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Aquatic cycling—What do we know? A scoping review on head-out aquatic cycling

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1 Department of Epidemiology, Faculty of Health, Medicine and Life Sciences, Care and Public Health Research Institute (CAPHI), Maastricht University, MD Maastricht, The Netherlands, 2 Department of Physical Therapy, Maastricht University Medical Center, Maastricht, The Netherlands, 3 Department of Sports Therapy, Kliniken-Valens, Reha Graber Klinik Valens, Valens, Switzerland, 4 Faculty of Kinesiology and Rehabilitation Sciences, KU Leuven, Leuven, Belgium, 5 Faculty of Sport and Health Sciences, University of Jyväskylä, Jyväskylä, Finland

* These authors contributed equally to this work.
* stefanie.rewald@maastrichtuniversity.nl

Abstract

Over the past few years, aquatic cycling has become a trending fitness activity. However, the literature has not been reviewed exhaustively. Therefore, using scoping review methodology, the aim of this review was to explore the current state of the literature concerning aquatic cycling. This study specifically focused on study designs, populations and outcomes. A comprehensive search of seven databases (PubMed, MEDLINE, Cinahl, Embase, PEDro, Web of Science, WorldCat) was conducted up to 30th September 2016. Google Scholar, World Cat, ResearchGate, specific aquatic therapy websites and aquatic therapy journals were searched to identify additional literature. Full-text publications in English, German or Dutch were included. Studies were included when the intervention involved head-out cycling carried out in 10˚ to 35˚ Celsius water. Exclusion criteria were the use of wet suits or confounding interventions that would affect participants’ homeostasis. 63 articles were included and the study parameters of these studies were summarized. Using three grouping themes, included studies were categorized as 1) single session tests comparing aquatic versus land cycling, or 2) aquatic cycling only sessions investigating different exercise conditions and 3) aquatic cycling intervention programmes. Although the experimental conditions differed noticeably across the studies, shared characteristics were identified. Cardiovascular parameters were investigated by many of the studies with the results suggesting that the cardiac demand of aquatic cycling seems similar to land-based cycling. Only six studies evaluated the effect of aquatic cycling interventions. Therefore, future research should investigate the effects of aquatic cycling interventions, preferably in individuals that are expected to gain health benefits from aquatic cycling. Moreover, this comprehensive outline of available literature could serve as a starting point for systematic reviews or clinical studies on the effects of aquatic cycling on the cardiovascular responses.
Introduction

Water-based fitness equipment has gained popularity within aquatic fitness leading to a development of dryland training machines, such as stationary exercise bikes and treadmills, into water-proof exercise gear. Although aquatic cycling has become a trending fitness activity, the modification of standard ergometer bicycles for aquatic programs is nothing new and stems from the late sixties. Researchers used water immersion as an effective simulation of prolonged weightlessness, moreover, the utilization of the aquatic environment has been recognized as useful in rehabilitation [1, 2]. Similar to land-based cycling, the repetitive circular movement of pedalling against the water resistance ensures a use of a large range of motion (ROM) of the lower limbs to improve cardiovascular fitness and muscle strength. The fact that individuals are sitting on the aquatic bike can be beneficial for those who have problems with balance and independent gait. However, in contrast, while the sitting position and hydrostatic pressure assist with postural control, the loss of free movement i.e. reduced challenges to balance, and the few variation of the exercises may limit its effect on functional capacity. A shared characteristic with other types of aquatic exercise is the decrease of joint loading due to the buoyancy of the water. During aquatic cycling participants are immersed in water up to the chest and the buoyancy of the water unloads the joints of the lower extremities and the lower spine, a condition appealing for patients experiencing pain or problems with physical functioning during exercising on land [3, 4]. Despite the potential benefits of aquatic cycling and its long history, the application of aquatic cycling in an exercise and clinical context still appears to be low. Limitations that might prevent clinicians using aquatic cycling for therapeutic purposes could include the investment costs, storage space requirements, and the elaborate set-up of the aquatic bikes. In particular, getting the bikes in and out of the pool, without an adjustable floor, is demanding.

The scientific evidence on the potential benefits of aquatic cycling seems to be scarce as well. Obvious search terms like aqua(tic) cycling, aqua(tic) bike or water cycling yield very few relevant results from scientific search engines. Moreover, the small number of references about aquatic cycling, used in previously published reviews on aquatic exercise, further emphasizes the impression of a scarcity of literature [5–7]. These reviews summarize the effects on head-out aquatic exercise, including aquatic cycling, or compared physiological responses of different types of aquatic exercise and swimming with each other [5–7]. Further, the aquatic cycling interventions were not described in detail in these prior reviews with these reviews only including cross-over studies.

Thus, the questions remain how has aquatic cycling been investigated in previous research, and whether a search effort solely on “aquatic cycling” would reveal additional publications and research investigating the effects of aquatic cycling intervention programmes. A systematic review with a meta-analysis would not suit this aim and therefore a scoping review study design was chosen. Systematic reviews are guided by specific research questions leading to strict in- and exclusion criteria. The primary aim for performing a scoping review is to map the available literature that meet a comprehensive research question combined without restricting inclusion criteria [8]. Where systematic reviews evolve out of an initial understanding of the research field, scoping reviews are employed to identify research and explore their features such as target populations, interventions, study designs and outcomes [8, 9]. As a result scoping reviews help to develop an understanding of the extent and possible gaps and uncertainties in the existing literature. Furthermore, a scoping review might identify a sufficient amount of studies that would facilitate a systematic review [9].

Therefore, the main objective of this study was to identify the scope of available research with regard to aquatic cycling as an exercise activity. Specifically, this scoping review aimed to
explore the aquatic cycling exercises, study designs, comparison of training effects (if applicable), populations and outcomes utilised in research investigating aquatic cycling. To enable a comprehensive coverage of available literature the following research question was formulated: What is the available research on head-out aquatic cycling exercise?

Methods

Framework of a scoping review

The procedure of performing a scoping review follows similar steps as those used in systematic review approaches without limiting for study design of included studies and without a quantitative synthesis. The framework of Arksey and O’Malley for scoping reviews was implemented in this study [9]. The framework consists of five essential stages and one additional stage; 1) identifying the research question, 2) identifying relevant studies, 3) study selection, 4) charting the data, 5) collating, summarizing and reporting the results, and additionally 6) consultation of experts (optional). All stages can be performed in an iterative manner allowing refining of search parameters.

Identifying relevant studies

A comprehensive literature search was conducted in August 2015 and updated to 30th September 2016 in seven electronic academic databases (PubMed, MEDLINE, Cinahl, Embase, PEDro, Web of Science, WorldCat). The search strategy was documented by title of the database searched, date of the search, the complete search string that was used and the number of articles found (Table 1). The development of each search string was an iterative process and familiarisation with the literature revealed additional search terms for aquatic cycling such as “immersed cycling” or ”underwater pedalling”. These terms were combined with more general terms for aquatic therapy (e.g. hydrotherapy) the search included the following key terms: ergometer, immersion, hydrotherapy, aqua(tic), cycling, underwater (bi)cycle ergometer, immersed ergocycle.

Additionally, ResearchGate, GoogleScholar and relevant aquatic therapy websites (http://www.wcpt.org/apti, http://www.atri.org, https://www.aewave.com) were examined. Moreover, the table of contents of the accessible key journals ‘International Journal of Aquatic Research and Education’ and ‘Journal of Aquatic Physical Therapy’ of the American Physical Therapy Association were checked for additional literature. Finally, reference lists of all included articles were hand-searched for new articles and the authors of this paper, all experts in the field of aquatic therapy and aquatic fitness, checked their own libraries for additional literature. The table of contents and reference lists were screened for the key words related to cycling and (immersion) exercise (testing) on land and in water. Throughout the search process it was noticed that no consistent terminology exists with regard to aquatic cycling. To ensure that the search terms used were correct and complete, the terminology used in included articles was re-evaluated. This post-hoc analysis (S1 File) addressing the terminology used to describe aquatic cycling confirmed our choice of search terms.

Study selection

The inclusion and exclusion criteria were developed in two stages. In phase one, the authors agreed to include all formats of full-text reports that focused on the effects of head-out aquatic cycling exercise on the human body (Table 2, stage one). After familiarisation with the literature the selection criteria were further specified (Table 2, stage two). In each step of the selection procedure two or more reviewers were involved and inclusion discrepancies were solved
by discussion. Screening of titles and abstracts was performed by two reviewers (BW and SR) with the online programme “Covidence” (Covidence systematic review software, Veritas Health Innovation, Melbourne, Australia, available at: www.covidence.org). Next, all authors were involved with the full-text screening and all results were independently imported into a Microsoft Excel file and compared after completion of the review process. Information on the two-stage development of the inclusion criteria is available in a supporting file (S2 File).

