# Instrumentation of a handbike for biomechanical measurements

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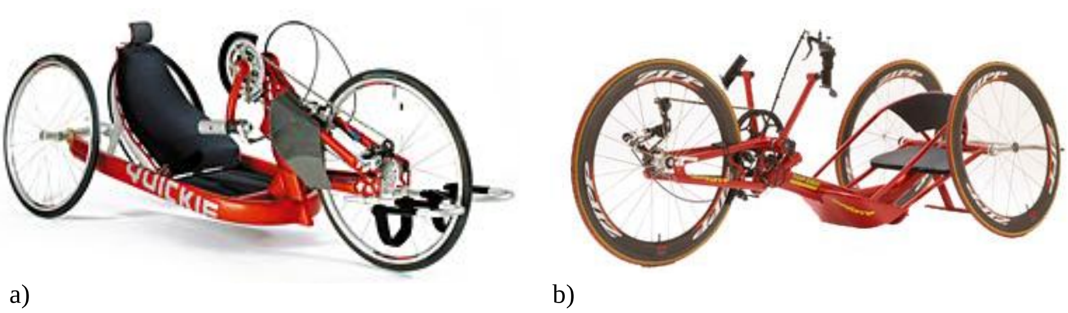
SUMMARY. The work describes a new instrumented cycloergometer simulating the use of a handbike. It allows the collection of several biomechanical and physiological data during exertion at a predefined mechanical work while simulating real road conditions. The cycloergometer is intended for various applications such as biomechanical and physiological studies, periodical clinical evaluations and training sessions.

## 1 INTRODUCTION

A handbike (Figure 1 a, b) is a device for the locomotion of disabled people with impaired use of the legs; it has a stiff chassis and three wheels. Steering and propulsion are provided by the front wheel which is actuated by the rotation of the handles controlled by the subjects. Handles and propelling wheel are connected by a standard bicycling chain drive, including free hub and sprocket wheels. Handcycling is a paralympic discipline.

On the handbike the athletes can stay seated or supine, (Figure 1, a) or knelt (Figure 1, b) depending on their disability condition.




a) b)

Figure 1 examples of handbike

Typically, seated handbikes are used by people with an upper spinal cord injury, while “kneeling” handbike are suitable for amputees or people with lower spine damage.

Subjects with spinal cord injury (SCI) present impairments in muscle function as well as in cardio-respiratory control. The degree of the resulting disability is mainly related to the level of the lesion. During exercise SCI subjects need specific restrains to stabilize the body. Moreover, a careful monitoring of the cardio-respiratory function is crucial to avoid the risks of derangement of the medullary control of the heart and pulmonary performance. On these bases, it is clear that the reduction of the exercise-related risks is linked to a better understanding of handbiking biomechanics and physiology in order to have the best possible matching between subject’s fitness and bike characteristics.

Figure 2 kneeled handbike competition

These considerations prompted the planning of researches aimed to assess the functional performance during handcycling activity, paying special attention to the following topics:

- determination of the energetic cost and estimation of the oxygen consumption;
- biomechanical and neuromuscular study of handcycling activity;
- assessment of the best postural configuration on the handbike;
- definition of test protocols and training planning;
- prevention of sport activity overload traumas.

To achieve these targets, a particular instrumentation system is required, but while many similar devices are available for normal bikes (the “ergometers”), nothing exists strictly dedicated to handbikes.

For this reason, the design of a system that allows to impose and regulate the energetic cost of handcycling and the study of biomechanical, physiological and neuromuscular parameters during this activity has been requested. The project includes the choice of a simple, reliable and easily controllable braking device to simulate several torque-velocity profiles and also a wireless system to measure the mechanical parameters of the handles, composed by as few components as possible to reduce weight.

## 2 PROJECT DESCRIPTION

### 2.1 *The structure of cycloergometers*

As shown in Figure 3 and Figure 15, the frame of a handbike is placed on a static structure, all the wheels have been removed but the anterior shaft, with the sprocket wheels, is left in place. The braking action is performed by a brushless motor. Each handle has been equipped with strain-gages to measure the propulsion force, while the crank shaft mounts an encoder for the measurement of the angular position. Force measurements are sent via radio frequency to the host PC.

