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Biomechanical and Perceptual Evaluation of the use of a Servo-Controlled Power-Assistance System in Manual Wheelchair Mobility

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***Abstract*—This preliminary study investigated the effect of the implementation of a servo-controlled power assisted mechanism in a manual wheelchair on the demands of the upper limb muscles and the subjects' perception about the effort and difficulty to perform mobility tasks. The electromyographic activity of four upper limb muscles (pectoralis major, anterior deltoids, triceps and biceps) and the rate of perceived exertion and difficulty in six different wheelchair mobility tasks performed by eight subjects were analyzed comparatively with the use of two different wheelchairs: a standard manual device and a prototype of a servo-controlled power assisted wheelchair. The results show that the subjects considered easier and less strenuous to perform most of the wheelchair mobility tasks with the use of the power-assisted chair, in comparison to the manual wheelchair. Data from muscles' activity showed that moving on an ascent ramp with the servo-assisted wheelchair reduced the biomechanical demand on the upper limbs, in comparison with the standard wheelchair. However, the other five mobility tasks did not have the same results, suggesting that the servo-controlled mechanism still needs to be improved to provide consistent benefits for the users in terms of reducing the biomechanical loads during manual propulsion.**

Keywords—Wheelchairs, Mobility, Propulsion, Robotics, Biomechanics.

I. INTRODUCTION

An increased amount of research has shown that manual wheelchair propulsion is a very inefficient and strenuous mean of mobility [1-3]. As a result of the long-term use of manual wheelchairs, users tend to develop pain and injuries that, ultimately, may affect their independent and safe mobility. Studies have shown a high prevalence of problems related to the biomechanical overload that the upper limb' muscles are exposed when repetitively pushing the handrims to move with a wheelchair [1,4]. As maintaining the integrity of the upper limbs' function is a key factor for independence, reducing the demand on the upper limbs and improving mobility efficiency is therefore important to benefit user's participation and quality of life.

Ergonomic solutions for the design of the wheelchair and its components have been reported in previous studies [5-8]. Robotic systems for wheelchairs have also been proposed to address conditions and barriers that users find in daily mobility and transfers [9,10].

When it comes to improving manual propulsion efficiency, pushrim-activated power assisted wheelchairs (PAPAWs) have been proposed to provide complementary torque for the user's forces applied to the handrims, in an attempt to reduce the biomechanical demand as well as to improve mobility efficiency. Such systems comprise in hub sensorial and motor system that detect and increase the user's actions on each rear wheel separately. While studies have found positive results of reduced demand on the upper limbs and increased distance travelled [11-12], problems with maneuverability have also been reported [13]. It is possible that the independent action of the motors on each rear wheel result in some difficulty in maneuvering the chair as it alters the turning radius originally intended by the user. Therefore, reducing the biomechanical demand on the upper limbs while maintaining similar drivability to a manual wheelchair may benefit user's mobility.

This study aimed to investigate the effect of the implementation of a servo-controlled power assisted mechanism in a manual wheelchair on the demands of the upper limb muscles and the participants' perception about the effort and difficulty to propel the wheelchair in different mobility tasks.

II. MATERIAL AND METHODS

A. Participants

A sample of eight subjects without disabilities, all male (average age of 28$\pm$16.33 years, average weight of 74.5$\pm$10.74 kg and average height of 1.7$\pm$0.05m) were recruited at Sao Carlos School of Engineering (University of São Paulo, São Carlos, Brazil), and voluntarily participated in this study. Participants met the following inclusion criteria: (1) minimum age of 18 years; (2) had no upper limbs pain, injuries or disorders that could influence the activity of manual wheelchair propulsion. Prior to data collection, participants read and signed an informed consent form that had been submitted and approved by the Ethics Committee of the Faculty of

Architecture, Arts and Communication - UNESP (Process. N. 800.500).

B. Wheelchairs and procedures

Two wheelchairs were used to compare biomechanical and perceptual data from the subjects: a standard manual wheelchair with foldable frame (AVD Alumínio Reclinável, ORTOBRAS), total mass of 17 kg (Fig. 1); and a prototype of a servo-controlled power assisted wheelchair (Fig. 2).

Fig. 1. Standard foldable-frame manual wheelchair.

