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Comparison of strategies and performance of functional electrical stimulation cycling in spinal cord injury pilots for competition in the first ever CYBATHLON

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Abstract

Functional Electrical Stimulation (FES) can elicit muscular contraction and restore motor function in paralyzed limbs. FES is a rehabilitation technique applied to various sensorimotor deficiencies and in different functional situations, e.g. grasping, walking, standing, transfer, cycling and rowing. FES can be combined with mechanical devices. FES-assisted cycling is mainly used in clinical environments for training sessions on cycle ergometers, but it has also been adapted for mobile devices, usually tricycles. In October 2016, twelve teams participated in the CYBATHLON competition in the FES-cycling discipline for persons with motor-complete spinal cord injury. It was the first event of this kind and a wide variety of strategies, techniques and designs were employed by the different teams in the competition. The approaches of the teams are detailed in this special issue. We hope that the knowledge contained herein, together with recent positive results of FES for denervated degenerating muscles, will provide a solid basis to encourage improvements in FES equipment and open new opportunities for many patients in need of safe and effective FES management. We hope to see further developments and/or the benefit of new training strategies at future FES competitions, e.g. at the Cybathlon 2020 (www.cybathlon.ethz.ch).

Key Words: spinal cord injury, FES cycling, FES for denervated muscles, competition context, CYBATHLON

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Functional Electrical Stimulation (FES) can elicit muscular contraction and restore motor function in paralyzed limbs.^{1,2} Furthermore, electrical stimulation, though known under different names, such as pace-maker or auditory implanted devices, provides successful clinical approaches that benefit millions of disabled individuals. FES is a rehabilitation technique applied to various sensorimotor deficiencies and in different functional situations, e.g., grasping, walking, standing, transfer, cycling and rowing.³⁻⁵ FES can be combined with mechanical devices.⁶⁻⁸ FES-assisted cycling is mainly used in clinical environments for training sessions on cycle ergometers,⁹⁻¹¹ but it has also been

adapted for mobile devices, usually tricycles.¹²⁻¹⁴ In October 2016, twelve teams participated in the CYBATHLON competition in the FES-cycling discipline for persons with complete lower-limb spinal cord injury (SCI).¹⁵ It was the first event of this kind and a wide variety of strategies, techniques and designs were employed by the different teams.¹⁶⁻²¹ Seven teams were able to cover the 750 m distance of the race with timings ranging from 178 s to 467 s to complete the race. However, beyond the competition scores, the main achievement of this event was to highlight the potential of FES to provide exercise and fitness to a variety of people in a recreational setting. Pilots in the race were 21 to 59 years old and had lesions at levels from C4 to

T9. As participants in this competition, we believe it is important for our community to document the scientific and technological approaches used by the different teams in order to help advance our understanding of FES-cycle training and racing strategies. We therefore prescribed a number of important aspects to be analyzed by each team in order to allow for a synthesis and comparison between solutions and performance. The articles in this EJTM special issue, FES Cycling/Cyathlon, introduce case studies gathering multidisciplinary points of view and approaches. These case studies may serve as a starting point to overcome current and future challenges. FES cycling requires several weeks to months of physical preparation to improve the pedalling performance of SCI individuals to reach competition levels. FES cycling is also used in other situations including post-stroke hemiplegia and in the elderly.^{10,22} Furthermore, FES cycling is a sport that can be practised by SCI individuals in whom permanent denervation results in degeneration of muscles (DDM). In the latter case, prevention and even recovery from muscle degeneration can occur if FES for DDM is performed at a 5-day a week training level for several months.²³⁻⁵⁰

We hope to see further developments and/or the benefit of new training strategies at future FES competitions, e.g. at the Cyathlon 2020 (www.cyathlon.ethz.ch).⁵¹

List of acronyms

EJTM – European Journal of Translational Myology
 FES – Functional Electrical Stimulation
 SCI – Spinal Cord Injury
 DDM – denervated and degenerating muscle

Author's contributions

All authors designed, implemented and approved the typescript.

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Conflict of Interest

The authors declare no conflict of interest.

Ethical Publication Statement

The authors confirm that they have read the Journal's position on issues involved in ethical publication and affirms that this report is consistent with the guidelines of the EJTM.

