Recent advances on lower limb hybrid wearable robots.

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***Abstract*— Hybrid wearable robots, comprised by the combination of a motor neuroprosthesis and a lower limb exoskeletal robot, was proposed aiming at reducing the energy demands of the robot and/or improving joint movement elicited by the neuroprosthesis. Hybrid technology has a considerable potential for improving rehabilitation outcomes. This work aims at updating the state-of-the-art of hybrid exoskeletons presented some years ago. While the number of publications found is relatively low, advances have been identified in the area of hybrid MNP-WR control, aiming at exploit respective characteristics. Recent advances that can benefit hybrid exoskeletons are identified, such as synergy-inspired control, 3D printing, multi-electrode and asynchronous stimulation and soft exoskeletal technology. Evidence of the rehabilitation outcomes attained with hybrid robots is still missing in literature.**

I. Introduction

Common rehabilitation approaches for rehabilitation walking are based on the principles of neural plasticity, muscles strengthen and learning of compensation strategies [1], combining exercises and device-mediated therapy depending on patient progression and ability. Nowadays it is common finding neuromuscular stimulation (NMES) among the treatments, intended as a mean to potentiate the muscles and/or counterbalance the effects of spasticity or atrophy, being commonly applied in isometric contractions. Although the application of NMES for obtaining joint movements in the form of a motor-neuroprosthesis (MNP) is also known, its use for rehabilitation is not widespread, although many developments are found for functional compensation of movement [2]. The rationales for not using MNPs for rehabilitation are still not perfectly identified, although the difficult of adaptation of the stimulation patterns to specific subjects, muscle conditions and the appearance of fatigue can be accounted for, as well as the lack of evidence that supports the superiority of MNP versus NMES and/or traditional therapy.

In the last decade we are witnessing a growing interest in the use of lower limb robots for either rehabilitation or functional compensation of walking. From the introduction of the first robotic trainers more than fifteen years ago various devices have been presented, either stationary (robotic treadmill trainers) or ambulatory (hereafter wearable robots WR). While there are a considerable amount of research concerning the rehabilitation outcomes of the former [3], there is a growing interest in the performance of ambulatory exoskeletons for either rehabilitate or compensate walking although the level of evidence still remains low [4]. In any case, common already identified drawbacks of ambulatory exoskeletons are bulkiness, adaptability of the walking pattern and lack of versatility for community ambulation.

The combination of a MNP and WR, shaping a hybrid exoskeleton was proposed aiming at reducing the energy demands of the WR and/or improving joint movement elicited by the MNP [5]. Hybrid MNP-WR technology has a considerable potential for improving rehabilitation outcomes by maximizing the beneficial effects of NMS. We already reviewed this specific kind of technology [5], but recent advances in technology as well as new perspectives on neurorehabilitation claims for an update on the review. Therefore the aim of this work is to provide an updated overview of hybrid WR technology, providing new insights from the latest advances in the field, as well as a perspective for future research.

II. Recent Advances in Hybrid WR Technology.

Hybrid WR were classified regarding the implementation of the MNP control, in either open or closed loop, as well as with regard to the actuation principle of the WR joints in semi-active, purely dissipative actuation, or fully active, in which the actuator can either add or dissipate energy in the joint [5]. Since this classification still is valid, due the relatively small amount of papers found in literature, none classification is followed here. Furthermore, we have included some examples hybrid WR that are not intended for walking, but which concepts are worth to be considered in further ambulatory hybrid WR. Table 1 shows the actuation characteristics for the WR and the MNP of the hybrid WR revised in this work.

Most of the hybrid WR reviewed in [5] have neither improved nor undergo clinical experimentation. Up to our knowledge, only the group of Kobetic et al. has improved their device, incorporating a controlled damper in the knee joint [6] which improved the device, allowing for more natural knee kinematics [6], potentially reducing stimulation during stance, and controlled stair descent [7]. Also, a powered, fully active, version of the hybrid WR was recently reported [8]. It has to be noted here that the device showed in [7] is the only one that has targeted other functions than walking, such as stair climbing and descent.

A semi-active hybrid orthosis (SEAHO) was presented by Kirsch et al [9]. SEAHO is a relatively simple device in terms of design and control, but account for three main concepts which are of the most interest to implement in any hybrid WR: assisting push-off by stimulating gastrocnemius muscles, locking the knee during stance, and providing external (WR) power to the hip joints. The realization of the controller is simple but effective, which triggers an on-off stimulation of quadriceps, hamstrings and gastrocnemius muscles regarding the kinematics of the hip. The same group have recently published an interesting work in which muscles synergy are explored for control of the hybrid orthosis [10].