**Charting the data**

Descriptive data were extracted into Microsoft Excel tables including name of the first author, year of publication, primary research question, sample size, age, gender, health status of participants, exercise parameters, main results reported in the abstract, water temperatures, aquatic bike used and level of body immersion. Information on effects of resting immersion was not discussed for this review, but might have been part of the experimental set-up of the included studies. The tables were organised by the body position on the aquatic bike (upright and semi-recumbent), because physiological responses might vary with immersion level related to the body position on the ergometer [2]. All tables include information on interventions with healthy participants and patients. If patients were involved, information on the disease characteristics is reported in the tables. Articles that originated from the same data set, but focusing

<table>
<thead>
<tr>
<th>Table 1. Search strategy and results.</th>
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</thead>
<tbody>
<tr>
<td><strong>Database</strong></td>
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<tr>
<td>PubMed</td>
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<tr>
<td>MEDLINE</td>
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<tr>
<td>CINAHL</td>
</tr>
<tr>
<td>EMBASE</td>
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<tr>
<td>PEDro</td>
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<tr>
<td>Web of Science</td>
</tr>
<tr>
<td>WorldCat</td>
</tr>
<tr>
<td>Total number of records</td>
</tr>
</tbody>
</table>

af, all fields; TX, text; TS, topic; ti, title; kw, key word; su, subject.

https://doi.org/10.1371/journal.pone.0177704.t001
on different outcomes, were summarized and represented as one study in the tables, but references from all studies are included to aid identification of the separate articles.

**Results**

The search revealed 465 potential studies. After screening of the titles and abstracts, 350 studies were excluded and the full-text versions of 115 publications were read (Fig 1). Finally, 63 articles met the inclusion criteria. The reasons for exclusion during the full-text screening and the references of these excluded articles are presented in a supporting file (S3 File). Nevertheless, some of these publications might contain useful information and were therefore used as supportive literature. All included articles were published in peer-reviewed journals. Three of the included articles were published in German with an English abstract [10–12].

The included articles were categorized in three groups according to the intervention characteristics. The first group consisted of comparisons using the aquatic bike as a tool for evaluating land versus aquatic cycling. The second group consisted of studies on the physiological responses to single sessions of aquatic cycling under different exercise conditions (e.g. different water temperatures). Research on the effects of multiple aquatic cycling sessions was clustered in a third group. According to these three grouping themes the extracted data was organised in three tables (Table 2, Table 3 and Table 4).

**Land-based cycling compared to aquatic cycling**

Thirty-one studies compared aquatic cycling with land cycling (Table 3). Half of the studies (n = 15) used a maximal incremental exercise test to investigate the physiological responses during immersion versus on land exercise testing [11, 13–26]. Submaximal incremental exercise tests were conducted in six studies [27–32]. Increments were mostly achieved by an increase in pedalling frequency. Seven studies of the aforementioned studies controlled exercise intensity by electronically regulated pedalling resistance [10, 21, 24–27, 31]. An additional six studies compared submaximal continuous aquatic cycling with land cycling [33–38]. Three

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**Table 2. Two stage expert consensus on inclusion and exclusion criteria.**

<table>
<thead>
<tr>
<th>INCLUSION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage I</strong></td>
</tr>
<tr>
<td>• Full-text articles or master or doctoral theses written in English, Dutch, German</td>
</tr>
<tr>
<td>• Most of the following is described: intensity, duration of the session, body position on the bicycle, water temperature, and type of aquatic bike used</td>
</tr>
<tr>
<td>• Effect of head-out aquatic cycling on the human body is described</td>
</tr>
<tr>
<td><strong>Stage II</strong></td>
</tr>
<tr>
<td>• Participants have to be seated upright or semi-recumbent during immersed exercise</td>
</tr>
<tr>
<td>• The exercising limb has to be fully immersed in water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EXCLUSION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage I</strong></td>
</tr>
<tr>
<td>• Full-body (above head) immersion of participants</td>
</tr>
<tr>
<td>• Use of self-contained underwater breathing apparatus (SCUBA)</td>
</tr>
<tr>
<td><strong>Stage II</strong></td>
</tr>
<tr>
<td>• Long duration resting immersion (&gt;30 min) prior to exercise</td>
</tr>
<tr>
<td>• Confounding interventions that would affect participants homeostasis e.g. manipulation of participants’ glucose level or oxygen saturation</td>
</tr>
<tr>
<td>• Water temperatures below 10˚C or above 41˚C for resting immersion and water temperatures above 35.5˚C for exercise conditions</td>
</tr>
<tr>
<td>• Use of wet-suits</td>
</tr>
</tbody>
</table>

https://doi.org/10.1371/journal.pone.0177704.t002
other studies evaluated aquatic cycling as a mean for active recovery after an extensive exercise bout on land [39–41]. Furthermore, one study compared the effect of moderate intense dry-land cycling with high-intensity interval training (HIIT) on land and in water [42]. Two-third of the aquatic cycling sessions (n = 22) were conducted in an upright body position. Nine studies [11, 24–26, 30, 31, 34–36] compared semi-recumbent cycling on land and in water. Four semi-recumbent bikes also had arm pedals [11, 24, 30, 36]. The level of body immersion of the participants varied from chest level to chin level. The water temperature during the exercise sessions ranged from 18˚C to 35˚C.

All but three studies used a cross-over design to compare both environments. Additional study designs were a randomized controlled trial [41, 42] and a quasi-experimental study [27].
Table 3. Land-based cycling versus aquatic cycling.

