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ORIGINAL ARTICLE

Biomechanical analysis to determine the external power output on an immersible ergocycle

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Abstract

The external power output (P_{ext}) is unknown during chest-level immersion exercise on water immersible ergocycles (IE). This knowledge will allow the practitioner to prescribe accurately exercise on an IE to the same workload on dryland ergocycle (DE). To develop a mathematical model to calculate P_{ext} during chest-level immersion exercise on IE at different pedalling rates (rpm) taking into account the water external force exerted on the legs and pedalling mechanism. Thirty healthy participants (age: 33 ± 10 years) performed a maximal incremental exercise test on IE (chest-level immersion) and on a DE. Pedalling rate was increased by 10 rpm every minute beginning at 40 till 120 rpm. P_{ext} was calculated by applying the general fluid equation $F_d = 1/2\rho A v^2 C_d$ on all elements exposed to water external force exertions (legs and pedalling system). Regression analysis yielded the following equations to determine (1) IE P_{ext} (W) based on pedalling rate (rpm): P_{ext} (W) = 0.0004 (rpm)$^{2.993}$ (r^2 = 0.99, SEE = 7.6 W, $p < 0.0001$) and (2) when DE P_{ext} (W) is known, IE pedalling rate (rpm) = 13.91 × DE P_{ext} (W)$^{0.329}$ (r^2 = 0.99, SEE = 1.5 W, $p < 0.0001$). This study provides a mathematical model based on the general fluid equation to calculate IE P_{ext} during chest-level immersion exercise using pedalling rate (rpm), IE pedalling system physical characteristics and lower limb size. This model can be used to determine P_{ext} for any IE type for exercise training prescription.

Keywords: *Immersible ergocycle, external power output, pedalling rate*

1. Introduction

Aquatic exercise is becoming increasingly popular as it appears to be widely suitable for numerous users including athletes, sedentary healthy, elderly or obese individuals (Benelli, Ditroilo, & De Vito, 2004). A possible advantage is that the water environment provides buoyancy that may allow participants to undergo hard workouts at intensities similar to land training regimen, but without the weight-bearing-related impacts on various joint articulations (Frangolias & Rhodes, 1996). Nonetheless, one apparent limitation with ergocycle immersed exercise is the precise quantification of the external power output (P_{ext}).

In recent years, many different models of immersible ergocycles (IE) have been introduced for water exercise training (Giacomini et al., 2009). One apparent advantage of the IE is that it may favour an easier P_{ext} calculation when compared to walking or running in water because only leg movement associated to pedalling rate (rpm) can be considered. Previous authors have used mathematical models to identify hydrodynamic forces acting on human body parts or with the use of a robotic hand moving in water while immersed (Gardano & Dabnichki, 2006; Poyhonen, Keskinen, Hautala, & Malkia, 2000; Takagi, Nakashima, Ozaki, & Matsuuchi, 2013).

Other investigators have used customized IE mounted with a water resistant electronically controlled torque device to control intensity (Bréchat et al., 2012), but without taking into account the

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water external force exerted on the legs as a function of pedalling rate. Thus, despite several investigations, the P_{ext} developed during cycling in water is currently not known and remains controversial.

The resistance to a given movement (or the drag force), depends of the body surface and shape, the hydrodynamic form, the temperature dependent water density (nearly 800 times the density of air; Brubaker, Ozemek, Gonzalez, Wiley, & Collins, 2011) and, if present, the water current velocity (Poyhonen et al., 2000). The external forces during exercise on an IE are mainly caused by the mechanical components of the pedalling system (paddles, pedals and rods) (Leone, Garzon, Dionne, Bui, & Comtois, 2013) and by leg movement drag (calf, foot and thigh) that is dependent on the surface area of the lower limbs and the pedalling rate (rpm) (Garzon et al., 2011; Shapiro, Avellini, Toner, & Pandolf, 1981).

