2023

Investigation of the coordination of human lower and upper limb movements from various aspects
This year, we focused on the simultaneous cyclic movements of the human arm and leg. In cyclic movements, there is an interaction between the upper and lower limbs, for example in walking or in swimming. The cycling task is well known and widely used in the rehabilitation of people with movement disorders, so we focused on this task.

Muscle synergies in simultaneous arm and leg cycling task. — In the first project, the healthy participants performed the leg cycling and the arm cranking task simultaneously on an arm-leg cycle ergometer. The kinematic data of the body and the muscle activity data with EMG were measured. We investigated the muscle coordination, in terms of muscle synergies by the non-negative matrix factorization algorithm in the different cycling conditions. Interlimb muscle synergies were represented by synergy vectors, explored during the simultaneous arm and leg cycling in a case study [1]. We found that 6 synergy vectors were sufficient to reconstruct 12 muscle's original (measured) activity.

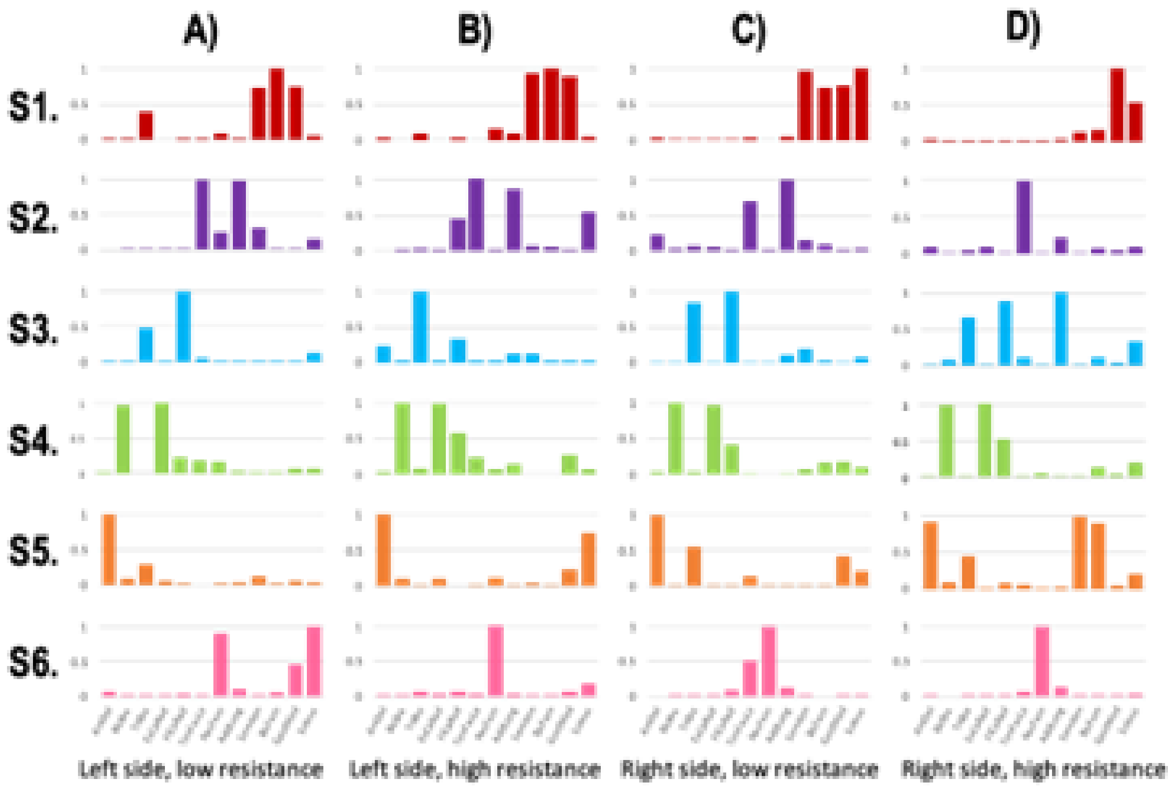


Figure 1. Interlimb synergies between arm and leg muscles in 2 different crank resistance conditions.

Further question is, whether leg cycling has an effect on arm cycling at the level of muscle synergies? We compared the arm muscle synergies when participants performed the cycling simultaneously with arms and legs to that case in which cycling was performed only with the arms. We are working on a manuscript on this topic with our Spanish colleagues.