<table>
<thead>
<tr>
<th>Author Year</th>
<th>Study design</th>
<th>Study aim</th>
<th>Sample</th>
<th>Exercise parameters</th>
<th>Key findings</th>
<th>T&lt;sub&gt;water&lt;/sub&gt;</th>
<th>Aquatic bike used</th>
<th>Immersion depths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garzon [16] 2016</td>
<td>Cross-over</td>
<td>To compare the early decay of HR recovery, a marker of parasympathetic reactivation, after a maximal incremental exercise on AC vs. LC</td>
<td>n = 15 (F/M: 2/13); age: 30±7</td>
<td>Land protocol: • Initial workload: 25W • Increments: 25W every min until exhaustion • Rpm: minimal 60 Water protocol: • Initial rpm: was set at 40 rpm (corresponding to P&lt;sub&gt;ext&lt;/sub&gt; of 25W) • Increments: 10 rpm until 70 rpm and thereafter by 5 rpm until exhaustion</td>
<td>• HR&lt;sub&gt;ext&lt;/sub&gt; did not differ between AC and LC • More rapid* deceleration of HR in AC in the first minute of recovery • No difference in recovery HR in the late phase (minute 2–5 of recovery)</td>
<td>30°C</td>
<td>Hydridoride®</td>
<td>Chest</td>
</tr>
<tr>
<td>Yazigi [17] 2013</td>
<td>Cross-over</td>
<td>To compare cardiorespiratory response, BL, and thermal comfort during AC in neutral and warm water and LC</td>
<td>n = 10 M</td>
<td>Land protocol: • Initial workload: 75W • Increments: 30W every 3min until exhaustion • Rpm: 70 Water protocol: • Initial rpm: 50 rpm, • Increments: 10 rpm every 3min until 75 rpm and thereafter by 5 rpm every 3min until exhaustion</td>
<td>• HR&lt;sub&gt;max&lt;/sub&gt; and VO2max were not sig. different in AC and LC • BL values were lower** in AC trials, • VO2, HR, BL and thermal comfort scores were higher** at the end of the AC test compared to submaximal cadences in AC • Participants were more comfortable with AC in lower T&lt;sub&gt;water&lt;/sub&gt;</td>
<td>27°C, 31°C</td>
<td>Hydridoride®</td>
<td>Xiphoid process</td>
</tr>
<tr>
<td>Wahl [41] 2016</td>
<td>RCT</td>
<td>To investigate the effect of AC vs. LC on heart rate and BP response after a maximal incremental exercise and the subsequent recovery, a marker of parasympathetic reactivation, and perceived physical state</td>
<td>n = 20 M; age: 24.4±2.2</td>
<td>• Exercise: steady AC (vs. passive lying in supine position on land) after an strenuous exercise bout on land • Duration: 30min</td>
<td>• No differences between passive rest on land and AC with regard to performance, muscle damage and soreness and perceived physical state</td>
<td>31°C</td>
<td>Aquarider®</td>
<td>Chest</td>
</tr>
<tr>
<td>Sosner [42] 2016</td>
<td>RCT</td>
<td>To compare BP response after moderate LC, HIIT AC and HIIT LC</td>
<td>n = 42 (F/M: 21/21); BP &gt; 130/85 mmHg; age: 65±10</td>
<td>Land protocol (moderate exercise): • 24min at 50% peak power output Land and water protocol (HIIT): • 6min warm-up at 50% peak power output, 2 sets of 10min: 15s 100% peak power output interspersed by 15s of passive recovery, 4 min passive (seated) recovery between sets</td>
<td>• HIIT LC and AC decreased 24hr BP* • HIIT AC modified 24-hour pulse-wave velocity</td>
<td>30°C</td>
<td>Hydridoride®</td>
<td>Chest</td>
</tr>
<tr>
<td>Garzon [15] 2015</td>
<td>Cross-over</td>
<td>To compare VO2, central hemodynamics and C(a-v)O2 during incremental maximal exercise and the subsequent hemodynamic recovery after AC and LC.</td>
<td>n = 20 (F/M: 6/14); age: 32±7</td>
<td>Land protocol: • Initial workload: 25W • Increments: 25W every min until exhaustion • Rpm: minimal 60 Water protocol: • Initial rpm: was set at 40 rpm (corresponding to P&lt;sub&gt;ext&lt;/sub&gt; of 25W) • Increments: 10 rpm until 70 rpm and thereafter by 5 rpm until exhaustion</td>
<td>• Similar means of %HR&lt;sub&gt;resid&lt;/sub&gt;, %HR&lt;sub&gt;max&lt;/sub&gt; and %VO2&lt;sub&gt;resid&lt;/sub&gt; for AC and LC • Predicted VO2 (L/min) = 0.000542 x rpm&lt;sup&gt;2&lt;/sup&gt;–0.026 x rpm + 0.739 (r = 0.91, SEE = 0.319 L/min)</td>
<td>30°C</td>
<td>Hydridoride®</td>
<td>Xiphoid process</td>
</tr>
<tr>
<td>Garzon [13] 2015</td>
<td>Cross-over</td>
<td>To develop a mathematical model to calculate P&lt;sub&gt;ext&lt;/sub&gt;, during AC with chest-level immersion for different pedalling rates and accounting for the drag forces exerted on the legs.</td>
<td>n = 20 (F/M: 6/14); age: 33±10</td>
<td>Land protocol: • Initial workload: 25W • Increments: 25W every min until exhaustion • Rpm: minimal 60 Water protocol: • Initial rpm: was set at 40 rpm (corresponding to P&lt;sub&gt;ext&lt;/sub&gt; of 25W) • Increments: 10 rpm until 70 rpm and thereafter by 5 rpm until exhaustion</td>
<td>• P&lt;sub&gt;ext&lt;/sub&gt; (W) in water based on rpm = 0.00044 x rpm&lt;sup&gt;2&lt;/sup&gt;–0.025 x rpm + 0.739 (r = 0.91, SEE = 0.319 L/min) • When the P&lt;sub&gt;ext&lt;/sub&gt; was obtained on land, the rpm to generate an equal P&lt;sub&gt;ext&lt;/sub&gt; in water = 13.91 x DE P&lt;sub&gt;ext&lt;/sub&gt; (W) +0.99* (r = 0.99, SEE = 1.5 W, p &lt; 0.0001)</td>
<td>30°C</td>
<td>Hydridoride®</td>
<td>Xiphoid process</td>
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(Continued)
<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Year</th>
<th>Design</th>
<th>Objective(s)</th>
<th>Experimental Details</th>
<th>Results/Findings</th>
</tr>
</thead>
</table>
| Finkelstein [27] | 2011 | Quasi-experiment | To compare BP and VO₂ responses between pregnant and non-pregnant women, during AC and LC | • n = 20 F (10 non-pregnant F and n = 10 pregnant F at 27–29 wk gestation)  
• age: 31.9±3.1 (pregnant), 32.3±2.8 (non-pregnant)  
• Land + Water protocol: Series 1:  
• Initial workload: 25W  
• Increments: 25W every 2min until first ventilator threshold  
• Rpm: 50  
• Series 2:  
• 30min at the HR corresponding to the first ventilator threshold  
• BP was lower** during AC in pregnant and non-pregnant F  
• No differences in VO₂ between AC and LC and pregnant and non-pregnant F  
• After the first five-minute recovery period, both BP and VO₂ were similar to pre-exercise values in pregnant and non-pregnant women, no difference between AC and LC | 32.4°C Sculptor–RGS, Brazil  
Xiphoid process |
| Fereira [40] | 2011 | Cross-over | To compare lactate removal on land and in water | • n = 10 cyclists  
• age: 26.2±5.5  
• Land protocol:  
• Wingate Anaerobic Test on an ergometer  
• Passive recovery (land = water):  
• 60min in supine position on land or in water (floating)  
• Active recovery (water):  
• 30min of AC at up to 85% of the anaerobic threshold in water + 30min of sitting on the aqua bike  
• After 15min the BL values were lower* in AC trials compared to passive recovery on land and in water  
• No difference between passive recovery on land and in water | 28–30°C Water Bike® NR |
| Wiesner [18] | 2010 | Cross-over | To investigate the effect of water immersion on exercise-induced ANP release, lipid mobilization and lipid oxidation | • n = 17 M  
• age: 31±3.6  
• Land protocol:  
• Initial workload: 50W  
• Increments: 50W every 6min until exhaustion  
• Water protocol:  
• Workload was increased by an increased number of fins to the flywheel  
• Rpm: NR  
• HR, systolic BP and VO₂ at the anaerobic threshold and during peak exercise were comparable in AC and LC  
• Respiratory quotient was lower* in AC  
• BL and glucose levels were lower* in water during peak AC  
• Free fatty acid concentrations were increased** with AC  
• Water immersion attenuated** (nor)epinephrine concentrations during peak exercise  
• ANP release was increased** in AC | 28°C Hydronike Evolution®  
Xiphoid process |
| DiMasi [39] | 2007 | Cross-over | To compare lactate removal during active recovery with AC or LC | • n = 11 M  
• age: 22.7±1.9  
• Land protocol:  
• Exercise bout on land treadmill: 2min warm-up, 6min at a speed 10% above the of the individual ventilatory threshold  
• Land and water recovery protocol:  
• 15min AC or LC at 65% estimated HRmax (220-age)  
• BL at 6 and 15min of recovery was lower* in AC | 30–31°C Hydrorider®  
Xiphoid process |
| Bréchat [33] | 1999 | Cross-over | To compare ventilator and metabolic requirements during AC and LC | • n = 15 M  
• age: 30±8, 29±8 (Series 1, 2)  
• Land and water protocol:  
• Series 1: subjects (n = 9), AC and LC at 60% VO₂max for 30min; Rpm: NR  
• Series 2: subjects (n = 9), AC and LC at workload of 122W for 30min; Rpm: NR  
• BR, Q and SV did not differ between AC and LC  
• HR, Q and SV did not differ between AC and LC  
• No change in exercise response when patients with beta-blocker medication and exercise-induced ST-segment depression were excluded separately from the analysis | 33°C EM designed in the authors laboratory  
Xiphoid process |
| Hanna [28] | 1993 | Cross-over | To evaluate the effect of head-out water immersion on Q, SV and HR (at rest) and during graded submaximal AC and LC in men with a healed MI | • n = 15 M with history of MI  
• age: 49±9  
• Land protocol:  
• Initial workload: 40% of the subject’s VO₂peak  
• Increments: 25W every 6min until 75% of VO₂peak  
• Rpm: 50  
• Water protocol:  
• Initial workload: 40% of the subject’s VO₂peak  
• Increments: increase in rpm (range 35–46) every 6min until 75% of VO₂peak  
• HR, Q and SV did not differ between AC and LC  
• No change in exercise response when patients with beta-blocker medication and exercise-induced ST-segment depression were excluded separately from the analysis | 31°C Modified Monark EM (Morlock & Dressen-dorfer)  
Suprasternal notch |
<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Objective</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheldahl [19]</td>
<td>1992</td>
<td>Cross-over</td>
<td>To examine the influence of AC and LC on fluid-regulating hormones</td>
<td>Table 3. (Continued)</td>
</tr>
<tr>
<td>Mc Murray [52]</td>
<td>1988</td>
<td>Cross-over</td>
<td>To compare the cardiovascular responses during AC and LC in patients with coronary artery disease</td>
<td>• n = 10 M with coronary artery disease • age: 52</td>
</tr>
<tr>
<td>Christie [21]</td>
<td>1990</td>
<td>Cross-over</td>
<td>To compare cardiovascular responses during dynamic LC and AC exercise testing</td>
<td>• n = 10 M • age: 21–35</td>
</tr>
<tr>
<td>Katz [38], McMurray [37]</td>
<td>1990, 1993</td>
<td>Cross-over</td>
<td>To compare the effects of AC and LC on the mother and foetus</td>
<td>• n = 7 F at 25 wk gestation • age: NR</td>
</tr>
</tbody>
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<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Objective</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheldahl [19]</td>
<td>1987</td>
<td>Cross-over</td>
<td>To assess the effects of central shift in blood volume on cardiorespiratory responses to dynamic AC and LC in middle-aged men</td>
<td>• n = 19 M • age: 48±6</td>
</tr>
<tr>
<td>Connelly [20]</td>
<td>1990</td>
<td>Cross-over</td>
<td>To compare the sympathoadrenal response to graded dynamic AC and LC</td>
<td>• n = 9 M • age: 22–36</td>
</tr>
</tbody>
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<th>Design</th>
<th>Objective</th>
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<td>Sheldahl [19]</td>
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<th>Key findings</th>
<th>T_{water}</th>
<th>Aquatic bike used</th>
<th>Immersion depths</th>
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</table>
| Sheldahl [22]   | 1984 | Cross-over   | To investigate the effect of different levels of central blood volume on cardiac performance during submaximal exercise in supine and upright posture on land and in upright posture in water | n = 12 M | • Initial workload: 50W  
• Increments: 25W every 2min until exhaustion  
• Rpm: NR  
• At submaximal workloads mean left ventricular end-diastolic/—systolic dimension were greater* in AC  
• At submaximal conditions HR did not differ between land and water trials  
• At a mean VO_{2} of 2.4 l/min, HR was greater** in the upright land posture than in upright posture in water  
• VO_{2max} did not differ between groups | 31°C  
• Modified Monark EM (Morlock & Dressen-dorfer) | Shoulder |
| Dressen-dorfer [23] | 1976 | Cross-over   | To determine the effect of head-out water immersion on cardiorespiratory responses to maximal aerobic work | n = 7 M | • Individual prescribed maximal workloads to achieve exhaustion within 4 to 5min  
• HR, volume of expired gas per unit of time and maximum voluntary ventilation were lower* in AC  
• VO_{2max} did not differ between AC and LC | 30°C  
• Modified Monark EM (Morlock & Dressen-dorfer) | Neck + chin |

