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

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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 \( F_d = \frac{1}{2} \rho V^2 C_d \) 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): \( P_{\text{ext}} (\text{W}) = 0.0004 (\text{rpm})^2.993 \) \( (r^2 = 0.99, \text{SEE} = 7.6 \text{ W}, p < 0.0001) \) and (2) when DE P_ext (W) is known, IE pedalling rate (rpm) \( = 13.91 \times \text{DE} P_{\text{ext}} (\text{W})^{0.329} \) \( (r^2 = 0.99, \text{SEE} = 1.5 \text{ W}, p < 0.0001) \). 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...
water external force exerted on the legs as a function of pedalling rate. Thus, despite several investigations, the $P_{\text{ext}}$ 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 $P_{\text{ext}}$ 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 $P_{\text{ext}}$ 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 $P_{\text{ext}}$ 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 ($\dot{V}O_2$, $\dot{V}CO_2$, VE 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 $P_{\text{ext}}$ (Max$P_{\text{ext}}$) achieved on this device with the Max$P_{\text{ext}}$ achieved on the IE which was tested according to the criteria defined above with respect to a maximal test. This allowed to correlate

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>33 ± 10</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>72 ± 9</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.74 ± 0.06</td>
</tr>
<tr>
<td>BMI (kg/m$^2$)</td>
<td>23.77 ± 2.51</td>
</tr>
<tr>
<td>Circumference of thigh (m)</td>
<td>0.51 ± 0.04</td>
</tr>
<tr>
<td>Circumference of calf (m)$^a$</td>
<td>0.31 ± 0.02</td>
</tr>
<tr>
<td>Length of thigh (m)</td>
<td>0.40 ± 0.03</td>
</tr>
<tr>
<td>Length of calf (m)</td>
<td>0.48 ± 0.02</td>
</tr>
</tbody>
</table>

$^a$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 MaxPext (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 (catelye 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 Pext expressed in W was calculated by multiplying the total net force overcoming (Fnet) 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 Fnet (Poyhonen et al., 2000; Shames, 1982):

\[ F_{\text{net}} = \frac{1}{2} \rho Av^2 C_d \]  

where \( \rho \) is the density of water (at 30°C = 9957 kg/m³; Darby, 2001), \( A \) is the projected area (m²) 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:

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

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

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

\[
\text{Thigh velocity} = 2(2\pi (r/2)/360°) \text{(rpm)/60 sec} \quad (5)
\]

\[
\text{Calf velocity} = 2(2\pi (r/2)/360°) \text{(rpm)/60 sec} \quad (6)
\]

In these equations (equations 2–6), \( \pi \) 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 (m²) 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

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:

\[
T_{net} = F_{d1} + F_{d2} + F_{d3} + F_{d4} + F_{d5}
\]

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):

\[
F_{net} = T_{net}/d3
\]
Thus, \( P_{\text{ext}} (W) \) was obtained by multiplying \( F_{\text{net}} \) expressed in Newton by the velocity \( (\nu, \text{in metre per second}) \) of the pedal:

\[
P_{\text{ext}}(W) = F_{\text{net}} \times \nu (\text{m/s})
\]

(9)

2.2. Statistical analysis

Data are presented as means ± standard deviation. \( P_{\text{ext}} \) on IE was calculated using equations 1–9. Curve fitting analysis was performed to obtain the best prediction equation of \( P_{\text{ext}} \) for the IE according to pedalling rate (rpm). An analysis of variance for repeated measures was used to compare Max-\( P_{\text{ext}} \) 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 Max\( P_{\text{ext}} \) on DE and IE.

3. Results

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

\[
\text{IE}P_{\text{ext}}(W) = 0.0004 (\text{rpm})^{2.993}
\]

(10)

\( r^2 = 0.99, \text{SEE} = 7.6W, p < 0.0001 \)

The level of agreement between both methods (calculated \( P_{\text{ext}} \) vs. predicted \( P_{\text{ext}} \) equations 1–9 vs. equation 10, respectively) for calculating \( P_{\text{ext}} \) 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 \( P_{\text{ext}} \).

Maximal \( P_{\text{ext}} \) (Max\( P_{\text{ext}} \)) achieved on both IE and DE (Figure 3C) did not differ (IE: 254 ± 58 W vs. DE: 252 ± 55 W, \( p = 0.56 \)). The Bland–Altman plot (Figure 3D) shows a level of agreement between IE Max\( P_{\text{ext}} \) and DE Max\( P_{\text{ext}} \) that is less than 2 (mean = 1.93 ± 17.3 W) with a dispersion of 36.6 and −32.7 W.
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 Max$P_{ext}$ 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 Max$P_{ext}$ 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 Max$P_{ext}$ 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 Max$P_{ext}$ difference and Avg Max$P_{ext}$.](image-url)
calculating the specific $P_{\text{ext}}$ (W) based on individual anthropometric measurements (see Figure 2B).

In conclusion, the current study offers a means for quantifying the $P_{\text{ext}}$ 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 $P_{\text{ext}}$ (W) on DE. It may now be possible to explore the physiological response to immersion cycling at similar $P_{\text{ext}}$ (W) and pedalling rates (rpm) using IE vs. DE.

4.1. Practical implications

- Determination of the $P_{\text{ext}}$ on IE taking into account the drag force exerted on the legs and not just the drag force on the pedalling system ($P_{\text{ext}} = \text{approximately } 15\%$ 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 $P_{\text{ext}}$ 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 $P_{\text{ext}}$ 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 $P_{\text{ext}}$ (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

\[
P_{\text{ext}} = \text{approximately } 15\% \text{ higher; }
\]

\[
P_{\text{ext}} = 3.91 \times \text{DEP}_{\text{ext}}(W)^{0.329}
\]

($r^2 = 0.99$, SEE $= 1.5$ rpm, $p < 0.0001$) (11)

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References


