Prototyping of manual wheelchair with alternative propulsion system

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Abstract

Aim: This paper presents the study, design and prototyping of a manual wheelchair, named handwheelchair.q, with an innovative propulsion's system. The research is based on a novel system of propulsion that is more efficient and ergonomic than the hand rim one. The main goal of the designed prototype is to facilitate the mobility and to extend the reachable areas while reducing the required time.
Methods: The propulsion is realised through a rowing-inspired gesture.
Results: This gesture avoids the damages caused on shoulders by the compressive force of the hand rim and lever systems.
Conclusion: The prototyping allowed the analysis of the project parameters and their influence on the kinematic characteristics of the prototype and the biomechanical characteristics of the gesture. The same propulsion's system can be adopted on wheelchairs devoted to sport activities, representing the starting point for a future prototype of racing wheelchairs. In this regard, the wheelchair's braking system has been redesigned in order to improve efficiency and safety.

Keywords: wheelchair; paraplegic aid; handwheelchair.q

Sir Ludwing Guttman recognised the importance of sport for disabled people from a physiological and psychological [1] point of view, the sports contributed significantly to medical rehabilitation environment [1]. The first edition of Paralympic Games were held in Rome in 1960. All 400 participants were spinal injured, actually the Paralympic Games include not only spinal cord injuries [1]. During the 2016 Summer Paralympics Games participated 4,342 athletes from 159 nations, in 22 different sports [2]. As shown in [3, 4, 5], sport has a significant impact on quality of life of persons with disabilities.

Only in the United States of America, 1.3 million people suffer from spinal cord injury, which leads secondary health conditions such as osteoporosis, cardiovascular disease and diabetes [6]. The rowing is a rehabilitation therapy

very important to reduce the secondary problem caused by spinal cord injury [6, 7]. Through the Functional Electrical Stimulation enables to exercise a large number of muscles of the body [6, 8]

The rowing stroke can be performed without employing the muscle of the legs, but the muscles of the trunk and of the upper limb are involved.

Since the handrim system has a low efficiency [9, l0], the rowing can be a good alternative for two reasons: 1) It is a rehabilitation therapy performed outdoor in a park on a cycle path to practice a sport activity [11] ; 2) It is a means of mobility with an alternative system of propulsion.

Introduction

The hand rim system is the world's most used propulsive method in everyday lives thanks to its extreme firmness and manoeuvrability [12] to provide people with disabilities independent locomotion [13]. Nevertheless, this system shows various issues [14]. First, the ring-system gesture is not efficient and does not allow to reach high speed [15]. Moreover, shoulder injuries may occur. Many studies show that 60 to 100% of the long-term user has suffered at least once of shoulder pain. Specifically, in [16] the users who took part to the survey used for at least one year the wheelchair as the main transport for personal mobility; 73% of the users declared to suffer of shoulder pain. In detail 25.5% had problems with the left shoulder, 25.5% had problems with the right shoulder and 49% had shoulder pain on both sides. Only the 27% of the users did not suffer shoulder pain. Another study [17] shows how the percentage of shoulders pain increases with the time spent on the wheelchair and the age of wheelchair users.

The main causes of shoulder pain are three:

- Shoulder destabilization [18]

  The shoulder is held in position from the stabilizer muscles, in particular from the supraspinatus which gives stability to the glen humeral joints in every position. During the pushing phase the force direction applied by the user has to change continuously. The repetition of those movements may result in the muscle fatigue that causes the shoulder destabilization.

- Soft-tissue friction [19]

  The shoulder joint is not as strong as the ankle or the knee joint. The compressive force released on the shoulder might damage the soft-tissues like the humerus' joint capsule, ligaments and tendons.

- High force peaks on the shoulder [20]

  The high peaks of force on the glen humeral joints, caused by the limited time of the pushing phase increase the chance of the mentioned above shoulder issues.

One of the ring system's issue concerns the braking system in which the user has to create friction by using the hands on the hand rim [21]. This triggers an acceleration of heat production which can be uncomfortable especially when high speed is reached on steep roads.

In order to solve the above-mentioned problems, it was thought to study an alternative system of propulsion inspired by the rowing gesture [22]. In this paper the prototype named Handwheelchair.q will be presented. The same propulsion's system can be adopted on wheelchairs devoted to sport activities [23] and for wheelchair used in everyday lifes. The Handwheelchair.q used in sport configuration, different parameters have to be study accurately to increase the performance [24].