#### SEMI-RECUMBENT BODY POSITION

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</table>
| Fenzl [34]      | 2013 | Cross-over   | To compare the release of ANP and free fatty acids during prolonged AC with the release after an LC | n = 6 M | • Age: 35.1±5.4  
• Overweight  
• Initial workload: 50W  
• Increments: 25W every 2min until exhaustion  
• Contribution of arms during arm-leg exercise: 20%  
• Rpm: 70  
• VO_{2}—work rate relationship is similar for arm-leg and leg exercise in AC and LC  
• Extra O_{2} cost by adding arm exercises is lower** with AC  
• At the ventilatory threshold two, exercise capacity, expressed as workload, is lower** in AC  
• ANP was higher** in AC  
• Free fatty acids were increased* post-exercise compared to baseline with no difference between AC and LC  
• Similar increase in epinephrine and decrease in insulin in AC and LC | 27–28°C  
• Modified Monark EM (Chen) | Xiphoid process |
• Arm-leg workload ratio: 1:3  
• Rpm: 70  
• The respiratory determined threshold heart rate is different* during AC and LC  
• Quantitative comparison of gas exchange measurements with HRV showed a strong correlation between both parameters | 28°C  
• Modified Monark EM (Craig & Dvorak) | Xiphoid process |
| Perini [25]     | 1998 | Cross-over   | To evaluate the effect of water immersion on the power spectrum of HRV (at rest) and during AC and LC | n = 7 M | • Age: 22.0±0.9 (SEM)  
• Land protocol: Series 1:  
• Initial workload: 0W  
• Increments: 20, 40, 60 rpm for 6min each  
• Arm-leg workload ratio: 1:3  
• Rpm: 70  
• The changes in power spectrum distribution of HRV occurring during exercise were similar in AC and LC  
• The central frequency of high frequency peak increased linearly with VO_{2} showing a tendency to be higher in AC at medium to high intensities | 30°C  
• Modified Monark EM (Chen) | Chin level |
| Chen [26]       | 1996 | Cross-over   | To compare exercise tests with a semi-recumbent underwater exercise EM used on land and in water with a upright standard EM on land | n = 10 (F/M: 3/7) | • Age: 30.6±6.5  
• Initial workload: 0W  
• Increments: 44W (males) or 28W (females) every 2min until subjects could no longer maintain 60 rpm  
• Rpm: 60  
• VO_{2max} did not differ between semi-recumbent positions  
• The upright position in LC resulted in greater* total exercise duration and maximal T_{exhaustion}  
• The upright position in LC resulted in greater* total exercise duration and maximal power output than the semi-recumbent positions | 33°C  
• Modified Monark EM (Chen) | Clavicles |

(Continued)
In 19 out of 31 studies participants were young, healthy males. Five studies included healthy participants of both sexes [13–16, 26, 36] and three studies included pregnant women [27, 37, 38]. In four other studies participants were middle-aged men [29], males with cardiovascular diseases [28, 32] and men and women with hypertension [42].

Studies (n = 21) investigating the difference in cardiovascular responses between aquatic versus land cycling compared oxygen consumption (VO$_2$), heart rate (HR), stroke volume, cardiac output and blood pressure [15–23, 26–33, 37, 38, 42]. In total eight studies investigated the maximum VO$_2$ response during land and aquatic cycling, with all but one study [15] reporting equivalent VO$_2$max values achieved by the participants on land and in water [17–23, 26]. Maximal HR was found to be lower during aquatic cycling at intensities higher than approximately 80% of the VO$_2$max in seven from ten studies [20–23, 26, 29, 30]. The remaining three studies reported similar maximal HR for the land and water conditions [16–18]. In men, following recovery from a myocardial infarction, no difference in submaximal HR on land and in water was found [28]. McMurray et al. reported a trend toward a lower HR at submaximal intensities in water in men with coronary heart disease [32]. In pregnant women moderate

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**Table 3. (Continued)**

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Design</th>
<th>Protocol</th>
<th>Sex and Age</th>
<th>Temperature</th>
<th>VO$_2$ (L/min)</th>
<th>HR (bpm)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Israel [36]</td>
<td>1989</td>
<td>Cross-over</td>
<td>To determine a $T_{max}$ that would attenuate the core rise that occurs with cardiovascular exercise</td>
<td>M: 26.8±4</td>
<td>21°C, 25°C, 29°C</td>
<td>2.4±0.8</td>
<td>81±10</td>
<td></td>
</tr>
<tr>
<td>Mc Ardle [36]</td>
<td>1984</td>
<td>Cross-over</td>
<td>To compare thermo-regulatory responses to continuous exercise in different $T_{water}$ and on land in males and females</td>
<td>M: 23.1, F: 23.1, range: 18–29</td>
<td>18°C, 24°C, 28°C</td>
<td>1.3±0.2</td>
<td>75±15</td>
<td></td>
</tr>
<tr>
<td>Mc Ardle [30]</td>
<td>1976</td>
<td>Cross-over</td>
<td>To compare metabolic and cardiovascular adjustment to exercise on land and in different $T_{water}$</td>
<td>M: 26±5.5, F: 26±5.5</td>
<td>18°C, 25°C, 33°C</td>
<td>2.6±0.4</td>
<td>72±12</td>
<td></td>
</tr>
<tr>
<td>Craig [31]</td>
<td>1969</td>
<td>Cross-over</td>
<td>To compare cardiorespiratory responses during AC and LC</td>
<td>NR</td>
<td>18°C, 30°C, 35°C</td>
<td>2.2±0.3</td>
<td>70±10</td>
<td></td>
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</table>

AC, aquatic cycling; ANP, atrial natriuretic peptide; BL, blood lactate; BP, blood pressure; C(a-v)O$_2$, arteriovenous difference; C, Celsius; EM, ergometer; F, female; HIIT, high-intensity interval training; HR, heart rate; HRV, heart rate variability; LC, land-based cycling; M, male; MI, myocardial infarction; min, minute(s); NR, not reported; $P_{ext}$, external power output; Q, cardiac output; Rpm, revolution per minute; SE, Standard Error; SEM, standard error of mean; SV, stroke volume; T, temperature; VO$_2$, oxygen uptake; W, Watts; wk, week(s); yrs, years

*significant at p-value <0.05
**significant at p-value <0.01

*If not stated otherwise participants are healthy and age is presented in years as mean ± standard deviation.

https://doi/10.1371/journal.pone.0177704.1003
Table 4. Aquatic cycling only (under various exercise conditions and in comparison to passive rest or immersion).

