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# Experimental study on a novel manual wheelchair

Andrea Botta<sup>\*</sup>, Paride Cavallone, Luigi Tagliavini and Giuseppe Quaglia Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Torino, Italy

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#### Abstract.

BACKGROUND: Traditional manual wheelchair users suffer from upper limbs injuries due to the propulsion gesture.

**OBJECTIVE:** This paper presents the experimental activity addressed to define the dynamic characteristics of a novel manual wheelchair. The design and realization of the wheelchair aim to reduce injuries of the upper limbs related to conventional wheelchairs. A new index called *Peak Of Force*, *POF*, is defined and applied to the different wheelchair manual propulsion systems.

**METHODS:** The wheelchair speed and the left and right-hand forces exerted by the user are monitored. The tests have been performed by changing the transmission ratio of the wheelchair and the wheelchair speed.

**RESULTS:** The indices *MEF* and *FEF* are lower than 100% due to the lateral and radial forces for hand-rim wheelchairs and handbikes. For Handwheelchair.Q these indices are equal to 100%. The mean value of index *POF* for Handwheelchair.Q is 51.75%, while it is about 42.5% for the hand-rim wheelchair, and 57.6% for the handbike.

**CONCLUSIONS:** The user forces for Handwheelchair.Q depend on the wheelchair speed and the pulley radius. The larger pulley radius reduces the average and the maximum force. A variable transmission ratio can be implemented on the proposed wheelchair.

Keywords: Manual wheelchair, Handwheelchair.Q, spinal cord injury

#### 1. Introduction

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2 Wheelchair users often present injuries and pain of the upper extremity joints due to the overuse of 3 the upper limbs [1]. In fact, many daily activities as 4 wheelchair propulsion and transfers strongly overload 5 the wrist, the elbow, and the shoulder joints [2]. The 6 pain of the upper limbs interferes significantly with 7 their personal life with repercussions on a psycholog-8 ical level [3,4]. There are different possibilities to re-9 duce injuries of the upper limbs, such as optimizing 10 the handrim wheelchair propulsion [5,6], optimising 11 or using devices for the transfers [7,8], and using an 12 alternative system of propulsion, manual or electric, 13

\*Corresponding author: Andrea Botta, Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy. E-mail: andrea.botta@polito.it. in order to avoid the same repetitive mechanical loading [9,10]. For wheelchair users, practising physical activity [11,12] is an essential tool for rehabilitation from a physical and psychological point of view [13]. There are different modes of manual propulsion such as handbike [14], lever system [15] as well as handrim. Table 1 summarises the main architectures advantages, drawbacks and principal use.

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In this scenario, the research group at the Politecnico di Torino has designed an innovative prototype of a wheelchair named "Handwheelchair.Q" characterised by an alternative propulsion system described in detail in different papers [16–19]. The prototype, shown in Fig. 1, is based on a frame of a standard lightweight wheelchair with an adjustable seat.

Two cables, one per side, to spin the wheels. Each cable is wrapped around a pulley connected to the wheel with a freewheel; then, it goes around a return pulley mounted on a telescopic rod and ends with a handle

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	Main wheelchair architectures	and their advantages, drawbacks and typical usag	ge
Architecture	Pros	Cons	Typical use
Hand-rim	Simple Compact Turn on the spot	Propulsion gesture in a fixed plane Can lead to shoulder joint overuse and pain Not suited for long distances	Every day use Indoor and outdoor
Handbike	Suited for long distances User applies almost constant force Has a transmission system	Propulsion gesture in a fixed plane Not suited for indoor activities Can't turn on the spot It is a dedicated wheelchair	Long distances Sport activities Outdoor



Fig. 1. Prototype of Handwheelchair.Q.

with the brake lever. The return pulley enables the user 33 to drive the wheelchair by pulling the cable using a 34 movement similar to that of rowing. Figure 2 shows 35 how the return pulley is connected to the frame with a 36 joint C2. The return pulley has two degrees of freedom, 37 it can rotate around joint C1 and can pivot around the 38 joint C2. This solution has been adopted in order to 39 limit the friction of the cable on the two sides of the 40 pulley, and for having a self-adapting pulling direction 41 imposed by the user. In addition to that, the telescopic 42 rod regulates the return pulley distance and height to 43 accommodate a wide range of users. 44