Effect of the hybrid FES cycling therapy on gait parameters of incomplete spinal cord injured patients. — The other main topic is the investigation of the role of the arm in functional electrical stimulation (FES) assisted cycling therapy. During the FES therapy the paralized muscles are electrically stimulated to perform a predefined task. During the hybrid FES, the FES assisted leg cycling are supplemented with voluntary arm cranking. In our study we work together with colleagues from the National Institute for Medical Rehabilitation. The improvement of walking ability of incomplete spinal cord injured patients is examined in response to hybrid FES cycling therapy. The patients take part a 12 week long rehabilitation training program, they have hybrid FES cycling therapy twice a week, and we measure gait parameters and gait dynamics before the start of the training, then in every third week and finally at the end of the training. The processed data show that walking ability improved, that is reflected in gait parameters, e.g. in the length of center of pressure that acts on the body during walking [2]. Our first case study has been accepted in the "Rehabilitáció" journal [3] ,

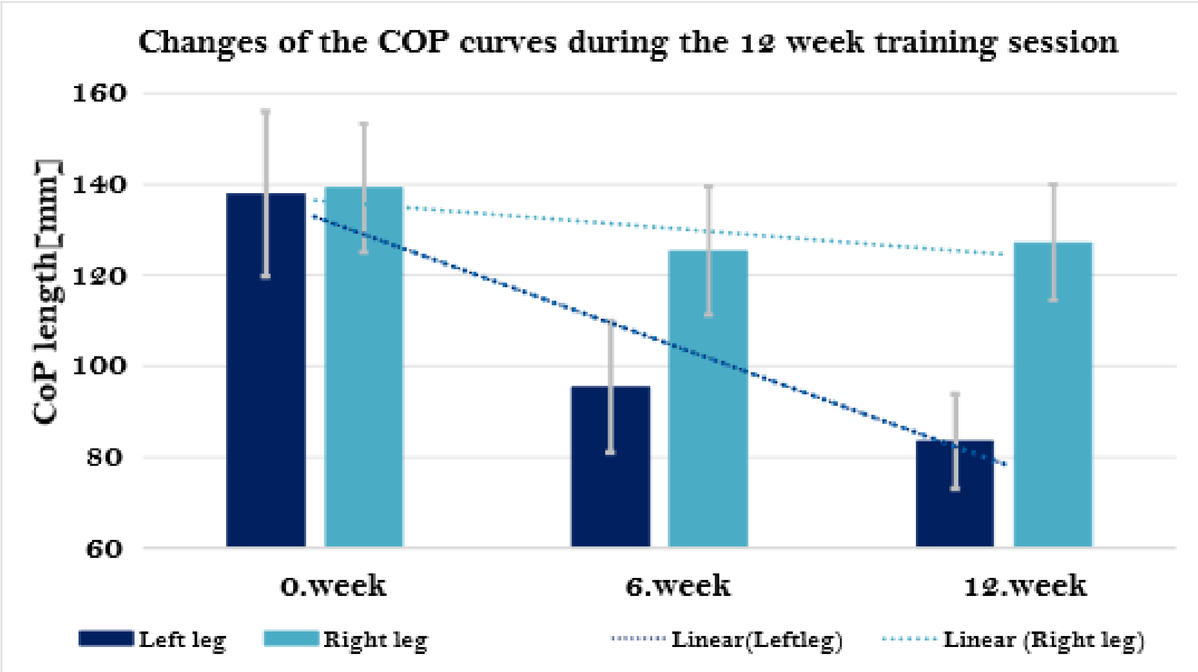


Figure 2. Decreasing of the lengths of the Center of Pressure curves during the training sessions. This suggests that the gait stability has improved as a result of the rehabilitation therapy.

References:
[1] Botzheim L., Radeleczki B., Mravcsik M., Barroso F.O.,Laczko J., Investigation of Muscle Synergies during Simultaneous ARM-LEG cycling – Case Study. In: Progress in Motor Control XIV : Abstract Book, p51. Ambino Gesù Children Hospital (2023) p. 75
[2] B. Radeleczki, L. Botzheim, N. Nagy, J. Laczkó, and M. Mravcsik, "Change of ground reaction force and center of pressure in walking of spinal cord injured patients after FES cycling training – case studies.," in Progress in Clinical Motor Control - Neurorehabilitation II., Program Abstracts, 2023, p. 120.
[3] B. Radeleczki, N. Nagy, M. Mravcsik, P.Szemerédi, M. Futó, L Ware, M. Fehér, A. Klauber, P. Cserháti, J. Laczkó, L. Botzheim. "A hibrid FES kerékpározó terápia szerepe részleges gerincvelősérültek rehabilitációjában – esettanulmány " accepted in Rehabilitáció Journal, 2023.

