Preliminary developments towards closed-loop FES-assistance of posture and gait

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Abstract: This article presents a general approach and some on-going developments to restore coordination between unaffected and paretic limbs in the context of functional electrical stimulation (FES) assisted posture and gait. The principle is to ensure posture global control through local muscle control when considering functional assistance. This supposes that both natural and artificial controllers are provided with sufficient information concerning the global state of the system. In other words, voluntary movements of unaffected limbs should cooperate with artificially controlled deficient limbs in order to guarantee an optimal behaviour and posture. The approach is described from a theoretical and technical aspect and some experimental results are presented. The system is based on a Body Area Network (BAN) embedding both sensor and actuator (electrical stimulators) nodes. In the present paper only surface FES is discussed through two main applications: gait assistance in post-stroke hemiplegia and sit-to-stand transfer in complete paraplegia. The approach is transposable to other applications as well as to implanted neuroprosthetics from a conceptual point of view.

Keywords: Functional Electrical Stimulation (FES), Body Area Network (BAN), Closed loop control, gait assistance, posture, transfer assistance, neuroprosthetics.

1. INTRODUCTION

Functional Electrical Stimulation (FES) allows to assist or restore muscle contraction. Artificial control of natural actuators can benefit from automatic control and robotics theoretical framework. In the context of lower limb stimulation, many studies have investigated closed-loop control of joints using various kinds of approaches (Lynch and Popovic, 2012). Local control of individual joints has to be also considered from the global perspective of the function to restore (walking, standing...) ensuring a safe and optimal posture. Posture control has also been investigated by several teams (Ajoudani and Erfanian, 2009). Consequently the controlled variable can concern individual joint state (Qiu et al., 2014), joint stiffness (Jaime et al., 2002) or a more global variable such as body center of mass (Jovic et al., 2012a), (Vette et al., 2009).
In order to improve efficiency, robustness and adaptability closed-loop control has been considered in many published studies. Feedback control implies the availability of information related to the state of the controlled variable. Various sensors have been used for this purpose: goniometers (Qiu et al., 2014), instrumented walker, instrumented orthotic devices (Jezernik et al., 2004), Electro Myography (EMG) (Zhang et al., 2013). If, electrical stimulation (ES) can be external, i.e applied at the skin surface, it can also be implanted (Guiraud et al., 2014) and in this latter context Electro Neurography (ENG) measuring afferent nerve fibers activity could be a solution (Hansen et al., 2004; Djilas et al., 2010, 2009).
Sensors have to be adapted to the type of neuroprosthesis (implanted/ surface) and to the function to be assisted or restored. Depending if FES is applied acutely hoping for functional recovery of the patient or chronically, the technological choices also have to be adapted.
In a research context and for validation purposes, multiple sensors are commonly embedded on the patients. From a practical point of view, this will not be acceptable for an every-day use. This also means that in real applications, only partial and imprecise information might be available. Similarly, complex models with constraining parameter identification process will be hardly considered. These consideration lead our team to investigate solutions to extract from a minimum number of sensors with a minimum of calibration procedure, a maximum of knowledge about the considered motion (Sijobert et al., 2015; Azevedo Coste et al., 2014b).
In this paper we will only discuss external FES. In this context we have investigated the body area network (BAN) framework (Chelius et al., 2011). Our team has proposed solutions for architectures of networks of sensors and stimulators both for surface (Toussaint et al., 2010) and implanted contexts (Andreu et al., 2009).