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</table>
| Dionne [46]     | 2016 | Cross-over   | To determine the effect of aquatic cycling and different levels of immersion on respiratory responses in healthy participants and people with a heart disease | n = 34  
   (FM: 10/24)  
   n = 21 (heart disease), n = 12 (controls)  
   age: 64.7 ± 7.8 (heart disease), 61.0 ± 7.8 (controls) | Exercise: incremental, at different levels of body immersion  
   Initial rpm: 40 rpm  
   Increments: 10 rpm every 2 min until at least one of the following was obtained:  
   HR max, VO2 peak, %VO2max and cadence | • Immersion reduced ventilation in phase 1 of hyperpnoea by 79% at pedalling cadences of 40, 50 and 60 rpm in the heart disease group | 29°C    | Hydorider®         | Cell, hip, xiphoid process |
| Pinto [62]      | 2015 | Cross-over   | To compare the heart rate deflection point method with the ventilator method to determine the anaerobic threshold during AC | n = 27  
   M | Exercise: continuous and interval AC in seated and out-of-saddle-positions  
   Duration: 31 min  
   Intensity: 75, 80, 85 and 92% VO2peak  
   Rpm: 80–100 | • No difference between exercise protocols in HR, %HR max, VO2 peak, %VO2max and cadence related to the anaerobic threshold | 30°C    | Hydorider®         | NR |
| Brasil [45]     | 2011 | Cross-over   | To investigate whether the type of exercise affects the physiological response to a AC and the perception of effort | n = 10  
   F  
   age: 32.8 ± 4.8  
   n = 16  
   M  
   age: 31.7 ± 5.8 | Exercise: incremental exercise test on 4 aqua bikes: with no resistance, with resistance added to the bottom bracket axle, with resistance added to the pedals  
   Initial rpm: 40 rpm  
   Increments: 5 rpm every 2 min until the participant was unable to maintain the set rpm | • No differences between exercise protocols in HR, arterial BP, double product and BL concentration  
   • Central RPE was higher at 92%VO2peak of the continuous trial  
   • Peripheral RPE was higher at 85 and 92%VO2peak of the continuous trial | 30°C    | Hydorider®         | Xiphoid process |
| Giacomini [44]  | 2009 | Cross-over   | To assess HR and VO2 responses in men and women exercising on four different water EM | n = 16  
   F/ M = 8/8  
   age: 31.5 ± 5.8 | Exercise: incremental exercise test on 4 aqua bikes: with no resistance, with resistance added to the bottom bracket axle, with resistance added to the pedals  
   Initial rpm: 40 rpm  
   Increments: 5 rpm every 2 min until the participant was unable to maintain the set rpm | • No difference in VO2peak, HRpeak and rpm for gender  
   • No difference in VO2peak and HRpeak between different bikes  
   • Time to exhaustion and rpm at volitional exhaustion was different across the 4 bikes  
   • At 70 rpm the 4 aqua bikes generated different HR and VO2 peak  
   • BMI and change in Tcore were partial correlated during 35˚C water trials | 25°C    | 4 different aqua bikes | Hips and thighs are immersed |
| White [51]      | 2005 | Cross-over   | To describe the acute effect of cold water temperature on post-exercise energy intake | n = 11  
   M  
   age: 25.6 ± 5 | Exercise: steady cycling  
   Duration: 45 min  
   Intensity: 60% VO2peak  
   Rpm: NR | • Post-exercise energy intake was higher after the cold water AC  
   • Energy expenditure was similar for the cold and neutral water temperature trials | 20˚C, 25˚C  
   30˚C, 35˚C | Modified Monark EM (Morlock& Dressen-dorfer) | Mid-sternum |
| McMurray [52]   | 1994 | Cross-over   | To investigate the effects of anthropometrics and VO2peak on plasma cortisol and urine excretion of catecholamine and dopamine during exercise in different Twater | n = 11  
   M  
   age: 17–25 (range) | Exercise: steady cycling vs. resting immersion  
   Duration: 30 min  
   Intensity: 60% VO2peak  
   Rpm: NR | • Change in Tcore was related to Twater  
   • Plasma cortisol increased from resting to exercise in 30˚C and 35˚C water and decreased in 30˚C and 35˚C water  
   • Dopamine and norepinephrine were higher during 20˚C and 35˚C water AC exercise compared to exercise in 25˚C and 30˚C water  
   • VO2peak and change in Tcore were partial correlated in 30˚C water AC trial  
   • BMI and change in Tcore were partial correlated during 35˚C water trials | 20˚C, 25˚C  
   30˚C, 35˚C | Modified Monark EM (Morlock& Dressen-dorfer) | Neck |

(Continued)
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<th>Exercise Protocol</th>
<th>Measurements</th>
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</table>
| Katz [53, 54] McMurray [47, 55, 56] | 1990 | Cross-over | 12 F at 15, 25 and 35 wk gestation and at 8 to 12 wk post-partum | Exercise: steady cycling | FO fetal HR were normal and unchanged from those at rest during exercise [54]...
| | | | | | Post-exercise stress tests were reactive within 10 min in 21 of 23 cases [55]...
| | | | | | There was no uterine activity seen at 25 and 35 wk gestation [54]...
| | | | | | Maternal serum alphafetoprotein was unaffected at all gestational ages [54]...
| | | | | | T maternal and calculated plasma volume did not change during exercise [54]...
| | | | | | Diuresis was greater during pregnancy than postpartum, natriuresis was similar for all conditions [53]...
| | | | | | Compared to 10 weeks postpartum, pregnancy reduced heat storage, lowered T skin, and increased evaporative heat loss during immersion and exercise [56]...
| | | | | | VO\textsubscript{2} during AC was similar for all trials, but workload to achieve 60% VO\textsubscript{2max} decreased\textsuperscript{*} during 35th wk of pregnancy [55]...
| | | | | | Post-partum exercise cardiac output was lower\textsuperscript{*} [47]...
| | | | | | Post-partum total peripheral resistance was higher\textsuperscript{*} [47]...
| Shapiro [64] | 1981 | Cross-over | 6 M athletes | Exercise protocol described | Changes in metabolic rate were greater\textsuperscript{*} for runners in 20°C water and for swimmers in 30°C and 35°C water...
| | | | | | Runners had higher\textsuperscript{*} sweat rates during exercise in 35°C water...
| | | | | | Swimmers thermoregulated better in 20°C water than on land during pregnancy and postpartum [47]...
| McMurray [57] | 1979 | Cross-over | 11 M athletes | Exercise: steady AC | Changes in metabolic rate were greater\textsuperscript{*} for runners in 20°C water and for swimmers in 30°C and 35°C water...