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References

1. Ho CH, Triolo RJ, Elias AL, Kilgore KL, DiMarco AF, Bogie K, Vette AH, Audu M, Kobetic R, Chang SR, Chan KM, Dukelow S, Bourbeau DJ, Brose SW, Gustafson KJ, Kiss Z, Mushahwar VK. Functional Electrical Stimulation and Spinal Cord Injury. *Phys Med Rehabil Clin N Am*. 2014; 25(3):
2. Azevedo Coste C, Mayr W, Bijak M, et al., FES in Europe and Beyond: Current Translational Research. *Eur J Transl Myol* 2016;26(4):6369. eCollection 2016 Sep 15.
3. Liberson WT. Functional electrotherapy: stimulation of the peroneal nerve synchronized with the swing phase of the gait of hemiplegic patients. *Arch Phys Med Rehabil*. 1961;42:101-5.
4. Lopes AC, Ochoa-Diaz C, Baptista RS, et al. Electrical Stimulation to Reduce the Overload in Upper Limbs During Sitting Pivot Transfer in Paraplegic: A Preliminary Study. *Eur J Transl Myol* 2016;26(4):6223. doi: 10.4081/ejtm.2016.6223. eCollection 2016 Sep 15
5. Salchow C, Valtin M, Seel T, Schauer T. A New Semi-Automatic Approach to Find Suitable Virtual Electrodes in Arrays Using an Interpolation Strategy. *Eur J Transl Myol* 2016;26(2):6029. doi: 10.4081/ejtm.2016.6029. eCollection 2016 Jun 13.
6. Andrews B, Shippen J, Armengol M, et al. A Design Method for FES Bone Health Therapy in SCI. *Eur J Transl Myol* 2016;26(4):6419. doi: 10.4081/ejtm.2016.6419. eCollection 2016 Sep 15.
7. Laursen CB, Nielsen JF, Andersen OK, Spaich EG. Feasibility of Using Lokomat Combined with Functional Electrical Stimulation for the Rehabilitation of Foot Drop. *Eur J Transl Myol* 2016;26(3):6221. eCollection 2016 Jun 13.
8. Resquín F, Gonzalez-Vargas J, Ibáñez J, Brunetti F, Pons JL. Feedback Error Learning Controller for Functional Electrical Stimulation Assistance in a Hybrid Robotic System for Reaching Rehabilitation. *Eur J Transl Myol* 2016;26(3):6164. eCollection 2016 Jun 13.

