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Upper limbs cranking for post-stroke rehabilitation: a pilot study on healthy subjects

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***Abstract*—Since one of the major consequences of stroke is hemiparesis, the rehabilitation of upper limbs is necessary to improve the quality of life. Arm cranking gesture represents an alternative rehabilitation tool, especially if accompanied by a biofeedback involving and motivating patients. The aim of this pilot study was twofold: (1) to evaluate the effect of a visual and virtual biofeedback on arm cranking gesture and (2) to estimate the duration of pull and push phases of the crank cycle. Nine healthy and young subjects were involved in the test and were asked to perform the arm cranking gesture in different conditions. A stereophotogrammetric system was adopted to create a virtual, visual and real time biofeedback of cadence, to measure the real cadence of participants and to estimate push and pull phases durations. Results showed that the biofeedback helped subjects to follow an externally imposed cadence. Furthermore, the pull phase resulted to be slightly longer than the push one, although the angular amplitude of the two phases suggested they were the same.**

Keywords—cranking, rehabilitation, stereophotogrammetric system, upper limbs, biofeedback

I. Introduction

The consistent population aging is determining a higher incidence of stroke and neurodegenerative diseases, that negatively affect people's lives [1]. Stroke compromises brain functions, such as movement, walking, language, balance, vision, mood and sensory perception [2]. In addition to aphasia and incapacity of walking without assistance, one of the major consequences of stroke is represented by hemiparesis, which is the motor impairment of the body side contralateral to the brain hemisphere of lesion [3].

Within this negative context, the recovery of upper limbs functionality becomes essential in order to carry out tasks of daily life and consequently to regain independence [4]. Conventional physiotherapy exercises are accompanied by alternative rehabilitation methods, which adopt new technologies [4]–[7]. In addition to all these procedures, also a simple discipline such as the upper limbs cranking is spreading in the clinical context. Previous literature works have highlighted that the arm cranking gesture has positive effects on hemiplegic patients: it helps the assessment of cardiorespiratory fitness [8], it improves motor learning and function recovery proposing repetitive movements and it reduces the affected upper limb spasticity [9].

All these positive aspects can be enhanced with the insertion of an extrinsic feedback displaying the performance metrics during the exercise. The feedback can help the assessment of the patient's medical state and increase his participation to the rehabilitation process [1]. When the artificial feedback refers to biological quantities of the human body during the exercise, it is called biofeedback. The main advantage of a biofeedback is its ability to enhance neural plasticity, establishing itself as a rehabilitation tool [10]. Articles in literature have already adopted biofeedback of work [3], speed [11] and cadence [12] for post-stroke patients during cycling. However, the possibility to use a biofeedback for upper limbs rehabilitation of post-stroke patients through arm cranking seems to be still unexplored.

Another important aspect related to the arm cranking gesture is the muscular activation during each cycle, which has been investigated by previous literature works [13]–[15]. Considering the activation intervals of biceps (0°-180°) and triceps (180°-360°), two important phases can be defined: a pull phase and a push phase [14]. This partition has been widely assessed considering muscles forces, but no previous work was found investigating the duration of the two phases and consequently the activation timing of biceps and triceps.

For all these reasons, the purpose of this pilot study was twofold: (1) to evaluate the effects of a visual, virtual and real time biofeedback on arm cranking gesture, in order to verify its contribution in following the imposed cadence and its effectiveness for the rehabilitation of hemiplegic patients; (2) to estimate the duration of pull and push phases of the crank cycle.

II. Materials and Methods

The aims of this study were fulfilled by realizing an experimental arm cranking test. Nine young and healthy subjects performed different arm cranking sessions. Participants were asked to cycle with different imposed cadences, with/without a visual feedback, with/without a sound input. Since previous pre-tests of arm cranking revealed no statistically significant differences between right and left cadences, subsequent tests were made by recording and evaluating only the right arm motion for the assessment of the cranking real cadence.

A. Participants

Nine young healthy subjects (males, age: 25.7 ± 3.2 years, BMI: 22.4 ± 1.3 kg/m^2) with no neurological or musculoskeletal disease were involved in the study after giving their written informed consent.