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<td>Dresen-dorfer</td>
<td>[23]</td>
<td>Cross-over</td>
<td>To determine the effect of water temperature on V̇O₂max and HRmax</td>
<td>n = 4</td>
<td>- Individual prescribed maximal workloads to achieve exhaustion within 4 to 5 min</td>
<td>• Twater had no significant effect on V̇O₂max</td>
<td>25°C</td>
<td>Neck</td>
<td>18˚C</td>
</tr>
<tr>
<td>Morlock</td>
<td>[63]</td>
<td>Cross-over</td>
<td>To modify a standard land EM for underwater use and to measure V̇O₂ as a function of rpm</td>
<td>n = 6</td>
<td>- Exercise: incremental exercise</td>
<td>• Pressure frequency product was higher* during AC in 35˚C compared to AC in 26˚C water</td>
<td>30˚C</td>
<td>Neck</td>
<td>18˚C</td>
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SEMIRECLUMBENT BODY POSITION

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<th>Aquatic bike design</th>
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<td>Fujimoto</td>
<td>2016</td>
<td>Cross-over</td>
<td>To investigate the effects of Twater on cardiorespiratory responses and exercise per-formance</td>
<td>n = 10</td>
<td>- Exercise: incremental exercise</td>
<td>• VO₂max did not differ between Twater</td>
<td>18˚C</td>
<td>Aerobike 330</td>
<td>Shoulders</td>
</tr>
<tr>
<td>Fenal</td>
<td>2010</td>
<td>Cross-over</td>
<td>To compare the effects of different Twater on BP, HR and pressure frequency product</td>
<td>n = 8</td>
<td>- Exercise: 3 trials in 26˚C, 32˚C and 36˚C water</td>
<td>• HR was highest* during AC in 35˚C water</td>
<td>26˚C</td>
<td>Hand-breath</td>
<td>Above xiphoid process</td>
</tr>
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<td>McArdle</td>
<td>1992</td>
<td>Cross-over</td>
<td>To compare the influence of exercise intensity on the muregulation in men and women in cool and cold water</td>
<td>n = 16</td>
<td>- Exercise: steady AC vs. resting immersion</td>
<td>• VO₂peak was greater* for women during resting immersion and level I exercise in 35˚C water</td>
<td>20˚C</td>
<td>Modified Collins EM (Craig &amp; Dvorak)</td>
<td>1st thoracic vertebra</td>
</tr>
<tr>
<td>Sogabe</td>
<td>1987</td>
<td>Cross-over</td>
<td>To describe a simple modification of a conventional row-bicycle EM applicable for graded horizontal exercise in water</td>
<td>n = 7</td>
<td>- Exercise: exercise tests with various combinations of pedalling speeds and size of fins</td>
<td>• VO₂peak was greater* for women during resting immersion and level I exercise in 35˚C water</td>
<td>31˚C</td>
<td>Modified row-cycle EM (Sogabe)</td>
<td>Neck</td>
</tr>
<tr>
<td>Golden</td>
<td>1987</td>
<td>Cross-over</td>
<td>To describe the thermal response of leg exercise compared to static immersion in cold water</td>
<td>n = 15</td>
<td>- Exercise: steady AC vs. resting immersion</td>
<td>• EM modifications: replacement of the saddle with a plastic seat, fastening of fins to the pedal cranks, removal of the handle</td>
<td>15˚C</td>
<td>Modified electronically braked Siemens bicycle EM</td>
<td>NR</td>
</tr>
<tr>
<td>Toner</td>
<td>1986</td>
<td>Cross-over</td>
<td>To investigate the role of morphology and body mass on thermal and metabolic responses to AC</td>
<td>n = 10</td>
<td>- Exercise: steady cycling (vs. resting immersion)</td>
<td>• VO₂ of 400–2000 ml/min</td>
<td>26˚C</td>
<td>Modified Monark EM (Shapiro)</td>
<td>Neck</td>
</tr>
<tr>
<td>Toner</td>
<td>1985</td>
<td>Cross-over</td>
<td>To examine the relationship between physiological and perceptual variables over time and across water temperature during various modes of AC</td>
<td>n = 6</td>
<td>- Exercise: leg vs. arm-leg vs. arm exercise</td>
<td>• VO₂peak did not differ between types of exercise and Twater</td>
<td>20˚C</td>
<td>Modified Monark EM (Shapiro)</td>
<td>Neck</td>
</tr>
<tr>
<td>Toner</td>
<td>1980</td>
<td>Cross-over</td>
<td>To compare the thermal and metabolic response during resting immersion and AC in cool and cold water</td>
<td>n = 9</td>
<td>- Exercise: steady cycling (vs. resting immersion)</td>
<td>• VO₂peak was greater* during AC than with resting immersion</td>
<td>18˚C</td>
<td>Modified Monark EM (Shapiro)</td>
<td>Neck</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Study</th>
<th>Year</th>
<th>Design</th>
<th>Objective</th>
<th>Participants</th>
<th>Exercise Details</th>
<th>Conditions</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toner [61]</td>
<td>1984</td>
<td>Cross-over</td>
<td>Thermal and metabolic response during arm, leg and combined arm-leg exercise</td>
<td>n = 8 M  age: 22.4 ± 3.6</td>
<td>Exercise: leg vs. arm-leg vs. arm exercise  Duration: 45 min  Intensity: high (60% VO$<em>{2peak}$) vs. low (40% VO$</em>{2peak}$) for leg and arm-leg exercises, only low intensity for arm exercises  RPM: 40</td>
<td>20˚C, 26˚C, 33˚C</td>
<td>In all T$<em>{rectal}$ there was no difference between exercise types in final metabolic rate during low intensity  Final T$</em>{rectal}$ during low intensity exercise for arm, arm-leg trials were lower* than for leg trials  At high intensities final T$<em>{rectal}$ were lower* for arm-leg than for leg exercise in all T$</em>{water}$  No difference between exercises in final T$_{skin}$ and heat flow values  Metabolic rate was lower in leg exercise compared to arm-leg exercise at high intensity in 20˚C water</td>
</tr>
<tr>
<td>Craig [50]</td>
<td>1968</td>
<td>Cross-over</td>
<td>To investigate thermal regulation during heavy and light exercise in cool and warm water</td>
<td>n = 10 M  age: 27 ± 5.8</td>
<td>Exercise: steady AC  Duration: 60 min  Intensity: light workload (VO$_2$ = 0.70 litres/min) vs. heavy workload (VO$_2$ = 0.92 litres/min). Workload was increased by an increase in pedaling resistance  RPM: 30</td>
<td>24–35˚C</td>
<td>VO$<em>2$ was higher during the last 30 min of light exercise in 24˚C  After an initial increase in T$</em>{ear}$, T$<em>{ear}$ decreased with light exercise in water with ≤ 32˚C and with heavy exercise in 24˚C water  T$</em>{rectal}$ continuously declined with light work load and in water with ≤ 32˚C, when exercising with heavy workload an initial decrease of rectal temperature was followed by and increase that persisted with T$_{water}$ of 28–32˚C</td>
</tr>
</tbody>
</table>

AC, aquatic cycling; BL, blood lactate; BMI, body mass index; BP, blood pressure; C, Celsius; EM, ergometer; F, female; HR, heart rate; HRV, heart rate variability; LC, land-based cycling; M, male; min, minute(s); NR, not reported RPE, rate of perceived exertion; RPM, revolution per minute; SE, Standard Error; T, temperature; VO$_2$, oxygen uptake; wk, week(s)

* significant at p-value <0.05

**, significant at p-value <0.01

*If not stated otherwise participants are healthy and age is presented in years as mean ± standard deviation.

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Aquatic cycling resulted in lower maternal and foetal HR compared to land-based cycling [38]. Four studies reported higher stroke volume and cardiac output in the aquatic cycling group consisting of healthy participants [15, 21, 29, 30]. Systolic blood pressure was similar in healthy males during an incremental exercise test when using aquatic versus land-based cycling [18, 21]. In pregnant women and in men with coronary artery disease the systolic blood pressure was reported to be lower during submaximal aquatic cycling [27, 32, 37, 38]. Sosner et al. reported a similar post-exercise reduction in blood pressure in patients with hypertension after a high-intensity cycling session on land and in water [42].

Other key outcomes were ventilation parameters [23, 31, 33], lipid mobilisation and oxidation [18, 34], sympathoadrenal response [18, 20, 34], lactate accumulation and removal [17, 18, 20, 39, 40], and thermoregulatory responses [35–37]. Further outcomes were the development of prediction equations to estimate oxygen consumption from pedalling rate during aquatic cycling [13, 14] and to calculate external power output of aquatic cycling [13]. Fenzl et al. compared the gas exchange measurements with the heart rate variability to estimate the ventilator threshold on an arm-leg aquatic bike [11].

Aquatic cycling under different exercise conditions

Twenty-five studies investigated the effect of several different exercise conditions during aquatic cycling (Table 4). The comparisons are based on cross-over studies with healthy young males with the exception that healthy (non-pregnant) females were included in three studies [43–45] and one study used a quasi-experimental design to compare age-matched healthy controls with heart disease patients [46]. Common core outcomes were cardiovascular [12, 23, 44, 47–50], metabolic [36, 51–55] and thermal response [43, 49, 50, 52, 56–61] to different exercise conditions. Furthermore, approaches to estimate and regulate exercise intensity during aquatic cycling were evaluated [62–64].