(a) (b) (c)

Fig. 2. Servo-assisted wheelchair prototype: (a) front view; (b) perspective view; (c) mechanical and electronic components under the seat.

The servo-assisted wheelchair prototype, model 2017, is an evolution of 2014 model [7], consisting in a hybrid model with a single central DC motor, model EC 45 brushless from Maxon, with a 4-Q-EC DEC 70/10 Maxon driver with setup in current mode. Between the wheels and the motor, there are two gears: the first is the motor output, being a planetary gear model Maxon GP 62 A with reduction ratio changed to 3.65:1; the second, between the planetary output and wheels, a differential transmission with 6:1 reduction ratio. The maximum linear speed reached by this configuration was 2.8 mph without any user input. For the control logic and data acquisition, it was implemented a National Instruments NI-DAQ USB 6009 board connected to a Microsoft Surface tablet running an executable Labview program. An operational amplifier with gain equals to two was also used once the maximum driver input was 10 V and the maximum NI-DAQ output was 5V, meaning that the motor was being underused. Currently, this model has fixed current output with three different options: 35%, 70% and 100% maximum current characterizing a proportional gain controller. In this configuration, the wheelchair weights 33 kg equipped with 24V lithium battery with 10AH charge that supplies the whole system.

Fig. 3 displays the block diagram proposal, where the user specifies the desired current options, leading to a reference current (*Iref*). This way, the Maxon driver tries to follow this current with a manufacturer internal control loop, which is simplified by the blocks inside the dotted block: a current error (*Ierr*) is the result between the reference current and the actual current (*Iact*), obtained via internal circuitry and sensors. As a result, the motor gives an output torque (*Tact*), helping the user input on the wheelchair (*Tuser*). The wheelchair, then, displays a linear translational velocity. It works open loop for the user input, only closed in the motor internal current tracking.

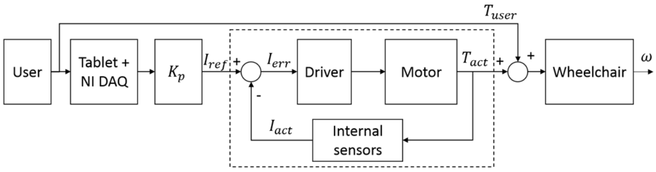

Fig. 3. Block diagram for the wheelchair control system

The test consisted of performing, with both wheelchairs, six different mobility tasks: 15-meters forward propulsion at self-selected speed; 15-meters forward sprint as fast as possible; circular trajectory (two-meters radius) in anti-clockwise direction; slalom course (15 meters course with aligned cones separated by decreasing distances of 2.5 m, 2.5 m, 2 m, 2 m, 1.5 m, 1.5 m, 1 m, 1 m, 1 m) as proposed in a previous study [3]; descent ramp; and ascent ramp. During the tests, surface electromyography (sEMG) data of *anterior deltoids*, *pectoralis major, triceps brachii* and *biceps brachii* were collected using wireless sensors and a Data Logger module (T-Sens, TEA Ergo, France) to register the EMG signals. Triode surface self-adhesive electrodes T3402M (Thought Technology, Canada) were placed in the respective positions for each muscle in accordance with the SENIAM project (www.seniam.org) on the dominant side of the subject's body to record the electrical activity of the respective muscles.

Surface EMG data were sampled at 2048 Hz with RMS frequency calculation of 128 Hz. EMG data analysis was performed with the CAPTIV L-7000 software (TEA Ergo, France). All EMG calculation was in mV and analyzed during the complete trajectory, and the first and last pushes were discarded, in order to analyze the muscle activity in plain motion. After each trajectory, subjects were asked to rate their perceived exertion (RPE) and the difficulty to perform each task in a Borg's Scale [14] and a ten-point analog visual scale, respectively. Data analysis of subjects' perception was performed using descriptive statistics with mean and standard deviation, and Students' T-test was applied to verify statistical difference between the subjects' perception with the two wheelchairs. For the EMG analysis, mean values were obtained for the four muscles of all subjects and presented descriptively by the means of the percentage of the activity relative to the maximum voluntary contraction (MVC). Significance level was determined by $p<0.05$. All statistical analyses were performed using the software SPSS version 22.0 (SPSS Inc., Chicago, IL, USA).