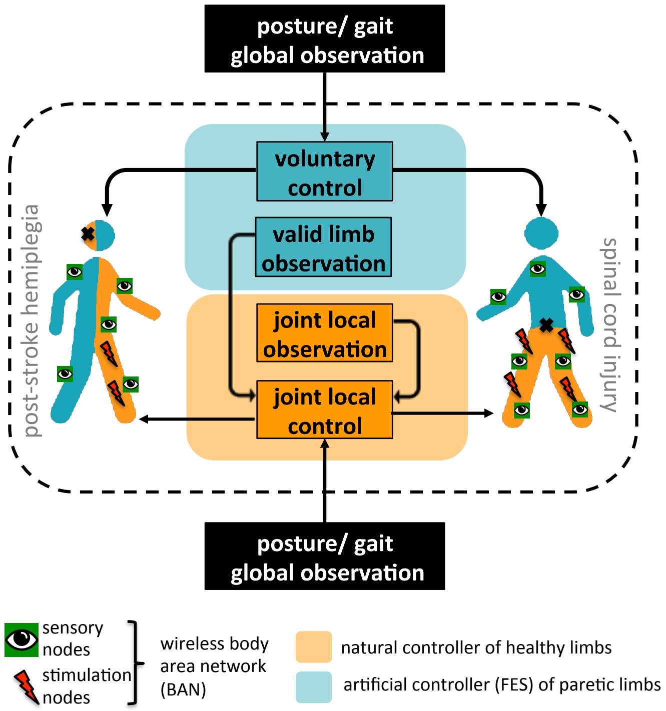

Fig. 1. Integrating global and local observations for a better coordination of valid and deficient limbs in posture and gait functional assistance involving FES. Illustration of drop-foot correction in post-stroke hemiplegic and transfer assistance in SCI contexts.

The present article intends to insist on two main aspects of closing the loop in FES-assisted gait and posture: local joint control and global function control. From a feedback point of view this implies to observe both local behaviors and global posture including voluntary movements (figure 1). Indeed, when dealing with FES assistance of posture and gait, an important characteristic is the co-existence of two controllers: the natural vs the artificial one. Artificial control of lower limb(s) needs to cooperate with voluntary motion (Azevedo Coste and Héliot, 2005). It is non sense to perform a local optimization without integrating a general vision of the function to restore (here posture and gait). From an application point of view, it is also important to keep in mind that observation should rely on a low number of sensors for the proposed solutions to be realistic. In the following, we illustrate this approach through two examples: transfer assistance in spinal cord injured (SCI) patients and gait assistance in post-stroke hemiplegic patients.

2. TRANSFER ASSISTANCE IN SCI: COORDINATING UPPER AND LOWER BODY

Restoring standing by means of functional electrical stimulation (FES) in spinal cord injured (SCI) individuals has been a subject of research since many years (Kralj et al., 1980). First approaches used open-loop stimulation to ensure knee locking and hyperextension of hips while subjects used their arms to maintain balance. In these conditions, due to early fatigue of artificially stimulated muscles, a paraplegic person is able to stand only for a few minutes mainly due to knee unlocking. Solutions have been proposed to face fatigue problem by optimizing stimulation parameters (Bijak et al., 2005), performing posture switching in order to allow muscles to relax (Krajl et al., 1986), or implementing closed-loop control laws (Braz et al., 2009; Matjai et al., 2003).

It is important to have in mind that SCI individuals intensively use their upper limbs during daily activities, such as performing pivot transfers and wheelchair propulsion. This overuse induces shoulder pain and damages. This is critical for these persons whose autonomy is highly linked to arm contribution. FES-assisted sit to stand (STS) should not increase the already existing risk of shoulder complications. In healthy population, STS can be achieved without arm participation and trunk role in this postural task is essential (Jovic et al., 2012b).

Trunk motions should not be considered as negligible disturbances in any postural task, indeed center of mass position is mainly influenced by trunk motion. Depending on the lesion level, the trunk control is totally or partially under subject voluntary control. In a STS task, trunk movements should participate with and not against the transfer.

We have proposed to restore a coordination between upper and lower parts of the body in order to optimize STS transfers in terms of reducing arm participation during the rising motion. We have developed an algorithm to observe trunk acceleration during STS transfer and trigger stimulation at the chosen moment (figure 2) and investigated the influence of the timing of muscle stimulation onset on the upper limb efforts. More details can be found here in previous publications (Jovic et al., 2012a, 2011).