B. Instrumentation

The instrumentation adopted for this study included an arm cranking machine and a stereophotogrammetric motion capture system.

Krankcycle. The arm cranking machine used for the experiment was the Krankcycle (JHT ITALIA SPA – Matrix), a tool that allows users training upper body. More in detail, the Krankcycle is a stationary handcycling machine with two independent crank arms allowing both synchronous/asynchronous and symmetrical/asymmetrical movements. Furthermore, the planetary gear torque combiner drives a single flywheel and the brake resistant torque is manually adjustable through a knob. In this pilot study, the Krankcycle was equipped with its own seat, keeping crank and flywheel assembly rotated to accommodate forward clockwise movements (Fig. 1). Moreover, the right crank handle was equipped with two rigid metal plates, in order to accommodate markers for motion capture. Plates rotated solidly with the right handle, thus forming a rigid body (Fig. 2.A).

OptiTrack. The stereophotogrammetric system was composed of a V120:Trio tracking bar (OptiTrack, USA) and eight markers. The bar was self-contained, pre-calibrated and equipped with three cameras able to detect infrared light. The bar was positioned to the right of the Krankcycle and was connected to a PC, on which the software Motive (OptiTrack, USA) was installed for data acquisition. The sampling frequency was set to 120 Hz. Furthermore, eight passive reflective markers with a diameter of 14 mm were fixed on the right crank handle and on its support. In detail, five markers were positioned asymmetrically on the two metal plates of the right crank handle and were used to define a rigid body on Motive (Fig. 2.A). Other three markers were placed on the right crank arm according to the configuration shown in Fig. 2.B. Subsequently, a static acquisition of these three markers was recorded with the OptiTrack bar for a few seconds. Starting from markers coordinates, a vertical y-axis and a support s-axis were defined and used to construct a Global Coordinate System (GCS) in which to convert data recorded by the bar [16], [17].

C. Visual feedback

The software Motive is able to automatically calculate in real time the coordinates of a rigid body geometrical centre defined from at least three markers. Considering the 5 markers fixed on metal plates, their centre was assessed. However, since there was no coincidence between the rigid body centre and the pivot point of the Krankcycle handle, the described trajectory was not a circumference. Consequently, it was necessary to perform a calibration rotation of the right handle around its pivot in order to estimate the distance between the rigid body centre and the pivot point.

A custom Matlab code was used to evaluate in real time the angle θ (°) described by the crank handle during the movement. Furthermore, the same code was adopted to assess the real cadence at the end of each complete rotation. First, the period Δt (s) was estimated as the time necessary for the crank angle to complete a single revolution. Then, for consecutive cycles, the cadence ω (rpm) was calculated. Starting from this value, a visual biofeedback was created. It consisted of a bar indicating the real cadence, that was updated at the end of every crank cycle. Furthermore, there was a threshold defined by a horizontal line. When the real cadence was within ±2 rpm with respect to the threshold, the bar became green; otherwise, it was yellow (Fig. 3).

Fig. 1. The Krankcycle configuration adopted for the test.

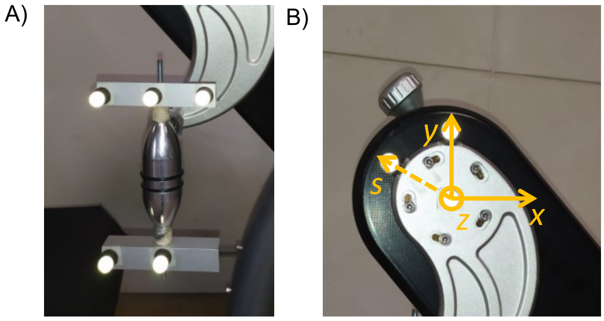

Fig. 2. A) Configuration of five markers on the right crank handle. B) GCS formed with three fixed markers on the support of the right crank arm.