In a previous study (Leone et al., 2013), we have calculated the P_{ext} at various pedalling rates using an IE based on energetic cost ($\dot{V}O_2$) and calculations of drag force on the IE pedalling mechanism with the general fluid equation (Poyhonen et al., 2000, 2002; Shames, 1982). In this study by Leone et al. (2013), however, the subjects exercised on the IE only at calf immersion and the authors did not calculate or present the drag forces exerted on the legs by having the subjects exercised at deeper immersions (e.g., chest level). Nonetheless, in daily practice, practitioners instruct subjects to exercise on IE at hip- or chest-level immersion (both legs are completely immersed). Thus, it appears essential to have a means to calculate accurately the P_{ext} deployed by participants using different models of IE. This practical approach will allow the practitioner to prescribe the exercise intensity on an IE to the same workload obtained on a dryland ergocycle (DE). Therefore, the aim of this study, by using a detailed biomechanical analysis, was to develop a mathematical model to calculate P_{ext} on an IE during chest-level immersion exercise for different pedalling rates (rpm) that specifically took into account the drag forces exerted on the legs.

2. Methods

Thirty healthy participants (age: 33 ± 10 years; 24 male/6 female, BMI: 23.7 ± 2.5 kg/m^2) took part in this study. The mean physical characteristics and lower limb anthropometry of the participants are shown in Table I. The study was performed in a cardiac rehabilitation centre and a university sports complex pool at a water temperature of about 30°C considered thermoneutral for water exercise (Christie et al., 1990). The study was approved by both Institutional Ethics Committees. Before testing, each subject was informed of the objective of the study, the testing procedures and was asked to provide their written informed consent. Participants were excluded from this study if: (1) they were less than 18 years of age, (2) they were unable to perform a maximal cardiopulmonary exercise test and (3) they had any documented cardiovascular, pulmonary, musculo-skeletal or metabolic diseases.

The singular purpose for measuring gas exchange ($\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$ in litre per minute) during exercise with a portable gas analyser [Cosmed, K4b^2 (Rome, Italy)] was to verify that all participants achieved maximum effort on IE and DE. These data did not take part in power output outcome analysis (no statistical tests), other than a criteria indicator of maximal exercise exertion reached (see below). Thus, the exercise tests on both IE and DE lasted until the attainment of one of the two primary maximal criteria (Duncan, Howley, & Johnson, 1997): (1) a levelling off of oxygen uptake (<150 mL/min) despite increased workload (plateau of $\dot{V}O_2$) and (2) an RER > 1.1 or, one of the two secondary maximal criteria: (1) inability to maintain the required workload or (2) patient exhaustion with exercise cessation caused by general fatigue. For all participants, this was their first experience exercising on an IE. No familiarisation session on IE was provided, since previous studies have suggested that the cardiovascular responses to head-out water immersion while performing leg cycle exercise in water at a thermoneutral temperature do not vary significantly with age and experience in water immersion (Yun, Choi, & Park, 2004).

Dryland experiments were performed on a DE (Ergoline 800S; Bitz, Germany) to compare the maximal P_{ext} (MaxP_{ext}) achieved on this device with the MaxP_{ext} achieved on the IE which was tested according to the criteria defined above with respect to a maximal test. This allowed to correlate

Table I. Physical characteristics and measures of the legs of 30 participants (6 women, 24 men)

Parameters	Mean ± *SD*
Age (yrs)	33 ± 10
Body mass (kg)	72 ± 9
Height (m)	1.74 ± 0.06
BMI (kg/m^2)	23.77 ± 2.51
Circumference of thigh (m)	0.51 ± 0.04
Circumference of calf (m)[a]	0.31 + 0.02
Length of thigh (m)	0.40 ± 0.03
Length of calf (m)	0.48 ± 0.02

[a]Average of three calf points [see Figure 2B, upper circumference (C), middle circumference (B) and lower circumference (A)]. Thigh circumference, thigh length and calf length are shown in Figure 1B (D, F and E, respectively). Length and thigh circumferences were measured with a soft tape (ERP Group, Laval, Canada).

the IE MaxP_{ext} (W) obtained through the mathematical model with a criterion measure (Leone et al., 2013).

Following the 3-minute rest period, the initial exercise load for incremental test on DE was of 25 (W) and was increased by 25 W/min until exhaustion (Garzon et al., 2011). The pedalling rate (rpm) was free but minimum at 60 rpm. Following the exercise test on the DE, participants cooled down for 5 minutes.