2021

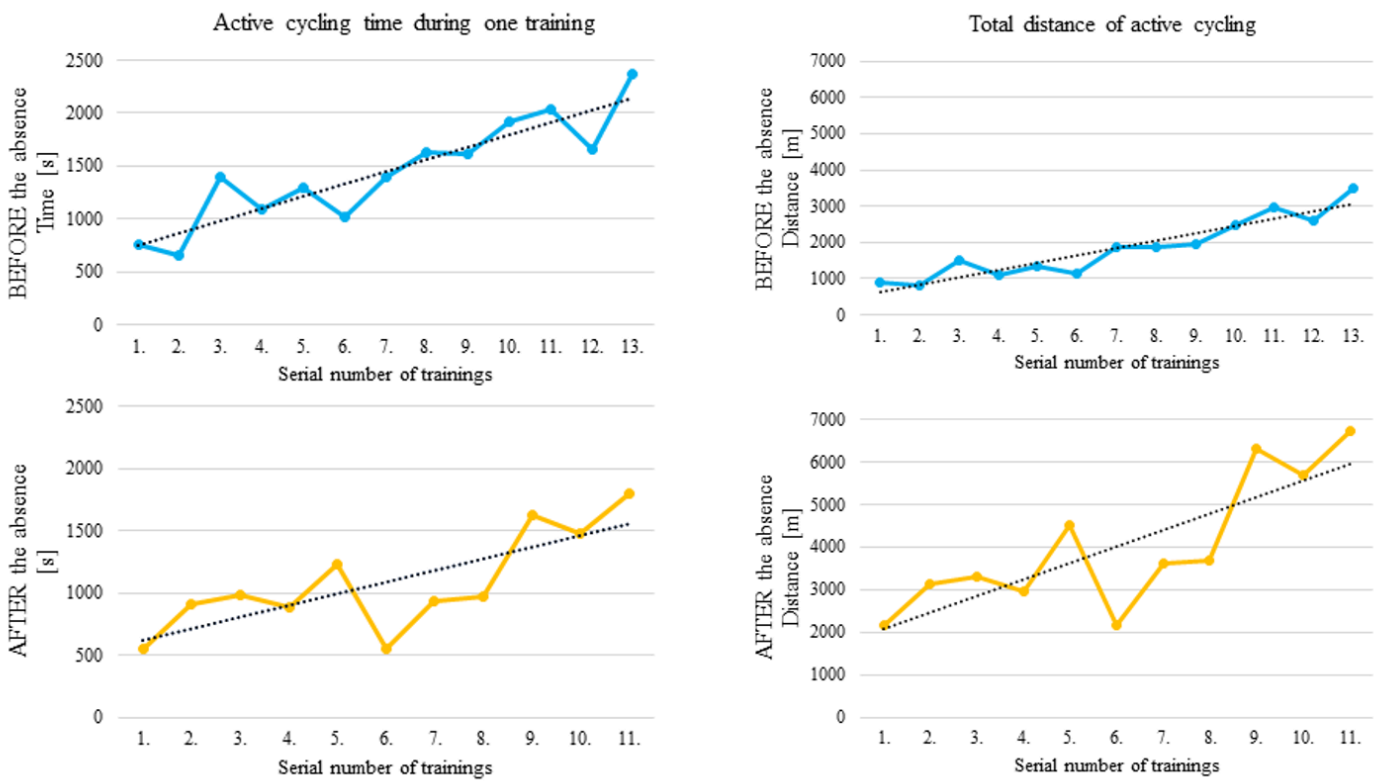
Artificial control of human arm movements for paralyzed persons, applying functional electrical stimulation.

We performed common research with the National Institute for Medical Rehabilitation focusing on application of Functional Electrical Muscle Stimulation (FES) methods in medical rehabilitation. We have already trained paralyzed persons for FES driven cycling movements. FES is a very useful technology and cycling movement is a beneficial motor task for persons who can't exert active muscle forces, because the motor command (manifested in electrical impulses) from their brain can't reach their muscles. We stimulated knee flexor and extensor and hip extensor muscles applying a multichannel electrical stimulator. Beside various beneficial physiological effects of FES cycling, for some people this might be a challenging sport activity. This year we investigated the efficiency of FES cycling trainings of a person whose legs are paralyzed due to a spinal cord injury, but we would like to prepare him for competitions of people with physical disabilities (https://cybathlon.ethz.ch/en).