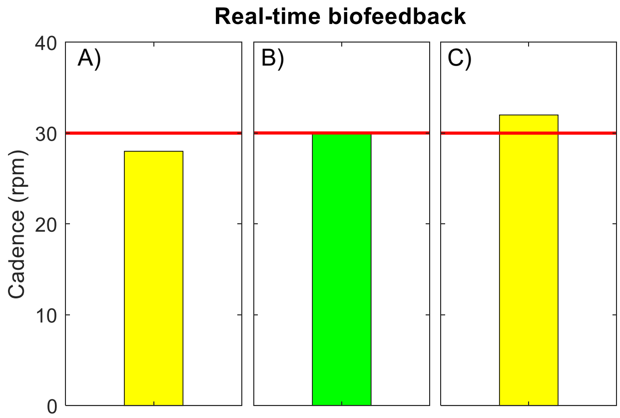

Fig. 3. The virtual, visual and real time biofeedback of cadence adopted for the test. Example for 30 rpm cadence, with a tolerance range of ±2 rpm with respect to the threshold. Value A) below the threshold, B) in the tolerance range with respect to the threshold, C) above the threshold.

D. Sound input

The sound input provided by a metronome was used during some of the tests. The input consisted of a series of consecutive beats produced by the metronome according to the imposed cadence. Each beat should correspond to the end of a complete cycle performed with the arm cranking machine.

E. Protocol

In order to plan the experiment, a Full Factorial Design was performed with four factors:

i) the imposed cadence, which was varied on three levels (30 rpm, 50 rpm, 70 rpm);

ii) the visual, virtual and real time biofeedback, which was present or absent. Accordingly, two levels were considered (Yes/No);

iii) the sound input, which was present or absent. Accordingly, two levels were considered (Yes/No);

iv) the subject, which was varied on nine levels (participants from 1 to 9).

The result was a set of 108 combinations, 12 for every subject.

The test was conducted indoor. Participants were asked to do a training test and to set themselves the desired Krankcycle resistance with the knob. They were asked to set the resistance by imagining to cycle for an hour at the cadence of 70 rpm. Tests consisted in cranking with a synchronous arms movement in different conditions. According to the previous Full Factorial Design, all subjects were asked to perform 12 trials of 1 minute each, with a break of 1 minute after each trial. The sequence of 12 trials was performed with a different randomized order for every subject. More in detail, for every cadence, every subject carried out 3 trials in 4 different conditions:

- Absence of both visual feedback and sound input (No feedback, No input = NN). In this case, before starting trials, subjects were asked to hear the sound input of a metronome to suggest the rhythm of the required cadence. Then, during these trials they did not receive external stimuli.
- Presence of sound input only (No feedback, Yes input = NY). During tests, subjects heard the sound input provided by a metronome.
- Presence of visual feedback only (Yes feedback, No input = YN). During tests, subjects looked at the visual feedback on a screen in front of them.
- Presence of both sound input and visual feedback (Yes feedback, Yes input = YY). During tests, subjects simultaneously heard the sound input provided by a metronome and looked at the visual feedback on a screen.

During all trials, handle centre coordinates were captured by the OptiTrack bar and communicated to Matlab. Simultaneously, the Matlab code estimated the crank angle θ and calculated the real cadence at the end of every crank cycle. Furthermore, during YN and YY trials, the real cadence was adopted to create the real time biofeedback previously described.

F. Signal processing and data analysis

Custom Matlab® routines were developed to process data, whereas the software IBM SPSS® was adopted to conduct statistical analyses. Trends of the angle θ and values of real cadence ω were saved for every cranking round of every test. For each level of imposed cadence (30 rpm, 50 rpm, 70 rpm), four sub-groups were identified considering the four conditions (NN, NY, YN, YY). According to this data partition, mean and standard deviation values of real cadence for each test of each subject were estimated. Furthermore, inter-subject mean and standard deviation values were calculated and represented through bar diagrams. After investigating the normality of data with the Shapiro-Wilk test, significant differences among the four conditions for each cadence were searched for. Subsequently, the θ angle progression of each trial of each subject was analyzed. Durations of pull and push phases were estimated from 0° to 180° and from 180° to 360°, respectively. Sectors were visualized from the right hand side of the cranking machine, as the literature convention requires (Fig. 4). Then, pull and push were evaluated as percentages of the full cycle duration, calculating inter-subject mean and standard deviation values for every imposed cadence and every condition. In addition, statistically significant differences of pull percentages were investigated inside each couple of conditions for every imposed cadence. Finally, mean and standard deviation values of pull and push percentages were estimated for the three cadences considering all the conditions together and were represented through bar diagrams.