III. Results

The results show that both the biomechanical load on the upper limbs muscles as well as the subjects' perception of exertion and the difficulty to perform the six different mobility tasks are influenced by the wheelchair type (standard manual wheelchair and servo-controlled power assisted wheelchair). Surprisingly, the results of the EMG showed that, in most of the situations investigated in this study, there were higher levels of muscular activity when moving with the servo-controlled power-assisted wheelchair prototype, except when moving on ascendant ramp (for the triceps, deltoids and biceps), as shown in Tables I to VI.

TABLE I. EMG ACTIVITY IN FORWARD PROPULSION.

	Forward propulsion			
	Pectoralis	***Triceps***	***Deltoids***	***biceps***
Manual wheelchair % mvc	4.28 (3.77)	3.49 (1.63)	10.9 (7.21)	2.7 (1.84)
Servo assisted wheelchair % mvc	8.3 (5.43)	3.98 (1.05)	10.68 (4.64)	3.31 (3.6)
difference	4.02	0.49	-0.22	0.61
Variation of the Mean (%)	68.34	26.56	-4.40	18.76

TABLE II. EMG ACTIVITY IN FORWARD PROPULSION SPRINT.

	Forward propulsion max			
	Pectoralis	***Triceps***	***Deltoids***	***biceps***
Manual wheelchair % mvc	12.67 (7.9)	9.76 (4.39)	18 (9.73)	4.63 (2.83)
Servo assisted wheelchair % mvc	19.21 (7.79)	13.81 (6.27)	16.06 (5.83)	6.95 (4.41)
difference	-6.54	-4.05	1.94	-2.32
Variation of the Mean (%)	51.61	41.49	13.22	3.84

TABLE III. EMG ACTIVITY IN CIRCULAR TRAJECTORY.

	Circular			
	Pectoralis	***Triceps***	***Deltoids***	***biceps***
Manual wheelchair % mvc	6.18(2.9)	3.66(1.53)	10.56(4.29)	3.79(2.71)
Servo assisted wheelchair % mvc	10.8(10.77)	4.12(1.91)	11.04(4.5)	3.57(2.61)
difference	-4.62	-0.46	-0.48	0.22
Variation of the Mean (%)	64.42	19.98	-2.76	-6.64

TABLE IV. EMG ACTIVITY IN ASCENT RAMP.

	Ascent ramp			
	Pectoralis	***Triceps***	***Deltoids***	***biceps***
Manual wheelchair % mvc	8.74 (4.54)	10.16 (3.96)	15.01 (3.56)	4.08 (2.28)
Servo assisted wheelchair % mvc	13.97 (14)	8.03 (2.67)	13.85 (5.39)	3.73 (2.58)
difference	-5.23	2.13	1.16	0.35
Variation of the Mean (%)	52.85	-22.54	16.11	-16.11

TABLE V. EMG ACTIVITY IN DESCENT RAMP.

	Descent ramp			
	Pectoralis	***Triceps***	***Deltoids***	***biceps***
Manual wheelchair % mvc	2.44 (0.76)	1.81 (1.36)	8.86 (4.09)	4.21 (3.56)
Servo assisted wheelchair % mvc	3.78 (2.91)	3.05 (1.08)	10.15 (4.75)	2.82 (2.62)
difference	-1.34	-1.24	-1.29	1.39
Variation of the Mean (%)	40.32	68.42	13.47	-40.23

TABLE VI. EMG ACTIVITY IN THE SLALOM COURSE.

	Slalom course			
	Pectoralis	***Triceps***	***Deltoids***	***biceps***
Manual wheelchair % mvc	9.29 (6.93)	3.87 (1.85)	9.87 (4.11)	4.05 (4.07)
Servo assisted wheelchair % mvc	8.53 (5.93)	4.51 (1.84)	10.56 (4.11)	3.77 (3.58)
difference	0.76	-0.64	-0.69	0.28
Variation of the Mean (%)	-4.74	21.32	3.19	-9.2