Water immersion experiments were performed on a commercially available IE (Hydrorider®, Bologna, Italy) no more than five days following DE exercise. Proper pool depth was determined for a water level set to xiphoid (chest-level immersion; Bressel, Smith, Miller, & Dolny, 2012; Yazigi et al., 2013). Pedalling rate (rpm) on the IE was controlled with the use of both a metronome (Qwik Time Quartz Metronome, China) and a pedalling rpm metre (cateye Echowell F2, Taiwan) to facilitate proper rate by each participant. The resistance on the IE was set at maximum by adjusting the four paddles on the pedalling mechanism to maximum length. The exercise protocol began at a pedalling rate of 40 rpm. The rpm was then increased each minute by 10 rpm until it reached 70 rpm. Afterwards, the rpm was increased by 5 rpm until the subject was unable to follow the pace or until exhaustion. Following the exercise test, participants cooled down for 5 minutes. For both DE and IE tests, saddle height was adjusted by sitting the participant on the bicycle with the heel of the foot pressed on the pedal at the lowest point and the leg completely extended (Belluye & Cid, 2001).

2.1. External power output calculation

The P_{ext} expressed in W was calculated by multiplying the total net force overcoming (F_{net}) the resistance of the system movement (pedalling system and legs) (Alberton et al., 2011; Poyhonen et al., 2000) by the velocity (m/s) of the pedal. We favoured this approach since it takes into consideration the resistance of water on the lower limbs and the pedalling system. An error that would occur if a dynamometer was used on the pedalling system since only pedalling system resistance would be measured while ignoring resistance on the lower limbs. Thus, the following general fluid equation (equation 1) was used to determine mathematically F_{net} (Poyhonen et al., 2000; Shames, 1982):

$$F_{net} = 1/2\rho A v^2 C_d \quad (1)$$

where ρ is the density of water (at 30°C = 9957 kg/m^3; Darby, 2001), A is the projected area (m^2) in the direction of the movement for all segments involved (lower limbs, paddles, rods and pedals), v is the velocity (m/s) according to pedalling rate that ranged from 40 rpm to 120 rpm, and C_d is the drag coefficient of every element shape (lower limbs, paddles, rods and pedals).

Velocity (v) for each element (paddles, pedals and rods) was determined per revolution of the pedalling system while angular (arc) velocity was used for the legs (Figure 1). The method proposed by Burke (1986) was used to calculate the arc displacement (mean range of motion) of the major leg joints and segments through one revolution of the pedal crank. It was determined, as shown in Figure 1A–B, that the mean arc displacement for the knee is 74° and that the thigh (hip joint) moves through a 43° arc (Figure 1C–D). The quantitative measure of leg arc displacements on the IE was obtained by video analysis (Dartfish Express. Ver. 2.2) during dryland cycling at a pedalling rate of 40 rpm on images sampled at 120 Hz (HD camera, IPHONE 5S, model A1533, Apple, CA). The camera was mounted on a tripod perpendicular to the participant positioned on the IE at a distance of 5 metres. The following equations were used to calculate specific element velocity (v) at pedalling rates ranging from 40 rpm to 120 rpm:

$$\text{Pedal velocity} = 2\pi r\ (\text{rpm})/60\ \text{sec} \quad (2)$$

$$\text{Pedal velocity} = 2\pi(r/2)\ (\text{rpm})/60\ \text{sec} \quad (3)$$

$$\text{Rod velocity} = 2\pi(r/2)\ (\text{rpm})/60\ \text{sec} \quad (4)$$

$$\text{Thigh velocity} = 2(\text{arc } 2\pi(\text{r}/2)/360^\circ)\ (\text{rpm})/60\ \text{sec} \quad (5)$$

$$\text{Calf velocity} = 2(\text{arc } 2\pi(\text{r}/2)/360^\circ)\ (\text{rpm})/60\ \text{sec} \quad (6)$$

In these equations (equations 2–6), π equals 3.1416, r is, respectively, the radius or length (see Figure 2C) of the pedal, paddle, rods and leg (thigh and calf of each participant) and rpm is revolutions per minute. In equations 3–6, however, the mid-point (r/2) of each respective element was used since as one approaches the axis of the pedalling system, less distance is covered by the element and vice versa. The velocity (v) of each element was then used in equation 1.