Other solutions to generate the braking action, for example an inclinable tread-mill ([1], [2], [3], Figure 4), have been rejected mainly to avoid safety problems and secondly because they do not ensure a stiff connection between the moving and the braking action as a chain can do.

Alternative solutions are based on braked rollers on which the propelling wheel is placed. The braking torque is transmitted by the friction between wheel and rollers ([4], [5]), but, since these devices have been built up for bike training, they are not easily connectable to other measurement systems and they could cause stability problems.

### 2.2 *Braking action*

In a cycloergometer the resistance depends on two factors: the braking action and the inertia action. The braking torque simulates the road slope and the friction. In this ergometer the braking torque is generated by a brushless motor connected by a chain to one of the free sprocket wheels of the front hub.

The choice of the motor size is based on the upper body exercises power output value found in literature [6].

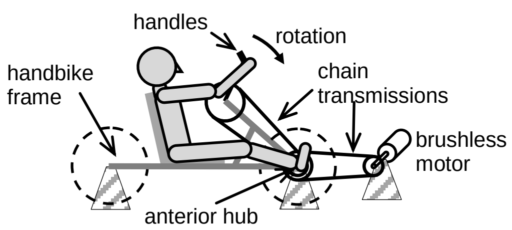



Figure 3 description of the ergometer layout

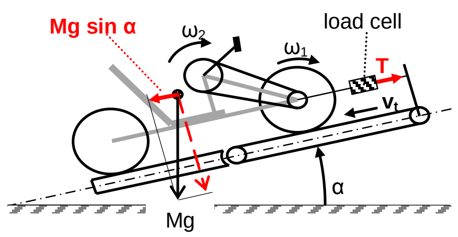
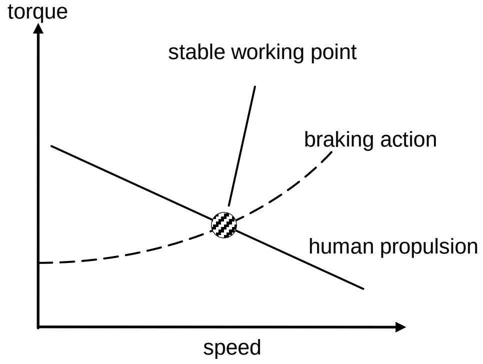



Figure 4 alternative ergometer layout

The employment of a torque-controlled brushless motor instead of a normal brake to generate the braking action is based on different reasons. At first the motor torque and speed can be easily measured and collected by a computer by means of the servo drive (the electronics used to control the motor). Moreover, the employment of a brushless motor permits the generation of various torque-speed profiles that can be easily programmed to simulate various working conditions and can be adapted to the characteristics of the examined subjects.

The programmability of the torque also makes the simulation of specific road profiles possible.



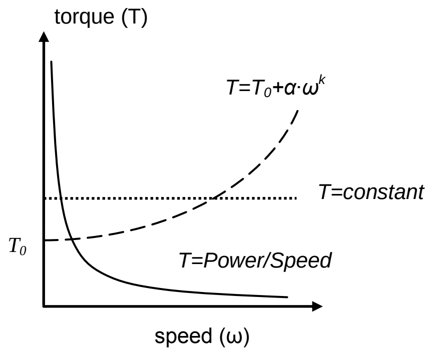




Figure 5 example of stable working point

Figure 6 examples of various braking profiles

As an example (Figure 5) it is possible to generate a breaking torque which increases with speed obtaining a situation which facilitates the maintenance of a stable velocity because the torque that can be generated by humans decreases with speed. The velocity is stable if the slope of the load is greater than that of the load. Figure 6 presents others possible load-speed profiles. One of them is the "constant power profile" in which the torque is inversely proportional to the speed. This profile cannot be used at very-low speed because it would require a torque too high that cannot be generated by the subject and by the motor. But it is quite convenient for high speed in order to ask the subject a well defined load power.