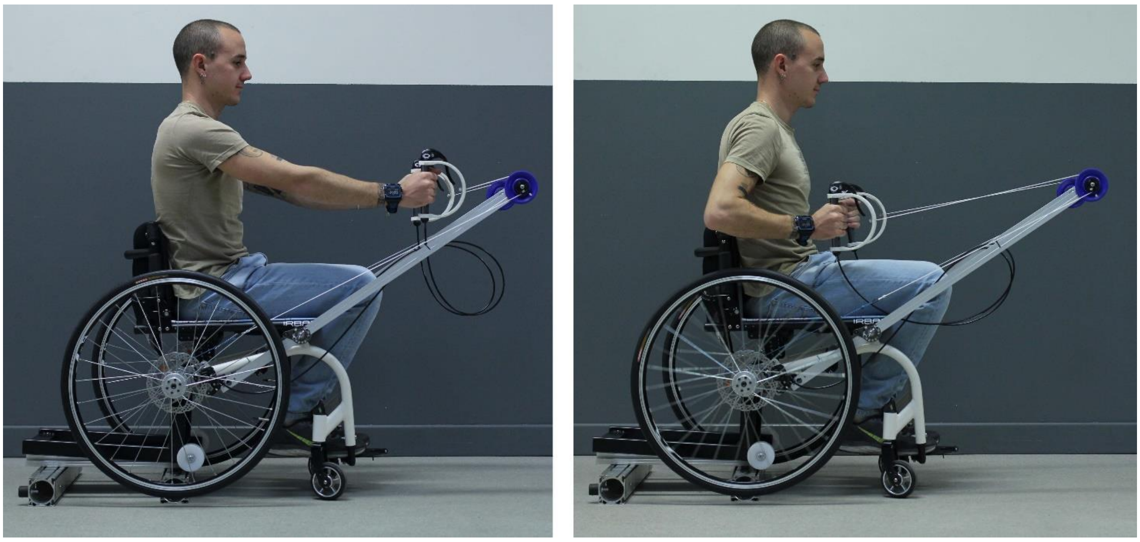
This paper is organized as follows: The introduction deals the biomechanics aspects of the hand rim, highlighting its issues and its causes. The second part deals the parametric modelling and analysis, first of all, general features are shown to analyse successively the kinematic characteristics, at the end of second part the parametric modelling is examined focusing about the influence of the main parameters. The third section shows the prototype named Handwheelchair.q, analysing all components and the constructive solutions adopted. Ultimately, the fourth section is about the conclusions.

Parametric modelling and analysis

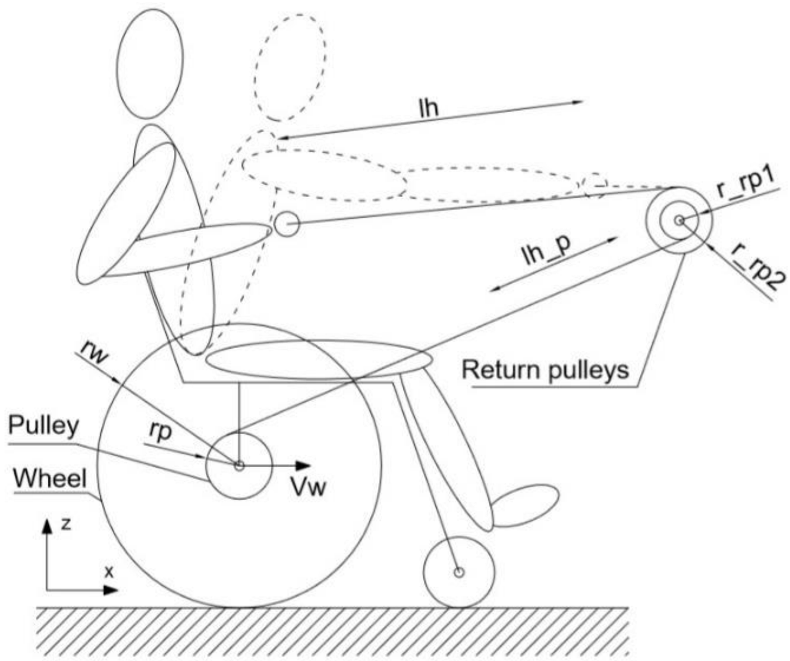
In this section the geometric characteristics and the kinematic analysis are examined.

General features

The innovative propulsive system is inspired by the rowing motion, without the employment of the inferior limbs. The stroke/pull movement can be performed in different ways - by the arms only but also with the torso forward-inclination's input - this depends on where the user's injury is. The rowing gesture is divided into two phases: the pushing phase and the recovery phase. During the pushing phase the user provides power while in the recovery phase the user goes back in the initial position in order to start a new pulling phase, as shown in Figure 1.



In figure 2, the main geometrical prototype characteristics are represented.