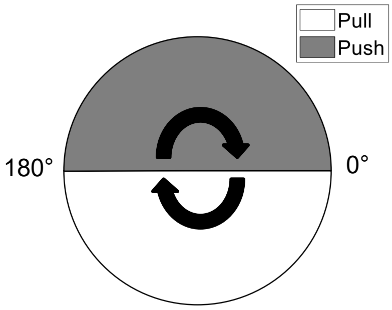

Fig. 4. Crank cycle phases of pull (0°-180°) and push (180°-360°) [14].

III. RESULTS

Mean and standard deviation values of real cadence for each test of each subject were evaluated. The following tables contain values obtained with an imposed cadence of 30 rpm (Table I), 50 rpm (Table II) and 70 rpm (Table III). Every row corresponds to a subject and every column corresponds to a testing condition.

Fig. 5 is divided into three panels, one for every imposed cadence. Each panel contains four bar diagrams representing inter-subject mean and standard deviation values of real cadence for every testing condition. Furthermore, the imposed cadence is indicated with a horizontal line. Since the Shapiro-Wilk test produced significance values greater than 0.05, a non parametric statistical analysis was conducted. In particular, the Wilcoxon-signed rank test (2 tails, significance level: α=0.05) was performed inside each couple of conditions for every imposed cadence. Asterisks on Fig. 5 represent statistically significant differences found with the analysis.

Table IV shows inter-subject mean and standard deviation values of pull and push percentages for every cadence and every condition. The last raw contains inter-subject mean and standard deviation values of pull and push percentages estimated considering all conditions together.

Fig. 6 shows inter-subject average values of pull and push percentages with respect to the complete crank cycle at the three cadences.

TABLE I. IMPOSED CADENCE OF 30 RPM

Subjects	**Real cadence Mean ± St. Deviation (rpm)**			
	NN	*NY*	*YN*	*YY*
1	33.2 ± 1.6	30.2 ± 1.8	30.2 ± 1.2	30.8 ± 2.9
2	41.3 ± 3.3	38.1 ±2.2	32.1 ± 1.4	30.4 ± 1.3
3	32.2 ± 1.4	29.9 ± 1.7	37.2 ± 9.4	29.3 ± 1.3
4	33.1 ± 2.2	30.6 ± 1.0	31.9 ± 1.4	29.7 ± 3.0
5	27.8 ± 1.6	38.6 ± 3.1	33.7 ± 4.2	30.6 ± 3.4
6	28.7 ± 1.4	37.1 ± 3.6	30.9 ± 2.2	35.5 ± 2.8
7	31.1 ± 2.7	31.7 ± 1.9	33.0 ± 4.9	30.3 ± 1.8
8	35.1 ± 1.6	29.9 ± 1.6	30.5 ± 1.7	29.6 ± 3.0
9	34.9 ± 2.0	34.8 ± 1.6	32.4 ± 1.4	31.0 ± 0.5

TABLE II. IMPOSED CADENCE OF 50 RPM

Subjects	**Real cadence Mean ± St. Deviation (rpm)**			
	NN	*NY*	*YN*	*YY*
1	52.0 ± 1.5	51.1 ± 3.9	58.5 ± 0.8	50.0 ± 3.8
2	59.0 ± 4.1	49.6 ± 2.7	48.1 ± 1.5	49.6 ± 1.4
3	55.6 ± 2.3	50.1 ± 1.2	53.2 ± 2.5	52.9 ± 2.5
4	45.2 ± 2.5	51.1 ± 1.2	51.1 ± 1.2	49.1 ± 3.6
5	49.5 ± 2.4	49.8 ± 3.1	51.2 ± 2.3	52.1 ± 4.0
6	60.2 ± 2.0	49.5 ± 5.4	49.7 ± 2.5	53.5 ± 2.4
7	57.1 ± 2.8	50.9 ± 3.7	49.6 ± 1.3	51.1 ± 2.1
8	51.1 ± 1.5	49.1 ± 2.9	51.0 ± 1.0	50.2 ± 2.2
9	51.6 ± 1.3	50.1 ± 1.8	51.8 ± 1.6	50.1 ± 0.9