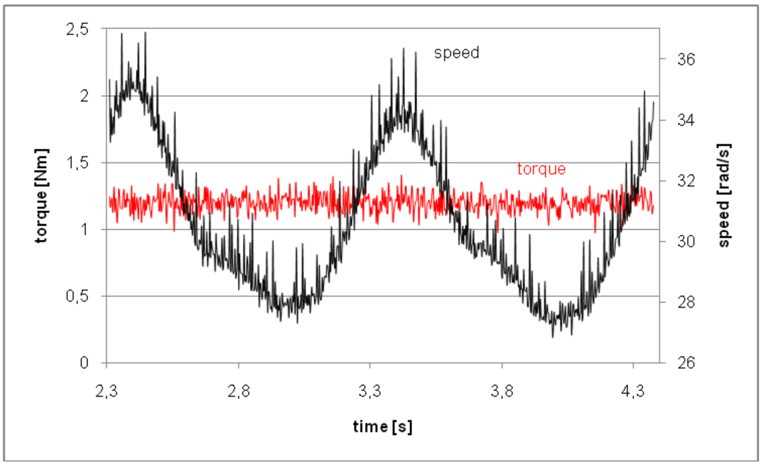



Figure 7 speed and torque signals of the ergometer, obtained from motor drive with a constant load torque and cranking rate of about 60 rpm

An example of constant braking torque is shown in Figure 7, where the red series shows torque values, while the black one shows the cranking speed which cyclically varies synchronously with the handle turn. In fact the subject cannot produce a constant torque but it varies with the posture and the handle position. In these conditions, the output power follows the speed profile, as shown in Figure 8. In this situation, the maintenance of a constant speed (and so constant power), if requested, is the subject's duty. This is not a simple task, especially when high intensity exercise protocol is performed.

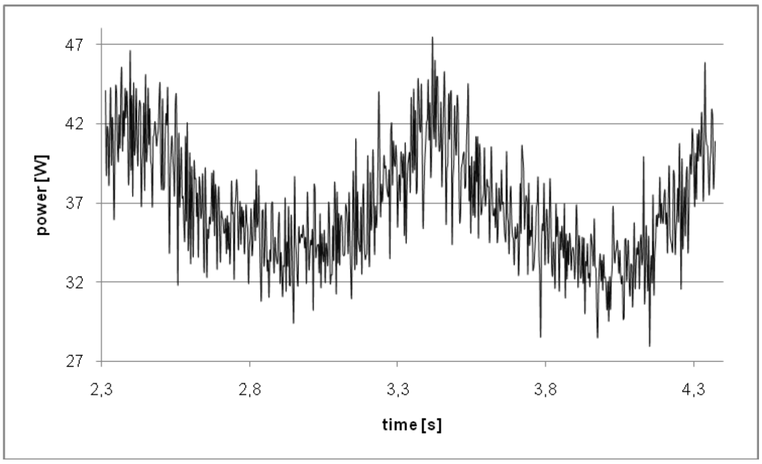
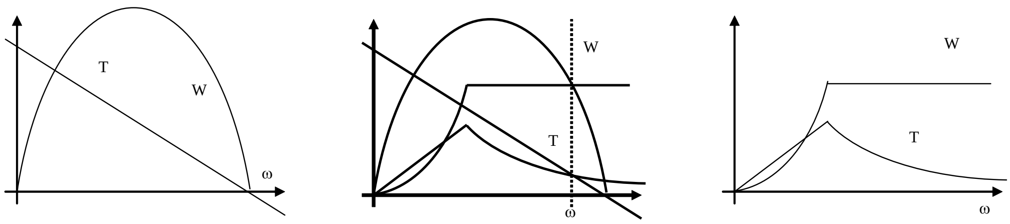



Figure 8 output power profile, calculated from speed and torque profiles of Figure 7




typical human torque and power curve versus speed

coupling of human propulsion with load and stable working point

programmed load for constant power with soft starting profile

Figure 9 Typical torque T and power W profiles versus speed

Sometimes a method to facilitate the production of a constant output power is requested. Figure 9, Figure 10 and Figure 11 display the theoretical load profile and actual data collected on the cycloergometer programmed with a constant power load. Since at low speed it is impossible to generate the corresponding torque, the load profile has been divided in two zones: for low velocity the torque is proportional to speed, then inversely proportional to speed. The first zone is intended to facilitate the reaching of the proper working zone, while the second zone is intended for the actual use.

