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Efficiency in Cycling for Road and Triathlon Disciplines: Determinants and Insights

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KEYWORDS: CYCLING; TRIATHLON; EFFICIENCY; PHYSIOLOGY; BIOMECHANICS

Dedication

Para aqueles que o coração já não sente,
mas que a mente nunca esquecerá.

Avó Olívia, Avô Zé, D.Fernanda e Fatinha

"I wish to preach, not the doctrine of ignoble ease, but the doctrine of the strenuous life, the life of toil and effort, of labor and strife; to preach that highest form of success which comes, not to the man who desires mere easy peace, but to the man who does not shrink from danger, from hardship, or from bitter toil, and who out of these wins the splendid ultimate triumph… We do not admire the man of timid peace. We admire the man who embodies victorious effort; the man who never wrongs his neighbor, who is prompt to help a friend, but who has those virile qualities necessary to win in the stern strife of actual life. It is hard to fail, but it is worse never to have tried to succeed. In this life we get nothing save by effort."

Theodore Roosevelt

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“Expressar a gratidão não é simplesmente dizer algumas palavras,
mas sim viver de acordo com elas”
John F. Kennedy

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Abstract

Cycling is a demanding endurance sport, and a key modality during triathlon events. Cycling efficiency is determinant on cycling, which can affect performance and predict race's outcome. Therefore, the aim of this Academic dissertation, written according to the Scandinavian method, was to identify and summarize the determinants factors that impact cycling efficiency. For the identification of the studies, we searched in the electronic databases of PubMed, Scopus and Web of Science including all studies until January 2025. In addition, conducted a manual search within the reference lists of the studies selected. The selection of the studies and the data extraction followed the PRISMA 2020 guidelines. We included only randomized controlled trials (RCTs). The eligibility criteria included athletes of all levels, ages, and genders, excluding any study involving participants with a metabolic disease or who were undergoing rehabilitation. The risk of bias was assessed using the Joanna Briggs Institute critical appraisal tools for RCTs. A total of 35 studies (589 participants) were included after the screening process. There was high heterogeneity regarding age and performance level, and the risk of bias was considered high while evidence certainty was judged as low. The studies investigated different cycling efficiency variables including delta efficiency, gross efficiency, net efficiency, and work efficiency. Lower cadence positively impacts cycling efficiency whereas prolonged cycling, hypoxia and hyperoxia negatively affects cycling efficiency. Other determinants such as strength training, sprint training, supplementation and heat acclimation need further investigation to clarify their effect(s). Given the high heterogeneity and the low level of evidence, further studies are needed to better clarify the effects of the factors that influence cycling efficiency, particularly those involving experimental studies testing the impact of the abovementioned determinants.

KEYWORDS: CYCLING; TRIATHLON; EFFICIENCY; PHYSIOLOGY; BIOMECHANICS

Resumo

O ciclismo é um desporto de resistência exigente e uma modalidade essencial em eventos de triatlo. A eficiência no ciclismo é determinante para o desempenho, pode afetar o mesmo e prever o resultado da prova. O objetivo desta Dissertação académica, escrita de acordo com o modelo escandinavo, foi identificar e resumir os fatores determinantes que afetam a eficiência no ciclismo. Para identificar os estudos a selecionar, as bases de dados *PubMed, Scopus* e *Web of Science* foram pesquisadas em janeiro de 2025. A seleção dos estudos e a extração dos dados seguiram as normas PRISMA 2020. Apenas ensaios clínicos randomizados (RCTs) foram incluídos. Os critérios de elegibilidade incluíram atletas de todos os níveis, idades e sexos, excluindo qualquer estudo envolvendo participantes com doença metabólica ou que estivessem em reabilitação. O risco de viés foi avaliado utilizando as ferramentas de avaliação crítica do *Joanna Briggs Institute* para RCTs. Um total de 35 estudos (589 participantes) foram incluídos após este processo de triagem. Uma alta heterogeneidade em relação à idade e ao nível de desempenho foi identificada. O risco de viés foi considerado alto, enquanto a certeza na evidência foi considerada baixa. Os estudos investigaram diferentes variáveis de eficiência do ciclismo, incluindo a variação da eficiência, a *gross efficiency*, a *net efficiency* e *work efficiency*. A adoção de cadências mais baixas tem um impacto positivo na eficiência, enquanto o ciclismo prolongado, a hipoxia e a hiperoxia a afetam negativamente. O treino de força, de sprints, a suplementação e a aclimatação ao calor precisam de mais investigação. Serão necessários mais estudos para esclarecer melhor os efeitos dos fatores que influenciam a eficiência do ciclismo, particularmente aqueles que envolvem estudos experimentais que testam o impacto dos determinantes acima mencionados.