Handwheelchair.Q is driven similarly to conventional 45 hand-rim wheelchairs except for the way the user pro-46 duces the propulsive force. If similar forces are applied 47 by the user on the left and right sides, the wheelchair 48 goes straight. If more force is applied to one side in-49 stead, the wheelchair turns to the side where less force 50 is applied. If needed, the user can still use the hand-rims 51 of Handwheelchair.Q to manoeuvre in tight places (the 52 telescopic rods can be retracted), to rotate on the spot, 53 or to go backwards. 54 The ratio between the rear wheel radius  $r_w$  and the 55

pulley radius  $r_p$  defines the transmission ratio of Hand-56 wheelchair.Q. The pulley radius can be changed in or-57 der to optimise the transmission ratio for each user. The 58 aforementioned handrim, lever system, and handbike 59



Fig. 2. Handwheelchair.Q scheme and variable definition.

manual propulsion systems have a common character-60 istic: the trajectory of the gesture is fixed. This means 61 that the force of the user has three components, but 62 only the tangential component is useful for the trans-63 mission of motion. Handwheelchair.Q, instead, uses a 64 cable transmission in which the user force is entirely 65 helpful for the transmission of motion. Multiple studies 66 have investigated the efficiency of common propulsion 67 systems and different indices such as FEF, Fraction 68 Effective Force, and MEF, Mechanical Effective Force, to compare different systems of propulsion [20,21]. These indices are described in detail in the discussion paragraph, and they are used to assess the performance of the proposed solution compared to the more typical ones. The aim of this paper is to define the dynamic characteristics of a manual wheelchair with an innovative rowing motion and to determine a new performance index in order to compare different manual wheelchairs.

### 2. Methods

#### 2.1. Subject

One able-bodied subject (29 years old, 170 cm, 65 kg) not familiar with wheelchair use, participated 81

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Fig. 3. Circuit diagram of the acquisition system.

in the experiment. This experimental test is a prelim-82 inary analysis of the dynamic of an innovative man-83 ual wheelchair, hence, in the preliminary test nobody 84 else was involved. The limitation of having just one 85 able-bodied male user is clear, however, each test was 86 repeated several times in order to obtain reliable results. 87 Prior to the trials, the participant provided written in-88 formed consent. Ethical approval was granted, and the 89

work was performed in accordance with the Declaration
 of Helsinki.

#### 92 2.2. Equipment

Two load cells, (Manufacturer: LCM Systems Ltd, Model DCE, City: Newport, Country: United kingdom) connected the handles with the traction cable to measure the user input forces  $F_R$  (right hand) and  $F_L$  (left hand), as shown in Fig. 2.

- 98 Specification of the load cells:
- 99 Rated load: 500 N,

- Non-Linearity  $<\pm$  0.25% of rated load,
- Non-Repeatability < 0.1% of rated load.

The angular speeds of the right and left wheels,  $\omega_R$  and  $\omega_L$  respectively, were obtained by measuring the frequency of the output signal of a hall sensor (Manufacturer: Honeywell, Model: SS490 MRL, City: Charlotte, Country: North Carolina, USA) mounted on the wheelchair frame that detects the passages of sixteen equidistant magnets positioned on each wheel, Fig. 2.

#### 2.3. Data acquisition

Force and angular speed data were recorded with a 110 National Instrument USB-6341 data acquisition device 111 with 1000 Hz sampling frequency. Such data are col-112 lected by the on-board PC and then they are processed 113 offline. The data processing phase mainly involves ap-114 plying a proper low-pass zero-phase digital filter to the 115 data and to compute all significant quantities that can 116 be derived from the raw data. The circuit diagram of 117 the acquisition system is detailed in Fig. 3. 118

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#### 119 2.4. Data processing

Once an experimental trial has been completed, the 120 collected data, namely the left and right wheel angular 121 speeds,  $\omega_L$  and  $\omega_R$  respectively, and the user exerted 122 forces with the left and right hands,  $F_L$  and  $F_R$  respec-123 tively, are filtered by means of low-pass filters. After 124 that, it is possible to compute some quantities useful 125 to analyse the wheelchair behaviour. From the wheels 126 angular speed, it is possible to compute the wheelchair 127 longitudinal velocity  $\dot{x}$  as follows: 128

$$\dot{x} = \frac{\omega_R + \omega_L}{2} r_w \tag{1}$$

where  $r_w$  is the rear wheel radius.