Trunk acceleration was acquired via a single-axis wireless accelerometer placed between subjects shoulders. Force sensors were mounted on handles to record arm efforts. Stimulation current amplitude was adjusted muscle by muscle to ensure maximum contraction.

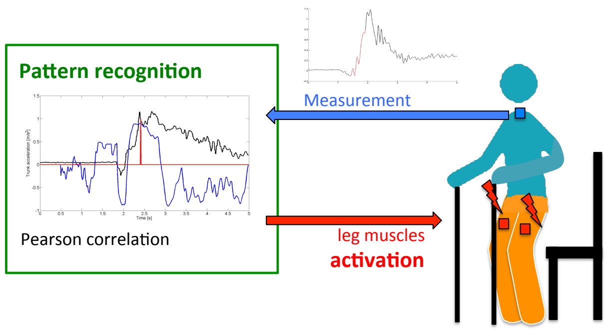

Fig. 2. Observing upper body to control deficient leg muscles in SCI FES-assisted transfer context.

Participants were instructed to bend their trunk forward at the signal. Leg stimulation (quadriceps, hamstrings) was first manually triggered by the experimenter. The corresponding measured trunk acceleration was the reference pattern. In subsequent sessions the participants had to repeat the same trunk motion and stimulation was automatically triggered in order to randomly explore various timings (i.e different stimulation onset values in regards to the maximal trunk acceleration signal). The detection algorithm consisted in comparing the acceleration of the ongoing motion with the reference pattern through a sim-

ple correlation. Once the pattern detected stimulation was triggered. By selecting a subpart of the reference pattern, the stimulation timing onset was defined indirectly.
We have shown, in the 6 participants, that when lower limb stimulation started before or around the maximum trunk acceleration peak, the applied arm forces during STS motion were significantly lower when compared with the situation when stimulation started after maximum trunk acceleration peak. We also showed that arm forces applied during STS motions were slightly higher when the onset of stimulation occurred after the maximum trunk acceleration signal, vs. when participants stood up using only arm support. In other words FES-assistance was worse than no assistance at all if triggered too late. For each participant, and also depending on training, the optimal moment for triggering FES can be different and has to be specific.
Coordinating lower and upper body in STS task is necessary to reduce arm support and preserve shoulders.

3. GAIT ASSISTANCE

This section is adapted from (Azevedo Coste et al., 2014a) where more details can be found about the method. The intention here is to illustrate the general concept of limb coordination in FES-assistance.

Walking impairment after stroke can be addressed through drop foot stimulators (DFS) (Lyons et al., 2002). Current DFS, through activation of the common peroneal nerve, elicit ankle dorsiflexion on swing phase of gait. Dropped foot stimulators are generally piloted by a force sensing resistor heel switch placed in the shoe of the affected side with stimulation triggered ON by heel rise of the affected foot and triggered OFF by heel strike. Other sensors have been proposed instead of foot switch such as tilt sensors (Shimada et al., 2005; Everaert et al., 2013). Eventhough closed-loop control in this context has been considered (Melo et al., 2015; Seel et al., 2014), real-time control of stimulation intensity is still not available in existing devices. The modulation of FES intensity to provide more optimized delivery of stimulation and also to regulate dorsiflexion in the presence of disturbances, such as fatigue, may increase the number of potential users of the technology (Breen et al., 2006). Modulation of stimulation parameters would enable adaptation to context and environment changes. Some studies have suggested that improvement in orthotic performance could be achieved using stimulus intensity shapes matching more closely the muscle biphasic activation pattern than the trapezoidal shape classically used in the stimulators (Byrne et al., 2007), this requires more than one event driven stimulation.