PALAVRAS-CHAVE: CICLISMO; TRIATLO; EFICIÊNCIA; FISIOLOGIA; BIOMECÂNICA;

List of Abbreviations

βHB - β-hydroxybutyrate

BP - Block periodization endurance training plan

BR - Beetroot

CAF - Caffeine

CE - Cycling efficiency

CHO - Carbohydrate

COMP - Competitive period

CON - Control group

DE - Delta efficiency

d - Effect size

EE - energy expenditure

ES - Effect size

EXP - Experimental group

FCC - Freely chosen cadence

FGS - Fatigued State

FS - Fresh state

GD - Glycogen depletion

GE - Gross efficiency

HA - Heat Acclimation

HC - High cadence

HCHO - High in CHO

HYPO - Hypoxia

HYPER - Hyperoxia

JBI - Joanna Briggs Institute

LC - Low cadence

LCHO - Low in CHO

LT - lactate threshold

MCHO - Moderate amount of CHO

NE - Net efficiency

NORM - Normoxia

OA - oxygen availability

OEMP - optimal efficiency for maximum power

p - p-values

PC - Prolonged cycling state

PLA - Placebo

PO - Power output

PREP - Preparatory period

PRISMA - Preferred Reporting of Systematic Reviews and Meta-Analysis

QUE - Quercetin

RCT - Randomized Controlled Trials

RPM - Revolutions per minute

ROT - Rotor pedaling system

SB - Sodium Bicarbonate

SD - Standard Deviation

SFF - Semi-fatigued state

SL - Sleep Low

SP - Sodium Phosphate

SS - Steady state

ST - Strength training

SPT - Sprint training

TC - Traditional cranks

TP - Traditional periodization endurance training plan

TRAN - Transition period

UC - Uncoupled cranks

$\dot{V}O_{2max}$ - Maximal oxygen consumption

W - Watts

WA - Water

WE - Work efficiency

WR - Work rate

Chapter I – Introduction

1.1. Rationale

Cycling is a mean of transport, used worldwide, which can provide health benefits to its practitioners (Oja et al., 2011). It has been recommended as an important alternative for public health promotion (Oja et al., 2011) and has been gaining interest, with a growing number of community participants. This is reflected in a clear expansion in the competitive setting into organized sport events (Faria et al., 2005b). Currently, there are many different modalities in competitive cycling, such as road cycling, mountain biking, track cycling, downhill cycling, time trials, and others with its own characteristics, specifications, rules, and requirements. Cycling is also one of the disciplines that composes a triathlon, which is a multidisciplinary sport combining swimming, cycling and running in the same event (Etxebarria et al., 2019). Like cycling, triathlon has different events. The official events in triathlon are the Super-Sprint distance race, the Sprint race distance, the Olympic distance, the Half-Ironman, mostly known as the 70.3 race, Ironman (the longest-distance triathlon), and the Mixed Team Relay Race (Etxebarria et al., 2019).

In fact, cycling plays the most important role in terms of time contribution to a triathlon's overall time as the discipline that has a bigger course extension (Sousa et al., 2019). Nevertheless, the impact that each one of these three disciplines has on a triathlon race's final performance varies among the race distances (Sousa et al., 2019). Sousa et al. (2019) reported that cycling performance is the best predictor for a performance of sub 8 hours in the Ironman events. Cycling is also the most important predictive discipline in the Mixed Team Relay format and in the Super-Sprint, Sprint and Half-Ironman distances (Nikolaidis et al., 2023; Quagliarotti et al., 2022; Sousa et al., 2021; Weiss et al., 2024). Regarding on how cycling could affect the performance in the triathlon events, Peiffer et al. (2016) suggest that there is an age-related decline in triathlon performance (which is discipline dependent). When comparing to running and swimming, cycling is the race segment with a lowest substantial decline. Hence, cycling seems to play an important role in triathlon, and cycling performance will most likely influence a triathlon's final performance.

Cycling is a demanding endurance sport (Kristoffersen et al., 2019) and have many determinants affecting its performance and race result. For instance, cycling efficiency (CE) is considered a key determinant for cycling performance (Artetxe-Gezuraga et al., 2019; Cámara et al., 2012; Carlsson et al., 2024; Clark et al., 2007; Fletcher et al., 2019; Jobson et al., 2009; Tang et al., 2022). The CE is a measure of effective work, representing total expended metabolic energy for a produced external work, usually expressed in percentage (Faria et al., 2005a).

There are some quantitative CE indices reported in the literature and between them, the most studied are gross efficiency (GE), delta efficiency (DE), net efficiency (NE) and work efficiency (WE) (Faria et al., 2005a; Hopker et al., 2009; Millet et al., 2002).

According to Matomäki et al. (2019), the following formulas represent each one of the indices.

GE formula is: $GE(\%) = \frac{W_{ext}}{E_{tot}} \times 100$, where W_{ext} is the accomplished mechanical work and E_{tot} the total metabolic energy expended.

DE formula is: $DE(\%) = \frac{\Delta W_{ext}}{\Delta E_{tot}} \times 100$, where ΔW_{ext} is the delta mechanical work accomplished and ΔE_{tot} the delta metabolic energy expended.

NE formula is: $NE(\%) = \frac{W_{ext}}{E_{tot}-E_{rest}} \times 100$, where W_{ext} is the mechanical work accomplished, E_{tot} the metabolic energy expended and E_{rest} the metabolic energy expenditure at rest.

