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Stereophotogrammetric Analysis of Pushing Kinematics of Wheelchair Rugby Players on an Inertial Ergometer †

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Abstract: The aim of the work was the kinematic analysis of pushing technique of four wheelchair rugby players using a stereophotogrammetric motion capture system. The four players presented an increasing level of ability expressed by their wheelchair rugby classification point. An original contribution of the work is the fact that exercises were recorded on an inertial drum ergometer with players using their own game wheelchair. The ergometer inertia was tuned to reproduce the linear inertia of each player: subjects performed sprint tests without additional resistance and Wingate tests. The Initial Contact and Hand Release values at the wheel were recorded for each test in the early stages and at the end. The shoulder flexion/extension angle and the elbow flexion angle were plotted against each other to highlight a tendency to a synchronous joint kinematics with increasing classification points.

Keywords: wheelchair rugby; motion capture; inertial ergometer; kinematic coordination

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1. Introduction

Biomechanics of the wheelchair propulsion has been investigated both for daily use wheelchair users and in wheelchair sports. Many were the aspects investigated with a biomechanical engineering approach: ergonomics of the equipment (not limited to the wheelchair itself: but also cushions, garments, etc.), shoulder injuries prevention, sport performance enhancement, validation of the classification systems among athletes, among others.

Injuries prevention received a great attention in sport clinical medicine due to its impact not only on sport performance but also in athletes' daily life. In wide terms (and not specifically to sports), manual wheelchair propulsion involves joints and muscles that in able-bodied people are not deputed to carry out such movements as frequently as the wheelchair propulsion requires. It has been assessed that shoulder complex is particularly sensitive to the efforts involved in the wheelchair propulsion. A percentage that spreads from 30% to 73% of manual wheelchair users suffer pain or injuries at level of the shoulder complex [1]. In wheelchair sports this condition is accentuated, due to the higher effort that the sports actions require in the propulsion; accelerations from standstill, sudden hard braking or turns, etc. This, obviously, has a great impact on sport performance. To this purpose, many studies regarding biomechanics of shoulder complex during wheelchair propulsion and its correlation with tears or pain at tendons or muscles level were conducted, both within sportive or non-sportive users [2,3].

In sports like wheelchair basket and wheelchair rugby, athletes are classified depending on the level of disability, and some game rules as well as the role of players depend on this classification. The International Wheelchair Rugby Federation (IWRF) classification process relies on characteristics of muscles of the upper part of the body and on athlete's ability in doing some tasks with the ball. Some studies investigated whether the classification system discriminates among athletes or not [4]. In other articles, the classification point has been used as a variable to study the differences in propulsion techniques between athletes, isolating some biomechanical quantities of interest [5].

In general, researches focused on *kinematics* (joint angles, velocities and accelerations) of wheelchair propulsion, on *kinetics (*forces and moments at the wheels or joints) or on *electromyographic* analysis of muscle activation and coordination. Aim of the present work was the kinematic analysis of pushing technique of four wheelchair rugby players using a stereophotogrammetric motion capture system. The four players were studied on an inertial drum ergometer with players using their own game wheelchair.

2. Materials

Four athletes of the Italian National Wheelchair Rugby team volunteered to participate at this pilot study. They satisfied the inclusion criteria of having performed metabolic, sprint and field performance tests without history of pain and trauma at the level of the upper limbs in the last three months. Moreover, they presented a certified good cardiovascular condition. The general characteristics of the athletes are shown in Table 1.