Projected area (m^2) and drag coefficient (C_d) (Shames, 1982) of the pedalling system and legs was calculated by considering the shape of each element as illustrated in Figure 2. Complex structures were broken down into simple geometries. The pedalling system (Figure 2A) was broken down into

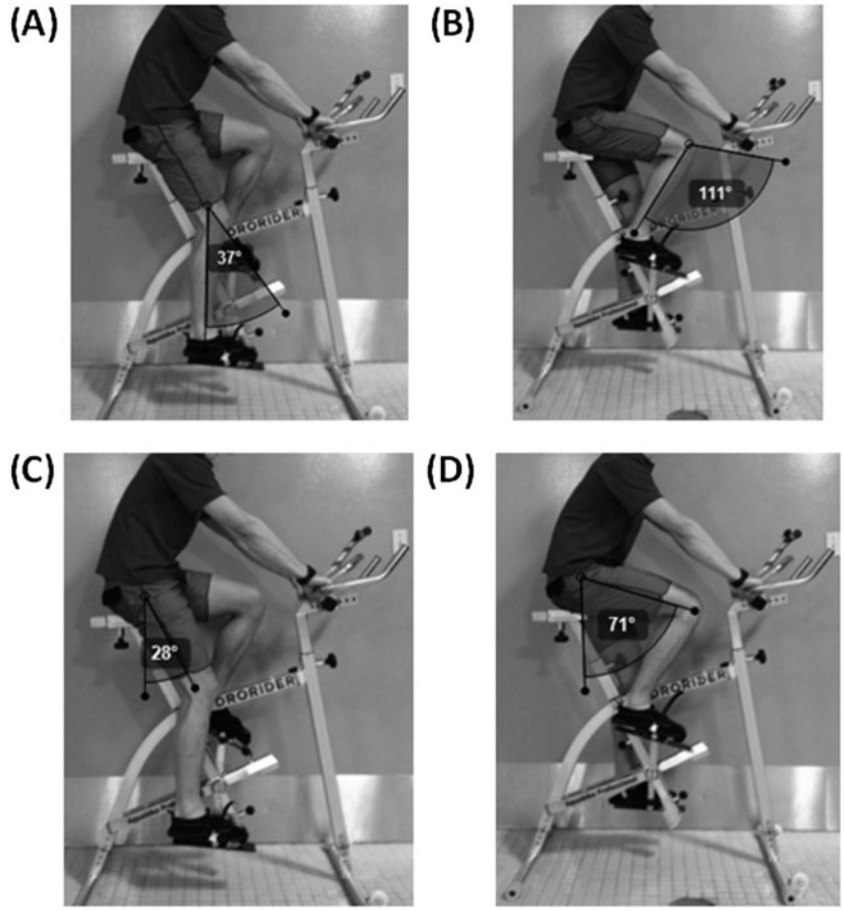

Figure 1. Lower limb arc displacement (range of motion) while pedalling on an IE. Seat height was adjusted as described in the methods section. (A–B) 74° arc displacement at the knee joint for the lower leg (111°–37°); (C–D) 43° arc displacement the hip joint for the thigh (71°–28°).

its various components, the paddle as a rectangle and cup (C_d = 1.42); and both pedals and rods as rectangles and cubes (C_d = 1.05). The leg shape (thigh and calf, Figure 2B) was represented as a cylinder (C_d = 0.38) where the length of the thigh was set as the distance (expressed in metre) from the *greater trochanter* to the lateral epicondyle (knee), whereas the length of the calf was the distance between the lateral epicondyle and the heel (ground). The detail of length measurements is shown by F and E in Figure 2B. The measurement of the circumference (in metre) of the thigh was taken at mid-point between the *greater trochanter* and the knee (D, Figure 2B). Calf circumference was calculated by taking into account the average of three points: upper, middle and lower circumference of the calf (C, B and A, respectively, as shown in Figure 2B).