WE formula is: $WE(\%) = \frac{W_{ext}}{E_{tot}-E_0} \times 100$, where W_{ext} is the mechanical work accomplished, E_{tot} the metabolic energy expended and E_0 the metabolic energy required by unloaded cycling, which is the energy cost of cycling at a zero load.

Despite being recognized as a poor WE muscle metric, GE has been the most used CE index, and it is considered the better whole-body efficiency metric (Faria et al., 2005a; Hopker et al., 2009).

1.2. Aims

Cycling efficiency is a key factor for cycling performance. Thus, the aim of this Academic Dissertation is to identify and summarize the determinants factors that influence CE. With this work, we hope to increase the knowledge in this scientific field through evidence-based insights and provide the scientific community and coaches tools to enhance performance on determinant factors for improving CE, according to the most recent evidence in the literature.

1.3. Academic Dissertation structure

This Academic Dissertation was written following the writing and presentation guidelines for thesis and dissertations of the Faculty of Sports - University of Porto (FADEUP, 2024). It was structured according to the Scandinavia model, given the opportunity to develop a scientific study, in this case a Systematic Narrative Review. It will be further submitted to an international peer-reviewed journal. Therefore, this Academic Dissertation is formed of chapters, one of these containing a scientific manuscript.

Chapter I delivers the introduction to this Academic Dissertation and gives a conceptual framework that supports the scientific investigation conducted. The lack of answers and research currently published in this specific topic (cycling efficiency determinant factors) outlines the relevance of this work to the scientific literature. This chapter also explains the aims of this study and presents a description of the Academic Dissertation structure.

Chapter II presents the Systematic Narrative Review developed (ahead of print). The review article, titled “Efficiency in Cycling for Road and Triathlon Disciplines: Determinants and Insights from a Systematic Narrative Review”, offers a synthesis and an analysis of the information obtained.

Chapter III is dedicated to a general discussion of the main findings of this Academic Dissertation, the limitations and the future avenues for research.

The supplements section includes one table, the PRISMA 2020 checklist, that will also be submitted as a supplement during the submission of this Systematic Narrative Review to an international peer-reviewed journal. According to the Scandinavian model, the references of each one of the chapters are presented at their end.

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Chapter II – Review Article

Title: **Efficiency in Cycling for Road and Triathlon Disciplines: Determinants and Insights from a Systematic Narrative Review**

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Abstract

Cycling is a demanding endurance sport, and a key modality during triathlon events. Cycling efficiency is determinant on cycling, which can affect performance and predict race's outcome. Therefore, the aim of this Systematic Narrative Review was to identify and summarize the determinants and factors that impact cycling efficiency. For the identification of the studies, we searched in the electronic databases of PubMed, Scopus and Web of Science, including all studies until January 2025. In addition, we conducted a manual search within the reference lists of the studies selected. The selection of the studies and the data extraction followed the PRISMA 2020 guidelines. We included only randomized controlled trials (RCTs). The eligibility criteria included athletes of all levels, ages, and genders, excluding any study involving participants with a metabolic disease or who were undergoing rehabilitation. The risk of bias was assessed using the Joanna Briggs Institute critical appraisal tools for RCTs. A total of 35 studies (589 participants) were included after the screening process. There was high heterogeneity regarding age and performance level and the risk of bias was considered high while evidence certainty was judged as low. The studies investigated different cycling efficiency variables including delta efficiency, gross efficiency, net efficiency, and work efficiency. Lower cadence positively impacts cycling efficiency whereas prolonged cycling, hypoxia and hyperoxia negatively affect cycling efficiency. Other determinants such as strength training, sprint training, some supplements and heat acclimation need further investigation to clarify their effect(s). Given the high heterogeneity and the low level of evidence, further studies are needed to better clarify the effects of the factors that influence cycling efficiency, particularly those involving experimental studies testing the impact of the abovementioned determinants.

KEYWORDS: CYCLING; TRIATHLON; EFFICIENCY; PHYSIOLOGY; BIOMECHANICS

1. Introduction

Cycling is one of the several means of transportation worldwide that can provide health benefits to its practitioners (Oja et al., 2011). For these reasons, cycling has been recommended as an important method to promote public health (Oja et al., 2011). Cycling has been gaining interest, with a growing number of community participants and an expansion in the competitive setting into organized sports (Faria et al., 2005b). In competitive cycling there are many different types of disciplines, such as road cycling, mountain biking, track cycling, downhill cycling, time trials, and others, each with its own characteristics, specifications, rules, and requirements.

Cycling it is also one of the disciplines that composes a triathlon, a multidisciplinary sport combining swimming, cycling and running in the same event (Etxebarria et al., 2019). Similar to cycling, triathlon races have a wide variety of race formats, but the official races are the Mixed Team Relay Race, the Super-Sprint distance race, the Sprint race distance, the Olympic distance, the Half-Ironman, mostly known as the 70.3 race, and the longest-distance triathlon, the Ironman (Etxebarria et al., 2019).