Furthermore, it is convenient to define the whole force exerted by the user  $F_i$  during the *i*-th cycle as:

$$F_i = F_{R,i} + F_{L,i} \tag{2}$$

To uniformly compare the test runs, the mean steady state force exerted by the user over the measured cycles
 *F* is defined as:

$$F = \frac{\sum_{6}^{n} F_i}{n-5} \tag{3}$$

where the subscript *n* is the number of the total cycles of the run and the steady-state phase starts at the 6<sup>th</sup> cycle, with i = 6.

The rowing gesture is characterised by two distinct 138 phases: an active phase, when the user pulls the cables 139 to propel the wheelchair, and a recovery phase, when 140 the user let the cables go back to their initial position 141 thanks to the retractable cable reel mechanism in the 142 pulleys. Therefore, it is possible to identify a period  $T_A$ 143 that corresponds to the duration of an active phase and, 144 conversely, a period  $T_R$  corresponding to the recovery 145 phase. In practical terms,  $T_A$  is the duration of the active 146 phase measured whenever the user forces are above 147 the threshold value of 5 N (the resolution of the load 148 cells plus a safety range). Conversely,  $T_R$  is the time in 149 which the user forces are below the threshold. Hence, 150 the overall rowing gesture period can be defined as 151  $T = T_A + T_R$ . F1, defined by Eq. (4) is the average 152 force during the complete cycle T, while F2, defined 153 by the Eq. (5) is the average force during the active 154 phase,  $T_A$ , and  $F_{max}$  is the peak of F. 155

$$F1 = \frac{1}{T} \int_0^T F \, dt \tag{4}$$

$$F2 = \frac{1}{T_A} \int_0^{T_A} F \, dt \tag{5}$$

The input powers  $PI_i$  of all the cycles of the steady state phase is:

$$PI_i = F_{R,i}r_p\omega_{R,i} + F_{L,i}r_p\omega_{L,i} \tag{6}$$

where  $r_p$  is the pulley radius. Their average over a single run *PI* is:

$$PI = \frac{\sum_{6}^{n} PI_i}{n-5} \tag{7}$$

where the subscript n is the number of the total cycles of the run and the steady-state phase starts at the 6<sup>th</sup> cycle, with i = 6.

Similarly to the forces, the average user power over a gesture cycle *PI*1 and over the active phase *PI*2 are defined as follows:

$$PI1 = \frac{1}{T} \int_0^T PI \, dt \tag{8}$$

$$PI2 = \frac{1}{T_A} \int_0^{T_A} PI \, dt \tag{9}$$

At last, the user exerted energy during the active phase is:

$$EI = \int_0^{T_A} PI \, dt \tag{10}$$

#### 2.5. *Experimental tests*

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The experimental tests consisted of propelling Hand-169 wheelchair.Q from a standing start on a flat hallway 170 covered with a dotted rubber flooring. The user was 171 asked to drive the wheelchair for about 60 m with dif-172 ferent intensities (low or high) and different transmis-173 sion ratios. The low intensity has been defined as the 174 intensity at which the user does not perceive fatigue, 175 comparable to a walk on a flat surface, that corresponds 176 to approximately 1.5 m/s. The high intensity has been 177 defined by increasing the wheelchair speed by 50%, 178 thus it corresponds to a velocity of about 2 m/s. In the 179 tests, the user was able to check the wheelchair speed 180 in real time with a speedometer to verify that he was 181 moving at a speed close to the desired one and to ad-182 just the rhythm of the rowing gesture accordingly. The 183 user was able to maintain an average speed of 1.57  $\pm$ 184 0.09 m/s during the low intensity tests and an average 185 velocity of  $2.33 \pm 0.05$  m/s during the high intensity 186 ones. 187

Four sets of tests were performed, each one composed of five runs (A, B, C, D, and E):

- Test 1: "Low speed" with the radius pulley  $r_{p1}$ ;
- Test 2: "Low speed" with the radius pulley  $r_{p2}$ ;
- Test 3: "High speed" with the radius pulley  $r_{p1}$ ;
- Test 4: "High speed" with the radius pulley  $r_{p2}$ .