The torque for each element was calculated by using the force in Newton (F) produced by each element (paddles, pedals, rods, thigh and calf) as determined by equation (1) and was multiplied by length (d). Thus, the sum of each element torque (F_d) of the pedalling system and lower limbs resulted in a net torque (T_{net}), as shown in equation 7:

$$T_{net} = F_{d1} + F_{d2} + F_{d3} + F_{d4} + F_{d5} \quad (7)$$

where F_{d1}, F_{d2}, F_{d3}, F_{d4} and F_{d5} are the torque exerted to overcome the resistance of the water according to rpm for each element of the pedalling system (Figure 2C) and $d1$ is the half length of the paddles; $d2$ is the half length of the rods; and $d3$ is the length of the rods where the pedals are attached. As for the legs, the thigh half length (F in Figure 2B) is $d4$ and the calf half length (E in Figure 2B) is $d5$.

The total net force overcoming (F_{net}) the resistance of the system movement (pedalling system and legs) was calculated as shown below in equation 8. The T_{net} (obtained with equation 7) was divided by the distance acting on the pedalling system ($d3$, as mentioned above):

$$F_{net} = T_{net}/d3 \quad (8)$$

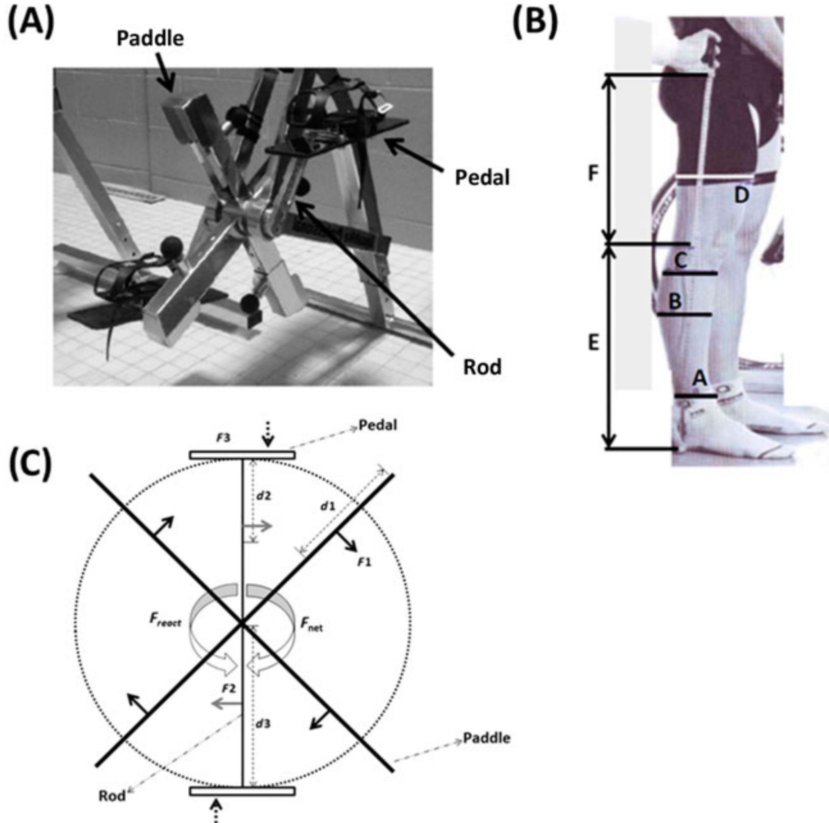

Figure 2. Illustrations of various measurement sites used for calculating P_{ext} (P_{ext} expressed in W) based on pedalling rate (rpm). (A) Picture of IE pedalling resistance/system. Simple geometry of pedalling system was used: paddle (rectangle and cup), pedals (rectangle and cube) and rods (rectangle and cube); (B) Measuring sites to establish length and circumferences of the leg to calculate calf and thigh areas. A, B and C, calf lower, middle and upper circumference, respectively. D, thigh circumference. E and F, calf and thigh length, respectively (see text for details); (C) Representation of forces acting on the pedalling system and the distances used to calculate the torque for paddle, pedals and rods: *d*1 is the half length of the paddles; *d*2 is the half length of the rods; *d*3 is the length of the rods where the pedals are attached (see Methods section for details).