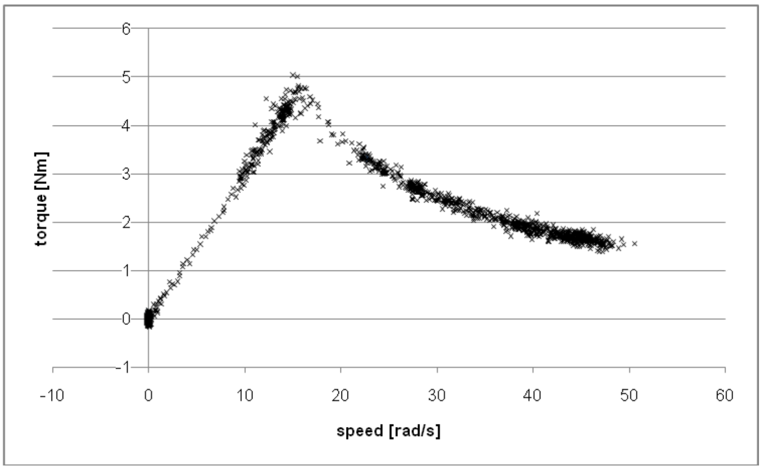



Figure 10 torque-speed relation to obtain constant output power (experimental data)

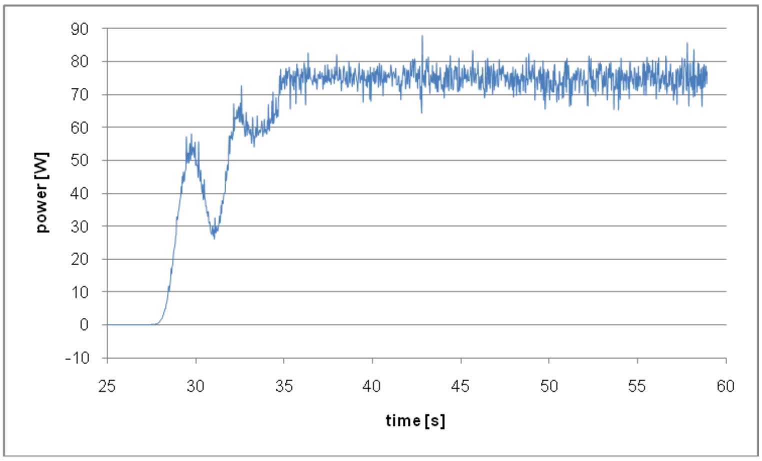



Figure 11 example of output power vs time graph with constant power range

2.3 *Inertia action*

On road condition the inertia action depends on the total mass of athlete and handbike and it is proportional to acceleration. This action can be in the same as well as in the opposite direction of the speed.

Generally inertia helps maintain the cranking rhythm even though its effect on energy expenditure is negligible in steady conditions [7].

Brakes can generate only negative torque, while motors can generate positive and negative torque, so the adoption of a motor instead of a brake makes the simulation of the inertia action of a flywheel, which is normally applied on traditional ergometers, possible.