TABLE III. IMPOSED CADENCE OF 70 RPM

Subjects	**Real cadence Mean ± St. Deviation (rpm)**			
	NN	*NY*	*YN*	*YY*
1	69.6 ± 5.2	70.2 ± 1.3	68.2 ± 2.0	68.2 ± 2.1
2	63.6 ± 9.4	69.5 ± 1.8	67.5 ± 2.7	67.7 ± 1.4
3	69.7 ± 2.3	61.4 ± 5.9	68.6 ± 2.6	68.3 ± 5.3
4	55.7 ± 2.5	59.8 ± 2.5	67.7 ± 3.1	69.7 ± 1.8
5	59.5 ± 4.2	54.0 ± 5.7	68.9 ± 5.3	69.9 ± 1.5
6	65.1 ± 1.3	70.8 ± 1.6	68.5 ± 3.7	67.3 ± 2.7
7	64.7 ± 3.5	53.7 ± 9.0	70.6 ± 1.4	69.8 ± 1.7
8	66.0 ± 2.4	63.8 ± 1.8	66.6 ± 5.8	68.8 ± 1.8
9	64.3 ± 2.3	66.2 ± 2.1	69.4 ± 1.0	67.8 ± 2.5

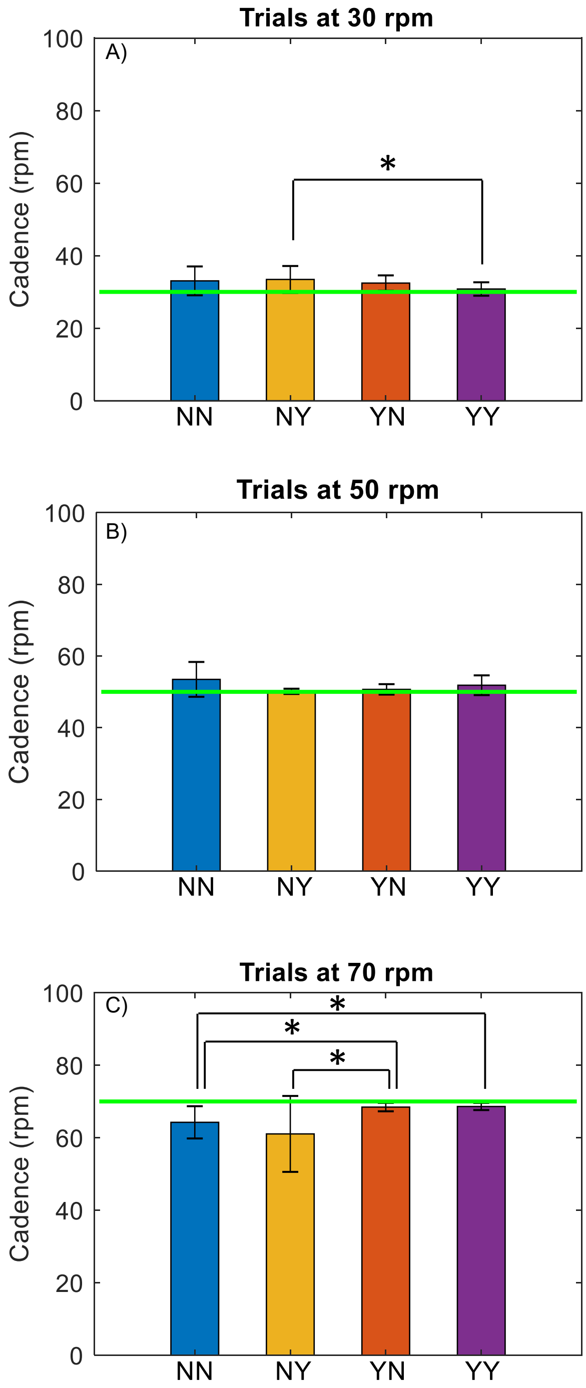

Fig. 5. Inter-subjects mean and standard deviation values of real cadence for each imposed cadence and for each condition. A) Trials with an imposed cadence of 30 rpm. B) Trials with an imposed cadence of 50 rpm. C) Trials with an imposed cadence of 70 rpm.

