pp. 2025–2030. IEEE Press, New York (2013)
24. Chowdhury, A., Meena, Y.K., Raza, H., Bhushan, B., Uttam, A.K., Pandey, N., Hashmi, A. A., Bajpai, A., Dutta, A., Prasad, G.: Active physical practice followed by mental practice BCI-driven hand exoskeleton: a pilot trial for clinical effectiveness and usability. IEEE J. Biomed. Health Inform. **22**(6), 1786–1795 (2018)
25. Ableitner, T., Soekadar, S., Strobbe, C., Schilling, A., Zimmermann, G.: Interaction techniques for a neural-guided hand exoskeleton. In: 8th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare, pp. 442–446. Elsevier, Amsterdam (2018)
26. López-Larraz, E., Trincado-Alonso, F., Rajasekaran, V., Pérez-Nombela, S., del-Ama, A.J., Aranda, J., Minguez, J., Gil-Agudo, A., Montesano, L.: Control of an ambulatory exoskeleton with a brain-machine interface for spinal cord injury gait rehabilitation. Front. Neurosci. **10**, 359 (2016)
27. Simkins, M., Fedulow, I., Kim, H., Abrams, G., Byl, N., Rosen, J.: Robotic rehabilitation game design for chronic stroke. Games Health J. **1**(6), 422–430 (2012)
28. Gui, K., Liu, H., Zhang, D.: Toward multimodal human-robot interaction to enhance active participation of users in gait rehabilitation. IEEE Trans. Neur. Syst. Rehab. Eng. **25**(11), 254–2066 (2017)

29. Sullivan, J.L., Bhagat, N.A., Yozbatiran, N., Paranjape, R., Losey, C.G., Grossman, R.G., Contreras-Vidal, J.L., Francisco, G.E., O'Malley, M.K.: Improving robotic stroke rehabilitation by incorporating neural intent detection: preliminary results from a clinical trial. In: International Conference on Rehabilitation Robotics, pp. 122–127. IEEE Press, New York (2017)
30. Liu, D., Chen, W., Pei, Z., Wang, J.: A brain-controlled lower-limb exoskeleton for human gait training. Rev. Sci. Instrum. **88**, 104302 (2017)
31. Costa, Á., Asín-Prieto, G., González-Vargas, J., Iáñez, E., Moreno, J.C., Del-Ama, A.J., Gil-Agudo, Á., Azorín, J.M.: Attention level measurement during exoskeleton rehabilitation through a BMI system. In: Wearable Robotics: Challenges and Trends, Biosystem & Biorobotics, pp. 243–247. Springer, Cham (2017)
32. Sarter, N.B., Woods, D.D.: How in the world did we ever get into that mode? Mode error and awareness in supervisory control. Hum. Fact. **37**(1), 5–19 (1995)
33. Hancock, P.A., Billings, D.R., Schaefer, K.E., Chen, J.Y.C., de Visser, E.J., Parasuraman, R.: A meta-analysis of factors affecting trust in human-robot interaction. Hum. Factors **53**(5), 517–527 (2011)
34. Benabid, A.L., Costecalde, T., Eliseyev, A., Charvet, G., Verney, A., Karakas, S., Foerster, M., Lambert, A., Morinière, B., Abroug, N., Schaeffer, M.C.: An exoskeleton controlled by an epidural wireless brain-machine interface in a tetraplegic patient: a proof-of-concept demonstration. Lancet Neurol. **18**, 1112–1122 (2019)