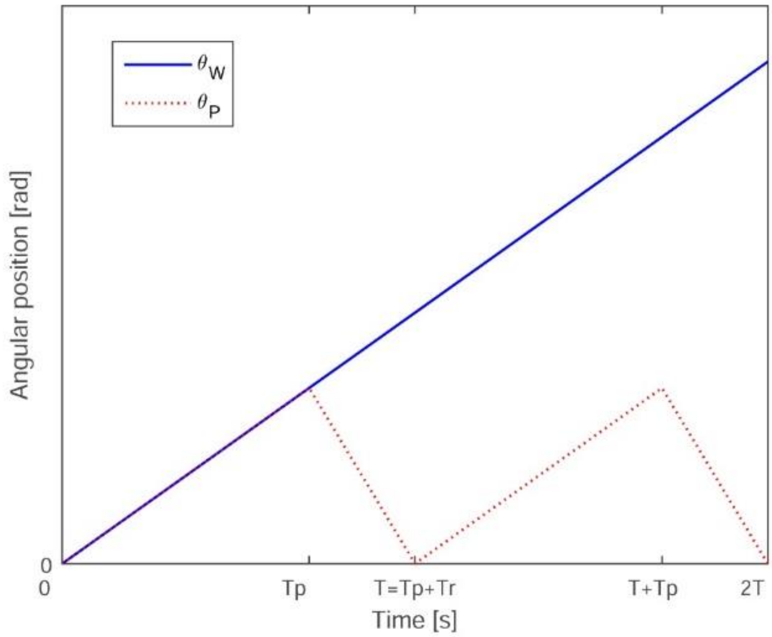
In order to evaluate the effect of the various parameters and to choose the proper values, some simplified parametric analysis was developed. The list of symbols for variables and parameters is reported in Table 1.

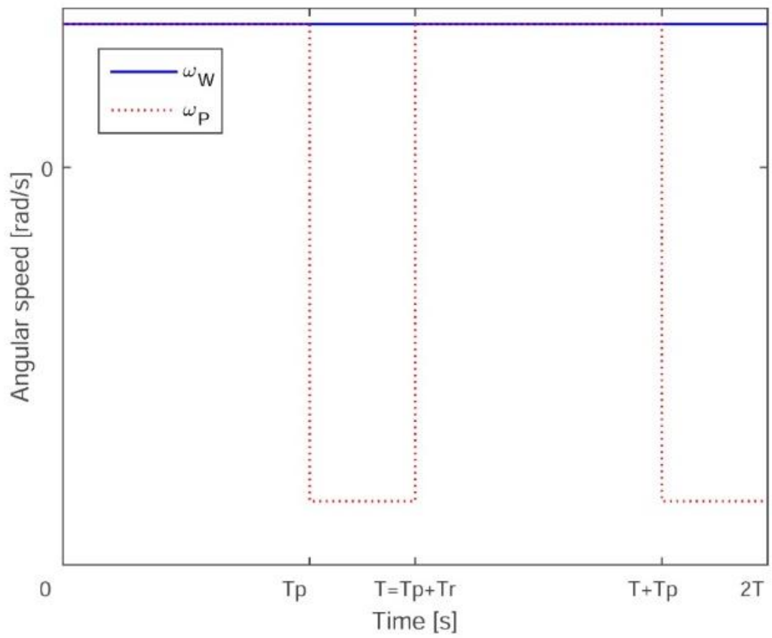
Symbol	Variable	Unite of measure
r_W	Wheel radius	m
θ_W	Wheel angular position	rad
ω_W	Wheel angular speed	rad/s
r_p	Pulley radius	m
θ_P	Pulley angular position	rad
ω_P	Pulley angular speed	rad/s

lh	Working stroke	m
V_W	Wheelchair speed	m/s
Vp	Pulley speed	m/s
Tp	Pushing time	s
Tr	Recovery time	s
f	Frequency	Hz
$\tau_1 = \frac{r_w}{r_p}$	Transmission ratio	/
$\tau_2 = \frac{r\_rp1}{r\_rp2}$	Transmission ratio	/

Kinematic analysis

The transmission of motion from the handle to the pulley is limited to the pushing time. Then, during recovery time, thanks to the ratchet-pawl mechanism between the pulley and the wheels, and the elastic elements that return the pulley in the original position, the rotation of the wheel and of the pulley are in the opposite direction. The figure 3 shows the wheel and pulley angular position during pushing phase and recovery phase. In order to evaluate the effect of various parameter we assume the hypothesis 1: $\omega_W = costant$.