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Fig. 4. Handwheelchair.Q experimental setup.

<sup>194</sup> Where the two different pulley radii used were  $r_{p1} =$ <sup>195</sup> 108 mm and  $r_{p2} =$  130 mm and the radius of the rear <sup>196</sup> wheels was  $r_w =$  292 mm.

Also, before all tests, the height of the return pulley, 197  $h_{rp}$ , was chosen by the user in order to get a comfortable 198 rowing motion based on his personal feelings and was 199 kept constant. Such position defines the rowing gesture 200 direction since it defines the direction in which the user 201 pulls the cables to propel the wheelchair. Hence the user 202 was able to set the wheelchair return pulley position to 203 match his preferences and size. Figure 4 presents the 204 experimental setup and the test environment. 205

#### 206 2.6. Performance indices

Being that the force peaks are dangerous for the upper limb joints [22], it is important to define a new index, called *POF*, *Peak of Force*, in order to evaluate the peaks of force. The higher the index is, the better, in order to reduce the peaks of force. The index *POF* is defined as:

$$POF = \frac{F_u}{F_{max}} \tag{11}$$

where  $F_u$  is the mean over the active phase of the useful 213 component of the total force F exerted by the user (left 214 and right hand contributions are added together), i.e., 215 it is the only portion of user exerted force contributing 216 to the wheelchair propulsion. The useful component 217  $F_u$  that produces the wheelchair motion depends on 218 the wheelchair propulsion system.  $F_{max}$ , instead, is the 219 peak value of the total force F applied by the user. In 220

other terms, the *POF* index compares the maximum total force and the average useful force exerted by the user with different wheelchair architectures. A *POF* close to 1 means that, in the corresponding propulsion architecture, the average value of the useful force and the peak value of the total force are similar and therefore there are limited peaks of force during the wheelchair operation and the exerted force is almost constant. Conversely, a low *POF* index represents an architecture where the user-exerted force varies considerably and there are significant peaks of force during the wheelchair use.

In a standard wheelchair with a hand rim system of radius  $r_{hr}$ , only the portion of exerted force tangential to the hand rim,  $F_{tan}$ , contributes to the rotation of the wheels, all the other components are wasted instead. Hence,  $F_u = F_{tan}$  in traditional wheelchairs. Similarly, in handbikes, the portion of the user-exerted force that is tangential to the hand crank is the useful force contributing to the motion. In the proposed novel wheelchair, Handwheelchair.Q, the whole force exerted by the user pulling the cable is transmitted to the pulley to produce motion, therefore, in this case, the useful force corresponds to the whole pulling force.

In literature also exists other indices to evaluate wheelchair performance. The indices *MEF (mechanical effective force)* and *FEF (fraction effective force)*, are defined. by Eq. (3) [23] and Eq. (4) [24], respectively. The two indices measure in a slightly different way how much of the user exerted force is used to produce motion. The difference between *MEF* and *FEF* is



Hand-rim Wheelchair

Fig. 6. Diagram showing the useful force  $F_u$  for each configuration.

that the MEF does not take into account the "gripping 252 moment" [24]. 253

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2}$$
(12)

$$M_z = \tau R_{eff} F_u \tag{13}$$

$$MEF = \frac{F_u^2}{F^2} \cdot 100 \tag{14}$$

$$FEF = \frac{M_z}{R_{eff}F} \cdot 100 \tag{15}$$

where F is the whole force exerted by the user,  $F_u$  is 254 the useful component of F that contributes to motion, 255  $M_z$  is the torque applied to the wheel,  $R_{eff}$  is the lever 256 arm of  $F_u$  that produces  $M_z$ , and  $\tau$  is the architecture 257 transmission ratio. 258