IV. DISCUSSIONS

The aim of the present pilot study was twofold: (1) to evaluate the effects of a virtual, visual and real time biofeedback on arm cranking gesture and (2) to estimate the duration of the two cycle phases of pull and push.

TABLE IV. PULL AND PUSH PERCENTAGE DURATIONS

Conditions	Mean ± Standard Deviation (% cycle)	
	Pull	***Push***
30 rpm – NN	52.3 ± 0.7	47.7 ± 0.7
30 rpm – NY	52.3 ± 1.0	47.7 ± 1.0
30 rpm – YN	52.8 ± 0.8	47.2 ± 0.8
30 rpm – YY	52.2 ± 0.8	47.8 ± 0.8
50 rpm – NN	53.2 ± 0.7	46.8 ± 0.7
50 rpm – NY	53.3 ± 0.4	46.7 ± 0.4
50 rpm – YN	53.1 ± 0.6	46.9 ± 0.6
50 rpm – YY	53.6 ± 0.8	46.4 ± 0.8
70 rpm – NN	53.9 ± 0.9	46.1 ± 0.9
70 rpm – NY	53.9 ± 0.4	46.1 ± 0.4
70 rpm – YN	54.1 ± 0.4	45.9 ± 0.4
70 rpm – YY	53.9 ± 0.6	46.1 ± 0.6
Mean value	53.2 ± 1.0	46.8 ± 1.0

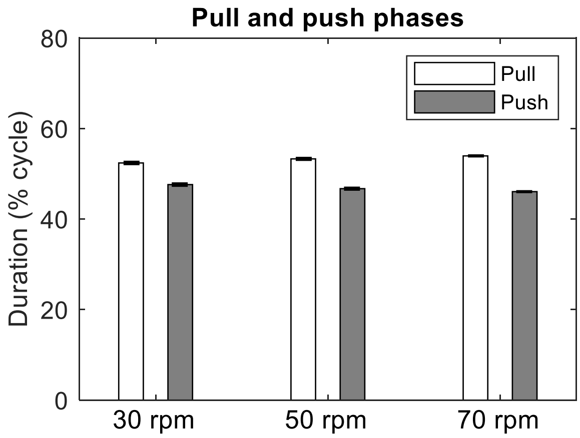

Fig. 6. Mean and standard deviation values of pull and push percentages with respect to the complete crank cycle at the three cadences.

According to the first purpose, the concept of biofeedback was investigated. Some literature articles have already adopted a biofeedback for the rehabilitation of post-stroke patients during cycling [3], [11], [12]. However, no previous works was found concerning the same use of biofeedback during arm cranking gesture. Furthermore, biofeedbacks adopted for cycling were not obtained through a stereophotogrammetric system, which was the instrumentation of the present work. In light of these differences from articles found in literature, a rigid body was defined starting from markers on the right handle of a Krankcycle. Then, subjects were asked to perform arm cranking tests at three different imposed cadences (30 rpm, 50 rpm and 70 rpm). Moreover, four testing conditions were investigated involving a virtual and visual biofeedback of cadence and a sound input (NN, NY, YN and NN). Subsequently, for every cadence, intra-subject mean and standard deviation values of real cadence reported in Table I, Table II and Table III were observed. A part from three cases (subject 3 – 30 rpm – YN, subject 2 – 70 rpm – NN, subject 7 – 70 rpm – NY), standard deviations lower than 6 rpm demonstrated the repeatability of the gesture for all subjects in all testing conditions.