Cycling plays the most important role in terms of time contribution to a triathlon's overall time as the discipline that has a bigger course extension (Sousa et al., 2019). Despite this, the impact that each one of these three disciplines has on a triathlon race's final performance varies among the race distances (Sousa et al., 2019). For instance, Sousa et al. (2019) reported that cycling performance is the best predictor for a performance of sub 8 hours in the Ironman events (swimming: 3.8 kilometers; cycling: 180 kilometers; running: 42 kilometers). Cycling is also the most important predictive discipline in the Mixed Team Relay format (swimming: 0.3 kilometers; cycling: 6.6 kilometers; running: 1 kilometer) and in the Super-Sprint (swimming: 0.4 kilometers; cycling: 10 kilometers; running: 2.5 kilometers), Sprint (swimming: 0.75 kilometers; cycling: 20 kilometers; running: 5 kilometers) and Half-Ironman (swimming: 1.9 kilometers; cycling: 90 kilometers; running: 21 kilometers) distances (Nikolaidis et al., 2023; Quagliarotti et al., 2022; Sousa et al., 2021; Weiss et al., 2024). Peiffer et al.

(2016) reported an age-related decline in triathlon performance that is discipline dependent. Interestingly, when compared to running and swimming, cycling is the race segment with a lowest substantial decline. Therefore, cycling plays an important role in triathlon, and cycling performance will most likely influence its overall performance.

Cycling is a demanding endurance sport (Kristoffersen et al., 2019) and many determinants impact cycling performance and race outcome. Cycling efficiency (CE) is considered a key factor for cycling performance (Artetxe-Gezuraga et al., 2019; Cámara et al., 2012; Carlsson et al., 2024; Clark et al., 2007; Fletcher et al., 2019; Jobson et al., 2009; Tang et al., 2022) forming a measure of effective work, representing total expended metabolic energy for a produced external work, usually expressed in percentage (Faria et al., 2005a). There are some CE indices reported in the literature and between them, the most studied are gross efficiency (GE), delta efficiency (DE), net efficiency (NE) and work efficiency (WE) (Faria et al., 2005a; Hopker et al., 2009; Millet et al., 2002).

GE is defined as the ratio of mechanical work accomplished to the total metabolic energy expended (Artetxe-Gezuraga et al., 2019; Bossi et al., 2020; Cámara et al., 2012; Faria et al., 2005a, 2005b; Fletcher et al., 2019; Groot et al., 2018; Hopker et al., 2009; Millet et al., 2002; Tang et al., 2022; van Erck et al., 2019) and DE as the ratio of delta mechanical work accomplished to the delta metabolic energy expended (Faria et al., 2005a; Hopker et al., 2009; Millet et al., 2002; Santalla et al., 2009). The subtraction of the metabolic energy expenditure (EE) at a lower work rate (WR) is obtained from the metabolic EE at a higher WR (Hopker et al., 2009). NE represents the subtraction of the metabolic EE at rest (after measured and assigned to internal work performance) from the overall metabolic energy expended for the external work completed (Faria et al., 2005a; Hopker et al., 2009; Millet et al., 2002). The WE considers baseline and the metabolic energy required by unloaded cycling, which is the energy cost of cycling at a null WR (Chavarren & Calbet, 1999; Faria et al., 2005a; Hopker et al., 2009; Millet et al., 2002). Arkesteijn et al. (2013) report that changes in GE impact cycling performance. Carlsson et al. (2024) and Clark et al. (2007) both detailed that for a given power output (PO), a higher GE will have a lower metabolic EE compared to a lower GE. Despite being recognized as a poor WE muscle metric, GE has been the most used CE index, and it is considered the better whole-body efficiency metric (Faria et al., 2005a; Hopker et al., 2009).

The purpose of cyclists and their coaches is to improve performance to obtain better results and conquer the established goals. Since efficiency is considered a key factor for cycling performance, the aim of this Systematic Narrative Review was to identify and summarize the determinants and factors that influence CE. With this work, we hope to increase the knowledge in this scientific field through evidence-based insights and provide the scientific community and coaches tools to enhance performance on determinant factors for improving CE according to the recent evidence in the literature.

2. Methods

2.1. Study Design and Protocol Registration

The study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021), and the protocol was pre-registered on a public repository on PROSPERO [no. CRD 42025635996].

2.2. Eligibility Criteria

This review was conducted according to the PICOS approach as follows:

i. Participants: Athletes of all levels, ages, and genders, excluding any study that included participants with metabolic disease or who were undergoing rehabilitation.
ii. Intervention: Any intervention involving the study of efficiency in road cyclists and/or triathletes.
iii. Comparator: No comparisons were made.
iv. Results: Efficiency variables provided that were related to the topic of the study in question.
v. Study design: Only randomized controlled trials (RCT) were eligible for inclusion. No restrictions were placed on the date or language of publication of the studies.