9. Scremin AM, Kurta L, Gentili A, Wiseman B, Perell K, Kunkel C, Scremin OU. "Increasing muscle mass in spinal cord injured persons with a functional electrical stimulation exercise program." in *Arch Phys Med Rehabil* 1999;80:1531-6.
10. Peri E, Ambrosini E, Pedrocchi A, et al. Can FES-Augmented Active Cycling Training Improve Locomotion in Post-Acute Elderly Stroke Patients? *Eur J Transl Myol* 2016;26:6063. eCollection 2016 Jun 13
11. Kressler J, Ghersin H, Nash MS. Use of Functional Electrical Stimulation Cycle Ergometers by Individuals With Spinal Cord Injury. *Topics in Spinal Cord Injury Rehabilitation* 2014;20:123-6. doi:10.1310/sci2002-123.
12. Gfoehler M, Lugner P. Cycling by means of functional electrical stimulation. *IEEE Transactions on Rehabilitation Engineering* 2000;8:233-43.
13. Petrofsky JS, Heaton H, Phillips CA. Outdoor bicycle for exercise in paraplegics and quadriplegics. *Journal of Biomedical Engineering*, 1983;5(4):292-6.
14. Heesterbeek, P.J.C, Berkelmans H.W.A., Thijssen D.H.J., van Kuppevelt H.J.M., Hopman M.T.E., Duysens J. Increased physical fitness after 4-week training on a new hybrid FES-cycle in persons with spinal cord injury. *Technology and Disability* 2005;17:103-10.
15. Riener R. The Cybathlon promotes the development of assistive technology for people with physical disabilities. *J Neuroeng Rehabil* 2016;13:49.
16. Aksöz EA, Laubacher M, Binder-Macleod S, Hunt KJ. Effect of Stochastic Modulation of Inter-Pulse Interval During Stimulated Isokinetic Leg Extension. *Eur J Transl Myol* 2016;26:6160. eCollection 2016 Jun 13.
17. Laubacher M, Aksöz EA, Binder-Macleod S, Hunt KJ. Comparison of Proximally Versus Distally Placed Spatially Distributed Sequential Stimulation Electrodes in a Dynamic Knee Extension Task. *Eur J Transl Myol* 2016;26:6016. doi: 10.4081/ejtm.2016.6016. eCollection 2016 Jun 13.
18. Wiesener C, Schauer T. The Cybathlon-RehaBike: Inertial-Sensor-Driven Functional Electrical Stimulation Cycling by Team Hasomed. *IEEE Robotics & Automation Magazine* 2017;PP(99):1-1.
19. Guimarães JA, da Fonseca LO, Dos Santos-Couto-Paz CC, et al. Towards Parameters and Protocols to Recommend FES-Cycling in Cases of Paraplegia: A Preliminary Report. *Eur J Transl Myol* 2016;26:6085. eCollection 2016 Jun 13.
20. McDaniel J, Lombardo LM, Foglyano KM, Marasco PD, Triolo RJ. Setting the pace: insights and advancements gained while preparing for an FES bike race. *Journal of NeuroEngineering and Rehabilitation* 2017;14(1):118.
21. Padilha Lanari Bo AP, Fonseca L, Guimaraes J., Fachin-Martins E, Gutierrez Paredes ME, Brindeiro GA, Cardoso de Sousa AC, Cristina Dorado M, Ramos F. Cycling with Spinal Cord Injury: A Novel System for Cycling Using Electrical Stimulation for Individuals with Paraplegia, and Preparation for Cybathlon 2016. *IEEE Robotics & Automation Magazine* 2017; PP(99):1-1.
22. Peng, C.-W. et al. 2011. Review. Clinical Benefits of Functional Electrical Stimulation Cycling Exercise for Subjects with Central Neurological Impairments. *Journal of Medical and Biological Engineering*. 31(1):1-11.
23. Kern H, Hofer C, Löffler S, et al. Atrophy, ultrastructural disorders, severe atrophy and degeneration of denervated human muscle in SCI and Aging. Implications for their recovery by Functional Electrical Stimulation, updated 2017. *Neurol Res* 2017;39:660-666. doi: 10.1080/01616412.2017.1314906. Epub 2017 Apr 13.
24. Kern H, Carraro U, Adami N, et al. One year of home-based functional electrical stimulation (FES) in complete lower motor neuron paraplegia: recovery of tetanic contractility drives the structural improvements of denervated muscle. *Neurol Res*. 2010;32:5–12. DOI:10.1189/184313209X385644
25. Kern H, Carraro U, Adami N, et al. Home-based functional electrical stimulation rescues permanently denervated muscles in paraplegic patients with complete lower motor neuron lesion. *Neurorehabil Neural Repair* 2010;24:709-21.
26. Boncompagni S, Kern H, Rossini K, et al. Structural differentiation of skeletal muscle fibers in the absence of innervation in humans. *Proc Natl Acad Sci U S A*. 2007;104:19339–44.
27. Kern H, Boncompagni S, Rossini K, et al. Long-term denervation in humans causes degeneration of both contractile and excitation-contraction coupling apparatus that can be reversed by functional electrical stimulation (FES). A role for myofiber regeneration? *J Neuropath Exp Neurol* 2004;63:919–31.
28. Fiorucci R, Piscioneri A. FES for large denervated muscles: comments of patients and practical demonstrations. *Eur J Transl Myol*. 2013;23:162–164.
29. Kern H, Rossini K, Carraro U, et al. Muscle biopsies show that FES of denervated muscles reverses human muscle degeneration from

