Towards parameters and protocols to recommend FES-Cycling in cases of paraplegia: a preliminary report
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Abstract— Functional Electrical Stimulation assisted cycling (FES-Cycling) is increasingly becoming an alternative option recommended to people with spinal cord injury struggling with paraplegia and interested in practicing sports. In order to propose preconditions to guide FES-Cycling recommendation, we aimed to investigate some features and their potential relationships with responsiveness to Neuromuscular Electrical Stimulation (NMES). Fourteen volunteers attended a public recruitment forum to be assessed about their responsiveness through the 16-sessions of NMES. Volunteers were separated in two groups (responsive and non-responsive to NMES) which were investigated in the light of some personal, clinical, structural and functional features. Fifty seven percent of the initial sample responded to electrical stimulation with a visual contraction. This responsive group was predominantly composed by subjects presenting traumatic spinal cord injuries above T12 vertebral level. Only two subjects became responsive at the 3rd and 16th sessions. Among the observed features, the etiology and level of injuries seems to be more associated to responsiveness. Our observations seem to indicate that subjects with traumatic spinal cord injury above T12 level were the best potential candidates for FES-cycling.

I. INTRODUCTION

Several research studies have proposed ergometers for Functional Electrical Stimulation (FES) as an option to provide active lower limbs involvement in alternative therapy [1], and to develop locomotion devices for daily and leisure activities in cases of paraplegia [2]. Among such alternatives, we have also found FES assisted cycling (FES-Cycling), may be also perceived as a potential opportunity for people living with spinal cord injuries and interested in practicing sports [3]. In these different contexts, we could find detailed reports about technical advances and benefits arising out of the FES-Cycling training by which natural and artificial muscular recruitment is triggered by sophisticated system, in contrast, we could hardly find information of what would be the preconditions and the parameters to recommend and prepare a FES-Cycling training in the cases of paraplegia.

In order to explore the characteristics of the concerned public and get insights to guide protocols to recommend FES-Cycling, we aimed to investigate some personal, clinical, structural and functional characteristics of people with paraplegia interested in sports, assessing their responsiveness to neuromuscular electrical stimulation (NMES) and the potential aspects linked to this issue.

Following, we described how the target public was recruited and assessed to compose responsiveness and non-responsiveness groups for analysis.

II. METHODS

A. Target public and recruitment

In order to identify population with paraplegia who may be interested participating in this experimental protocol (target public), we launched a public recruitment forum offering FES-Cycling training. No elective criterion was considered, since we wanted to explore the responsiveness to electrical stimulation from people of all backgrounds interested in attending FES-Cycling.

After clarification was provided and informed consent was signed (CAAE 50337215.1.0000.0030, approval number 1.413.934, local ethical committee), a screening visit was scheduled with volunteers to register information about their personal (age, gender and sports practice) and health conditions (history of spinal cord injury, time since injury and clinical features).

During the same visit, the international standards for the Classification of Spinal Cord Injury were applied according to recommendations from the American Spinal Injury Association (ASIA) [4], followed by physical assessment in order to record some structural and functional variables. At the end of the physical assessment, an interview guided by the Functional Independence Measures (FIM) was performed [5].

On completion of the screening visit, the participants followed a 16-sessions protocol of NMES in order to investigate the responsiveness to electrical stimulation among the subjects recruited in this convenience sample.

B. Protocol

The participants were enrolled in a 16-sessions protocol starting with a knee extension program via surface NMES applied on quadriceps muscle and progressing to other muscle groups as the responsiveness was positively visualized by means of contractions strength classified as grade 3/5 (movement possible against gravity). A 16-sessions protocol was applied because the most responsive participant had responded to NMES at the first session (NMESs), and got a stimulation sequence of progression through the muscular groups starting from quadriceps to hamstrings, glutei, tibialis anterior and triceps sural muscles in this period of time.
Muscles strength was rated using the Medical Research
Council (MRC) scale of 0/5 to 5/5 in which 0/5 represented
no contraction; 1/5 muscle flicker, but no movement; 2/5
movement possible, but not against gravity when the join
was tested in its horizontal plane; 3/5 movement possible against
gravity, but not against resistance by the examiner; 4/5
movement possible against some resistance by the examiner
and 5/5 normal strength.