2.3. Search strategy

The search strategy was designed by all authors and conducted by the first author. Three electronic databases PubMed®, Web of Science®, and Scopus® were searched from inception to January, 31, 2025. The supporting information on Appendix 1 fully details the strings used for the search strategy. Relevant studies from reference list of included studies (snowball technique) were also screened. Two authors independently performed the search (AL and AB), individually assessed the eligibility criteria through title and abstract screening, and inspected the full text whenever detailed information was needed. Duplicate records were then removed, and all records of potential interest were saved to an Endnote database (version 21.5; https://endnote.com, London, United Kingdom). Additionally, the records that weren't in English or Portuguese (reviewers' native language), were translated using "DeepL" (https://www.deepl.com, Cologne, Germany), an online automated translator website. Disagreements and ambiguity were solved by discussion and consensus among authors.

2.4. Data Collection Process

Two authors independently collected all the data items of interest following a pre-defined data extraction Excel sheet (https://www.microsoft.com, Redmond, United States). These data included information regarding title, authors, publication date, study design, efficiency variables and participants characteristics such as sample size, age, sex and performance metrics (relative and/or absolute maximal oxygen consumption ($\dot{V}O_{2max}$), training hours, years of cycling experience, and relative peak power output) to determine participants performance level classification. Participants levels were reclassified based on De Pauw et al. (2013) guidelines for subject groups in sport-science research. The data collected were subsequently compared between authors for consistency assessment. Whenever the necessary data were not available in the text or tables, the Web Plot-Digitizer tool (version 4.8; https://plotdigitizer.com) was used to extract the relevant information from the included studies.

2.5. Data Items

Variables relevant for efficiency in cycling in relation to the study implementation context, intervention or assessments characteristics were collected. The variables of efficiency in cycling included were GE, DE, NE and WE. The unit used for most efficiency variables (outcomes) was primarily percentage (%) and each one of these variables was calculated in a different manner, as reported previously.

2.6. Methodological Quality of Assessment

Risk of bias was assessed using the Joanna Briggs Institute (JBI) critical appraisal tool for the assessment of RCT study design studies (Barker et al., 2023). Two reviewers independently performed the risk of bias assessment, and a third reviewer resolved disagreements and guaranteed quality and independency. The JBI risk of bias checklist for RCT includes 13 domains for each of the included studies. Domain 1 (D1) is related to participants randomization, domain 2 (D2) to the allocation to treatment groups, and domain 3 (D3) to the group's similarity at baseline. Blinding of participants to treatment, those delivering the treatment and the outcome assessors form domain 4 (D4), domain 5 (D5) and domain 6 (D6), respectively. Domain 7 (D7) addresses whether identically treatments are administered between tested groups, domain 8 (D8) is about follow up, domain 9 (D9) to participants analysis randomization, domain 10 (D10) and domain 11 (D11) refers to measurement of outcomes, domain 12 (D12) to the statistical analysis used and domain 13 (D13) to trial design. After each domain was rated, an overall ranking was given to each included study and justification for this ranking is clarified in the Results section. The figures depicting the risk of bias assessment were created using Robvis online software (McGuinness & Higgins, 2021).

2.7. Synthesis Methods

Given the heterogeneity observed in the study populations, intervention types, and outcome measures, a meta-analysis was not conducted. Instead, a qualitative synthesis approach was used to summarize and interpret the findings across studies. All extracted data were organized into structured summary tables, including details such as study characteristics, participant demographics, outcome variables related to CE, and key findings. A narrative approach was employed to synthesize the findings, allowing for identification of trends, similarities, and differences between studies. This method enabled detailed evaluation of the overall direction and consistency of the evidence, while accounting for variations in study quality and design.

2.8. Strength of the Body of Evidence Assessment

The certainty of the evidence for each outcome was assessed using the Grading of Recommendations, Assessment, Development, and Evaluation (GRADE) approach (Guyatt et al., 2011). The GRADE comprises 5 categories: risk of bias, inconsistency, indirectness, imprecision, and publication bias and is graded as high, moderate, low, or extremely low. The certainty of evidence was quantified specifically for efficiency study type, when each efficiency type had pooled more than one study (>1). Two authors independently performed the analyses, and disagreements were resolved by consensus.

3. Results

3.1. Study Selection

The initial search in the three public electronic databases retrieved 4643 results. From this number, 141 studies were removed due to duplication, leaving 4502 articles to be screened. After screening titles and abstracts, 4370 studies were excluded. Subsequently, of the 132 records that were eligible for a complete full-text analysis, 17 were not retrieved, resulting in 115 full papers to be assessed for eligibility. Out of these 115 studies, 9 were removed due to a modeling methodology (Andersson et al., 2023; Bos et al., 2024; Davis & Hull, 1981; Kistemaker et al., 2023; Kohler & Boutellier, 2005; Lee & Park, 2021; Mognoni & di Prampero, 2003; Rosero & Martinez, 2018; Umberger et al., 2006). One paper had an efficiency metric that did not meet the intended purpose given the way it was calculated, (Callard et al., 2000) and 70 studies did to not met the study sample inclusion criteria (Albero et al., 2023; Almquist et al., 2023; Bodner et al., 2002; Boone et al., 2010; Brand et al., 2020; Brennan et al., 2019; Burke et al., 1977; Burtscher & Gatterer, 2013; Caritá et al., 2013; Carpes et al., 2010; Carpes et al., 2011; Chang et al., 2016; Cho et al., 1999; Citterio & Agostoni, 1984;