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Vanderbilt exoskeleton (licensed to Parker Hannifin as Indego Exoskeleton) has a stimulator board that can be directly plugged into the main control board, allowing the microcontroller of the exoskeleton controlling also two stimulation channels for each leg [11]. Combination of both NP and WR attempts to circumvent the non-linear nature of muscle force production under stimulation, by implementing a stimulation strategy based on discrete-adaptive control, assuming a constant square-like stimulation profile within steps. Experimental results with tree motor-complete SCI volunteers showed good trajectory tracking and considerable reduction on motor power requirements of roughly 20% in both knee and hip joints [11].

Device name / Group	WR	MNP	Evaluation
VHCM [6]	Hip and knee semi-active.	16 percutaneous channels	1 motor-complete SCI
Vanderbilt (Indego) [11]	Hip and knee active; ankle passive	4 surface channeels for Quadriceps and Hamstrings	3 motor-complete SCI
SEAHO [9]	Hip active, Knee semi-active; Ankle passive	4 surface channeels for Quadriceps and Hamstrings	1 healthy
Kinesis [12]	Knee active; Ankle passive	4 surface channels for Quadriceps and Hamstrings	3 healthy; 3 motor incomplete SCI
Kurokawa et al. [13]	Hip active;	8 surface channels for Gastrocnemius, Soleus, Tibialis Anterior and Quadriceps	7 healthy; 2 motor incomoplete SCI
Alibeji et al. [10]	Hip active, Knee semi-active; Ankle passive	4 surface channeels for Quadriceps and Hamstrings	Simulation
Vallery et al. [14]	Knee active	4 surface channeels for Quadriceps and Hamstrings	Simulation
Chen et al. [15]	Knee active	2 surface channels for Quadriceps and Gluteus Maximus	Simulation

Table 1: Comparison of actuation and evaluation of the Hybrid WR revised in this work.

Another hybrid WR appeared in the last years is a KAFO-type exoskeleton Kinesis. Kinesis' cooperative control of MNP and WR is, up the best of author's knowledge, the one hybrid exoskeleton which aims at actively manage muscle fatigue by a twofold strategy [16]: firstly by optimizing the stimulation control output, and secondly by estimating fatigue of stimulated muscles by monitoring the physical interaction and implementing a previously validated strategy intended to delay fatigue [16]. Similarly to other hybrid exoskeletons, Kinesis aims at maximizing MNP contribution, by optimizing stimulation output via a closed-loop controller comprised by a PID for knee extensor muscles and an Iterative Learning Controller for the knee flexor muscles. On the other hand, Kinesis features an Assis-As-Needed controller of the WR, which provides good adaptability features to user lower limb movements. It was evaluated on three SCI patients, in which improvements in gait function and muscle strength were observed after 4 days of treatment and at follow-up [12]. Evaluation of the physiological and subjective effects of Kinesis showed that the use was well tolerated by the patients, with a good perception overall of the device [12].

A. Non-validated approaches.

Kurokawa et al. [13] proposed a hybrid WR based on the principle of passive walking, stimulating the muscles involved in ankle push-off. Besides, the M-wave was monitored for control and fatigue monitoring purposes. Nevertheless, results of this approach are controversial, as only certain improvements in ankle and hip kinematics were reported.

Vallery et al. [14] proposed an interesting approach for cooperative control, based on a spectral analysis of the torque command elicited by the motor task. In this approach, the low frequency component of the torque command is derived to the MNP controller, while the high frequencies are directed to the motor controller. This way, each actuator (i.e. MNP and electric motor) are exploited regarding their characteristics, claiming that the overall system is optimized with regard to performance, energy consumption and muscle fatigue [17]. However, this validation results of this interesting approach have not being presented yet.

The muscle synergy-inspired controller proposed by Alibeji et al. in [10] is reported to successfully control a system comprised by 4 degrees of freedom and 10 outputs (MNP and motors) using two synergies and feedback control of the motors. This interesting approach relies on dynamic optimization of subject-specific characteristics, such as restricted degrees of freedom and strength of the user.

Chen et al. [15] proposed a hybrid controller for conducting leg press exercise, in which stimulation is modulated using a previously calibrated model of the ability of the patient to exert torque using his/her muscles, while the WR compensate gravity effects via an AAN tracking of exercise trajectory.

III. TRENDS FOR FUTURE RESEARCH

Despite the advances made in the field of hybrid WR, there is considerable room for research in several areas. Control of the combined MNP-WR system is an area in which the MNP and the WR are solely combined, compensating the WR the poor trajectory and fatigue from the NP. Being this the main objective of any hybrid WR, actual combination (or cooperation) of the MNP and the WR within a single controller may improve the outcomes of the devices for gait compensation and/or rehabilitation. Bioinspired rehabilitation principles such as synergistic muscle activation [18][10], and results derived from current research in physical and cognitive interaction with WR [19] are two examples of further areas of research.

