DESCRIPTION OF POSTURAL COORDINATION PATTERNS DURING FES-ASSISTED STANDING IN COMPLETE PARAPLEGIA

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Abstract

We investigate the postural organization of external FES-assisted sit to stand and standing in patients suffering from complete spinal cord lesion. The protocol was to stand in between parallel bars and maintain postural balance by aligning head, pelvis and ankles with minimum arm support. In order to help patients to adopt the correct posture, visual feedback assistance was provided: a screen was set up in front of the patients where they could see their own profile. A video motion analysis system recorded the positions of reflective markers placed on relevant body points. Force sensors mounted to handles fixed on the parallel bars recorded arm support efforts. Insoles, fitted in the patient's shoes, recorded plantar pressure distribution. This study aimed at determining whether or not sensors placed on a walker could be sufficient to inform about patient posture and be used to trigger stimulation and observe fatigue evolution. The results are promising as they show that a large amount of knowledge concerning valid movements can be obtained through the proper analysis of arm support. Concerning fatigue of lower limbs, additional sensors are needed; pressures insoles could be used, which remains practically acceptable for a daily use of the system.

Introduction

Functional electrical stimulation (FES) is a mean to perform standing in complete paraplegic patients. Benefits of an active verticalization are both psychological and physiological. FES creates a split-body situation where the body is in part controlled externally, whereas the rest of the body remains under the voluntary influence of the central nervous system. Several issues remain to be solved before making **long term arm-free standing** achievable. We address two of these issues here: **fatigue** and **sit to stand transfer**. Muscle contractions induced by functional electrical stimulation (FES) tend to result in rapid muscle fatigue, which greatly limits standing. Some solutions to reduce fatigue are starting to appear but the problem of detecting and evaluating fatigue remains open. The idea is to investigate the possibility of producing relevant feedback to FES controller using an instrumented walker associated to pressure insoles; the goal being to develop a safe, simple and practical system to the patients. We do not intend to propose a complex control law, based on accurate modelling of dynamics, but to propose solutions which can be directly implanted on our existing stimulation system (PROSTIM©). Classically, studies investigate the use of body mounted sensors in order to provide feedback to FES controllers [4]. They have the advantage of providing accurate information but are not very practical from a patient's view. The standing-up manoeuvre in paraplegia, considering the body supportive forces as a potential feedback source in functional electrical stimulation FES-assisted standing-up, has been previously studied [3]. Arm, feet, and seat reaction signals were used to reconstruct the centre-of-mass trajectory, the use of a sensory system incorporating a six-dimensional handle force sensor and an instrumented foot insole was recommended. We extended the use of this type of sensors to fatigue estimation. As suggested in [2] force sensors can give a feedback to the patients so that they should "feel" that their leg muscles are tiring and be able to voluntary modify his posture in order to indirectly relieve efforts on the fatigued muscle.

Material and Methods

Patient selection and training to FES

15 volunteer complete paraplegic patients (T5-T12) were selected to participate in our study. The patients went through a muscle mapping session during which we first tested the compatibility with surface electrical stimulation. We investigated only muscles involved in standing: quadriceps vastus medialis, hamstring biceps femoris, gluteus maximus and tibialis anterior. But we had to be flexible on the target muscles: in some patients ankle flexion was not controllable and quadriceps vastus lateralis was stimulated instead. Concerning tibialis anterior, one group of patients received muscle stimulation whereas the other received peroneal nerve stimulation. The muscles have been

selected to allow knee and ankle locking. The second aspect of mapping session consisted in testing muscles one by one in order to evaluate threshold current amplitudes: contraction initiation, diffusion to other muscles, joint locking and contracture onset. MRC (Medical Research Council) grades were also evaluated. Stimulation frequency and pulse width were respectively 25Hz and 300µs (this stands for all the study).

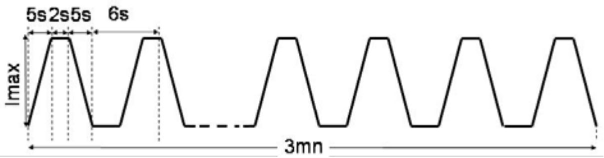

Fig. 1: Training session stimulation sequences.