In contrast to the EMG findings, the participants' RPE was lower when performing mobility tasks with the servo-assisted wheelchair compared to the standard manual wheelchair (Fig. 4). Significant differences were found in the forward propulsion at self-selected speed (p=0.01), forward sprint (p=0.01) and slalom course (p=0.03). Although not statistically significant, the only situation with higher average of RPE was moving down on a ramp, suggesting that the torque provided by the motor enhancing the inertia lead to an increased effort to decelerate the chair. Similar results were found in the participants' perception of difficulty with lower rates with the use of the prototype of the servo-controlled power-assisted wheelchair, with statistical difference found in the following mobility tasks: forward propulsion at comfortable self-selected speed (p=0.03), circular (2-meters radius) trajectory (p=0.02), slalom course (p=0.03) and ramp ascent (p=0.02), as shown in Fig. 5.

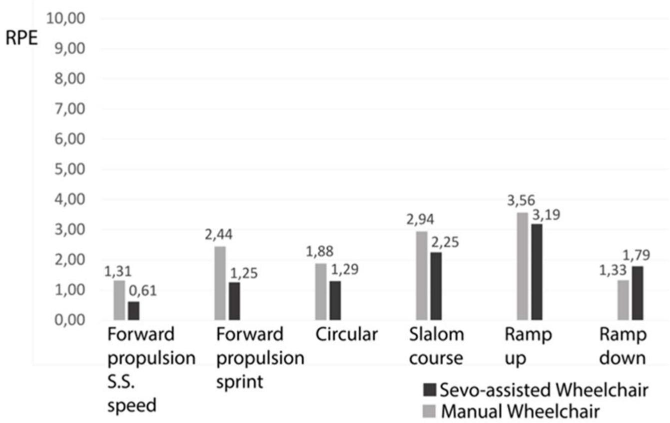

Fig. 4. Perceived effort during different mobility tasks with the two wheelchairs. * p<0.05.

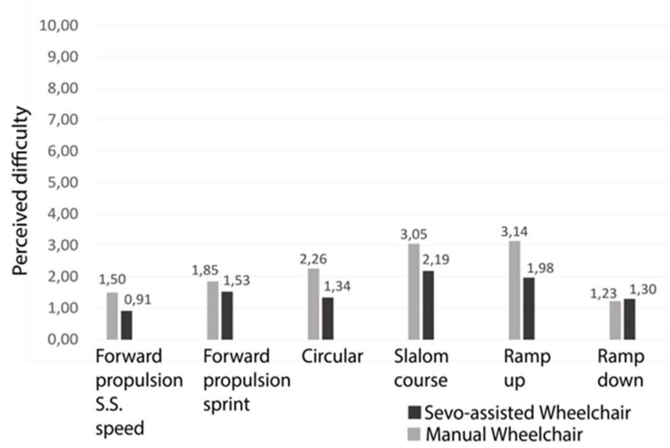

Fig. 5. Subjects' perception of difficulty in performing mobility tasks with the two wheelchairs. * p<0.05.

To illustrate the comparison of the results of the EMG measurements during the mobility tasks with the two wheelchairs, Fig. 6 presents the ratio between the standard manual wheelchair and the servo-controlled assisted wheelchair (MW / SCAW) in terms of the mean EMG activity of all muscles for all the trajectories. Values above the 1-line means that the biomechanical demand was higher with the manual wheelchair in comparison to the servo-controlled wheelchair. In turn, values below the 1-line reveals the opposite: higher demand on the upper limb muscles when propelling the servo assisted wheelchair.