Due to the pandemic, we had to stop the series of training sessions and we had to keep a three months long break in the serial of trainings when the patient had to stay away from the rehabilitation center. We compared the changes in the measured parameters before and after these three months. The cycling time and elapsed distance in the training sessions and the improvements in these parameters are presented at the Figure.

The break caused a significant relapse in each measured physical parameter. Nevertheless, the improvement in the parameters after restarting the trainings was higher than before the absence from the training sessions and the patient reached the same performance level what he had before pausing the trainings. This suggests that during the preparation for a FES cycling competition a pause in the serial of trainings may not prevent a pilot from reaching proper performance [1].

Another control approach for lower limb FES cycling is to control the lower limb movements by voluntary upperlimb movement.
We modeled whether electrical stimulation of lower limb muscles may be controlled by real time electromyography (EMG) signals of arm muscles during hybrid arm and leg cycling. In hybrid arm and leg cycling an arm and leg cycle ergometer is used and arm cycling is performed voluntarily while leg cycling is driven by functional electrical stimulation. In particular we are developing neural network algorithms to predict lower limb muscle activities from arm muscle activities.
We continued our research on the effect of external load on arm cycling movements, in particular the effect of crank resistance on variances and smoothness of the movement. We found that with higher load the jerkiness of the movement increases while the change in the arm pose becomes more consistent [2].



1.Figure. Total active cycling time (left panels) and the elapsed distance (right panels) in each training before and after the break (absence of the patient from the training essions due to the pandemic). Dotted line represents the trend of improvement.

References:
[1] Botzheim, L., Ernyey, D.M., Mravcsik, M., Varaljai, L., Klauber, A., Cserhati, P. & Laczko, J. “Changes in active cycling time and distance during FES assisted cycling before and after the pandemic closure – a case study”. In: 24th Annual International Functional Electrical Stimulation Society Meeting, Rovinj, Croatia, 23-24. September 2021. https://3eventrovinj.com/ifess-3/

[2] Mravcsik M, Botzheim L, Zentai N, Piovesan D, Laczko J (2021): The Effect of Crank Resistance on Arm Configuration and Muscle Activation Variances in Arm Cycling Movements. Journal of Human Kinetics volume. Vol 76, pp. 175-189. https://pubmed.ncbi.nlm.nih.gov/33603933

2020

Control of human arm movements was studied. We investigated the effects of gravity and kinematic constraints on the coordination of human limb muscles. In particular, we have continued our research on cycling limb movements, that are used in medical rehabilitation of people with motor impairments. Human arm cycling is a motor task used both in medical rehabilitation and in sports training. We used the muscle synergies framework to have insight into motor control of multi-muscle systems. The theory of muscle synergies suggests that the central nervous system co-activate groups of muscles with specific activation patterns. We extracted muscle

synergies in 8-dimensional "muscle space" by non-negative matrix factorization. Results showed that synergies were affected by body position (respect to gravity) and cranking mode but practically unaffected by movement size (Figure 1.). These results suggest that the central nervous system may employ different motor control strategies in response to external constraints such as cranking mode and body position [1].
We investigated the variances of joint rotations and muscle activations and the dependence of these variances on external load manifested in crank resistance. With changing external load, motor noise and changing joint stiffness may affect arm configuration even though the hand trajectory is unchanged in arm cycling. However, our results show that joint configuration variance in the course of arm cranking was not affected by crank resistance, whereas muscle activation variance was proportional to the square of muscle activation. This suggests that the central nervous system is able to separate of kinematic- and force-control, via mechanisms that are compensating for dynamic non-linearities. These studies have implication on medical rehabilitation as they show the suitability of arm cycling exercises when the aim is to perform training under different external conditions [2].