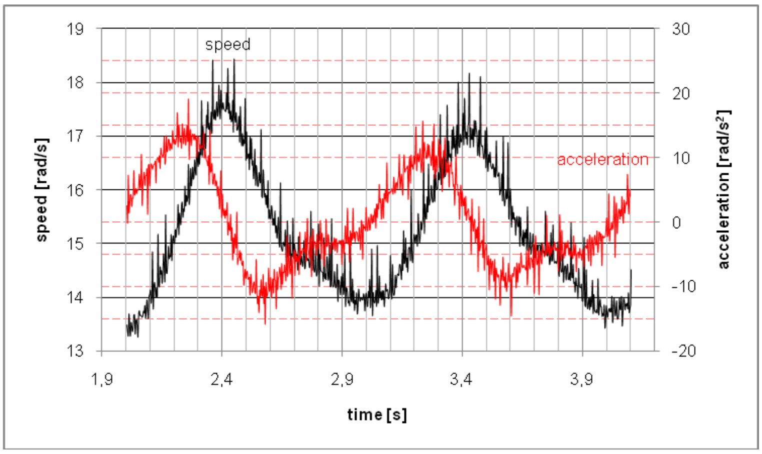



Figure 12 example of measured speed and computed acceleration

Moreover, simulating a part of the inertia action by the motor permits a simplification of the whole structure allowing the application of a smaller flywheel, secondarily, since the value of the inertia action is calculated run-time, it is possible to adapt it to the characteristics of the examined subject.

The acceleration is esteemed by numerical algorithms starting from the speed signal. Since noise is present a suitable numerical filter is currently being designed to have a good acceleration signal with a negligible time delay.

### 2.4 *Safety protection*

The usage of a motor could be dangerous in case of algorithmic errors or electronics faults, so to avoid that in abnormal conditions the motor produces dangerous high speed of the handles, mechanical protections are provided by two freewheels. The first protects the handbiker from motor overspeed in the correct direction of handle rotation, the second freewheel protects against rotations in the wrong direction.

### 2.5 *Force measurements*

For biomechanical evaluations of the kinematic chain that involves trunk, shoulders and arm there is the need to know the forces that each subject exerts on the handles.

For these reasons a bi-axial load cell is mounted on each crank as shown in the scheme of Figure 13, to measure the radial (**$F_R$**) and the tangential (**$F_T$**) component of the applied force **F**.

An encoder then measures the angular position **α** of the crankshaft employed to relate the measured force **F** to the crank position φ:

$$\begin{cases} |\mathrm{F}| = \sqrt{\mathrm{F}_R{}^2 + \mathrm{F}_T{}^2} \\ \varphi = \alpha - \left( \pi/2 - \mathrm{atan2}(\mathrm{F}_R, \mathrm{F}_T) \right) \end{cases}$$

Forces in the third direction, i.e. perpendicular to the plane defined by **$F_R$** and **$F_T$**, are not considered in this study because they are dedicated only to steering and controlling the vehicle's direction and so they have only limited intensity and do not influence the energy expenditure. Data from the handles are wireless transmitted, in order to avoid the application of cables that obstruct the subject's movements or may damage the instrumentation.

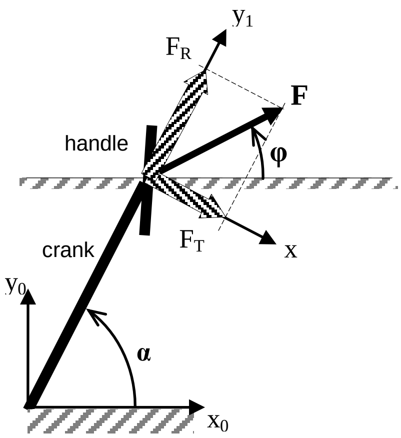



Figure 13 schematic representation of the measured forces on the handles

2.6 *Control system and data acquisition*

According to the medical topics concerning the practice of sport activities in disabled people, especially those who suffer from spinal injuries, there is the need of a high level of attention and control.