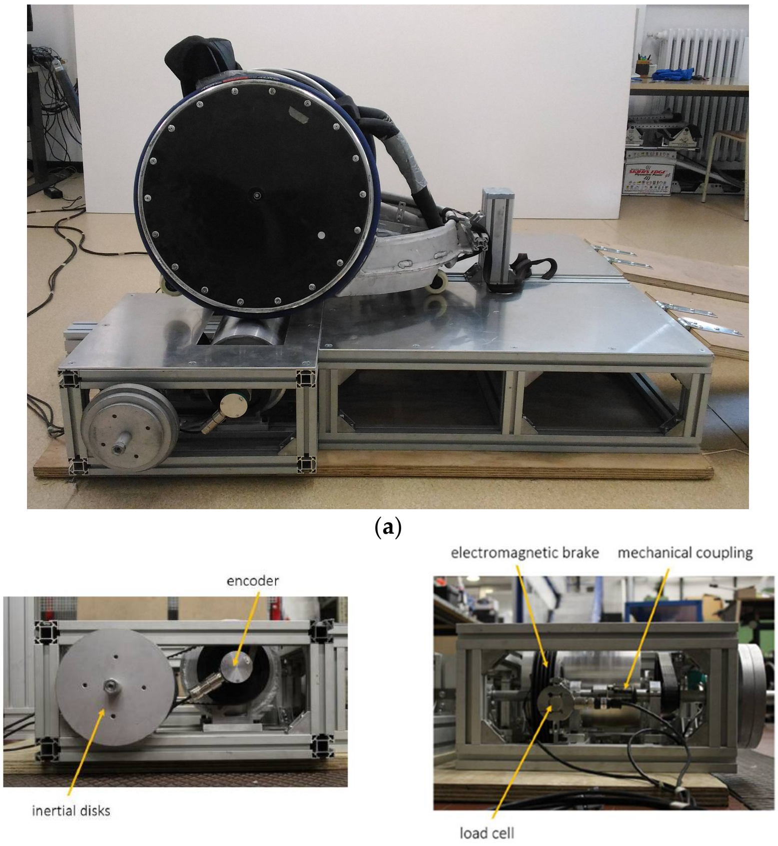
Table 1. Characteristics of the athletes participating at this work. *IWRF point*: classification point established by the International Wheelchair Rugby Federation. *SCI*: spinal cord injury level.

ID	*IWRF* Point	Mass (kg)	Age	*SCI*
SJ1	0.5	87.0	28	C5
SJ2	1.5	70.4	42	C6–C7
SJ3	2.5	68.0	44	C7–T1
SJ4	3.5	95.4	37	C5–T1

All tests took place on an inertial drum ergometer for wheelchairs developed at the Department of Industrial Engineering of the University of Padua (Figure 1). The ergometer is composed of four modules that can be easy disassembled for transportation to the team meetings. Two modules at the front act as support and a restraint for the anterior part of the wheelchair; two modules on the back have two drums supporting the wheels. An encoder is connected at each drum shaft allowing to measure the rotation speed of the drum during the propulsion. A second shaft rotates at three times the speed of the drum: this shaft can support different disks that can be chosen and combined to simulate the equivalent inertia of the athlete-wheelchair system. An electromagnetic brake, mounted on a third shaft, inserted when needed by a clutch, can be connected and activated to simulate a slope, forcing the athlete to develop more power. A load cell is connected to the brake shaft to measure the braking torque when the brake is inserted. If needed, the two shafts of the drums can be coupled, to force the drums to rotate synchronously.

This allows the players to use their sport wheelchair, therefore respecting the posture and the setup they keep during the game or training. The ergometer can be adapted to wheelchairs of various sizes, since the modules with the drum are free to be adjusted as needed; velocity, acceleration, power developed can be measured either independently or in pair at the left or right side at 100 Hz.