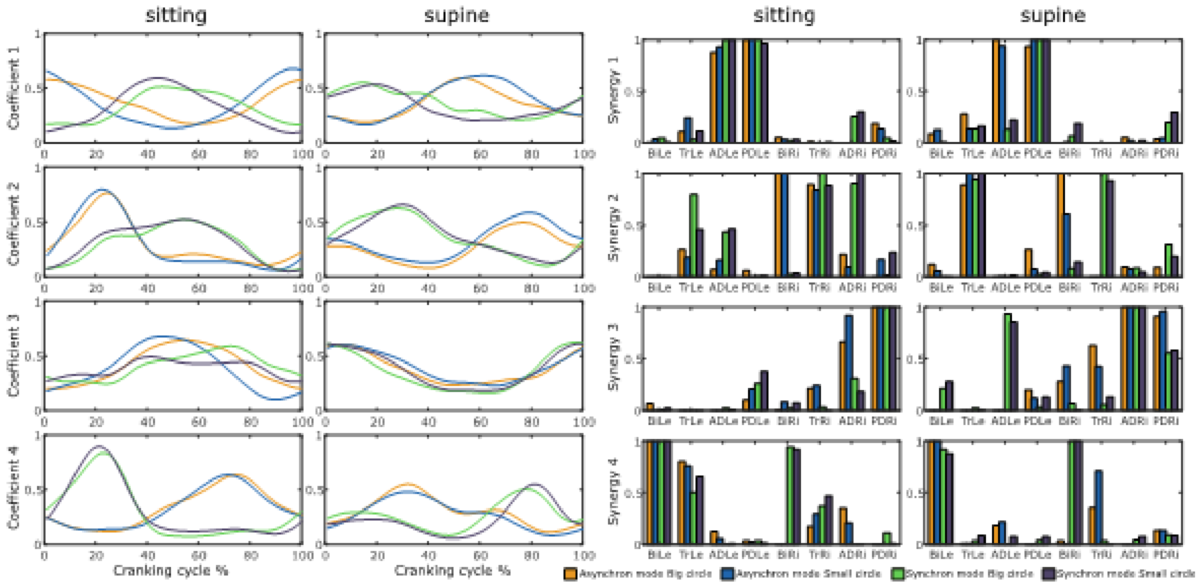


Figure 1. *Left: activation coefficients (as function of normalized time) of synergy vectors obtained in eight cycling conditions (4 conditions in supine and 4 in sitting position). Blue and orange lines relate to asynchronous cycling (blue – big circle, orange – small circle); green and grey lines relate to synchronous cycling (green - big circle, grey - small circle). Right: bar diagrams show the weights of four synergy vectors extracted in the cycling conditions separately. The height of the bar represents the relative activation level of individual muscle's in the synergy.*

Regarding lower limb cycling, a new aspect of our work on functional electrical stimulation driven cycling of spinal cord injured people, was to prepare for competitions of people with physical disabilities who compete to perform everyday tasks using state-of-the-art technical assistance systems, as functional electrical neuro-muscular stimulation. We continued this project with the National Institute for Medical Rehabilitation, the University of Pecs, and the Pázmány Péter Catholic University using the special "Berkelbike" tricycle (Figure 2.)

Figure 2. *A person with spinal cord injury and paralayzed lower limbs, is "tricycling" on a Berkelbike tricycle. He propels the tricycle with his paralyzed limb using functional electrical muscle stimulation (FES). His leg muscles (quadriceps, hamstrings and gluteus maximus) excert active forces controlled by FES.*

References:
[1] Lilla Botzheim, Jozsef Laczko, Diego Torricelli, Mariann Mravcsik, Jose L. Pons, Filipe O. Barroso: Effects of gravity and kinematic constraints on muscle synergies in arm cycling. Submitted to the Journal of Neurophysiology, after minor review.

[2] Mravcsik M, Botzheim L, Zentai N, Piovesan D, Laczko J (2021): The Effect of Crank Resistance on Arm Configuration and Muscle Activation Variances in Arm Cycling Movements. Journal of Human Kinetics volume. Vol 76, pp. 175-189 DOI: 10.2478/hukin-2021-0053.

2019

Control of human arm movements was studied. — One particular interest was the jerkiness and tremor that occur in voluntary arm movements. The jerk is the 3rd time derivative of position, that quantitatively represents the smoothness of the movement. Special types of movements, namely arm cycling exercises are often included in medical rehabilitation protocols to improve motor performance and motor control of individuals with spinal cord injury or stroke. In this exercises people perform arm cranking on arm-cycle ergometers. The research of the group presented that in arm cranking movements the jerk of hand movement is not sufficiently explained by angular jerks in the joints, instead the change of arm configuration (arm pose) and its time derivatives are equally well contribute to the jerk of the hand. This is in contrast compared to the results obtained in goal oriented, reaching movements. The structure of jerk is task dependent and this should be considered in planning medical rehabilitation protocols. The reported result can provide a new perspective on the creation of robotic devices and rehabilitation therapies [1].