5 patients could not be included in our protocol. 1 patient presented flaccidity, 1 patient had unpleasant sensation to stimulation, 1 patient had over-spasticity and the last 2 patients had non stimulable gluteus maximus. 10 patients were finally selected for the next phases of the study. Muscular reinforcement, to prepare muscles to verticalization, consisted in 4 training sessions. The session consisted, for each muscle, in 3mn stimulation sequence application followed by 3mn rest, 4 times. Stimulation sequences were composed of ramp-hold-ramp cycles as presented in (Fig. 1). The maximum current amplitude was increased over the sessions to improve joint locking. One patient decided to quit the protocol after one training session. The 9 remaining patients presented large inter-variability in terms of lesion level and injury occurrence.

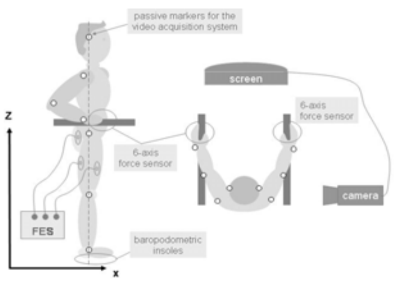

Fig. 2: Description of the experimental protocol.

FES-assisted verticalization protocol

Two sessions of five trials were performed: a first session to adjust the stimulation parameters and for the patient to get familiarized with the protocol, a second session where kinematics and dynamics information were recorded. The protocol was to stand in between parallel bars and maintain postural balance by **aligning head, hips and ankles** with **minimum arm support**. In order to help patients to adopt the correct posture, visual feedback assistance was provided: a screen was set up in front of the patients where they could see their own profile. A video motion analysis system recorded the positions of 16 passive markers. Six-degrees of freedom force sensors were mounted to handles fixed on the parallel bars in order to record upper limbs efforts. Insoles were fitted in the patient's shoes to record plantar pressure distribution (Fig. 2). One group of patient received tibialis anterior (TA) stimulation whereas the other not. The goal was to evaluate the contribution of ankle locking during arm supported standing.

Results

We present in this section some typical recordings which sound relevant to better understand the FES-assisted verticalization issues. Patient #2 training did not succeeded in functional verticalization, only few seconds of standing was possible. Patient #5 received additional training session as the first verticalization was not successful. Patients performed 5 to 6 tries-out (duration=45sec ±12). No relevant difference was found when comparing the group of patients who received TA stimulation (ankle lock) and the other one.

Body alignment

8 patients were able to achieve a vertical trunk orientation. This was true despite the fact that in 3 patients legs were not straight. One patient was not able to keep his hips on the alignment of his ankles without help (this patient also presents some overweight).

Arm support vs. foot support

We measured the total efforts applied to the handles and the ground during sit-to-stand transfer and standing (Fig. 3). As expected in all the patients, transfer (phase ❶) is mainly ensured by arm support. The maximum total force applied on handles is comprised between 1100N to 1600N, which is critically high. During early standing (phase ❷) some patients (#1, #3, #6) managed to ensure the gravity compensation by supporting their weight mainly through ground support forces. When fatigue starts to take place (phase ❸) and when fatigue really occurs (phase ❹) the contribution of foot support decreases in favour of arm support. In some patients (#5) joint lock is not good enough and from phases ❷ to ❹ the support forces are constantly transferred between arms to feet. 4 patients never succeeded in supporting themselves mainly on their legs (#7, #8, #9) but only moderately. Patient #4 almost completely supported himself through his arms.

