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# Validity and reliability of an alternative method for measuring power output during 6 s all out cycling

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**Running title**: *Six-second all-out cycling power output*

**Abstract**

In a laboratory setting in which both a mechanically-braked cycling-ergometer and a motion analysis (MA) system are available, flywheel angular displacement can be estimated by using MA. The purpose of this investigation was to assess the validity and reliability of a MA method for measuring maximal power output (Pmax), in comparison to a force transducer (FT) method. Eight males and 8 females undertook 3 identical sessions, separated by 4-6 days, the first being a familiarisation. Individuals performed three 6-s sprints against 50% of the maximal resistance to complete two pedal revolutions with a 3-min rest between trials. Power was determined independently using both MA and FT analyses. Validity: MA recorded significantly higher Pmax than FT ($P<0.05$). Bland and Altman plots showed that there was a systematic bias in the difference between the measures of the two systems. This difference increased as power increased. Repeatability: intraclass correlation coefficients were on average $0.90 \pm 0.05$ in males and $0.85 \pm 0.08$ in females. Measuring Pmax by MA, therefore, is as appropriate for use in exercise physiology research as Pmax measured by FT, provided that a bias between these measurements methods is allowed for.

***Keywords:*** motion analysis; force transducers; flywheel; acceleration; instrumented pedal.

**Word Count:** 1,992 words

## Introduction

Maximal muscle power (Pmax) generated during an all-out action lasting a few seconds is an important physiological measurement that can provide valid information as to the training status of individuals[1-7]. Pmax is closely related to athletic performance and many athletes aim to develop muscle power to enhance performance[3-5]. In addition, there are general fitness benefits and rehabilitation advantages from developing maximal muscle power as it has been shown that improvements in maximal muscle power are accompanied with an increase in functional ability in elderly individuals [6,7].

Repeated bouts of short duration, high-intensity exercise are common in certain team sports, and muscle power in these exercise regimens has been correspondingly investigated[8,9]. In addition to the amount of power produced, the rate at which the peak power occurs also has performance implications for athletes[3], and for recreationally active[1] and older individuals[10,11].

Pmax can be estimated from the measure of flywheel angular displacement of a frictionally braked cycle ergometer, typically measured by means of incremental encoders[12,13]. However, biomechanics laboratories often have motion analysis systems able to measure the kinematics of pedalling[14]. We propose that motion analysis can also be used to measure flywheel angular displacement and hence estimate Pmax. The purpose of this study is therefore to measure the reliability and validity of using motion analysis to determine Pmax compared to the direct measure of power using pedal-mounted strain gauges.

## Methods

### Participants

Eight men (age 28.5±5.2 y; stature 1.78±0.04 m; body mass 77.0±11.5 kg; mean±SD) and eight women (age 23.1±3.4 y; stature 1.65±0.06 m; body mass 60.4±5.0 kg; mean ± SD) volunteered for the study. Participants were required to be exercising at least three times per week, either aerobic or strength training, for at least 30 min, and free from any current muscular or joint injury and cardiovascular or metabolic disease. Volunteers were advised not to alter their current training program and they attended the laboratory at the same time of day to avoid day to day variability[15]. The study was approved by the Ethics Committee of the University of Strathclyde.

**Equipment**

***Motion Analysis.*** Three reflective markers were placed equidistant around the edge of the flywheel of a Monark ergometer (Figure 1A, Monark 812E, Stockholm, Sweden). A reference marker was placed midway between these markers to allow consistency of marker labelling and identification. Two markers were placed on the pedal and the centre of the crank. All markers were 1cm in diameter and placed on the left hand side of the ergometer.

Kinematic data were collected using a five camera motion analysis system (Vicon 612, California, USA) operating at 250 Hz. All subsequent calculations were made using Matlab 6.5.1 (Mathworks, MA, USA).

**Insert Figure 1 here.**

***Force transducers.*** An instrumented pedal (Figure 1B) was used to measure two force components applied to the pedal[16-18]. Using a reference system related to the pedal (Xp,Yp,Zp), $F_z$, defined perpendicular to the pedal load plane and directed downward (Zp axis), and $F_x$, defined parallel to the pedal load plane and directed forward (Xp axis) were determined. .