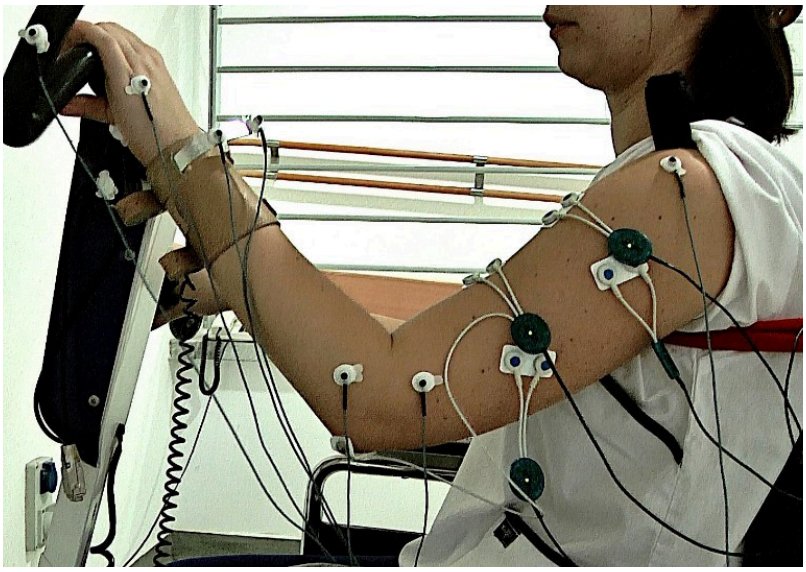


Figure 1. During arm cranking movements, kinematic and electromyographyc (EMG) data were recorded. Markers were placed on anatomical landmarks of the arm and surface electrodes above the muscles.

Muscle coordination in arm cranking movements. — It was investigated, how muscle coordination changes when biomechanical constraints are changing. Biomechanical constraints arise due to the size of the movement or due to body position. In arm cranking movement, the movement size relates to the length of the crank of the ergometer, and the studied body position was sitting and supine. It is an interesting question that how muscle activities change when the direction of gravity respect to body position is changing. Muscle synergies were revealed from multichannel electromyography time series, applying non-negative matrix factorization. It was presented that one-sided muscle synergies (obtained from one arm) do not give adequate information about neural control, but two-sided synergies may discern synergistic control in bimanual cranking. Furthermore, the results suggest that muscle synergies are affected by body position but not by movement size. Understanding changes in muscle coordination across different biomechanical conditions is a step towards improved rehabilitation approaches and can maximize the outcome of the training.

Functional Electrical Stimulation for substituting lost motor functions of paralyzed persons. — By applying research on functional electrical stimulation (FES), special tricycling trainings were performed and muscle activities were artificially controlled for spinal cord injured, lower limb paralyzed persons who had either spastic or flaccid muscles. This work has been performed in cooperation with the National Institute for Medical Rehabilitation, the University of Pécs, Pécs and the Centre for Medical Physics and Biomedical Engineering of the Medical University of Vienna.

Figure 2. Lower limb paralyzed, spinal cord injured person is cycling on a tricycle. Coordinated muscle activities are generated by functional electrical muscle-stimulation, applying stimulating (surface) electrodes.

This FES related research provides a noninvasive modality used in spinal cord injury rehabilitation and opens new perspectives in physical activities of the injured persons [2].

2018

A graph based dimension reduction method was proposed for analyzing kinematic data sets assessed from human arm movements. This analysis was performed in cooperation with the University of Pecs and the HAS Wigner Cloud service. The combinatorial graph based dimension reduction method was applied to locate 1-dimensional subspaces in high dimensional task specific kinematic spaces. Identifying such subspaces, it can be shown that which variables can be controlled together by one common centrally controlled parameter. This method has been validated, by applying it to arm cycling. Particularly, kinematic variables (certain coordinates of markers placed on the arm) were identified whose time series differed only in amplitude. This may help to simplify the control of motor tasks.

Lower limb cycling movements were generated for paralysed individuals in the National Institute for Medical Rehabilitation during the year twice a week, using functional electrical muscle stimulation. These cycling and tricycling trainings for spinal cord injured (SCI) people was provided by the research group. Accomplishing functional electrical stimulation driven tricycling trainings for lower limb paralyzed SCI persons, it was shown that cycling speed increased during the series of trainings. This demonstrates the significance of the neurorehabilitation technique applied by the group in cooperation with the Centre for Medical Physics and biomedical Engineering of the Medical University of Vienna (Fig 1).