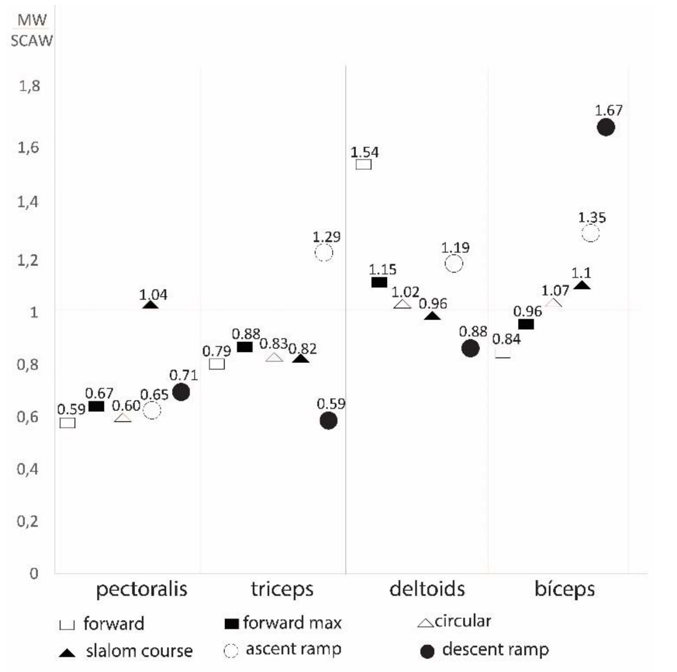

Fig. 6. Ratio (MW/SCAW) of the mean EMG for the manual wheelchair (MW) and servo-controlled assisted wheelchair (SCAW).

IV. DISCUSSION

This study found that providing power assistance complimentary to manual propulsion influences the biomechanical demand on the upper limbs' muscles and the subjects' perception of effort and difficultness in performing different mobility tasks. However, the EMG findings and the subjects' perceptions have some controversial results: while the perceived effort and difficulty was higher with the manual wheelchair in most of the mobility tasks, the measurements of muscular activity were lower with the manual wheelchair in comparison to the servo assisted device in many of the situations. A possible reason for the increased EMG activity with the power assistance may be the resistance that the motor transmits to the rear wheels axle that, ultimately, results in a slight resistance for the user to start pushing the handrims. Also, the increased mass (33 kg) of the prototype may have influenced, and future work should focus on reducing the mass of the prototype. However, EMG findings indicate that when moving up on a ramp - a problematic mobility situation for wheelchair users - the demand on the upper limbs muscles was reduced in comparison to the manual wheelchair.

Based on the results presented in Figure 5, it can be noted that both pectoralis and triceps muscle had lower activation with the use of the manual wheelchair compared to the power-assisted one, while the ratio for the anterior deltoids and biceps are close to the 1-line and above it in some tasks. For ascending a ramp - one of the most challenging mobility task to perform with a manually propelled wheelchair – the muscle activity was lower with the use of the power-assisted device for three (anterior deltoids, triceps and biceps) of the four muscles investigated, suggesting that power-assistance may facilitate moving on ramps and incline terrains.

Subjects considered easier and less strenuous to move with the power assisted chair in comparison to the standard manual one in all the mobility tasks, except in one situation. This is a positive finding, considering that problems in maneuvering PAPAW's have been reported [13]. Improving the drivability and maneuverability is an important issue for manual wheelchairs with power-assistance system.

This study has limitations that need to be noted. First, the sample size is relatively small and only subjects without disabilities participated. Therefore, the results may not be fully representative of a wheelchair user. Furthermore, it is possible that the knowledge of using an automated wheelchair may have influenced the perception of the participants. Future studies with larger sample size and real wheelchair users may provide a clearer view on the influence of the use of the servo-controlled power assisted wheelchair on the biomechanical demands and subjects' perceptions.

Additionally, the proportional controller is not the solution that will be implemented in future works, due to the fact of low assistance to the user: it may be another cause of the high efforts by the user. Interaction control, such as impedance controller [15], is a good candidate to aid the user in the process of maneuvering the wheelchair. The gear friction and other effects due to unmodeled dynamics can be minimized using other compensators [16], giving the user the sensation of transparency of the motor [17].

V. CONCLUSION

The current study found that the prototype of a servo controlled power assisted wheelchair has the potential to benefit the users' mobility by reducing the perceived effort and difficultness in performing different wheelchair mobility tasks, as well as reducing the biomechanical load on the upper limbs muscles when ascending a ramp. However, electromyography data showed an increased demand on the upper limbs in forward propulsion at comfortable speed, forward sprint, circular trajectory and slalom course. Besides the increased mass of the prototype, another possible explanation for these findings is that the motor acting on the rear wheels' axle adds a resistance to the initial phase of pushing the handrims forward. Future work should focus on reducing the total mass of the power-assisted system as well as minimizing the resistance of the motor in the wheels movement resulted from the user's pushes on the handrims, and on implementing other control techniques for user aid and transparency of the system.

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