Technological advances made in the last years can also be explored within hybrid WR concept. 3D printing offers a great opportunity for improving by customizing the shape of the contact areas, and providing support for electrodes. On the other hand, the arising concepts of *soft exoskeletons* [20] may also be of application, providing and optimized way of combining both MNP and WR.

Stimulation control is an area in which vast knowledge is available, although the fatigue and joint controllability problem remains unsolved. Up to date, the main approach is maximizing stimulation contribution and compensate with the WR. While effective, this approach could not be the most appropriate strategy to minimize muscle fatigue, and yet, authors claim that the controller is aimed to circumvent muscle fatigue [11], [16], [12], [21]. Multi-electrode, asynchronous stimulation strategies are showing good results in muscle fatigue reduction [22]. Further research in control of force production under this approach will improve the performance of MNPs.

Evidence of the outcomes attained with hybrid WRs is still missing in literature, which can partially explain the relatively low interest in the scientific community. Meaningful clinical validations with larger sample sizes are essential to seize the effects on people with neurological injuries. Clinical studies, ideally as randomized-controlled trials, comparing hybrid VS robotic-only therapies would allow to better understand the performances of the hybrid therapy within a rehabilitative context.

IV. Conclusion

This work aims at updating the state-of-the-art of hybrid exoskeletons presented in [5]. While the field of hybrid WR is a reduced filed of research, the number of publications is relatively low. Advances have been identified in the area of hybrid MNP-WR control aiming at exploit respective characteristics, although there no experimental data on the performance attained. Furthermore, criteria for balancing muscle-robot balance, maximizing muscle contribution while minimizing muscle fatigue, torque contribution is still missing, although some preliminary proposals have been presented [10], [16].

Hybrid WR technology can further be improved by incorporating recent technological advances: 3D printing, multi-electrode and asynchronous stimulation, soft exoskeletons and electronic boards for development.

Evidence of the outcomes attained with hybrid WRs is still missing in literature. Larger samples along with better study designs are needed in order to understand the potential benefits of hybrid WR for rehabilitation of walking.

References

[1] A. Curt, H. J. a Van Hedel, D. Klaus, and V. Dietz, "Recovery from a spinal cord injury: significance of compensation, neural plasticity, and repair.," *J. Neurotrauma*, vol. 25, no. 6, pp. 677–85, Jun. 2008.

[2] P. H. Peckham and J. S. Knutson, "Functional Electrical Stimulation for Neuromuscular Applications*," *Annu. Rev. Biomed. Eng.*, vol. 7, no. 1, pp. 327–360, 2005.

[3] J. Mehrholz, J. Kugler, and M. Pohl, "Locomotor Training for Walking After Spinal Cord Injury," *Cochrane Libr.*, vol. 33, no. 21, pp. 768–777, 2008.

[4] S. Federici, F. Meloni, M. Bracalenti, and M. L. De Filippis, "The effectiveness of powered, active lower limb exoskeletons in neurorehabilitation: A systematic review," *NeuroRehabilitation*, vol. 37, no. 3, pp. 321–340, 2015.

[5] A. J. del-Ama, A. D. Koutsou, J. C. Moreno, A. de los Reyes-Guzmán, A. Gil-Agudo, J. L. Pons, A. De-los-Reyes, N. Gil-Agudo, and J. L. Pons, "Review of hybrid exoskeletons to restore gait following spinal cord injury," *J. Rehabil. Res. Dev.*, vol. 49, no. 4, pp. 497–514, 2012.

[6] T. C. Bulea, R. Kobetic, M. L. Audu, and R. J. Triolo, "Stance controlled knee flexion improves stimulation driven walking after spinal cord injury.," *J. Neuroeng. Rehabil.*, vol. 10, no. 1, p. 68, 2013.

[7] T. C. Bulea, R. Kobetic, M. L. Audu, J. R. Schnellenberger, G. Pinault, and R. J. Triolo, "Forward stair descent with hybrid neuroprosthesis after paralysis: Single case study demonstrating feasibility.," *J. Rehabil. Res. Dev.*, vol. 51, no. 7, pp. 1077–94, 2014.

[8] K. M. Foglyano, R. Kobetic, C. S. To, T. C. Bulea, J. R. Schnellenberger, M. L. Audu, M. J. Nandor, R. D. Quinn, and R. J. Triolo, "Feasibility of a hydraulic power assist system for use in hybrid neuroprostheses," *Appl. Bionics Biomech.*, vol. 2015, pp. 1–8, 2015.