Different exercise conditions were created mostly by changes in water temperature [12, 23, 43, 48–52, 57, 60, 61] and different exercise intensities (high versus low) [23, 43, 44, 50, 58–61, 63–65]. With regard to the exercise parameters intensity and duration, studies (n = 11) utilised continuous, submaximal exercise (40 and 60% of VO$_{2_{max}}$) with a duration of 30 to 60 minutes [12, 23, 43, 49, 51, 52, 57, 60, 61]. Exercise intensities were either based on graded exercise testing on land [12, 23, 44, 45, 47, 50, 51, 53–56, 58] or in water [23, 43, 46, 48, 52, 57, 62–64]. The water temperatures that were compared ranged from cold (18–20°C) and cool (25°C) to thermoneutral (30–35°C). Other studies compared different levels of body immersion [46], different types of exercise (interval versus continuous cycling, arm versus arm-leg versus leg exercise) [45, 49, 61] and different aquatic bikes with each other [44]. Furthermore, the maternal and foetal response to submaximal (60% of VO$_{2_{max}}$) aquatic cycling during different stages of pregnancy was studied [47, 53–56].

Fifteen studies used upright aquatic bikes [23, 44–47, 51–57, 62–64]. In all these studies pedalling frequency regulated exercise intensity while two studies focused on the influence of pedalling resistance provided by additional fins to the flywheel [44, 64]. Sogabe et al. used the additional fins to increase pedalling resistance in semi-recumbent cycling [65]. In all other semi-recumbent bikes intensity was set with electronically controlled pedalling resistance mechanisms [43, 48–50, 58–61].

Aquatic cycling intervention programmes

In total eight intervention studies, investigating the effects of a multiple sessions aquatic cycling exercise programme, were found [66–73]. The exercise programmes (Table 5) lasted between three and 36 weeks with an exercise frequency between two and five times per week.
<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Study design</th>
<th>Study aim</th>
<th>Sample</th>
<th>Exercise parameters</th>
<th>Key findings</th>
<th>$T_{\text{water}}$</th>
<th>Aquatic bike used</th>
<th>Immersion depths</th>
</tr>
</thead>
</table>
| Boidin     | 2015    | Retro-spective cohort: AC vs. LC | To compare the effects of a lifestyle intervention in addition to AC or LC on cardiometabolic and exercise parameters in obese patients | n = 95 obese people (F/M: 59/36) age: 58 ± 9 | Exercise programme: HIIT AC + water-based resistance training, 5x Mediterranean diet counselling | • Reduction** in body mass, WC, total and trunk fat mass; no group difference
• Improvement* in resting BP, maximal aerobic capacity, resting HR; no group difference
• Improvement* in fasting glycaemia, triglyceride levels; no group difference
• Improvement* in abdominal and thigh muscle endurance; no group difference | NR | Hydrorider® | NR |
| Bansri     | 2013    | RCT: AC vs. LC       | To investigate the influence of exercise in cytokine response, health-related QoL, fatigue, neurotrophin concentrations and cardiorespiratory values | n = 60 MS patients (F/M: 17/8), age: 50, range: 44.6–55.1 | Exercise programme: steady AC + usual care rehabilitation | • Short term immune adaptations and increased VO$_2$ lactate values were associated with improved health-related QoL and reduced fatigue [73]
• Improved health-related QoL; no group difference [73]
• Improved self-reported physical fatigue; no group difference [73]
• Cytokines and neurotrophins showed no change over time and between groups [72]
• Fatigue scores associated with baseline and post-intervention exercise tests remained unchanged in both groups [72]
• Cardiorespiratory values improved** over time; no group difference [72] | 28°C | Aquarider Professional® | 1,30m |
| Young      | 1995, 1993 | Quasi-experiment: hot vs. cold water | Comparison of metabolic and thermal adaption to endurance training in hot and cold water and its effect on aerobic capacity | n = 18 M, 20°C water: n = 9, age: 20 ±1, 35°C water: n = 9, age: 20 ±1 | Exercise programme: steady AC in hot or cold water | • Reduced* post-exercise muscle glycogen use; no group difference [20]
• Lactate accumulation was equal for hot and cold water [70]
• 13% post-intervention increase** of VO$_2$ max; no group difference [69, 70]
• 4% increase** of erythrocyte volume; no group difference [69]
• Unchanged plasma volume; no group difference [69]
• 38% increase** of vastus lateralis citrate synthase activity; no group difference [69] | 35°C vs. 20°C | Modified Monark EM (Shapiro) neck |  

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<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Study design</th>
<th>Study aim</th>
<th>Sample</th>
<th>Exercise parameters</th>
<th>Key findings</th>
<th>$T_{\text{Water}}$</th>
<th>Aquatic bike used</th>
<th>Immersion depths</th>
</tr>
</thead>
</table>
| Avellini    | 1982 | Quasi experiment: warm vs. cold water vs. land | To determine how physical training on land compared to warm and cold water training affects heat tolerance | $n = 15$ M  
land: $n = 5$, age: 23.2±4.7  
$32^\circ$C water: $n = 5$, age: 20.8±1.8  
$20^\circ$C water: $n = 5$, age: 23.0±4.1 | Exercise programme: steady AC in warm and cold water. Groups were divided based on the maximal exercise capacity, body surface area, and % body fat.  
- Programme duration: 4wk  
- Frequency: 5/wk  
- Duration session: 60min  
- Intensity: 75% $V_O^{2\text{max}}$  
- Rpm: NR | Similar increase in $V_O^{2\text{max}}$: no group difference  
- Higher* post-training values of $T_{\text{rectal}}$ for LC compared to AC  
- 0.9°C reduction* of post-training mean $T_{\text{skull}}$ for LC and warm water AC  
- Post-training total body sweat: increased* only warm water AC (25%).  
- Post-heat acclimation: only cold water AC demonstrated an increase* in sweat rate (25%).  
- Decrease* in post-training HR in all 3 groups, greatest decline (29 beats min) in land group. HR in warm and cold-water AC HR decreased 14 and 18 beats min.  
- Post-heat acclimation HR: reduction* from post-training values in all groups | 20°C vs. 32°C | Modified Monark EM       | neck |
| Sheldahl    | 1986 | RCT: AC vs. LC vs. control | Comparison of land and water training to determine whether the cephalad shift in blood volume due to water immersion affects normal adaptations to aerobic endurance training | $n = 22$ M  
- age: 49±8  
- water: $n = 9$  
- land: $n = 9$  
- control: $n = 4$ | Exercise programme: steady AC  
- Programme duration: 12wk  
- Frequency: 3/wk  
- Duration session: 30min  
- Intensity: 60–80% $V_O^{2\text{max}}$  
- Rpm: NR | Increase* in SV at submaximal exercise intensities; no difference between AC and LC  
- Increase** in $V_O^{2\text{max}}$ in both exercise groups  
- Decrease** in HR at submaximal exercise intensities; no difference between AC and LC  
- Decrease* in BP at submaximal exercise intensities in LC and AC group | 31°C | Modified Monark EM (Morlock & Dressendorfer) | Shoulder |
| Sheldahl    | 1982 | Single group test-retest | To investigate if AC in cold water leads to weight loss | $n = 7$ obese F  
- age: 31.4±11.1 | Exercise programme: steady AC in cold water. $T_{\text{water}}$ was determined in preliminary tests in 31°C, 30°C, 28°C, 24°C and 20°C water.  
- Programme duration: 8wk  
- Frequency: 5/wk  
- Duration session: 90min  
- Intensity: 30–40% $V_O^{2\text{max}}$  
- Rpm: NR | No change in body weight, body fat, fat-free body weight  
- Constant caloric intake throughout the intervention  
- $V_O^{2\text{max}}$ did not change | 17–22°C | Modified Monark EM (Morlock & Dressendorfer) | neck |

AC, aquatic cycling; BL, blood lactate; BP, blood pressure; C, Celsius; EM, ergometer; F, female; HIIT, high-intensity interval training; HR, heart rate; LC, land-based cycling; M, male; m, meter; min, minute(s); MS, multiple sclerosis; NR, not reported; QoL, quality of life; RCT, randomized controlled trial; Rpm, revolution per minute; SV, stroke volume; T, temperature; $V_O^2$, oxygen uptake; W, Watts; WC, waist circumference; wk, week(s)

* significant at p-value <0.05
** significant at p-value <0.01
*If not stated otherwise participants are healthy and age is presented in years as mean±standard deviation.