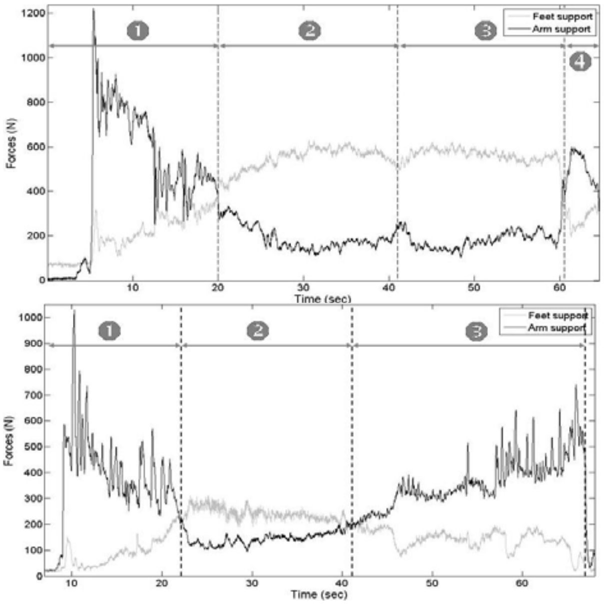

Fig. 3: Feet and arm support evolution. ❶ sit to stand phase, ❷ + ❸ standing, ❹ knee flexion. + **Top:** Patient #3, trial 6. **Bottom:** Patient #9, trial 3.

Fatigue

It is well known that one main issue with FES is the fatigue it induces. Indeed, patients could not maintain a long term upright position. The longest standing we managed was 73sec. Muscle fatigue implies that the torques initially generated by stimulation decrease if no update of parameters occurs. To counteract the effects of fatigue the patient's only solution is to increase arm support, if not, the "weak" leg flexes. We could observe visually that fatigue appears early after verticalization: it affects slightly the posture maintenance over the trial and the joint may suddenly unlock. Fatigue occurs earlier and is more important when the trials are repeated. In order to describe fatigue, we present the evolution of knee joint over time after sit to stand in Fig. 4.

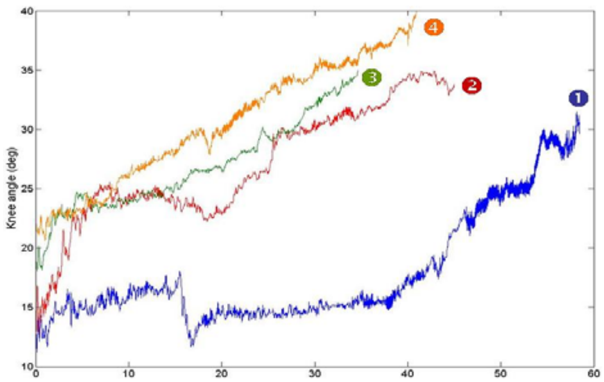

Fig. 4: Patient #1, Right knee flexion evolution over 4 trials (0° corresponds to knee stretched).

Four trials are illustrated. The angle increases (leg flexes) slowly along the trial. The leg is also less and less straight after the sit to stand transfer over the different trials. In this patient the slope of the angle variation remains the same (20° over 40sec).

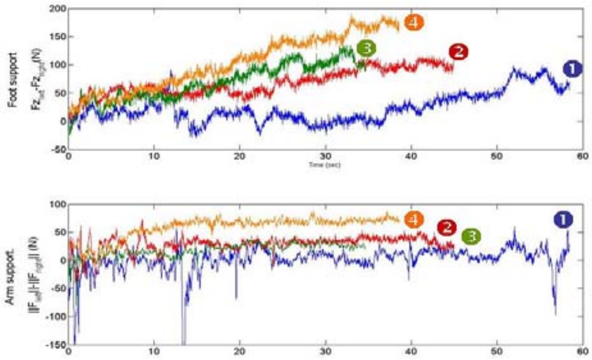

Fig. 5: Patient #1, Difference between recorded forces over 4 trials from left and right supports. Top: Foot support; bottom: arm support.

In Fig. 5, we plotted the corresponding arm and foot support variations. The patient maintains a constant effort on the handles and an identical repartition between left and right sides, while the force repartition tend to become asymmetrical when the leg is fatigued.