The 16-sessions of NMES training involved, at the
beginning, repeated series of isometric contractions in which
the subjects had their legs extended and feet fixed. The
sessions were numbered from NMES1 up to NMES16. When
the subjects started to respond with contractions reaching the
grade 3/5, the series with free joint were initialized.

As contractions progressed to higher grades (4/5 or 5/5),
more functional exercises simulating real situations were
introduced (i.e. sit-to-stand transfer, cycling, etc.). Each
session lasted one hour maximum with variable durations
determined by fatigue observation. One to three days of rest
between sessions was scheduled.

The NMES unit, a four channel stimulator providing
rectangular biphasic current (Dualpex 071 Quark®) was used.
During effective stimulation, frequency of 50Hz, intensity
ranging from 0 to 69 mA and pulse width of 800µs were used.
The intensity was increased from 0 up to a visual contraction
(1/5) or 50 mA, following the protocol FES training
employed. Electrodes (5x9 cm²) were placed on the skin at a
location in the quadriceps muscle where the better muscular
response was found.

III. RESULTS

Fourteen volunteers (3 males and 11 females) aging
between 23 and 56 years old living with paraplegia from 2 up
to 50 months responded to the call. Out of these (n=14), eight
(57%) presented a visible muscular contraction triggered by
the NMES (graded 1/5) at the first electrical stimulation
session (NMES1) taking part in the responsive group (Table
I). The participants without visible contraction at the NMES
(graded 0/5) composed the non-responsive group.

The total sample, considering responsiveness and non-
responsiveness, presented predominantly complete spinal
cord injury (64%, ASIA by completeness A classified  under
medical diagnosis) with people practicing from zero to four
different types of sports simultaneously.

A. Comparative analysis

Once the volunteers were separated into responsive or
non-responsive groups, they were compared to each other
and/or to the total sample (n=14).

In the Table I, values from quantitative variables are
presented by median between minimum and maximum
intervals (min-median-max), considering a non-Gaussian
distribution; in turn, qualitative variables are shown by
absolute (n) and relative (%) frequencies distributed by each
class. Each quantitative/qualitative variable has its
unit/classes indicated in the column “measures units/classes”.

Differences between proportions observed by responsive
behavior (responsiveness or non-responsiveness) were
detected by comparisons between groups, taking as a basis the
proportion expected in the total sample by the Fisher’s exact
test (p<0.05). The tables cells highlighted in boxes in the
“responsiveness” and “non-responsiveness” columns were
used to indicate significant differences (p<0.05) between
observed (groups) and expected proportions (sample).

As observed in the same table, all subjects from the
responsive group had their damage caused by traumatic
accident while in the non-responsive group it was found that
some damages were also caused by infections (Transverse
myelitis). Both proportions highlighted by the boxes in the
Table I were significantly different from the total sample
which presented 86% traumatic and 14% infectious causes.

Concerning the level of injury, above or inside/bellow the
twelfth thoracic level (T12), we observed, also highlighted in
Table I, a sub-sample totally composed by subjects with
injuries above T12 level in the responsive group, while in the
non-responsive group subjects with injuries above and
inside/bellow T12 level were present in equal proportions.
Both proportions observed were different from the expected
in the total sample (79% above and 21% inside/bellow T12).