- permanent spinal motoneuron lesion. *J Rehabil Res Dev* 2005;42:43–53.26. Hofer C, Mayr W, Stöhr H, et al. A stimulator for functional activation of denervated muscles. *Artif Organs* 2002;26:276-9.
30. Mayr W. Surface Electrode. Patent WO2007131248 (A1).
 31. Kern H, Hofer C, Mayr W, Carraro U. European Project RISE: Partners, protocols, demography. *Basic Appl Myol* 2009;19:211-6.
 32. Kern H, Hofer C, Mayr W. Protocols for clinical work package of the European project RISE. *Basic Appl Myol*. 2008;18:39–44.
 33. Carraro U, Kern H, Gava P, et al. Recovery from muscle weakness by exercise and FES: lessons from Masters, active or sedentary seniors and SCI patients. *Aging Clin Exp Res* 2017;29:579-590. doi: 10.1007/s40520-016-0619-1. Epub 2016 Sep 3. Review.
 34. Kern H, Carraro U. Home-based functional electrical stimulation (h-b FES) for long- term denervated human muscle: history, basics, results and perspectives of the Vienna rehabilitation strategy. *Eur J Transl Myol*. 2014;24:27–40.
 35. Edmunds KJ, Gíslason MK, Arnadottir ID, et al. Quantitative computed tomography and image analysis for advanced muscle assessment. *Eur J Transl Myol* 2016 Jun 22;26:6015. DOI:10.4081/ejtm.2016.6015. eCollection 2016 Jun 13.
 36. Carraro U, Edmunds KJ, Gargiulo P. 3D False Color Computed Tomography for Diagnosis and Follow-Up of Permanent Denervated Human Muscles Submitted to Home-Based Functional Electrical Stimulation. *Eur J Transl Myol* 2015;25:5133. doi: 10.4081/ejtm.2015.5133. eCollection 2015 Mar 11. Review.
 37. Ortolan P, Zanato R, Coran A, et al. Role of Radiologic Imaging in Genetic and Acquired Neuromuscular Disorders. *Eur J Transl Myol* 2015 Mar 11;25(2):5014. doi: 10.4081/ejtm.2015.5014. eCollection 2015 Mar 11. Review.
 38. Gíslason MK, Ingvarsson P, Gargiulo P, et al. Finite Element Modelling of the Femur Bone of a Subject Suffering from Motor Neuron Lesion Subjected to Electrical Stimulation. *Eur J Transl Myol* 2015;24:2187. doi: 10.4081/ejtm.2014.2187. eCollection 2014 Sep 23.
 39. Gargiulo P, Helgason T, Ramon C, et al. CT and MRI Assessment and Characterization Using Segmentation and 3D Modeling Techniques: Applications to Muscle, Bone and Brain. *Eur J Transl Myol*. 2014;24:3298. doi: 10.4081/ejtm.2014.3298. eCollection 2014 Mar 31.
 40. Gargiulo P, Reynisson PJ, Helgason B, et al. Muscle, tendons, and bone: structural changes during denervation and FES treatment. *Neurol Res*. 2011 Sep;33(7):750-8. doi:10.1179/1743132811Y.0000000007.
 41. Carraro U, Rossini K, Mayr W, et al. Muscle fiber regeneration in human permanent lower motoneuron denervation: relevance to safety and effectiveness of FES-training, which induces muscle recovery in SCI subjects. *Artif Organs*. 2005;29:187–191.
 42. Carraro U, Boncompagni S, Gobbo V, et al. Persistent Muscle Fiber Regeneration in Long Term Denervation. Past, Present, Future. *Eur J Transl Myol* 2015 Mar 11;25:4832. doi: 10.4081/ejtm.2015.4832. eCollection 2015 Mar 11. Review.
 43. Carraro U, Kern H. Severely atrophic human muscle fibers with nuclear misplacement survive many years of permanent denervation. *Eur J Transl Myol*. 2016;26:76–80. DOI:10.4081/ejtm.2016.5894. eCollection 2016.
 44. Mussini I, Favaro G, Carraro U. Maturation, dystrophic changes and the continuous production of fibers in skeletal muscle regenerating in the absence of nerve. *J Neurophatol Exp Neurol*. 1987;46:315–31.
 45. Carraro U, Rossini K, Zanin ME, et al. Induced myogenesis in long- term permanent denervation: perspective role in Functional Electrical Stimulation of denervated legs in humans. *Basic Appl Myol* 2002;12:53–64.
 46. Scicchitano BM, Sica G, Musarò A. Stem Cells and Tissue Niche: Two Faces of the Same Coin of Muscle Regeneration. *Eur J Transl Myol* 2016;26:6125. doi: 10.4081/ejtm.2016.6125. eCollection 2016 Sep 15.
 47. Carlson BM. The Biology of long-term denervated skeletal muscle. *Eur J Transl Myol* 2014;24:3293. DOI:10.4081/ejtm.2014.3293
 48. Adami N, Kern H, Mayr W, et al. Permanent denervation of rat tibialis anterior after bilateral sciactomy: determination of chronaxie by surface electrode stimulation during progression of atrophy up to one year. *Basic Appl Myol* 2007;17:237–43.
 49. Lømo T, Westgaard RH, Hennig R, Gundersen K. The Response of Denervated Muscle to Long-Term Electrical Stimulation. *Eur J Transl Myol* 2014;24:3300. doi: 10.4081/ejtm.2014.3300. eCollection 2014 Mar 31.
 50. Lømo T. The Response of Denervated Muscle to Long-Term Stimulation (1985, Revisited here in 2014). *Eur J Transl Myol* 2014;24:13–9.
 51. Azevedo Coste C, Bergeron V, Berkelman R, et al. Comparison of strategies and performance of functional electrical stimulation cycling in spinal cord injury pilots for competition in the first ever Cybathlon. *Eur J Transl Myol* 2017;27:251-4.