Sit to Stand

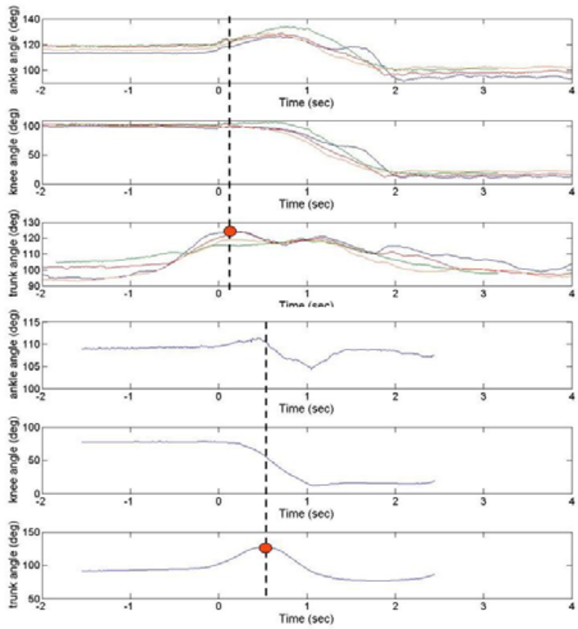

Fig. 6: Posture coordination during sit to stand. **Top:** Patient #1, over 4 trials, **Bottom:** valid subject.

In Fig. 6, we plotted the evolution of trunk, knee and ankle angles during the sit to stand transfer. We give instruction to the patients to bend their trunk in preparation to the chair rising. A first important observation is the low intra-variability between trials of one given patient. On the contrary, inter-variability between patients is important. A main difference between valid subjects and patients is the onset of leg movement in regards to trunk bending. To be efficient, trunk bending forward should start before and last during knee and ankle movement. This was never the case in our trials on FES-assisted standing.

Discussion

One main issue when working with paraplegic patients is the important differences which exist between patients such as lesion level, time since lesion occurred, presence of spasticity and available range of joint motion. These elements have an impact on the stimulation levels needed to contract muscles and therefore on muscle fatigue.

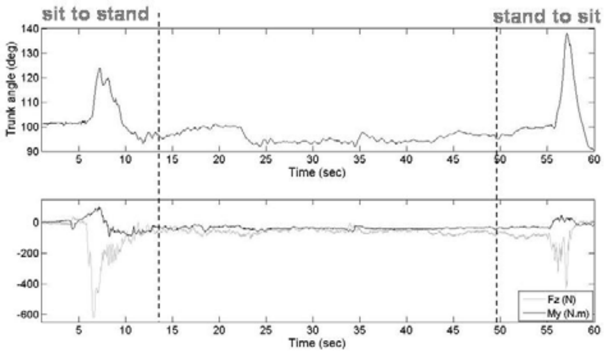

Fig. 7: Correspondence between trunk angle and handle information. Patient #1, Trial 1. **Top:** angle, **Bottom:** right side vertical force and momentum around hip axis.

This inter-variability implies that training should be adapted individually. In our study all the patients received the same type and amount of training sessions regardless their initial capacities (except patient #5 who received additional training). Performance should be carefully evaluated from the beginning and followed up till they are satisfactory to allow verticalization. Joint locking should be sufficiently efficient for reasonable stimulation levels. The stimulation levels used during muscle reinforcement should: 1) be as low as possible to reduce fatigue during verticalization and 2) leave a margin to increase levels for, and during, standing in order to cope with fatigue. A critical problem is that patients can not feel fatigue before it affects importantly their posture and thus do not ensure gravity compensation by arm support (Fig. 5). Observing knee and ankle angles show a continuous evolution before unlock occurs. This evolution is also observable from insoles measurement where the force repartitions evolves towards asymmetrical efforts when one leg becomes weaker (Fig. 5). Adapting stimulation parameters along asymmetry increase may lead to longer standing. Security margins on this asymmetry may also prevent risks of unexpected sudden unlock.

Sit to stand in valid persons implies a complex coordination between upper and lower limbs. Minimizing arm support help is possible only if trunk inertia is used [1]. This implies a good triggering of muscle contraction regarding limb movements. Trunk behaviour can be indirectly observed by analyzing efforts applied by arm support (Fig. 7). Indeed, normal force decreases (pulling) while momentum around transversal axis increases. A threshold on these signals could improve greatly the sit to stand. The same may be used for stand to sit as shown in Fig. 7. Anticipated postural adjustments should also be artificially created in order to prepare the actual standing, instead of switching from no stimulation to maximum levels of current.

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