In the case of hand-rim wheelchairs and the proposed 259 one, the transmission ratio  $\tau$  is 1 since the useful force 260  $F_u$  directly produce a torque on the wheel. In hand-261

bikes, usually, there is a transmission system between the hand-crank and the wheel. The effective radius  $R_{eff}$ in a hand-rim wheelchair is the radius of the hand-rim and the useful force  $F_u$  is the tangential component of F to the hand-rim. In the proposed wheelchair, the effective radius  $R_{eff}$  is the pulley radius  $r_p$  and the useful force is the whole force exerted by the user F. At last, in a hand-crank wheelchair, the effective radius  $R_{eff}$  is the hand-crank radius  $r_{hc}$  and the useful force is the one tangential to it. Figure 6 depicts a diagram for each configuration.

#### 3. Results

Each test was performed five times, each run is com-274 posed of two phases: the acceleration phase and the 275 steady-state phase. During the acceleration phase, the 276

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in the complete cycle, steady-state phase, <i>PI</i> 1 <i>TA</i> is the time of the ac average wheelchair spec	F2 is the average for $F2$ is the input postive phase, $TR$ and in the steady	rage force in the a wer in the complet is the time of the y-state phase	active phase, Fri te cycle, <i>PI</i> 2 is the recovery phase,	hax is the peak of the input power in <i>EI</i> is the input e	f force $F$ in t the active pha energy and is t
	-	Low speed		High speed	
		Test 1	Test 2	Test 3	Test 4
Acceleration phase	$F_{1,max}$	141 (1.9)	146 (12.9)	222 (16.6)	223 (10.8)
-	$F_{2,max}$	163 (9.8)	172 (6.1)	255 (8.6)	242 (9.0)
	$F_{3,max}$	155 (12.7)	148 (9.5)	225 (7.0)	221 (15.1)
	$F_{4,max}$	136 (11.3)	134 (5.6)	211 (24.2)	175 (18.3
	$F_{5,max}$	114 (11.9)	118 (11.2)	180 (24.4)	181 (24.3)
Steady-state phase	F1 [N]	37.5 (3.8)	30.3 (5.8)	45.3 (4.7)	40.1 (3.9)
• •	F2 [N]	57.6 (1.8)	51.6 (2.5)	76.4 (4.2)	60.9 (2.7)
	$F_{max}$ [N]	101.4 (4.2)	95.4 (1.7)	147.2 (6.8)	133.2 (6.3)
	<i>PI</i> 1 [W]	20.9 (3.2)	21.9 (4.4)	38.3 (8.7)	42.1 (2.44
	<i>PI</i> 2 [W]	33.7 (1.7)	39.1 (1.8)	67.5 (4.3)	66.9 (0.98
	$T_A$ [s]	0.99 (0.03)	0.84 (0.04)	0.70 (0.05)	0.60 (0.02
	$T_R$ [s]	0.53 (0.01)	0.59 (0.06)	0.48 (0.04)	0.43 (0.03
	<i>EI</i> [J]	33.3 (2.7)	32.8 (3.0)	47.2 (6.3)	40.1 (1.9)
	$\bar{\dot{x}}$ [m/s]	1.51 (0.04)	1.63 (0.05)	2.29 (0.09)	2.36 (0.09



Fig. 7. Examples of overlap in the steady state phase of forces,  $F_i$  in grey and their mean F in black.

wheelchair accelerates from zero to the steady-state 277 speed. During the steady-state phase, the wheelchair 278 speed oscillates around an average speed, as shown in 279 Fig. 5. In Fig. 5 are also reported the right and left 280 forces, in red and blue respectively. At the beginning 281 of the acceleration phase, the wheelchair starts with 282 a speed equal to zero. After five cycles, the steady-283 state speed is reached. At each cycle, the active time 284 decreases because the wheelchair speed increases. 285

In Table 2, the means of the maximum forces,  $F_{i,max}$ (SD), calculated over the five trials, are reported for each cycle, where the subscript *i* is the number of the cycle. In all the tests, the maximum force peak takes



Fig. 8. Examples of overlap in the steady state phase of the input power,  $PI_i$ , in grey, and their mean PI in black, for a single run and the energy input EI, the red area.

place in the second cycle. The force peaks are influenced by the characteristic "low" or "high" speed of the test and by the pulley radius, during the acceleration phase. For example, there is a slight difference by comparing test 1 and test 2 and a clear difference comparing test 1 and test 3.