Human gait is a cyclic phenomenon which can be modeled as a non-linear oscillator (Héliot and Espiau, 2008). Based on this, we have developed a solution to continuously track the evolution of the ongoing gait cycle. The principle is to identify the parameters of a Van Der Pol oscillator from the signal of a sensor placed on a subject limb. Indeed, during walking the signal should elicit a cyclic behavior. We have shown that thigh and shank inclination can be good candidates. In the phase plane the periodic stable solution of the oscillator is a trajectory called limit cycle. The phase is a coordinate along this limit cycle ie

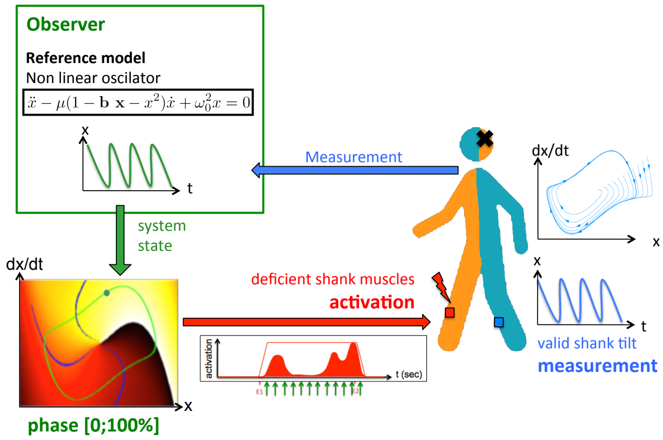

Fig. 3. Observing unaffected leg movements to control deficient leg muscles in drop foot correction context.

a continuous information on the gait cycle execution. An isochron matrix can also be defined in order to extend the phase to the vicinity of the limit cycle. Based on the oscillator properties, it can be demonstrated that a state observer of the system can be built. From the estimated state variables the phase of the oscillator can be computed (figure 3).

We have proposed to extract the tilt angle information from one inertial sensor fixed on patient shank. Extra details can be found in (Azevedo Coste et al., 2014a). A reference pattern is computed from several steps of a given individual and is used to identify the oscillator parameters. The phase can be then estimated online from ongoing measured data.

We have experimentally validated this model on 20 post-stroke hemiplegic subjects by analyzing the phase estimation corresponding to heel strike and heel off compared to information available from a walkway GAITRite system.
As a first attempt to use this real-time information, we show the feasibility of triggering an electrical stimulator based on the information provided by an inertial sensor placed on unaffected shank. We embedded our gait observation algorithm within a system involving a commonly used drop foot stimulator (Odstock ODFS III) to control deficient foot dorsiflexion. We compared the situation when ES was triggered from a heel switch and when ES was triggered when the phase values were comprised between 0 and 40%.
The observation of the unaffected leg shank angle could successfully be used to trigger the stimulator. Theoretically the stimulator can be triggered at any instant of the gait cycle from the continuous phase information.

Using only one sensor placed on the shank of the unaffected leg a complete information on the gait cycle evolution can be extracted, i.e a global knowledge on the task performance. Extending the body area network by including additional sensors could allow us to investigate advanced control laws (Héliot et al., 2013; Benoussaad et al., 2013).

4. CONCLUSION

We have described a general approach to functional assistance using functional electrical stimulation. Most of the concepts could be adapted to other assistive techniques (orthoses, exoskeletons...). The proposition is to consider this problematic from a multi-scale point of view. The controller should be hierarchic and include local and global levels, going from joint to posture considerations. This is very similar to human natural sensori-motor architecture (Azevedo et al., 2007). We insisted on the necessity to coordinate unaffected and paretic limb motions through the cooperation of voluntary and artificial controllers. This theoretical framework is associated to technical developments around body area networks (BAN) integrating sensors and actuators nodes. We have illustrated the interest of the approach in the context of two situations: sit to stand assistance in complete paraplegia and drop foot correction in hemiplegia. Some experimental validation has been achieved in both cases and from these preliminary results new investigation topics are on going.

This article presented ongoing developments towards a robust framework for body area network of sensors and stimulators in order to propose advance solutions of FES-closed loop control. The approach is illustrated through preliminary results in the context of post-stroke hemiplegic gait assistance and complete spinal cord injured patient transfer assistance.

ACKNOWLEDGEMENTS

This article is a synthesis of several contributions from former collaborations. Related articles are cited.

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