Thus, P_{ext} (W) was obtained by multiplying F_{net} expressed in Newton by the velocity (v, in metre per second) of the pedal:

$$P_{\text{ext}}(\text{W}) = F_{\text{net}} \times v(\text{m/s}) \tag{9}$$

2.2. Statistical analysis

Data are presented as means ± standard deviation. P_{ext} on IE was calculated using equations 1–9. Curve fitting analysis was performed to obtain the best prediction equation of P_{ext} for the IE according to pedalling rate (rpm). An analysis of variance for repeated measures was used to compare Max-P_{ext} on DE and IE. All statistical analysis was performed with SPSS for Windows, version 15. Bland and Altman's (1986) analysis was performed to assess the agreement between MaxP_{ext} on DE and IE.

3. Results

The relationship between P_{ext} (W) and rpm during incremental exercise on the IE is illustrated in Figure 3A. As shown, the relationship between IE P_{ext} (W) and pedalling rate is curvilinear and is best represented by the following equation:

$$\text{IE}P_{\text{ext}}(\text{W}) = 0.0004(\text{rpm})^{2.993} \quad (r^2 = 0.99, \text{SEE} = 7.6\text{W}, p < 0.0001) \tag{10}$$

The level of agreement between both methods (calculated P_{ext} vs. predicted P_{ext}, equations 1–9 vs. equation 10, respectively) for calculating P_{ext} is shown in Figure 3B. It can be observed that the regression line (filled line) is in near agreement with the line of identity (hashed line). The slope of the regression line is almost equal to 1 (0.959) suggesting that calculation with either method yields identical P_{ext}.

Maximal P_{ext} (MaxP_{ext}) achieved on both IE and DE (Figure 3C) did not differ (IE: 254 ± 58 vs. DE: 252 ± 55 W, p = 0.56). The Bland–Altman plot (Figure 3D) shows a level of agreement between IE MaxP_{ext} and DE MaxP_{ext} that is less than 2 (mean = 1.93 ± 17.3 W) with a dispersion of 36.6 and −32.7 W

(±2SD; Bland & Altman, 1986). The hashed line represents a non-significant regression suggesting that the 1.93 ± 17.3 W bias (mean level of agreement) is constant between 100 W to 400 W. As well, a similar prevalence of $\dot{V}O_2$ plateau was noted on IE and DE (IE: 97%, n = 29 vs. DE: 100%, n = 30, p = 0.30). Participants attaining an RER value >1.1 were not different on IE and DE (IE: 83%, n = 25 vs. DE: 87%, n = 26, p = 0.71).

4. Discussion

The main finding of this study is the quantification of the P_{ext} (W) based on lower limb physical characteristics of participants and physical characteristics of any IE pedalling resistance/system when participants are immersed to the xiphoid process level. As well, the P_{ext} pedalling rate relationship on the IE is curvilinear (Figure 3A) and provides a regression equation (equation 10) that may facilitate for practitioners the prediction of P_{ext} with an SEE of 7.6 W or vice versa the pedalling rate required to reach a P_{ext} previously determined on a DE (equation 11). Finally, all participants reached a similar MaxP_{ext} on IE and DE with a similar prevalence of $\dot{V}O_2$ plateau and RER >1.1 indicating that subjects reached a maximal effort in both IE and DE tests.

We have attempted to be as thorough as possible to consider all fluid dynamic properties that may affect the lower limbs during immersion and we are hopeful that our estimation is accurate by incorporating all body segments and IE mechanical components in the general fluid equation. To the best of our knowledge, previous studies used modified bicycle ergometers submerged in water in order to evaluate the physiological effects of the exercise