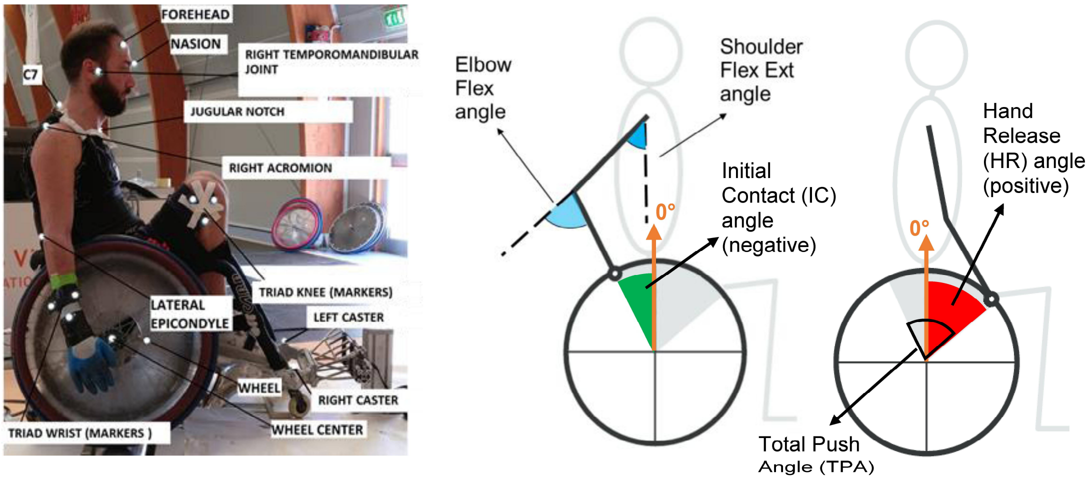
An optoelectronic BTS Bioengineering SMART motion capture system was used: six infrared cameras sampling at 60 Hz were mounted on orientable stands. Passive infrared-reflective markers were applied to the body of the subject as well as to the wheelchair (Figure 2a).



(**a**)

(**b**) (**c**)

Figure 1. The inertial drum ergometer used for the tests: (**a**) overall configuration with the wheelchair on; (**b**) a detail of the encoder and the inertial disks; (**c**) a detail of the brake, load cell and mechanical coupling assembly.



(**a**) (**b**) (**c**)

Figure 2. (**a**) Markers position on an athlete; (**b**,**c**) schematics of computed angles: flexion/extension angle for the shoulder, flexion angle for the elbow, the initial contact/hand release angles and the total push angle.

3. Methods

The subjects signed an informed consensus form and volunteered to perform the tests on the drum ergometer with their game wheelchair. A set of 13 reflective markers was applied to the right side of the body, following the protocol described in Figure 2a. In addition, four markers were applied on the wheelchair: two of these to the wheel (one at the center and the other at about 10 cm of distance) to evaluate its rotating speed by the motion capture system, and the other two on the casters attachments. The ergometer rotational inertia was set to be equivalent to each subject's plus wheelchair total mass by means of the proper number and type of disks.

Subjects performed two types of tests: (i) a sprint tests simulating a maximal sprint of 20 m length; (ii) a 30 s all out Wingate test with a power resistance which allowed the execution of the test as reported elsewhere [6].

The pushing cycles were defined from an initial contact to the following contact after matching the tangent speed of the wrist with the tangent speed of the wheel, within a narrow threshold. This approach differs necessarily from the one adopted in literature by researchers that used the SmartWheel [7–9], an instrument that provides the angular position and velocity of the wheel and the 3-dimensional forces and moments applied to the handrim. This procedure is similar to those where video images [4] or peaks in the acceleration [5] are employed to capture the instant in which hands touches the wheel. SmartWheel was not available in the present study: moreover, it would not be suitable to reproduce the usual pushing technique of the players that act directly on the tires of the rugby wheelchair wheels.

Angles of Initial Contact (IC), Hand Release (HR) and Total Push Angle (TPA) were evaluated for each test: attention was posed to the first 5 cycles of the sprint test (starting from zero speed) as well as on the final 5 cycles of the sprint when the speed was maximal or steady. This distinction was also applied to the early portion of Wingate tests (when the athletes initially received the braking action) and to the last cycles of the Wingate test (when the athletes was giving out all his energy to keep the speed against the brake resistance).