[9] N. Kirsch, N. Alibeji, L. Fisher, C. Gregory, and N. Sharma, "A Semi-Active Hybrid Neuroprosthesis for Restoring Lower Limb Function in Paraplegics," in *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2014, pp. 2557–2560.

[10] N. A. Alibeji, N. A. Kirsch, and N. Sharma, "A Muscle Synergy-Inspired Adaptive Control Scheme for a Hybrid Walking Neuroprosthesis," *Front. Bioeng. Biotechnol.*, vol. 3, no. December, pp. 1–13, 2015.

[11] K. Ha, S. Murray, and M. Goldfarb, "An Approach for the Cooperative Control of FES With a Powered Exoskeleton During Level Walking for Persons With Paraplegia.," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. PP, no. 99, p. 1, 2015.

[12] A. J. Del-Ama, A. Gil-Agudo, J. L. Pons, J. C. Moreno, J. Antonio, Á. Gil-agudo, J. L. Pons, J. C. Moreno, A. J. Del-Ama, A. Gil-Agudo, J. L. Pons, and J. C. Moreno, "Hybrid gait training with an overground robot for people with incomplete spinal cord injury: a pilot study.," *Front. Hum. Neurosci.*, vol. 8, no. May, p. 298, Jan. 2014.

[13] N. Kurokawa, N. Yamamoto, Y. Tagawa, T. Yamamoto, and H. Kuno, "Development of hybrid FES walking assistive system-Feasibility study," in *2012 International Conference on Advanced Mechatronic Systems*, 2012, pp. 93–97.

[14] H. Vallery and M. Buss, "Towards a hybrid motor neural prosthesis for gait rehabilitation: a project description," *J. Autom. Control*, vol. 15, pp. 19–22, 2005.

[15] Y. Chen, J. Hu, W. Wang, L. Peng, L. Peng, and Z. Hou, "An FES-assisted Training Strategy Combined with Impedance Control for a Lower Limb Rehabilitation Robot," in *IEEE 2013 International Conference on Robotics and biomimetics (ROBIO)*, 2013, no. December, pp. 2037–2042.

[16] A. J. del-Ama, A. Gil-Agudo, J. L. Pons, J. C. Moreno, Á. Gil-agudo, J. L. Pons, J. C. Moreno, J. Antonio, Á. Gil-agudo, J. L. Pons, and J. C. Moreno, "Hybrid FES-robot cooperative control of ambulatory gait rehabilitation exoskeleton.," *J. Neuroeng. Rehabil.*, vol. 11, no. 27, p. 27, 2014.

[17] H. Vallery, T. Stützle, M. Buss, and D. Abel, "Control of a hybrid motor prosthesis for the knee joint," in *IFAC Proceedings Volumes (IFAC-PapersOnline)*, 2005, vol. 16, pp. 76–81.

[18] S. Piazza, D. Torricelli, F. Brunetti, and J. L. Pons, "A novel FES control paradigm based on muscle synergies for postural rehabilitation therapy with hybrid exoskeletons," in *2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 2012, pp. 1868 – 1871.

[19] J. C. Moreno, G. Asin, J. L. Pons, H. Cuypers, B. Vanderborght, D. Lefeber, E. Cesaracciu, M. Reggiani, F. Thorsteinsson, A. J. Del-Ama, Á. Gil-agudo, S. Shimoda, E. Iáñez, J. M. Azorin, and J. Roa, "Symbiotic Wearable Robotic Exoskeletons: The Concept of the BioMot Project," in *Symbiotic Interaction. Proceedings of the hird International Workshop, Symbiotic 2014*, G. Jacucci, L. Gamberini, J. Freeman, and A. Spagnoli, Eds. Helsinki, Finland.: Springer International Publishing, 2014, pp. 72–83.

[20] D. G. Caldwell, S. Kousidou, N. Costa, and I. Sarakoglou, "'Soft' exoskeletons for upper and lower body rehabilitation - Design, control and testing," *Int. J. Humanoid Robot.*, vol. 4, no. 3, pp. 1–24, 2007.

[21] H. a Quintero, R. J. Farris, K. Ha, and M. Goldfarb, "Preliminary assessment of the efficacy of supplementing knee extension capability in a lower limb exoskeleton with FES.," in *34th Annual International Conference of the IEEE Engineering in Medicine and Biology Society.*, 2012, vol. 2012, no. 1, pp. 3360–3.

[22] R. Nguyen, K. Masani, S. Micera, M. Morari, and M. R. Popovic, "Spatially Distributed Sequential Stimulation Reduces Fatigue in Paralyzed Triceps Surae Muscles: A Case Study.," *Artif. Organs*, Apr. 2011.