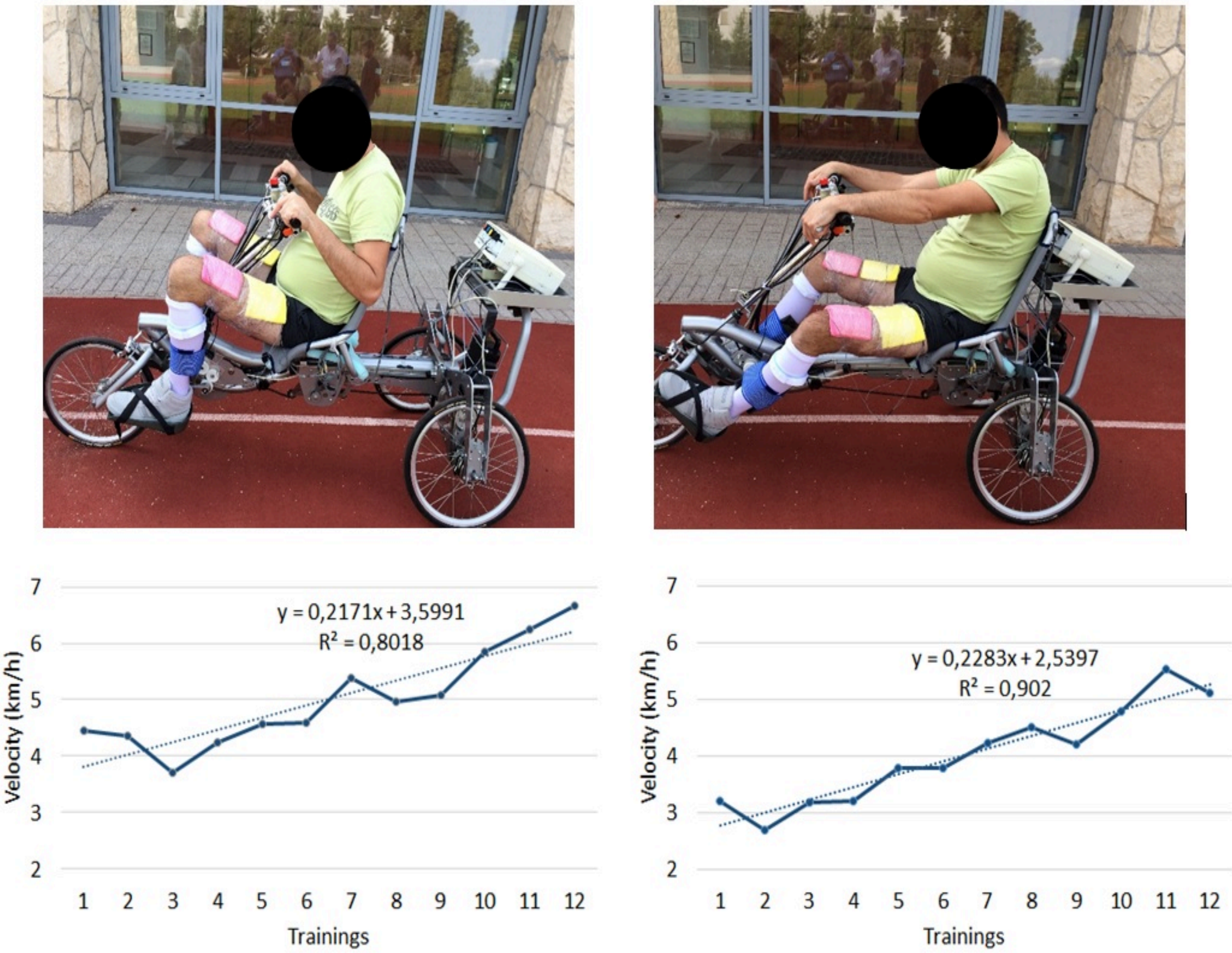


Figure 1. *Tricycling of lower limb paralyzed spinal cord injured individuals, applying functional electrical muscle stimulation for knee extension. Bilateral knee extension starts and actively drives the tricycle as the quadriceps muscles are stimulated (upper left picture). At the end of quadriceps stimulation (at the end of knee extension), start of "rowing mode" when the person starts to pull his body forward by his arm (upper right picture). The speed in 12 consecutive trainings of 2 spinal cord injured, paralyzed participants (lower diagrams): cycling speed increased during the series of trainings.*

Arm cycling movements of able bodied persons were analyzed The dependence of movement smoothness, jerkiness on joint angular velocities and accelerations was shown for arm cranking movements. The comparison of this result, with results previously found for reaching arm movements, supports the task specificity of smoothness and jerkiness of human movements.

The FES driven cycling movements (as a neuroprosthesis) for new paralyzed users and the TalkPad speech replacement system (as a speech prosthesis) became available for new autistic users as a result of the work of the research group.