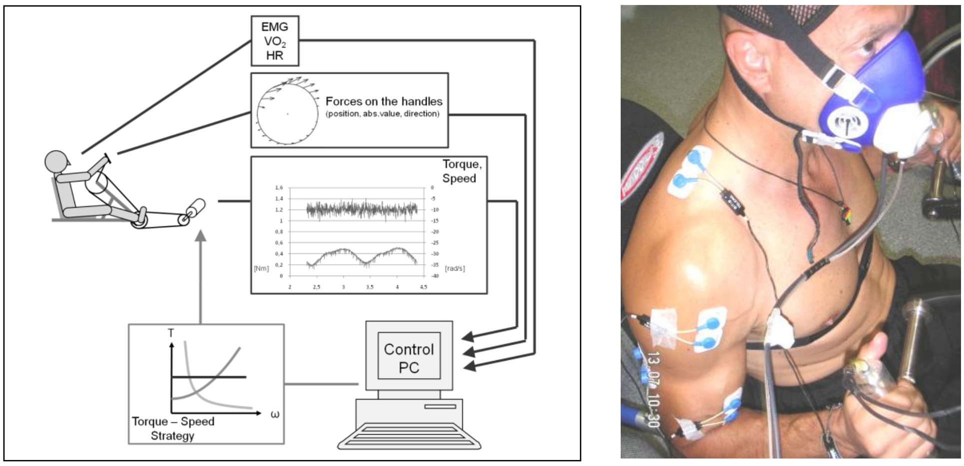



Figure 14 control system schematic layout and an example of measuring equipment

At the same time, all the data that have been collected during the tests have to be synchronized and easily analyzable. For these reasons, a control system monitors and records all the information coming from the examined subject: physiological parameters like muscle activation, oxygen uptake or heart rate, besides the motor parameters (speed, torque) and the measured forces.

The control system provides, as well as the synchronized data acquisition, the working load real time regulation. In order to increase safety, it is possible to regulate the braking torque in relation with the heart rate: unexpected and sudden variations could be the first sign of more serious problems, imposing the test interruption.

## 3 CONCLUSIONS

This innovative and fully-programmable ergometer allows synchronized measurements of biomechanical parameters in coordination with other physiological data, in order to study in depth the effect of sport activities in disabled people. Furthermore, it can be used for clinical evaluation ensuring total safety. Looking at the sports field, this ergometer can be used for training planning and evaluation, while biomechanical research can suggest handbike frame improvements, to enhance performances.

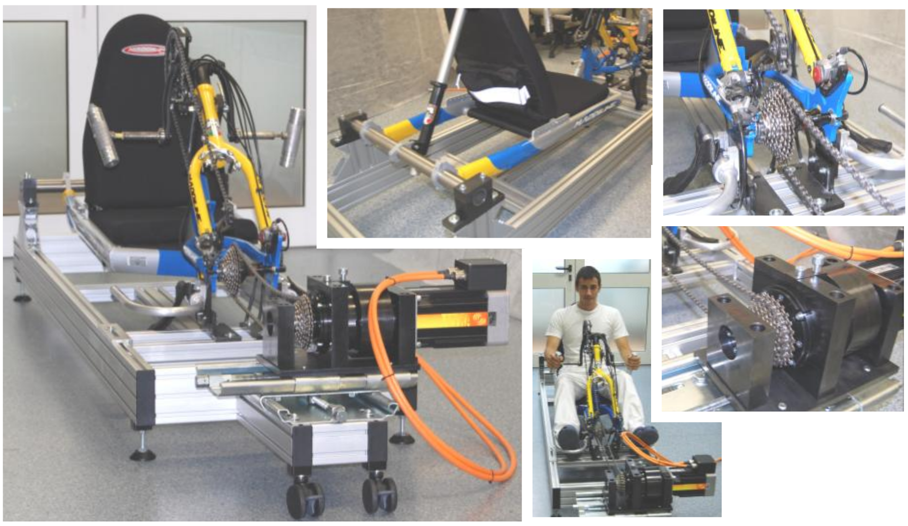


Figure 15 details of the instrumented ergometer for handbikes

The lack of literature about handcycling steered the project to reach the highest possible flexibility, so it can be used for different models of handbike and different experimentation protocols. For this reason, and also for time and budget bounds, the electronic and mechanical components used to build up the system come from industrial applications. With a few modifications it can be applied also to normal cycles, while, future applications are addressed to wheelchair.

The programmability of the torque also makes the simulation of specific road profiles possible.

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