The clipless fastening system (Shimano® Pedalling Dynamics) (1) was connected through two spacer screws to a specially designed load cell (2), which was fixed to a “U” shape stirrup (3) with two circular holes on its extremities. In these holes two ball bearings were fitted to allow the relative rotation of the stirrup and a transmission-shaft (5), fixed to the crank of the bicycle. The load cell transmitted force to the crank through the stirrup and the spindle, thus enabling the participant to cycle as though using a commercial pedal. Angle θp was measured using a smart encoder (4) positioned between the stirrup, using another stirrup of smaller dimensions, and the spindle, which had a cylindrical hole at the corresponding extremity. The load cell was based on a strain gauge system arranged in two full Wheatstone bridges. Pedal data were acquired at 1000 Hz and synchronised to the kinematic data using an Analog to Digital Converter card (ADC) in the Vicon workstation.

***Calibration.*** The instrumented pedal was calibrated by applying known loads from zero to 200 N to it. For the $F_z$ force, the pedal was loaded positioning it on a flat surface and adding weights to it in the middle of the clipless fastening system[19]. For the $F_x$ force the procedure was repeated with the pedal being rotated by 90°. Output signals from both channels were measured and a calibration matrix C was estimated, taking into account crosstalk, to obtain force values ($F_z$,$F_x$) from voltage output ($V_z$,$V_x$) as:

$$\begin{pmatrix} F_z \\ F_x \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix} \cdot \begin{pmatrix} V_z \\ V_x \end{pmatrix}$$

All the procedures described above were repeated once prior to the 1st day of testing and once after the last day of testing.

**Experimental procedure**

Volunteers attended the laboratory on three occasions, the first being a familiarisation. Four to six days elapsed between sessions. Warm up consisted of 5 minutes of sub-maximal cycling (100-150 W) followed by two six second sprints against frictional loads[12] of 0.25 N/kg and 0.75 N/kg. After a 5 minute rest, participants were tested for their maximal resistance to complete two pedal revolutions (2RM), according to Macaluso *et al*[6]. Three minutes of rest occurred between each attempt.

After a further five minute resting period, participants then performed three six-second sprints against 50% of 2RM, with three minute rest between trials. The participants left leg rested on the space between the two pedals at all times.

**Data processing**

***Power calculations through motion analysis.*** The following moments were assumed to act on the flywheel: the propulsive moment due to human effort, $M_H$, the resistive moment due to belt friction, $M_{B,}$ and the resistive moment due to other friction, $M_O$. The sum of these moments are equal to the inertial load of the ergometer, i.e.

$$M_H - M_B - M_O = I_1\alpha_1 + I_2\alpha_2 \qquad \text{(equation 1)}$$

where $I_1$ is the moment of inertia of the flywheel (manufacturer supplied data), $I_2$ is the moment of inertia of the crank, pedal and chain ring and chain, and $\alpha_1$ is the angular acceleration of the flywheel and $\alpha_2$ the angular acceleration of the other components. The resistive moment due to belt friction may be described by

$$M_B = \mu L r$$

where $\mu$ is the coefficient of friction, r is the radius of the flywheel and L is the applied load.

The coefficient of belt friction and $M_O$ were calculated by placing a known resistance against the flywheel (ranging from 9.81 N to 29.4 N) and decelerating the flywheel from 120 rpm similarly to Arsac *et al*[12] and Lakomy[13].$M_H$ was calculated from equation 1 assuming $I_2\alpha_2 = 0$. Finally, power was calculated using $P = M_H \times \omega$, where $\omega$ = angular velocity of the flywheel. Both $\omega$ and $\alpha$ were determined using marker coordinate data[20].

***Power calculations through force transducers.***

To evaluate the forces on the crank the following equations were used:

$$F_t = F_z \times \sin\theta_p + F_x \times \cos\theta_p$$

$$F_n = F_z \times \cos\theta_p - F_x \times \sin\theta_p$$

$$F_{tot} = \sqrt{F_x^2 + F_z^2} = \sqrt{F_t^2 + F_n^2}$$

The torque Tc applied to the chain ring was calculated as the product between the Ft and the moment arm d, represented by the crank (d = 170 mm). The torque Tf applied to the flywheel was obtained multiplying Tc by the gear ratio of the ergometer transmission. The power applied to the chain ring, which is the same applied to the flywheel, was calculated as the product of Tc and the angular velocity of the chain ring.

***Further analysis.*** Figure 2 shows a typical power output of one participant during a 50% 2RM trial obtained from MA and FT, respectively. Average power was defined as the average of the instantaneous values over the first 6 seconds.

**Insert Figure 2 here.**

**Statistics**

Comparisons of average power between the two methods (MA and FT) for each of the three trials were carried out by ANOVA for repeated measures, followed by Student's t-tests. Absolute agreement between the two methods was assessed by determining the mean difference (bias) and 95% limits of agreement as described by Bland and Altman[21]. Reliability was assessed using Intraclass Correlation Coefficient.