By hypothesis 1 in figure 4 wheel and pulley angular speed are shown. We can define the drive frequency f as

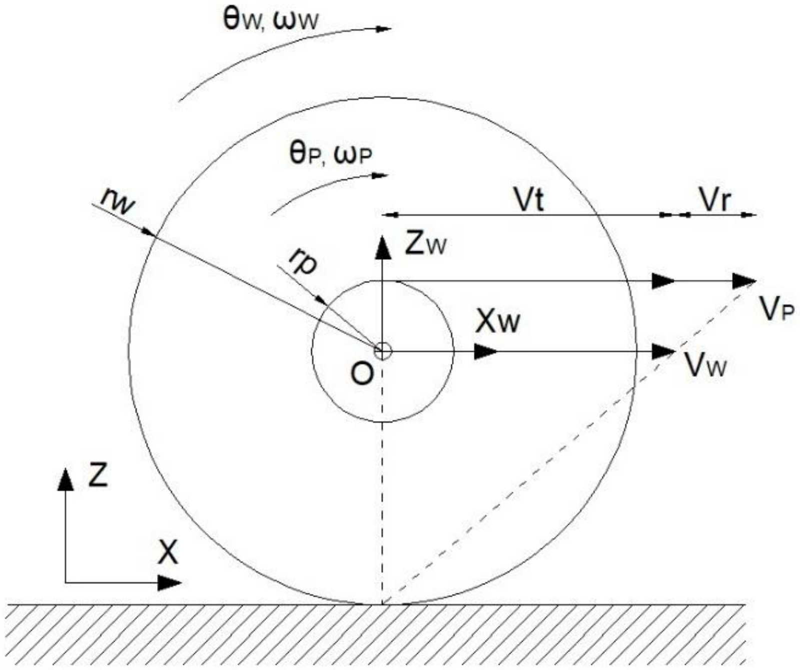
$$f = \frac{1}{Tp + Tr} = \frac{1}{T} \tag{1}$$

Hypothesis 2: Pure rolling motion, without slipping: $V_W = \omega_W r_W$

Observing that during Tp, $\theta_W = \theta_P$ and $\omega_W = \omega_P$

$$V_W = \omega_P r_W \tag{2}$$

Observing the figure 5 we can write the tangential absolute velocity V_P as the sum of relative velocity Vr and transportation velocity Vt relates to a mobile coordinate system Zw, Xw, centred in O, that moves together with the wheelchair frame.



$$V_P = V_r + V_t = \left(V_O + V_{P/O}\right) + V_W = (0 + \omega_P r_P) + \omega_P r_W \tag{3}$$

$$V_r = \frac{lh}{Tp} = \omega_P r_P \rightarrow \omega_P = \frac{lh}{Tp\, r_P} \tag{4}$$

Results:

$$V_W = \omega_P r_W = \frac{lh}{Tp\, r_P} r_W = \frac{lh}{Tp}\tau_1 \tag{5}$$

It is also possible to add another transmission ratio between two interlocked return pulleys as shown in figure 2. This option can be used to customize the performances of the wheelchair, or as solution to introduce a multi-ratio system.

We can write the follow equation

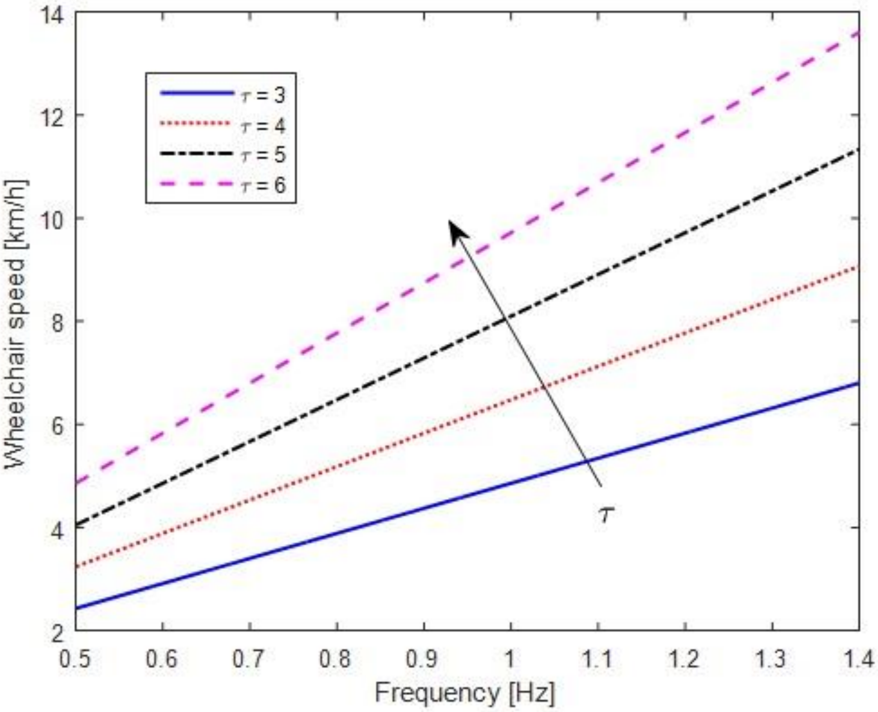
$$\frac{lh}{lhp} = \frac{r\_rp1}{r\_rp2} \rightarrow lhp = lh\frac{r\_rp1}{r\_rp2} = lh\,\tau_2 \tag{5}$$