TABLE I. CLUSTERS OF QUANTITATIVE AND QUALITATIVE VARIABLES
RECORDED BY RESPONSIVENESS AND NON-RESPONSIVENESS GROUPS

<table>
<thead>
<tr>
<th>Cluster of variable</th>
<th>Quantitative/qualitative</th>
<th>Responisiveness</th>
<th>Non-responisiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex</td>
<td>8 (57%)</td>
<td>6 (40%)</td>
<td></td>
</tr>
<tr>
<td>Personal factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>23,00 [12,50; 47,00]</td>
<td>28,00 [20,00; 56,00]</td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>3 (25%)</td>
<td>5 (40%)</td>
<td></td>
</tr>
<tr>
<td>Sports practice / Sports played</td>
<td>0,00 [0,00; 5,00]</td>
<td>2,00 [2,00; 5,00]</td>
<td></td>
</tr>
<tr>
<td>Health condition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damage by etiology</td>
<td>traumatic</td>
<td>8 (57%)</td>
<td>4 (29%)</td>
</tr>
<tr>
<td></td>
<td>infectious</td>
<td>0 (0%)</td>
<td>2 (13%)</td>
</tr>
<tr>
<td>Time since injury / day of event urge</td>
<td>2,00 [11,00; 24,00]</td>
<td>3,00 [3,00; 30,00]</td>
<td></td>
</tr>
<tr>
<td>Level of injury</td>
<td>above T12</td>
<td>8 (57%)</td>
<td>2 (13%)</td>
</tr>
<tr>
<td></td>
<td>inside/bellow T12</td>
<td>0 (0%)</td>
<td>2 (13%)</td>
</tr>
<tr>
<td>ASIA by completeness</td>
<td>A</td>
<td>5 (36%)</td>
<td>4 (29%)</td>
</tr>
<tr>
<td></td>
<td>B, C, D, E</td>
<td>3 (21%)</td>
<td>3 (21%)</td>
</tr>
<tr>
<td>Structural and functional domain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor right (cm)</td>
<td>15,00 [13,50; 21,00]</td>
<td>25,00 [23,50; 28,00]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>left (cm)</td>
<td>15,00 [13,50; 28,00]</td>
<td>25,00 [23,50; 28,00]</td>
</tr>
<tr>
<td>Sensory right (cm)</td>
<td>15,00 [13,50; 28,00]</td>
<td>22,00 [20,00; 35,00]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>left (cm)</td>
<td>10,00 [8,00; 20,00]</td>
<td>22,00 [20,00; 35,00]</td>
</tr>
<tr>
<td>BMI kg/m²</td>
<td>18,50 [18,00; 23,00]</td>
<td>20,00 [20,00; 25,00]</td>
<td></td>
</tr>
<tr>
<td>Thigh level right (cm)</td>
<td>40,00 [40,00; 50,00]</td>
<td>42,00 [40,00; 50,00]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>left (cm)</td>
<td>36,00 [35,00; 40,00]</td>
<td>40,00 [40,00; 50,00]</td>
</tr>
<tr>
<td>Circumferences</td>
<td>24,00 [20,50; 28,50]</td>
<td>22,00 [20,00; 28,00]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>left (cm)</td>
<td>28,00 [25,00; 30,00]</td>
<td>22,00 [20,00; 28,00]</td>
</tr>
<tr>
<td>Activity and participation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM index</td>
<td>6 (40%)</td>
<td>4 (29%)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 (21%)</td>
<td>3 (21%)</td>
<td></td>
</tr>
<tr>
<td>SBP at rest (mmHg)</td>
<td>90,00 [80,00; 95,00]</td>
<td>100,00 [95,00; 100,00]</td>
<td></td>
</tr>
<tr>
<td>Hemodynamic stability</td>
<td>60,00 [50,00; 90,00]</td>
<td>70,00 [60,00; 90,00]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30,00 [20,00; 40,00]</td>
<td>30,00 [20,00; 40,00]</td>
<td></td>
</tr>
<tr>
<td>Activity and participation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FM total score</td>
<td>70,00 [40,00; 110,00]</td>
<td>80,00 [40,00; 110,00]</td>
<td></td>
</tr>
</tbody>
</table>

The Mann Whitney test applied in the comparisons
between responsiveness and non-responsiveness (Table I)
only detected significant differences (p<0.05) for SBP at rest,
showing that all participants, in the non-responsiveness group,
presented systolic blood pressure (SBP) at rest higher than
110 mmHg while responsiveness group presented fifty
percent (50%) of their subjects recording SBP at rest lower
than 100 mmHg at rest.
B. Responsiveness through the 16-sessions of NMES

Not all participants had the same sequence of responsiveness to NMES (Figure 1). We had two subjects who only responded to electrical stimulation with contractions scored with 1/5 contraction strength at the third (NMES3) and sixteenth sessions (NMES16). The stimulation was just applied to the other muscle groups in the progression after they had obtained a 1/5 contraction in the previous muscle group of the established sequence of progression.

These two mentioned volunteers increased the responsiveness size from 57% to 64% at NMES3 and to 71% at the NMES16. At the NMES16, the proportion observed was significantly different from the expected (NMES1) as detected by the Fisher’s exact test (p<0.05).