## Results

Motion analysis methods recorded statistically higher average power outputs than force transducers during trials at 50% of 2RM for day 1 and day 2 in both male and female participants ($p < 0.05$, Figure 3 and 4). Bland and Altman plot showed that there was a systematic bias in the difference between the measures of the two systems in both males (Figure 3c and 4c) and females (Figure 3d and 4d), which increased with power.

**Insert Figure 3 and 4 here.**

Good reliability in average power at 50% of 2RM, as measured by the motion analysis system, was evident both between and within days, with average ICCs of 0.900±0.048 and 0.878±0.045 for males and females, respectively (Table 1).

**Insert Table 1 here**

## Discussion

Motion analysis provided a highly reliable measure of mechanical power output in short-duration explosive movements. However, it overestimated mechanical power output compared to the measure obtained by means of instrumented pedals. The difference between the measures increased with speed and therefore power.

The motion analysis measured the energy supplied per second to the flywheel, whilst the force transducers on the pedals measured the power applied to the chain ring. The power measured at the pedal was taken as more accurate, since it has fewer assumptions associated with its measurement. To make these measures equivalent, we accounted for the energy lost to the system by including a constant for system friction, $M_O$. Alternative representations for this loss of energy may be more appropriate. Another source of error could be the moment of inertia of the flywheel (1 kg·m$^2$) taken from the manufacturer's literature. If this was overestimated, then the inertia moment would have been overestimated too, resulting in the peaks and troughs being overshot, as shown in Figure 2. However, if this was the case, not only peaks and troughs would be observed, but also differences in the slopes of the ascending and descending phases of the power curves.

The estimation of power from the acceleration of a flywheel of a cycle ergometer is not a new technique and torque measured at the pedals has been previously found to be higher than that measured at the flywheel[22]. The differences with our findings can be attributed to the fact that Lakomi et al.[22] measured torque by means of a torque transducer attached to a split chain, which was affected by the inertia of the flywheel, thus underestimating torque.

Our ICC values data of around 0.9 represent good inter- and intra-day reliability and are comparable with tests of power output when pedalling on a constant load cycle ergometer (R=0.91-0.97) [23].

A major application of this research is the use of motion analysis to measure muscle power when direct measures with force transducers are not available. To enhance adoption, future methodological studies should address the issue of energy loss within the system, to better predict mechanical power measured at the pedal.

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## Figure Captions

**Figure 1 — A)** The flywheel with reflective markers (1-5) in place. Point 6 corresponds to the reflective reference marker to allow subsequent consistent labelling of the markers. **B)** The force transducer pedal and the two reference systems: (Xp, Yp, Zp) is related to the pedal, whilst (Xc, Yc, Zc) is related to the crank.

**Figure 2** — Typical power output from one participant during a 50% 2RM trial obtained from motion analysis (black circles) and force transducers (grey squares).

**Figure 3** — Average power (W) during 6 s sprint trials at 50% of 2RM at day 1. Average power from motion analysis (black bars) and force transducers (white bars) per each of the 3 trials in males (a) and females (b). Data are presented as mean ± SD (* p=<0.001). Corresponding Bland and Altman plots showing the differences in power between motion analysis and force transducers in males (c) and females (d). Bias and random error lines (95% limits of agreement) are included.

**Figure 4** — Average power (W) during a 6 s sprint trials at 50% of 2RM at day 2. Average power from motion analysis (black bars) and force transducers (white bars) per each of the 3 trials in males (a) and females (b). Data are presented as mean ± SD (* p=<0.001). Corresponding Bland and Altman plots showing the differences in power between motion analysis and force transducers in males (c) and females (d). Bias and random error lines (95% limits of agreement) are included.