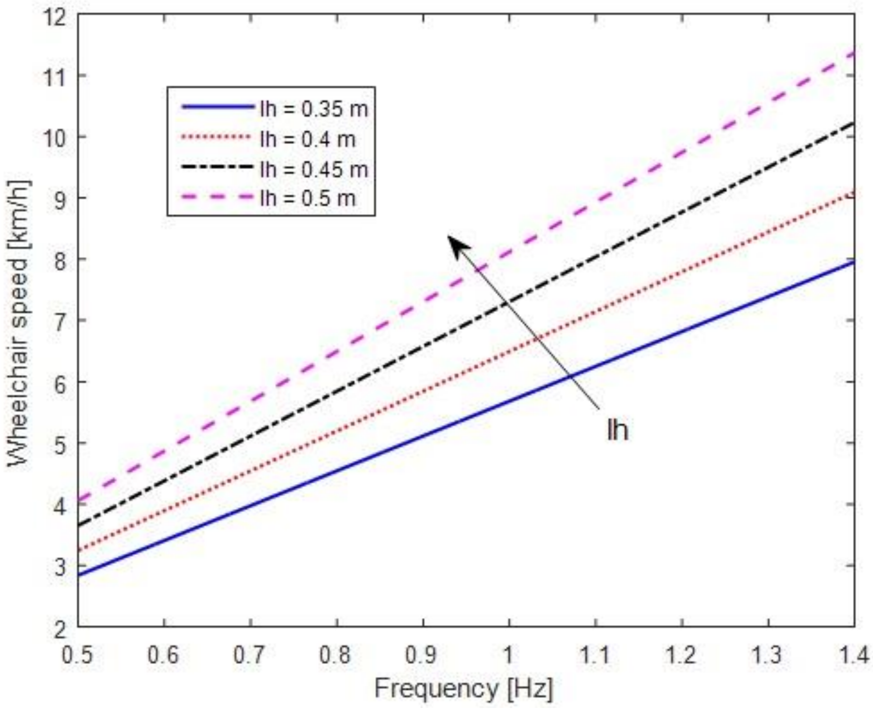
Now, we can write:

$$V_W = \omega_P r_P = \frac{lhp}{Tp\, r_P} r_W = \frac{lh}{Tp}\tau_1\tau_2 = \frac{lh}{Tp}\tau \tag{6}$$

Parametric modelling

The wheelchair speed is influenced by lh, f, that are controlled by the user, and by the design parameter τ. The working stroke lh partly depends on the prototype configuration and partially on the user. The working stroke could be included between $0 < lh < lh\_max$, where lh_max expresses the maximum stroke possible depending on the geometrical configuration of the wheelchair. Depending on each user's disability degree the user can vary the working stroke. The transmission ratio is determined by the pulley size compared to a wheel size and an additional return pulleys' transmission ratio. The two following figures show the variation of the wheelchair speed rate in relation to the τ and lh parameters. The Figure 6 shows the τ influence and the Figure 7 shows the lh influence.





We can observe that V_W increases as τ and lh increase.

Prototype

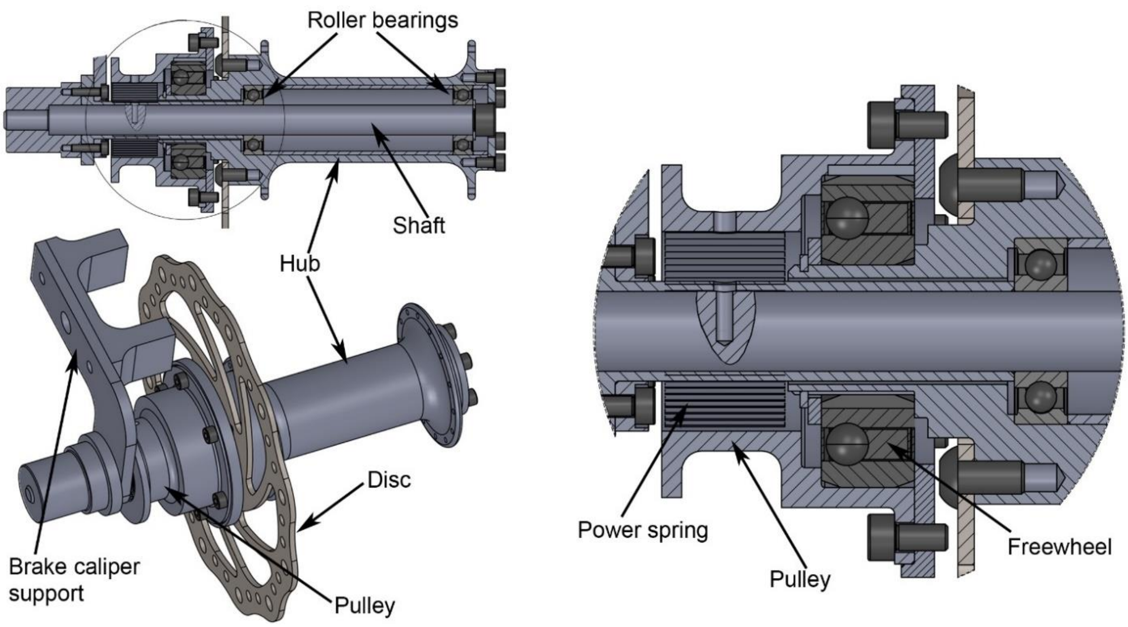
The prototype is composed by 6 main groups: wheelchair, power and recovery transmission mechanism, return pulleys' support rod, return pulleys, handles with brake levers and brake system.