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The duration of one session varied between 30 and 90 minutes. Exercise intensities were based on land-based maximal graded exercise-tests and the training intensities were set between 60 and 80% of the VO2max in all but one study [66]. In a one-group test-retest study, Sheldahl et al. assessed weight loss in obese women after a low intense (30 to 40% of VO2max) aquatic cycling programme [66]. Boidin et al. also evaluated the effects of aquatic cycling on cardiometabolic parameters in obese people [71]. In this retrospective study the participants underwent an extensive lifestyle programme including high-intensity aquatic cycling or land cycling. Furthermore, two randomised studies evaluated the cardiovascular effect of aquatic cycling compared to land cycling in young healthy males [68] and patients with multiple sclerosis [72, 73]. Two quasi-experimental studies investigated the influence of water temperature on heat tolerance and aerobic capacity [67, 69, 70].

Four studies reported a significant improvement of cardiorespiratory parameters compared to baseline in healthy (obese) people and multiple sclerosis patients [68, 71–73]. Aquatic and land cycling evoked similar improvements in cardiorespiratory parameters. Further, moderate land and aquatic cycling achieved similar improvements in health-related quality of life and self-reported physical fatigue in patients with multiple sclerosis [72, 73]. Boidin et al. reported comparable results in weight loss and reduction in fasting glycaemia and triglyceride levels in obese people [71]. In obese women, an eight week aquatic cycling programme in cold water did not lead to weight loss [66].

In young, healthy males, there was no superior effect of cold or warm water on the improvements in cardiovascular parameters [67, 69, 70], lactate accumulation lactate accumulation [69], dryland heat tolerance [67] and muscle glycogen utilization [69].

Discussion
This is the first review to scope the available literature on head-out aquatic cycling exercise. The aim of this review was to describe the study parameters of available research utilising aquatic cycling as an exercise modality. Sixty-three publications were identified and the review provides a full summary of the set-up of aquatic interventions and possible comparisons, core outcomes, involved participants and the study designs utilised in current literature. The exploration of the intervention parameters revealed great variety on the use and execution of aquatic cycling.

Land-based cycling versus aquatic cycling
The main body of the current research on aquatic cycling focuses on cardiovascular outcomes and the core findings for the comparison between land-based and water-based cycling showed similar trends. These latter studies [17–23, 26] reported comparable VO2max values of aquatic and land-based cycling and therefore, the cardiac demand of aquatic cycling seems similar to land-based cycling. The results for HR were less consistent with a tendency for a lower HR during aquatic cycling compared to land-based cycling [20–23, 26, 29, 30]. Further, cardiac output and stroke volume was reported to be higher during aquatic cycling [15, 21, 29, 30]. These results are in line with the general understanding concerning the effects of water immersion on the human body. Hydrostatic pressure exerts external pressure on the immersed body, which increases with increased depth [2, 74]. Due to the hydrostatic pressure exerted there is a shift of blood from the extremities to the chest cavity, increasing arterial filling, and thus cardiac output and stroke volume are increased [2, 74]. Because cardiovascular parameters are modified by immersion, this could explain why the literature is inconclusive on the optimal recommendations for exercise prescription during aquatic cycling. Another explanation maybe as most aquatic bikes are not equipped with an electronically controlled pedalling
resistance mechanism and approaches to estimate VO\textsubscript{2} from aquatic cycling are often based on pedalling frequency, with or without additional resistance. However, these equations cannot be used for all aquatic bikes, as the design and drag resistance created by pedals and resistance fins vary considerably across the aquatic bikes.

**Aquatic cycling under different conditions**

Due to the heterogeneous nature of aquatic cycling, many variables are involved when studying its impact on individuals, for example device-specific factors [44, 63–65] or environmental parameters as water temperature [12, 23, 43, 48, 49, 51, 52, 56–61]. Thus explaining why the cardiovascular response to different exercise conditions was frequently investigated. For example, it seems that VO\textsubscript{2max} is comparable across different water temperatures and that participants perceived exercising in warm water as more exhaustive [23, 48, 49]. Further, included studies concluded that exercise intensities up to maximal limits are achieved by an increase in pedalling frequency and that VO\textsubscript{2peak} does not differ between the different types of aquatic bikes [44, 64]. However, high-pedal frequencies are difficult to maintain during longer exercise sessions with a continuous character [44, 64]. To avoid discomfort with maintaining high pedal frequencies, exercise intensity can be modified by an increase in pedalling resistance or by utilising an interval training [45]. The latter was perceived less exhaustive than a continuous protocol [45].

**Aquatic cycling as an intervention**

Only six studies investigated the effect of multiple aquatic cycling sessions [66–73]. In four studies aquatic cycling was used in a clinical context for patients with multiple sclerosis and as exercise training for older adults and obese individuals. Research showed that aquatic cycling was equally effective than land-based cycling for improving cardiovascular fitness [66, 68, 71–73]. Furthermore, none of the included studies reported adverse events related to the training, suggesting that aquatic cycling is a safe exercise modality.

Most of the exercise protocols of the aquatic cycling intervention programmes consisted of steady cycling in a seated position with moderate intensity. Only Boidin et al. used an interval protocol for the training of obese individuals [71]. It seems that the full potential of aquatic cycling including out-of-saddle positions and arm and trunk exercises is not published yet in peer-reviewed journals [7]. Addition of these elements might prevent monotony especially in multiple session programmes [75] and results from supportive literature suggest that a full spectrum aquatic cycling programme is effective in patients with musculoskeletal disorders [76].

This scoping review has identified a number of areas for further research. Most of the included studies have a cross-over design with few cycling sessions and investigated the exercise response in young healthy males, because gender, body mass and morphology are known to affect the response to aquatic cycling [59, 77, 78]. Further, only six studies investigated the effect of an aquatic cycling intervention programme. To improve the use of aquatic cycling in healthcare, future studies, preferably RCTs, should investigate the effects of aquatic cycling interventions in different populations and on outcomes such as (joint) pain, muscle strength or physical functioning, which are yet to be investigated. Of specific interest may also be the biomechanics of aquatic cycling and differences of seated and out-of saddle cycling. Furthermore, the identified literature seems suitable for more systematic reviews. For example it seems worthy to synthesize the available evidence on cardiovascular responses to aquatic cycling.

To further improve the understanding of acute and long-term physiological adaptations to aquatic cycling training and facilitate between study comparisons, consistent reporting of the
following parameters is recommended. Studies should describe the type of aquatic bike, body position, level of immersion, water temperature, methods used to control and assess exercise intensity i.e. training frequency, duration, rpm and pedalling resistance. Furthermore, it should be stated whether or not adverse events occurred. In addition to an accurate description of the aquatic cycling intervention, an agreement of experts on uniform keywords to describe the exercise activity is also strongly advised since this would improve the search in scientific databases. In this review the terms “aquatic cycling” and “aquatic bike” were used, as these expressions nowadays are commonly associated with this type of exercise.

This review has strengths and weaknesses. The extensive search procedure in this review resulted in more than sixty publications on aquatic cycling only, which were summarized and displayed. However, the presented studies should be interpreted with caution, because no quality assessment of the internal validity of the included studies was made in order to cover a broad spectrum of literature. Furthermore, this review provides a very general overview of the research on aquatic cycling without focusing on certain details of the included studies. For example, only the main outcomes reported in the abstract of the included studies were reported in this review. Yet, this comprehensive outline of available literature in this scoping review could serve as a starting point for systematic reviews or clinical studies on the effects of aquatic cycling on the cardiovascular responses.

Conclusion

This is the first scoping review to summarise the literature on head-out aquatic cycling. There are numerous variables related to aquatic cycling e.g., the type of aquatic bike or environmental factors e.g., water temperature or immersion level. As a result, the objectives of the identified studies in this review are heterogeneous. Most of the included studies compared aquatic cycling with land-based cycling or examined how to quantify and modify exercise intensity. Very few studies evaluated the effect of aquatic cycling interventions. Cardiovascular parameters were investigated by many of the studies and the results suggest that the cardiac demand of aquatic cycling seems similar to land-based cycling. Therefore, further research should synthesize the effects of aquatic cycling on cardiovascular parameters in a systematic review. Future studies should evaluate the effects of aquatic cycling interventions in a clinical and rehabilitative context.

Supporting information

S1 File. Post-hoc analysis of search terms.
(DOCX)

S2 File. Development of the inclusion and exclusion criteria.
(DOCX)

S3 File. Excluded articles.
(DOCX)

Author Contributions

Conceptualization: SR IM AFL JB JL RAdB BW.

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Project administration: SR BW.

Supervision: BW IM RAdB.

Visualization: SR IM AFL JB JL RAdB BW.

Writing – original draft: SR.

Writing – review & editing: SR IM AFL JB JL RAdB BW.

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