Considering all subjects together, inter-subject mean and standard deviation values were estimated and represented through bar diagrams. For trials at 30 rpm (Fig. 5.A), all participants committed an error in excess. However, this error decreased by adding the biofeedback (conditions YN and YY). Furthermore, the difference between the condition with only the sound input NY and the condition with both stimuli YY was statistically significant (p-value = 0.02). For trials at 50 rpm (Fig. 5.B), all subjects performed the test with a cadence really near to the imposed one and no significant differences were found. The absence of both stimuli in NN condition provoked the greatest excess error, whereas the presence of sound input alone in NY condition and the presence of biofeedback alone in YN condition generated a cadence really near to the imposed one. Unlike tests at 30 rpm, in this case the presence of both stimuli in YY condition provoked a slightly increased error. A possible interpretation of this result lies in the fact that at a comfortable cadence the union of two stimuli can create confusion for subjects. For trials at 70 rpm (Fig. 5.C), all participants committed a negative error for all conditions. As the case of 30 rpm, the presence of biofeedback alone in YN condition or combined with sound input in YY condition reduced the error with respect to the imposed cadence. Significant differences were found inside three couples of conditions: NN-YN (p-value = 0.04), NN-YY (p-value = 0.02) and NY-YN (p-value = 0.05). Overall, the presence of the biofeedback helped participants to better follow the external imposed cadence.

The second purpose of this study was to evaluate the crank cycle and to estimate the duration of the two phases of pull and push. The analysis of muscles activation during the crank cycle have already been performed by several studies [13]–[15]. Considering the activation intervals of biceps (0°-180°) and triceps (180°-360°) respectively, pull and push phases have been identified [14]. Other works have defined a denser division of the propulsion cycle in six sectors, namely push up, push down, press down, pull down, pull up and lift up [18], [19]. All these studies have focused on the evaluation of muscular forces exerted in different phases, without estimating their duration. On the contrary, the present study considered the θ angle progression of each trial of each subject and identified the separation between pull and push phases. Consequently, pull and push phases were evaluated as percentages of the full cycle duration for every subject in every test and then averaged among participants. Values reported in Table IV show a high repeatability among subjects due to small values of standard deviation. Furthermore, the comparison between the two phases in terms of degrees (Fig. 4) and in terms of percentage durations (Fig. 6) was made. Considering the angular amplitude linked to muscles activation, the two phases are equal [14]. On the contrary, focusing on percentage durations, the pull phase (mean value of 53.2%) is slightly longer than the push one (mean value of 46.8%). Considering values in Table IV, it is possible to notice that the duration of pull phase slightly increases while increasing the imposed cadence. In order to understand if this trend was statistically significant, the Wilcoxon-signed rank test (2 tails, significance level: α=0.05) was performed inside each couple of conditions for every imposed cadence, only concentrating on pull percentages. Since the statistical analysis did not highlight significant differences, it was possible to deduce that the duration of the two phases was the same regardless of exercise conditions.

V. CONCLUSIONS

In conclusion, arm cranking gesture represents an alternative tool to traditional rehabilitation procedures for recovering upper limbs functionality in post-stroke patients. In particular, the maintenance of a constant cadence consists of a repetitive exercise that can improve motor learning and function recovery while reducing the spasticity of the affected upper limb. This pilot study was conducted on healthy subjects in order to test the efficacy of a virtual, visual and real time biofeedback of cadence realized through a stereophotogrammetric system and to estimate pull and push phases durations. Results showed that the presence of this biofeedback helped participants to better follow an external imposed cadence. Consequently, the proposed system proved to be a simple, fast and effective tool to combine with the classic rehabilitation methods for post-stroke hemiplegic patients.

Limitations of this work consist in the involvement of a small sample of young healthy subjects, in the evaluation of a synchronous movement and therefore in the calculation of the right cadence only. However, these limits are expected to be overcome in the future. In facts, next steps expect first to test a larger sample of healthy subjects, in order to better investigate the duration of pull and push phases. In particular, the intent is also to estimate the duration of all six cycle phases. Subsequently, both right and left cadences could be calculated by adopting two OptiTrack bars and by creating a single real time biofeedback for the evaluation of symmetry. Another future development could be the insertion of force sensors on the Krankcycle handles, in order to correlate the motion kinematics obtained with markers with the forces exerted by subjects. Finally, the intention is to repeat over time the test on post-stroke hemiplegic patients, in order to create a complete rehabilitation set up. Indeed, it could be interesting to correlate the duration of cycle phases with muscles recovery in subjects suffering from hemiplegia.

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