Wheelchair

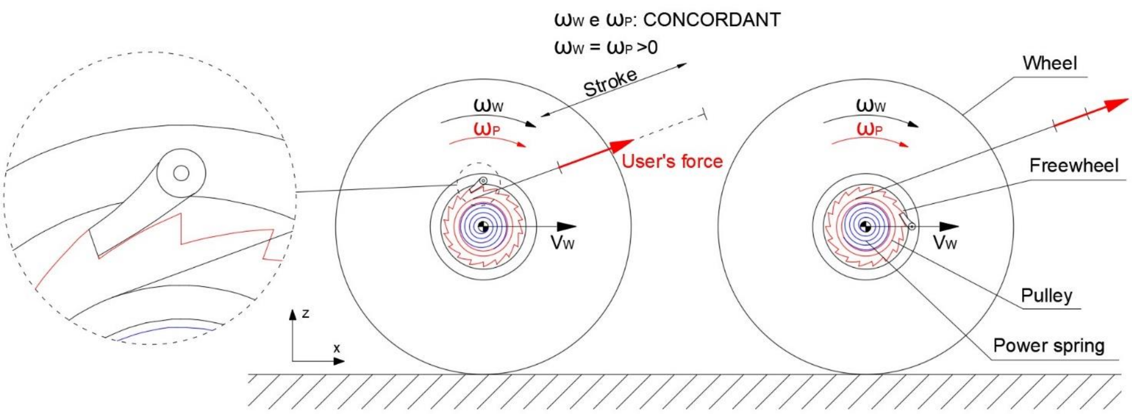
The wheelchair model is a super-light wheelchair with good weight and efficiency characteristics designed for dynamic users who use the wheelchair as main mobility vehicle.

Power transmission and recovery mechanism

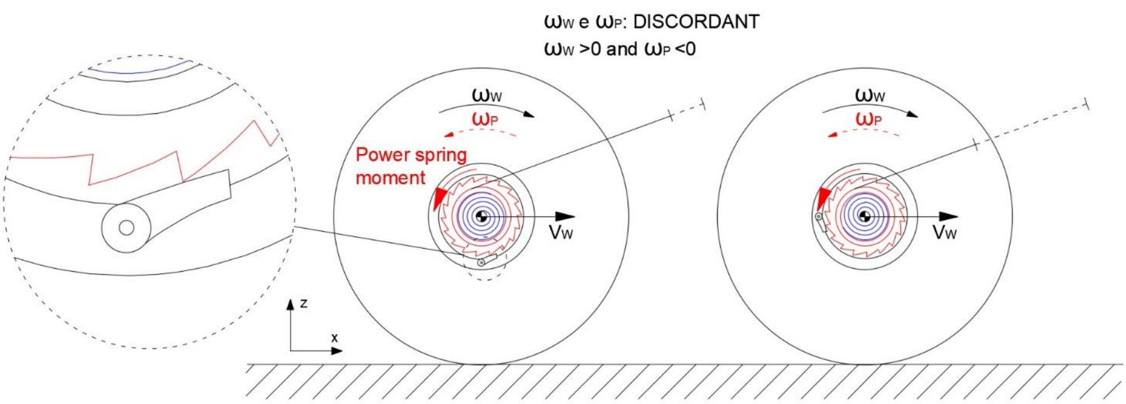
The power transmission and recovery mechanism has to manage the two phases of the rowing gesture: in the pushing-phase it transmits the power to the wheels and in the recovery phase it re-assets to its initial conditions in order to allow a new pushing phase. In figure 8 is shown the mechanism.