Connolly et al., 2024; Cross et al., 2014; Crouch et al., 2016; Dantas et al., 2009; Davies, 1992; Davies & Sandstrom, 1989; Dorel et al., 2005; du Plessis et al., 2022; Dunst et al., 2022, 2023; Edeline et al., 2004; Flatt et al., 1984; Gardner et al., 2007; Gilliéron et al., 2020; Graham et al., 2018; Green & Dawson, 1995, 1996; Green et al., 1996; Hansen et al., 2002; Hebisz et al., 2017; Hopker et al., 2013; Hopker et al., 2007; Hoshikawa et al., 1999; Jacobs et al., 2011; Koppo et al., 2004; Kordi et al., 2020a; Kordi et al., 2020b; Korff et al., 2011; Künstlinger et al., 1985; Leong et al., 2022; Lucía et al., 2004; Luhtanen et al., 1987; Lunn et al., 2009; Maillard & Gautier, 1981; Marsh et al., 2000; Marsh & Murlin, 1928; McClave et al., 2011; Medbo & Tabata, 1993; Millslagle et al., 2004; Mornieux et al., 2008; Moseley et al., 2004; Nimmerichter et al., 2011; Pereira et al., 2013; Pytka et al., 2024; Romeur et al., 2008; Rønnestad et al., 2021; Sassi et al., 2008; Seynaeve et al., 2009; Simon et al., 1986; Takaishi et al., 1998; Trama et al., 2023; van der Zwaard et al., 2018; Wackwitz et al., 2021; Wang et al., 2020; Whitty et al., 2009; Widrick et al., 1992).

After the screening process, a total of 35 records met the entire eligibility criteria and were included in the review (Almquist et al., 2022; Almquist et al., 2020a; Almquist et al., 2020b; Bastiaans et al., 2001; Cardinale et al., 2019; Carlsson et al., 2024; Christensen et al., 2013; Clark et al., 2007; Cole et al., 2014; Cole et al., 2018; Dumke et al., 2007; Dumke et al., 2009; Evans et al., 2018; Fröhlich et al., 2014; Garnacho-Castaño et al., 2018; Harnish et al., 2007; Karlsen et al., 2015; Kristoffersen et al., 2014; Kristoffersen et al., 2019; Marquet et al., 2016; Mikkelsen et al., 2019; Mumford et al., 2018; Passfield & Doust, 2000; Płoszczyca et al., 2021; Ramonas et al., 2023; Rodríguez-Marroyo et al., 2009; Rokkedal-Lausch et al., 2021; Ronnestad et al., 2015; Stebbins et al., 2014; Sunde et al., 2010; Taylor et al., 2021; Tebeck et al., 2020; Voskamp et al., 2020; Whitty et al., 2016; Williams et al., 2009). No additional eligible publications were identified or added to this review. No retractions or errata for the included studies were found. Figure 1 shows the detailed information regarding the literature search results.