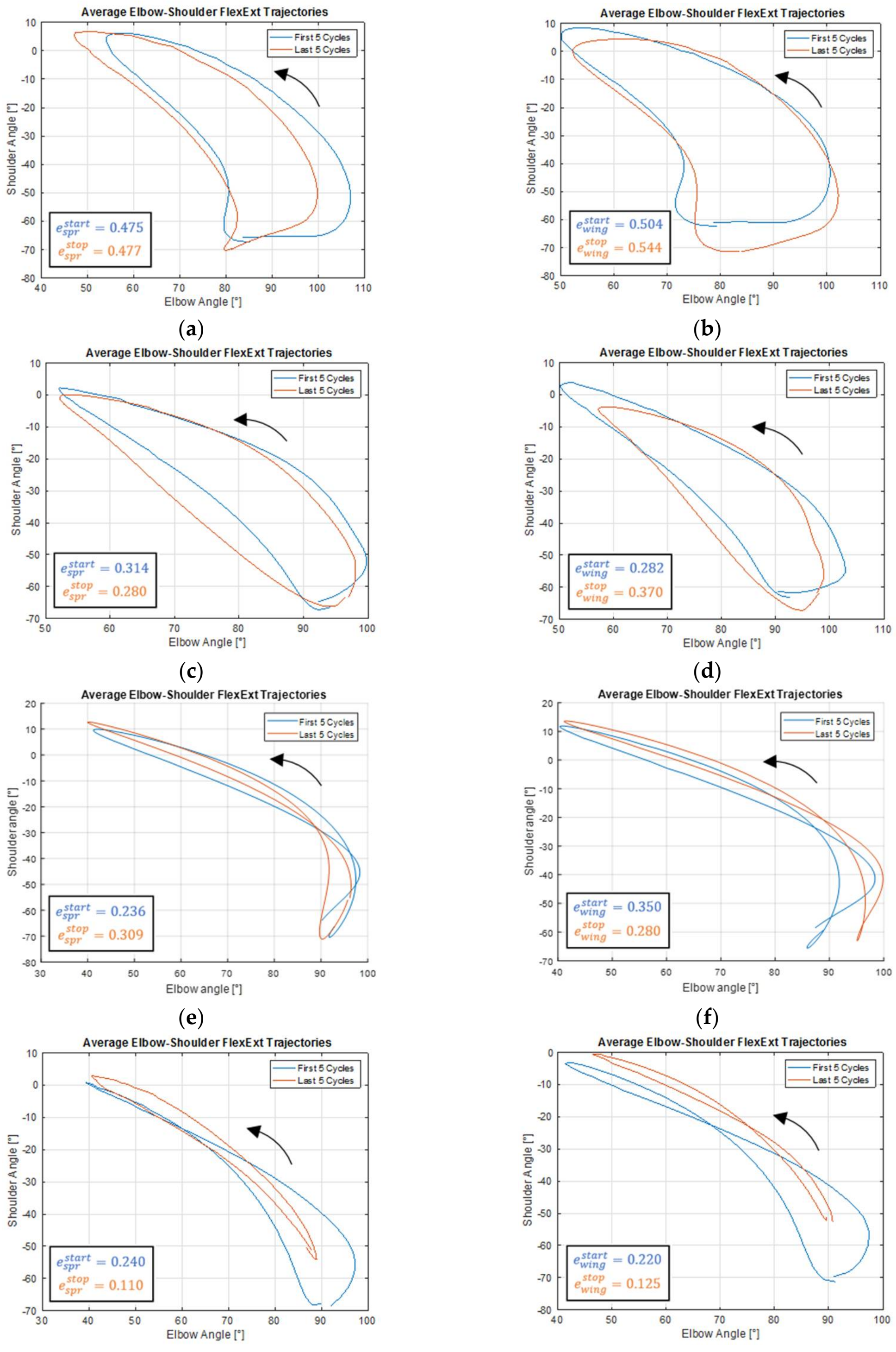
4. Results

Results of tests in terms of IC, HR and the percentage difference of TPA from start to the end of the tests are listed in Table 2. The arm joints coordination plots (Shoulder Flexion/Extension angle vs. Elbow Flexion Angle) are presented in Figure 3. These plots can be representative of the coordination among the shoulder and elbow joints: on the left side during the sprint tests, on the right side during the Wingate tests. In each plot, the early 5 cycles (blue) and the last 5 cycles (red) are reported for the four subjects with increasing IWRF classification.