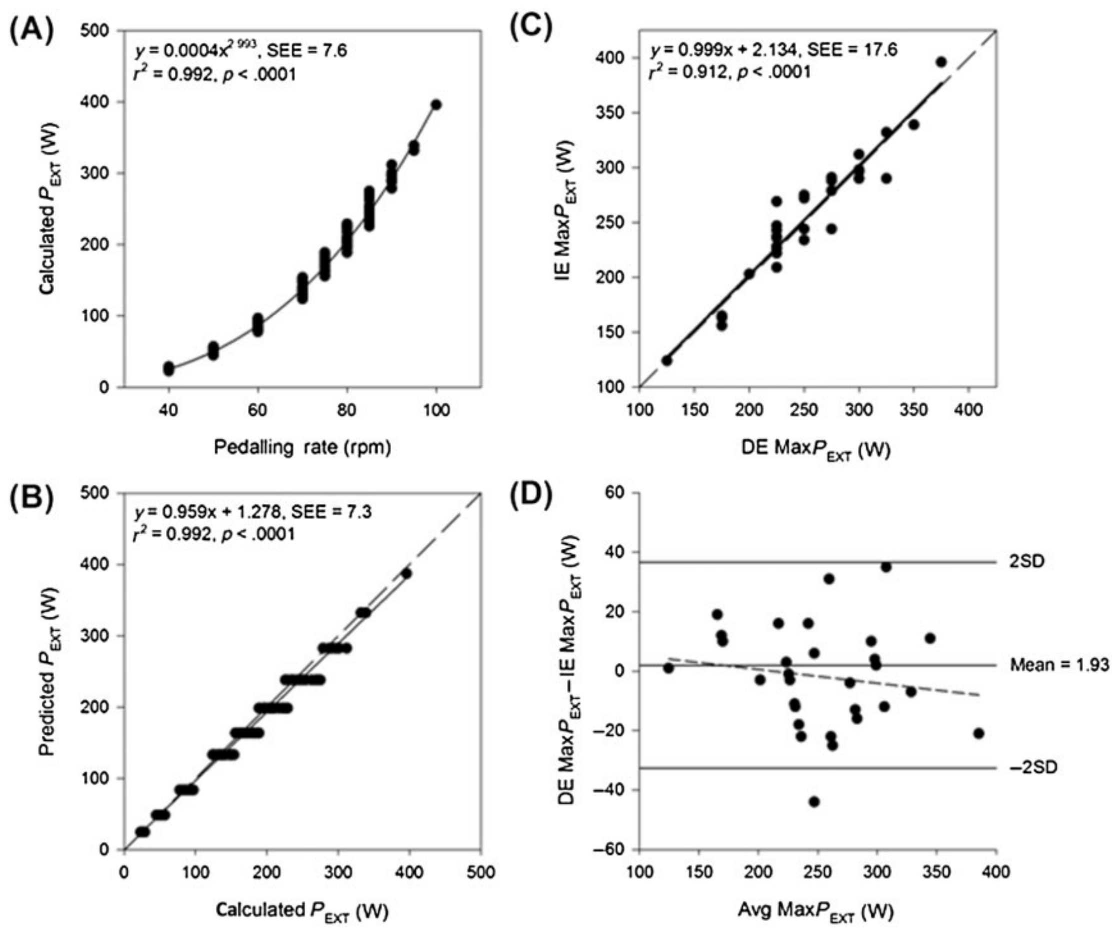

Figure 3. Estimated P_{ext} for an IE. (A) P_{ext} (W) as a function of pedalling rate (rpm) on the IE. The inset shows the significant regression equation and SEE of the relationship obtained with a total of 30 participants (r^2 = 0.992, p < 0.0001). (B) Relationship between the calculated P_{ext} (equations 1–8) and the predicted P_{ext} (predicted with equation 9). The filled line indicates the regression line and the hashed line represents the line of identity. The inset shows the significant regression equation and SEE (r^2 = 0.992, p < 0.0001). (C) The relationship between MaxP_{ext} attained by participants on both IE and DE. The filled line indicates the regression line and the hashed line represents the line of identity. The inset shows the significant regression equation and SEE (r^2 = 0.912, p < 0.0001). (D) Bland and Altman plot illustrating the level of agreement (filled line, 1.93 ± 17.3 W) between MaxP_{ext} reached on both IE and DE with dispersion (±2SD: +36.6 and −32.7 W). The hashed line represents the non-significant regression (−0.046x + 9.799, r^2 = 0.023, p = 0.425) between MaxP_{ext} difference and Avg MaxP_{ext}.