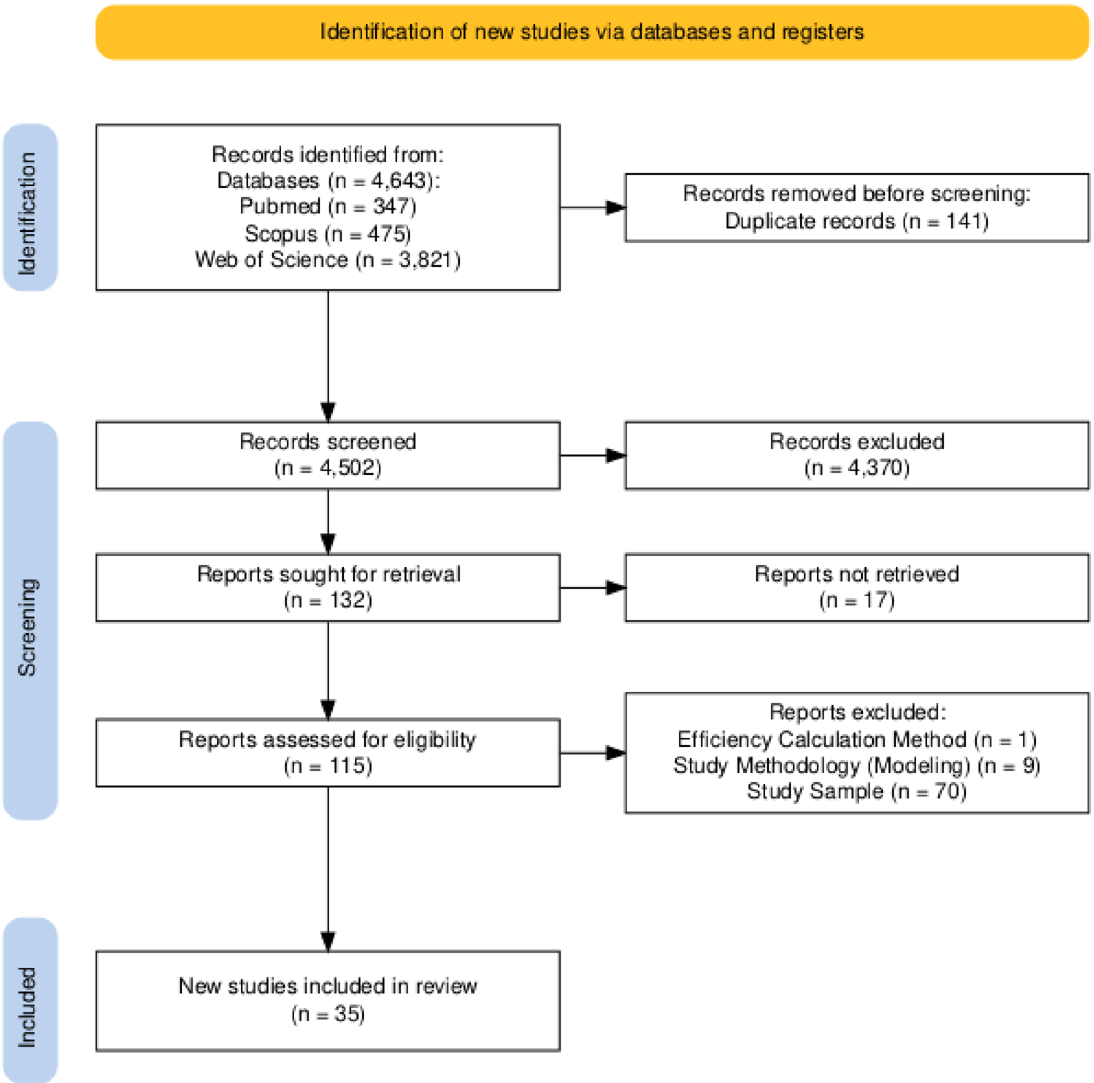

Figure 1. Flow diagram of the search and selection process results.

3.2. Study Characteristics

The 35 studies included a total sample of 589 participants. Overall, the study design of each study used distinct types of protocols in the field and in the laboratory with different types of cycling efficiency outcomes evaluated (e.g., DE, GE, NE, and others). Despite only athletes were included, participant's sports performance level varied from PL1 to PL5 (De Pauw et al., 2013) denoting a highly heterogeneous sample. The participant's characteristics are presented in Table 1, while Appendix 2 provides the criteria for classifying participant levels according to the Guidelines to classify subject groups in sport-science research (De Pauw et al., 2013).

Table 1. Study characteristics of the studies included after the screening process

Author	Sample size	Age	Performance Level (PL) (De Pauw et al. 2013)	Efficiency type
Almquist et al. (2020a)	12 male cyclists	26.2 ± 6.3 years	PL5	Gross Efficiency (GE)
Almquist et al. (2020b)	16 participants	SPR (n=7) 22.9 ± 3.0 years CON (n=9) 21.1 ± 3.9 years	PL5	Gross Efficiency (GE)
Almquist et al. (2022)	30 cyclists (26 males and 4 females)	TP males (n=14) 35.5 ± 12.8 years TP females (n=2) 34.4 ± 4.9 years BP males (n=12) 40.5 ± 12.0 years BP females (n=2) 42.0 ± 6.6 years	PL2 and PL3	Gross Efficiency (GE)
Bastiaans et al. (2001)	14 competitive cyclists	EXP(n=6) 24 ± 8 years CON (n=8) 29 ± 12 years	PL5	Gross Efficiency (GE) & Delta Efficiency (DE)
Cardinale et al. (2019)	23 cyclists (19 men and 4 women)	35.3 ± 6.4 years	PL3	Gross Efficiency (GE) & Work Efficiency (WE)
Carlsson et al. (2024)	10 elite male cyclists	25 ± 8 years	N.A.	Gross Efficiency (GE)
Christensen et al. (2013)	10 male elite cyclists	29 ± 4 years	PL5	Gross Efficiency (GE)
Clark et al. (2007)	10 well-trained male cyclists	28.4 ± 4.6 years	PL4	Gross Efficiency (GE)
Cole et al. (2014)	15 healthy trained male cyclists	40 ± 9 years	PL3	Gross Efficiency (GE)
Cole et al. (2018)	14 healthy trained male cyclists	42.6 ± 8.4 years	PL3	Gross Efficiency (GE)
Dumke et al. (2007)	15 trained male cyclists	28.7 ± 2.2 years	PL2	Gross Efficiency (GE)
Dumke et al. (2009)	40 trained male cyclists	Q (n=20) 26.1 ± 1.8 years P (n=20) 29.1 ± 2.4 years	PL2	Gross Efficiency (GE)
Evans et al. (2018)	19 trained cyclists (12 male and 7 female)	26.8 ± 7.6 years	PL3	Gross Efficiency (GE) & Delta Efficiency (DE)
Frohlich et al. (2014)	8 cyclists and 2 triathletes	26.2 ± 4.2 years	N.A.	Delta Efficiency (DE)
Garnacho-Castaño et al. (2018)	12 well-trained triathletes	39.3 ± 7.5 years	PL2	Cycling efficiency (CE) & Gross Efficiency (GE)
Harnish et al. (2007)	8 highly trained cyclists (7 males and 1 female)	25.8 ± 7.2 years	PL4	Net Efficiency (NE)
Karlsen et al. (2015)	18 well-trained male cyclists	CON (n=9) 39 ± 6 years HA (n=9) 33 ± 8 years	PL3	Gross Efficiency (GE) & Delta Efficiency (DE)
Kristoffersen et al. (2014)	22 well trained male veteran cyclists	47 ± 6 years	PL3	Gross Efficiency (GE)
Kristoffersen et al. (2019)	28 participants (26 men and 2 women)	29.6 ± 0.6 years	PL3	Gross Efficiency (GE)