Table 2. Results of the tests. For each athlete and for each test (sprint and Wingate) the mean values of IC and HR angles (Figure 2b,c) are reported, computed within the first five (for Start) and last five (for End) cycles. The percentage differences of total push angle within the tests are also reported.

ID	*IWRF* Point	Sprint Start IC/HR (°)	Sprint End IC/HR (°)	Δ(TPA) (%)	Wingate Start IC/HR (°)	Wingate End IC/HR (°)	Δ(TPA) (%)
SJ1	0.5	−37.4/+31.0	−35.6/+26.3	−9.5%	−41.0/+27.4	−36.3/+24.2	−11.5%
SJ2	1.5	−31.6/+29.2	−27.8/+12.3	−34.0%	−34.2/+22.2	−28.0/+15.5	−22.9%
SJ3	2.5	−30.9/+39.3	−24.4/+41.3	−6.41%	−29.9/+37.0	−27.1/+35.9	−5.83%
SJ4	3.5	−13.6/+50.4	−9.1/+54.4	−0.78%	−17.9/+63.0	−5.3/+35.2	−49.9%

Cyclic loops from top to bottom of Figure 3 show a tendency to the reduction of the aspect ratio between the two main orthogonal dimensions of the loops, or, in other words, to the decrease of the included area within the loops. The aspect ratio "*e*" was calculated for each loop as the ratio between the Minor and the Major sides of a rectangle circumscribing the loop and oriented with Major side parallel to a linear regression slope across the loop. These aspect ratio values are reported inside the plots.



(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

(**g**) (**h**)

Figure 3. Arm joints coordination plots. Shoulder Flexion/Extension angle vs. Elbow Flexion Angle. On the Left side the Sprint tests, on the Right side the Wingate tests. For each plot, the early cycles (blue) and the last cycles (orange) are reported, as well as the aspect ratio *e* values and an arrow indicating the direction of the stroke cycle. From (**a**) to (**h**) the four subjects with increasing IWRF classification points are reported. (**a**) SJ1 (0.5): Sprint; (**b**) SJ1 (0.5): Wingate; (**c**) SJ2 (1.5): Sprint; (**d**) SJ2 (1.5): Wingate; (**e**) SJ3 (2.5): Sprint; (**f**) SJ3 (2.5): Wingate; (**g**) SJ4 (3.5): Sprint; (**h**) SJ4 (3.5): Wingate.

5. Discussion

The work presents some limitations due to the small number of subjects involved in the study: only one subject for each IWRF classification point has been tested. Moreover, cycle identification was based on an optical method rather than on force measurements at the wheels.

Despite this, results show a tendency of players to have a smaller aspect ratio *e* (a more closed joint coordination loop) of the coordination plot between shoulder and elbow at increasing IWRF classification points. This expresses a more synchronous action of the two joints observed in "High-pointer" players with respect to "Low-pointer". Moreover, "Low-pointer" players tend to have an IC angle more negative, due to the tendency of using biceps muscle in the early stages of pushing, as already known from literature.

An effect of pushing speed can be seen in the reduction of the Total Push Angle TPA from the start top the end of the sprint tests. This evidence was also true when the workload increased on the athlete (comparison between Sprint and Wingate tests) and when muscular fatigue increased towards the end of the Wingate test (comparison between Start and End of Wingate tests).

These results need a further statistical validation but can give an insight to the pushing technique of players; the method can also be seen as a support to a correct IWRF classification process, as well as it can serve as a possible quantitative technical assessment for trainers when monitoring players physical coordination and fatigue resistance during a sport season.

6. Conclusions

Four players of the Italian National Wheelchair Rugby with increasing classification point were studied while pushing on an inertial drum ergometer on their own game wheelchair. The ergometer reproduced the linear inertia of each player: sprint tests and Wingate tests were observed with a stereophotogrammetric motion capture system. The Total Push Angle showed a tendency to decrease with the increase of speed and workload. The shoulder flexion/extension angle and the elbow flexion synchronicity showed an increase with higher classification points.

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