(Bréchat et al., 2012; Shapiro et al., 1981), but when reporting power output did not take into account the drag force exerted on the legs to analyse the results. We believe that the leg drag forces add significantly to the P_{ext} load generated by the pedalling resistance/system of the IE and, thus, cannot be ignored to estimate P_{ext}. In the current paper, we demonstrate, and in agreement with other studies, that P_{ext} increases in water as a function of velocity of movement (Bressel et al., 2012; Poyhonen et al., 2000) meaning that on IE, P_{ext} increases as an exponential function of rpm (Chen, Kenny, Johnston, & Giesbrecht, 1996; Yazigi et al., 2013). Likewise, we demonstrated that to calculate the P_{ext} on IE at different rpm it is necessary to take into account the drag force exerted on the legs and not just the drag force on the pedalling system (P_{ext} = approximately 15% higher; Dressendorfer, Morlock, Baker, & Hong, 1976; Garzon et al., 2011; Leone et al., 2013).

The leg drag force factor is essential to calculate accurately the P_{ext} given the large number of commercially available models of IE where the only way to increase or decrease the intensity of exercise is by varying the pedalling rate (Giacomini et al., 2009). We consider that the development of this mathematical model may contribute to calculate accurately the P_{ext} deployed by participants using different models of IE. Practitioners using any IE types, however, will have to consider the following four elements when calculating the power output: (1) the pedalling rate; (2) the seat height adjustment, as described above (leg angle for the angular velocity component in the fluid equation); (3) the precise characteristics of the pedalling system (length and width of paddles, pedals, and rods) that includes shape; and (4) participant leg anthropometric characteristics.

In the current study, we did not compare our results to measurements that could have been obtained with the use of a torque sensor on the pedal crank mechanism or a foot plantar pressure measurement system (Razak, Zayegh, Begg, & Wahab, 2012). A waterproof torque sensor or foot plantar pressure sensor might provide direct measurement of the force resistance or drag of the pedalling resistance/system; however, it will not include the drag force of the water on the legs. Thus, we believe that the calculation method provided herein (equations 1–9) is a better predictor of P_{ext} (W) during immersion exercise on IE. On the other hand, the regression equation (equation 10) predictive accuracy may differ if participant population has significant leg dimension differences (i.e., greater height, obese participants, etc.) when compared to ours. This, however, can be verified by comparing participant anthropometric measurements to those presented in Table I. Nonetheless, we provide in equations 1–9 the means of calculating the specific P_{ext} (W) based on individual anthropometric measurements (see Figure 2B).

In conclusion, the current study offers a means for quantifying the P_{ext} expressed in W (equations 1–9) for various water immersed bicycle models having different pedalling resistance/system characteristics (Hydrorider®, Archimedes®, Poolbike®, Aquabiking®, etc.), since each pedalling system (paddles, pedals and rods) has a different design. It is also provided the means to calculate the pedalling rate (rpm) on an IE corresponding to a prescribed P_{ext} (W) on DE. It may now be possible to explore the physiological response to immersion cycling at similar P_{ext} (W) and pedalling rates (rpm) using IE vs. DE.

4.1. Practical implications

- Determination of the P_{ext} on IE taking into account the drag force exerted on the legs and not just the drag force on the pedalling resistance/system are necessary for an accurate exercise prescription on IE based on power determination.
- This study provides relevant information for the exercise professional because it will be possible to prescribe accurately exercise intensity based on P_{ext} from rpm on IE.
- The quantification of P_{ext} on an IE will allow measuring the physiological response of immersion during exercise on an IE when compared to the same workload on a DE.

Accordingly, if exercise prescription P_{ext} (W) was obtained on a DE, then the exercise practitioner can use the equation below (equation 11) to calculate the pedalling rate (rpm) required on an IE to generate the equivalent P_{ext}.

$$\text{Pedalling rate (rpm)} = 13.91 \times \text{DE}P_{ext}(\text{W})^{0.329} \quad (r^2 = 0.99, \text{SEE} = 1.5\,\text{rpm}, p < 0.0001) \tag{11}$$

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