Pushing phase: In the pushing phase the user, by pulling the handles, by cable it allows the rotation of a pulley that is integral with a free wheel connects on the hub. With this configuration the power is transmitted to the wheels, as shown in figure 9. During the pulling phase also, a power spring is loaded which connects the pulley to the wheelchair chassis.

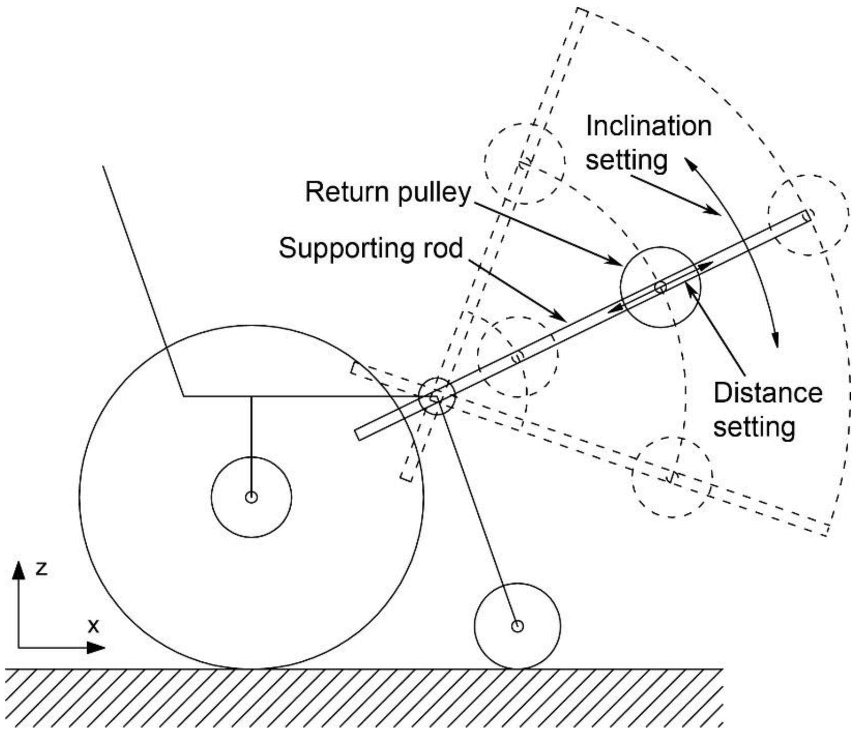


Recovery phase: In the recovery phase the user stops pulling the handles. At this point the force applied to the previously loaded power spring on the pulley triggers its rotation in the opposite direction while the wheel turns in the normal direction. This two-motion decoupling is possible thanks to the free-wheel, as shown in figure 10. The motion in the opposite direction of the pulley allows the cable to rewire on itself allowing a new pushing phase.



Return pulleys' support rod

For this first prototype the system of rod which support the return pulleys' has been designed in order to provide the maximum adjustment flexibility possible for the movement. The movement performed by the user is influenced by the return pulleys' distance, their position level and by the user himself/herself. Two hinges have been installed on the wheelchair chassis to support the two rods where return pulleys are connected. The rod can be regulated in order to adjust both the position level and their distance in relation to the user as shown in figure 11. That's how the maximum adjustment flexibility is allowed on the bases of each user's characteristics.