During the steady-state phase, the wheelchair speed oscillates around the average value of the wheelchair steady-state speed  $\dot{x}$  as it is shown in Fig. 5. In the steady-state phase, the active phase period  $T_A$  is almost constant for each test because the wheelchair speed oscillates around an average value. Figure 7 shows the overlap of the measured forces  $F_i$  of all the cycles of the

System of propulsion	Test	<i>x</i> [m/s]	POF	POF [%]
Handwheelchair.Q	1	1.51	$POF = \frac{F2}{F}$	56
	2	1.63	1 max	54
	3	2.29		52
	4	2.36		45
Hand rim [25]	1	1.17	$POF = \frac{\text{mean}(F_{tan})}{\text{max}(F_{tan})}$	39
	2	1.37	max(1 /es)	44
	3	1.42		51
	4	1.64		47
	5	1.71		50
	6	2.52		38
	7	2.37		40
	8	2.37		41
	9	2.52		42
	10	2.45		45
Hand rim [26]	1	1.11	•	46
	2	1.66		41
	3	2.22		38
Handbike [21] <sup>a</sup>	1		$POF = \frac{F_{tot\_trial}}{F}$	56
	2		1 peak	56
	3			61

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<sup>a</sup>[21] does not measure the longitudinal speed of the handbike.

steady-state phase, in grey, and their mean F, in black, 303 for a single run. Also, F1, the average force during the 304 complete cycle, F2, the average force during the active 305 phase  $T_A$ , and  $F_{max}$ , the peak of F, are shown in Fig. 7. 306 These values are listed for all tests in Table 2. 307

Figure 8 shows the overlap of the input powers  $PI_i$ 308 of all the cycles of the steady state phase in grey and 309 their mean *PI* in black, for a single run. Figure 8 also 310 depicts PI1, the average power during the complete 311 rowing gesture cycle, PI2, the average power during 312 the active phase  $T_A$ , and the energy input EI as the red 313 area under PI. These values for all tests are reported in 314 Table 2. 315

In Table 2 the mean (SD) of some values of the 316 steady state phase are reported. In the steady-state 317 phase, the duration of the active phase,  $T_A$ , depends 318 on the wheelchair speed and on the pulley radius. In 319 fact,  $T_A$  decreases with increasing the wheelchair speed 320 and with the increase of the pulley radius. On the other 321 hand, the duration of the recovery phase,  $T_R$ , is almost 322 constant. The mean of the input power over all complete cycles, PI1, increases when the wheelchair speed is in-324 creasing for all tests, as it should be. The average and 325 the maximum forces depend on the wheelchair speed 326 and on the pulley radius. In fact, in test 2 the forces are 327 smaller than the ones of test 1 because  $r_{p2} > r_{p1}$ , even 328 if the wheelchair speed of test 2 is higher than the one 329 of test 1. The same reasoning is valid also for tests 3 330 and 4. Generally, the forces of tests 3 and 4 are higher 331

than the forces of tests 1 and 2 due to the difference in wheelchair speed. A larger pulley enables the user to exert less force to achieve the same traction torque  $M_z$ . This is the reason why the forces in tests 2 and 4 are generally lower than the one in tests 1 and 3. Overall tests 3 and 4 requires more torque than tests 1 and 2 to move at a higher speed, thus the forces are higher during the faster tests. This pattern appears both during the acceleration phases and the steady-state phases. Obviously, during the acceleration phases, the peak force is larger than the steady state one because the wheelchair is accelerating.