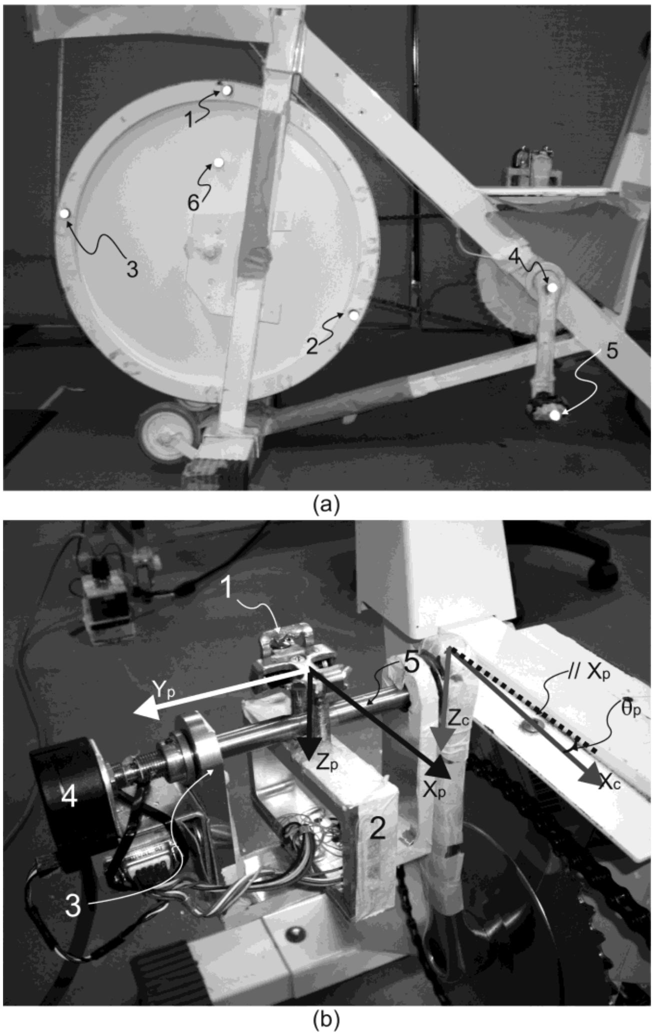


Figure 1

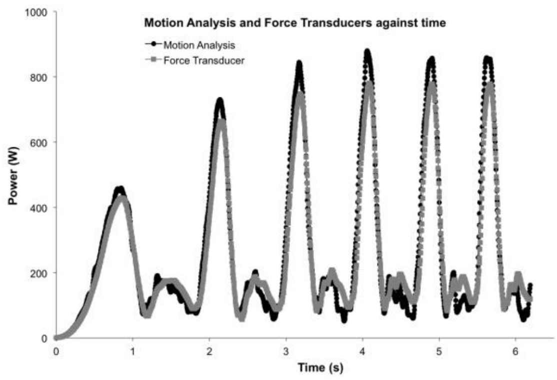
Motion Analysis and Force Transducers against time
Motion Analysis
Force Transducer
Power (W)
Time (s)
1000
800
600
400
200
0
0
1
2
3
4
5
6

Figure 2

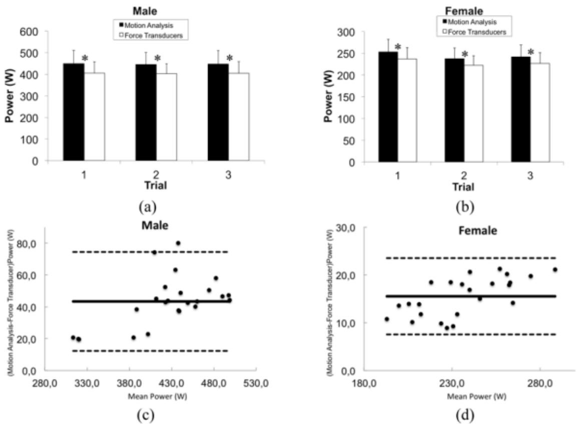
Male
Motion Analysis
Force Transducers
Power (W)
Trial
(a)
Female
Motion Analysis
Force Transducers
Power (W)
Trial
(b)
Male
(Motion Analysis-Force Transducer)Power (W)
Mean Power (W)
(c)
Female
(Motion Analysis-Force Transducer)Power (W)
Mean Power (W)
(d)

Figure 3

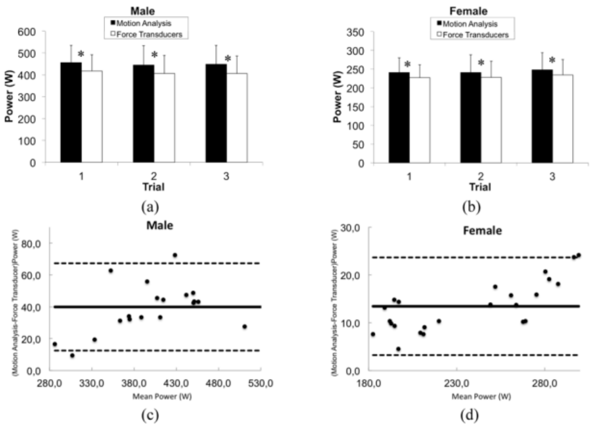
Male
Motion Analysis
Force Transducers
Power (W)
Trial
(a)
Female
Motion Analysis
Force Transducers
Power (W)
Trial
(b)
Male
Mean Power (W)
(c)
Female
Mean Power (W)
(d)

Figure 4