2017

Control and biomechanics of human limb movements, were studied to reveal hidden features of coordinated muscle activities and joint rotations. Spatiotemporal coordination of selected anatomical points of the body and electromyograms of selected muscles were recorded during limb movements of able-bodied participants. Muscle activity patterns were established, based on evaluation and statistical analysis of measured data. Such patterns were used to substitute missing neural control of spinal cord injured individuals through multichannel functional electrical muscle stimulation (FES). As a practical application in medical rehabilitation, several lower-limb paralyzed individuals with complete spinal cord injury (SCI), performed cycling movements against various loads on a stationary bike. These “trainings” were performed regularly twice a week, at the National Institute for Medical Rehabilitation. Two other SCI participants with denervated muscles performed cycling movements on a special tricycle equipped by a 4 channel electrical stimulator for denervated muscles. This kind of cycling were performed in open air track and the average cycling distance (across trainings and participants) was 2.16 km and the average cycling speed was 4.7 km/h. Power and energy output of the complete SCI participants were measured. The paralyzed people who participated in this FES assisted rehabilitation program were very motivated and enjoyed the physiological and psychological benefits and that they used their own paralyzed muscles to drive a stationary bike or tricycle and were able to produce mechanical work by active muscle force, even if their muscles were not controlled by their brain, but by artificial control through an external device. These cycling movements are advantageous for cardiovascular and respiratory well-being and can’t be done without FES.

Control of cycling upper limb movements were also investigated in young, able bodied people. Variances (and stability) of these movements were analyzed. Three joint angles (shoulder, elbow, wrist) and four muscles (biceps, triceps, anterior delta, posterior delta) were studied in each arm (dominant and non-dominant). There were no significant differences in the joint angular variances, observed in the two arms. It is concluded that at kinematic level the neural control is equally stable for the two arms in this motor task. Muscle synergies were established applying dimension reduction methods (non negative matrix factorization) and it was found that muscle activity vectors in the 4D muscle space can be well estimated from 2 modules (synergies) because the variance accounted for by 2 muscle synergies was over 93%. There were no significant differences between the two arms in this respect either, reflecting the speciality of cycling movements (Fig. 1).

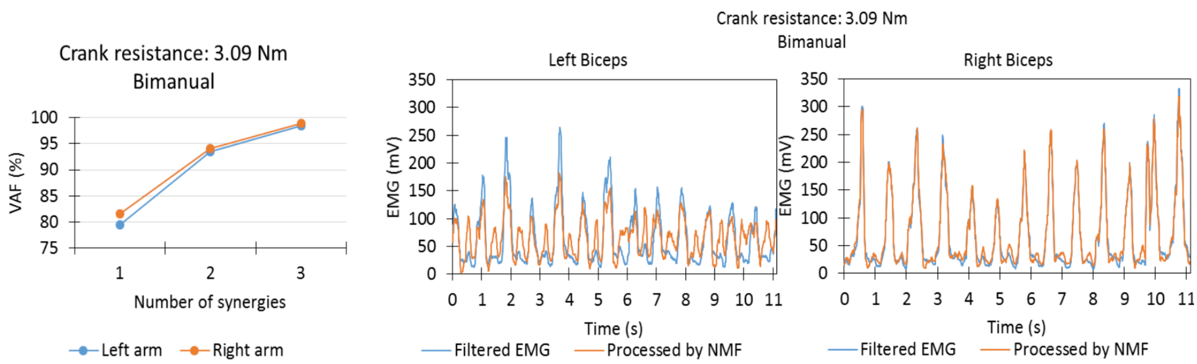


__Figure 1.__ The variance of muscle activities (EMG) was largely explained by 2 synergies as the variance accounted for (VAF) by 2 synergieswas over 93% in both arms (left panel). Measured left and right biceps activities are approximated by activities assembled from 2 synergies

Another motor task was investigated in able bodied people and in individuals who suffered stroke. The participants performed point-to-point reaching tasks: they moved their hand from a central starting position to targets in the horizontal plane. The smoothness (or amount of jerkiness) of the movement was investigated. The jerk of hand movement and its dependence on terms related to angular velocities, accelerations and jerks were analyzed. We showed that contribution of such terms to the jerk of the hand differs in healthy people and people who suffered severe stroke. The revealed differences may reflect deficits in neural control and impaired ability of stroke survivors to compensate for multi-joint interaction torques.

The research and development of assistive devices were continued for helping blind people to use braille input devices and mobile phones. The MOST (Mobile Slate Talker) devices for the blind and deaf-blind has been further advanced due to the challenges given by continuously changing operating system.