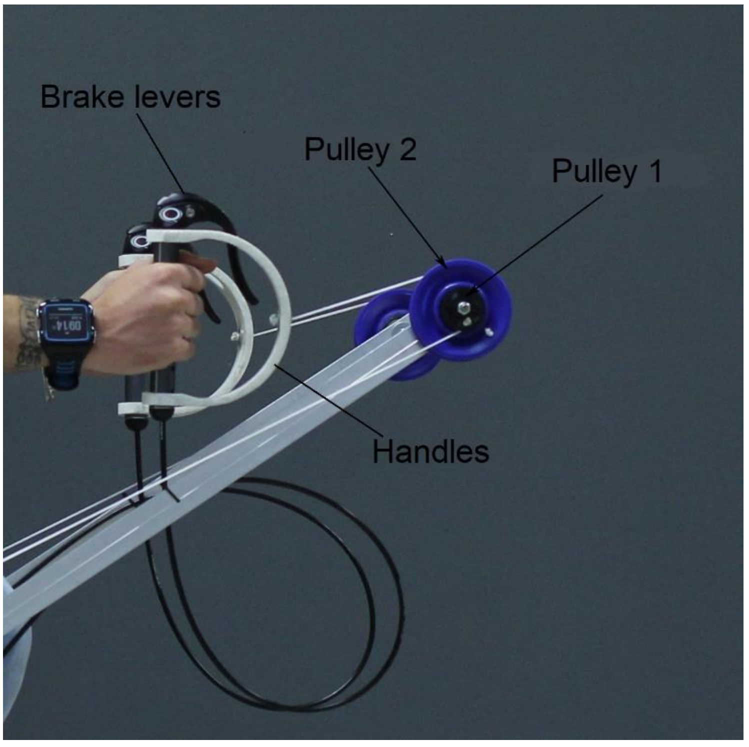


Return pulleys

On this first prototype the transmission ratio shift has not been implemented. In order to design a prototype to use for an optimal test phase it was however essential to vary the transmission ratio. In order to do so a shaft was installed on the rod to install a twin of return pulleys of different diameter to provide a further transmission ratio. This required the use of two different cord: one to link the handle to the return pulley with the widest diameter and another one to link the return pulley with the smallest diameter to the pulley as shown on Figure 12.

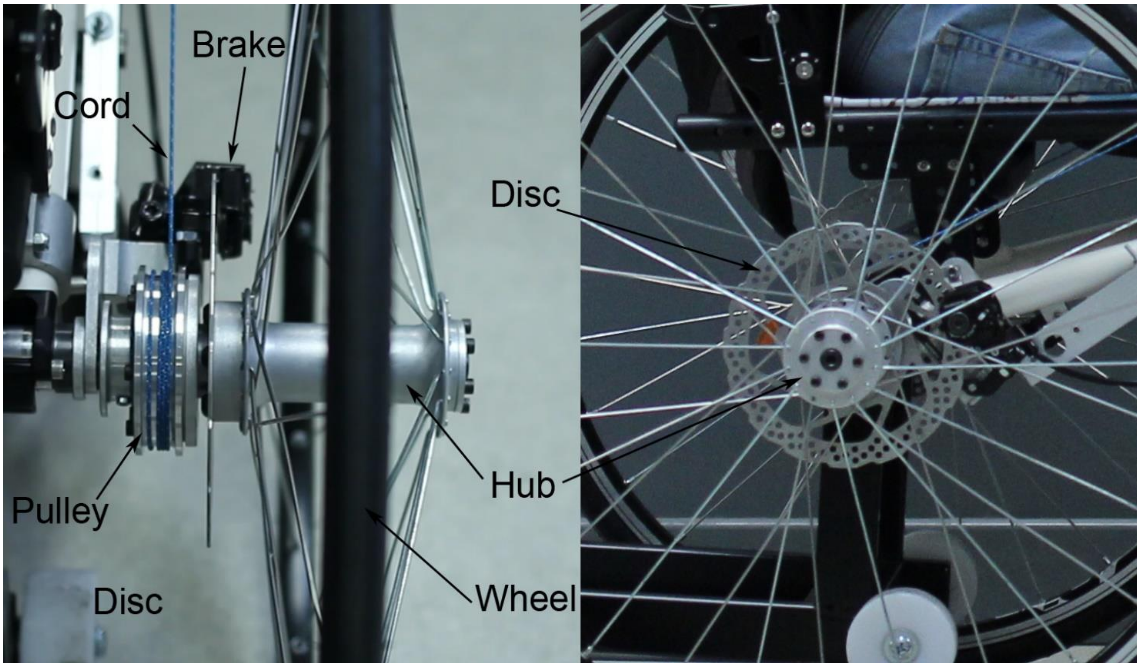
Handles with brake levers

The handles are designed in order to allow the connection between the handle and cable and to include a bicycle brake lever as shown on Figure 12.



Brake system

The brake lever allows to brake on a disc that is connected to the hub. In figure 13 is shown the disc brake with the hub. This braking system has been redesigned in order to improve efficiency and safety. In figure 13 is shown a photo concerns mechanism, wheel and brake system.



Conclusion

As the prototype was ready it was tested several times in order to test the kinematic and biomechanical functionality. The functionality of the mechanism employed to manage the pushing phase and the recovery phase has been confirmed by positioning the wheelchair on a support in order to lift the driving wheels. During the testing it was also possible to observe the gesture from a biomechanical point of view, and apply some positioning corrections in order to allow a more ergonomic movement for the users who tested the prototype. Afterwards both the indoor and the outdoor dynamic test has taken place. In order to analyse this kind of test a measurement system is being developed in order to measure the kinematic and dynamic scale and analyse the efficiency compared to other wheelchairs.

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Table 1. Variables and parameters

Figure 1. Handwheelchair.q

Figure 2. Geometrical characteristics

Figure 3. Wheel and pulley angular position

Figure 4. Wheel and pulley angular speed

Figure 5. Wheel and pulley speed

Figure 6. τ influence, lh = 0.4 m

Figure 7. lh influence, $\tau = 4$

Figure 8. Mechanism

Figure 9. Pushing phase

Figure 10. Recovery phase

Figure 11. Supporting rod

Figure 12. Handles with brake levers

Figure 13. Photo mechanism