C. Responsiveness and level of injury

All volunteers who responded to NMES1 had spinal cord injuries above T12 (responsive group) while among those who did not respond to NMES1 we found half above and half inside/below T12.

At NMES3, a volunteer who had a T5 level spinal cord injury started to respond with a 1/5 contraction, changing the non-responsiveness proportion to 40% above and 60% inside/below T12 level (Figure 2).

IV. DISCUSSION

Our preliminary public recruitment towards parameters and protocols to recommend FES-Cycling for people with paraplegia interested in sports reveals to be important to consider features related to etiology (physical trauma) and level of the spinal cord injury.

Before the analysis of the responsiveness observed in our sample, we had hypothesized that time since injury could be a feature responsible to non-responsiveness to NMES. Our initial hypothesis found basis in the evidences showing substantial tissue atrophies and motor/vascular dysfunctions enhanced by the time in non-responsive group. Maybe, the lack of difference could be explained by the fact that our sample was composed by active subjects who practiced different types of sports.

Other features not related to time since injury must be considered in order to analyze responsiveness, as aspects related the nature of the damage and its impact. To explain our results, we hypothesized that after spinal cord injury, the individuals in the responsive group present signals and symptoms related to the disconnection syndrome (i.e. damage in the descending motor fibers from the motoneurons situated in the motor cortex to the motoneurons in the spinal cord) [7] and the individuals in the non-responsive group present damage of the peripheral motor pathways (i.e. located at nerve roots and/or the axons of the motoneurons) [8]. Unfortunately we did not record variables related to disconnection syndrome, a limitation to confirm our hypothesis.

Nevertheless, it is interesting to notice that no subject whom damage cause was infectious responded to NMES, even above T12 level and after 16-sessions protocol. The two subjects presented diagnostic of transverse myelitis caused by infection, had neurologic impairment in ventral column of the cord [9] with damage in specific motoneurons inside and below their levels of injury. How the mechanism of action of the NMES involves electrical stimulation exciting the motor nerve going to muscle and not muscle itself [10], we believe that the peripheral motor pathways were damaged in the two subjects diagnosed with transverse myelitis, justifying the non-responsiveness.

In general, the subjects with traumatic spinal cord injury inside/below T12 level did not respond to NMES because the lumbarosacral spinal cord is almost entirely contained in the segments inside the vertebral T12 level where all motoneurons to innervate the hip and legs coming from [11]. However, we had a participant whom level of injury was T12 to 50% above and 50% inside/below T12 level and the responsiveness group came into possession a subject with spinal cord injury inside/below T12 (Figure 2).

It was interesting to point out that when we removed infectious cause from the level of injury analysis, as observed in the pairs of groups indicated by subjects having only traumatic spinal cord injuries remained in the distributions in the Figure 2, we could observe, with the exception of only one subject (T12 level); that all volunteer in the non-responsive group had spinal cord injuries inside or below T12 level.

When reaching the NMES16, another volunteer who had spinal cord injury at the T12 level started to respond with a 1/5 contraction, returning the non-responsiveness proportion
and, in the NMES_{16}, he began to respond. In this case it is important to consider that the levels were recorded from the medical diagnoses, not examining voluntary motor or conscious sensory function below the injury site (ASIA recommendations).

The clinical examination of the level, extent, severity [8] and motor impairment (disconnection syndrome or peripheral motor pathways) could be useful to explain his responsiveness at the NMES_{16}.

The systolic blood pressure (SBP) was the unique variable in the functional domain of this study to present a significant difference between groups. The non-responsive group manifested SBP higher than the responsive group. It could be interesting to investigate more detailed this behavior once the non-responsive group was mostly formed by low level of injury volunteers who had more intact sympathetic nervous system. However, the SBP was only measured before the protocol application, a limitation to discuss this point.

V. CONCLUSION

After having explored the characteristics of the people with spinal cord injury interested in practicing sports, searching for insights to guide protocols to recommend FES-Cycling, we conclude that a little more than half part of our subject sample (57%) responded to the NMES at the first application, increasing to 71% at the end of our 16-sessions knee extension protocol training.

Among the observed features, the etiology and level of injuries seems to be more associated to responsiveness, showing that the subjects with traumatic spinal cord injury above T12 level are the best potential candidates for FES-cycling.

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REFERENCES