The asymmetry of the right and left forces reported in Fig. 5, is due to the dominant side of the user, even if the trajectory of the test is straight. This asymmetry slightly affects the trajectory producing a minimal drift to one side, but, generally, the user keeps correcting unconsciously the trajectory by adjusting his/her force to maintain the trajectory straight. The same phenomenon appears also in conventional hand-rim wheelchairs because it is impossible to apply the exact same force to the two wheels. It is possible that part of the speed oscillations is due to the observed asymmetry. However, the main effect of this oscillation is the rowing gesture 355 itself since it is made of two distinct phases. The figure 356 clearly shows that during the active phase the measured 357 speed increases whereas during the recovery phase it 358 decreases.

Figure 9 is showing some details about the average acceleration phases of the four tests. The acceleration

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Fig. 9. Detail of average acceleration phases of the four tests.

phase duration is about the same for all tests regardless 362 of the pulley radius. Because the user applies a lower 363 force when a larger pulley is used and applies a larger 364 force with a smaller pulley, the overall torque applied to 365 the wheel is almost the same, therefore the acceleration 366 times are similar. In case the same force was applied 367 for both pulley radii, acceleration with the larger pulley 368 would be faster. 369

#### 370 **4. Discussion**

The indices *MEF* and *FEF* evaluate the efficiency of the wheelchair. For the standard wheelchair, these indices are lower than 100%, [21,25] due to the lateral and radial forces. For Handwheelchair.Q these indices are equal to 100% because the user force is entirely helpful for the transmission of motion under the hy-376 pothesis that the friction of the return pulley is negligi-377 ble. In this prototype the return pulley is mounted on a 378 couple of bearings, hence the actual value of the friction 379 mainly depends on their quality. The index POF can 380 be calculated for Handwheelchair.Q with the data of 381 Table 2. In addition, the index POF can be calculated 382 for a wheelchair with the hand rim system with the val-383 ues reported in the paper [25], Table 3, and paper [26], 384 Table 2, and for a handbike, [21], Table 3.1. Table 3 385 summarises the value of the index POF and Eq. (11) 386 adjusted with the respective nomenclature. In any case, 387 in the numerator, there is always the average useful 388 force exerted by the user and in the denominator, there 389 is the maximum force exerted. The mean value of POF 390 for Handwheelchair.Q is 51.75%, while for the hand 391

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rim wheelchair it is 43.7% in [25] and 41.6% in [26], 392 and for the handbike in [21] it is 57.6%. 393

#### 5. Conclusions 394

The aim of this paper was to analyse the propulsion 395 force of a manual wheelchair with an innovative sys-396 tem of propulsion, Handwheelchair.Q. The force and 397 the wheelchair speed were monitored during accelera-398 tion and steady-state phases of an experimental cam-399 paign. The paper shows that the forces depend on the 400 wheelchair speed and on the pulley radius. The input 401 power is obtained by the wheels' angular speed and the 402 force. Future studies should focus on comparing the 403 efficiency in the same test conditions of different man-404 ual wheelchair drive systems, such as handbikes, and 405 hand-rims. For equal or similar wheelchair speeds, the 406 larger pulley radius reduces the average and the maxi-407 mum force, which are important to reduce the stress on 408 the upper limb. The newly defined index *POF* has been 409 calculated for Handwheelchair.Q, for two wheelchairs 410 with the hand rim system and for a handbike. The index 411 *POF* is lower for wheelchairs with the hand rim system 412 than for Handwheelchair.Q, but it is higher for the hand-413 bike because in that system there is no recovery phase. 414 A variable transmission ratio can be implemented on 415 the proposed wheelchair in order to reduce the peak 416 of force during the acceleration phase.  $F_{max}$  remains a 417 fundamental parameter in order to evaluate the manual 418 wheelchair, in addition, the direction of the force is rel-419 evant because it defines whether the shoulder and elbow 420 joints are compressed or in traction. In future works, 421 Handwheelchair.Q will be compared with hand rim 422 wheelchairs, both from a mechanical and biomechanics 423 point of view. In the next tests more subjects have to 424 be included, wheelchair users in particular, in order to 425 consolidate and validate the results obtained here. In 426 addition, in the future it is important to compare the 427 standard manual wheelchair and the Handwheelchair.O 428 in the same research setup. 429

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