Marquet et al. (2016)	21 trained male triathletes	SL (n=11) 32.0 ± 4.2 years CON (n=10) 29.3 ± 5.2 years	PL3	Delta Efficiency (DE)
Mikkelsen et al. (2019)	21 well-trained, sub-elite male cyclists	Heat (n=12) 39 ± 9 years CON (n=9) 38 ± 9 years	PL3	Gross Efficiency (GE)
Mumford et al. (2018)	28 male cyclists	28.8 ± 9.8 years	PL1	Gross Efficiency (GE)
PassField and Doust (2000)	19 cyclists	N.A.	PL3	Gross Efficiency (GE)
Płoszczyca et al. (2021)	20 trained male cyclists	34.6 ± 4.3 years	PL5	Gross Efficiency (GE)
Ramonas et al. (2023)	8 male cyclists	N.A.	PL3	Gross Efficiency (GE)
Rodríguez-Marroyo et al. (2009)	15 professional road cyclists	24 ± 1 years	N.A.	Gross Efficiency (GE)
Rokkedal-Lausch et al. (2021)	12 well-trained cyclists	N.A.	PL4	Gross Efficiency (GE)
Rønnestad et al. (2015)	16 elite cyclists	ES (n=9) 19.1 ± 1.7 years E (n=7) 20.1 ± 1.6 years	PL5	Gross Efficiency (GE)
Stebbins et al. (2014)	8 healthy, competitive male road cyclists	33.6 ± 6.8 years	PL3	Gross Efficiency (GE)
Sunde et al. (2010)	13 well-trained and competitive (10 men and 3 women)	INT (n=8) 29.9 ± 7.2 years CON (n=5) 35.8 ± 11.8 years	PL5	Net Efficiency (NE)
Taylor et al. (2021)	11 elite male cyclists	22.0 ± 3.8 years	PL5	Gross Efficiency (GE)
Tebeck et al. (2020)	11 well-trained male cyclists	24 ± 4 years	PL5	Gross Efficiency (GE)
Voskamp et al. (2020)	32 cyclists	Males (n=16) 27.6 ± 6.9 years Females (n=16) 26.3 ± 6.0 years	PL3 (Males) and PL2 (Females)	Gross Efficiency (GE)
Whitty et al. (2016)	16 male endurance-trained cyclists	31.4 ± 6.2 years	PL3	Gross Efficiency (GE)
Williams et al. (2009)	14 well-trained cyclists (13 males and 1 female	32.4 ± 8.8 years	PL3	Gross Efficiency (GE)

Abbreviations: BP - Block-Periodized; CON - Control group; E - Endurance training; ES - Endurance and Strength training; EXP - Explosive training; HA - Heat Acclimatization; INT - Intervention group; N.A - Not available; P - Placebo; Q - Quercetin; SL - Sleep low; SPR - sprints; TP - Traditional-Periodized;

3.3. Risk of bias in individual studies

The risk of bias was assessed using the JBI critical appraisal tool of RCT's (Barker et al., 2023). The individual assessment of the risk of bias is listed in Figure 2 and the summary plot of risk of bias detailed in Figure 3.

After the evaluation of each study using all 13 domains of this tool, 8 studies were classified as "Low" risk of bias (Cardinale et al., 2019; Carlsson et al., 2024; Dumke et al., 2007; Garnacho-Castaño et al., 2018; Mumford et al., 2018; Rokkedal-Lausch et al., 2021; Voskamp et al., 2020; Whitty et al., 2016), 2 as “Some concerns” (Clark et al., 2007; Ramonas et al., 2023) and the other 25 ranked as “High” risk of bias (Almquist et al., 2022; Almquist et al., 2020a; Almquist et al., 2020b; Bastiaans et al., 2001; Christensen et al., 2013; Cole et al., 2014; Cole et al., 2018; Dumke et al., 2009; Evans et al., 2018; Fröhlich et al., 2014; Harnish et al., 2007; Karlsen et al., 2015; Kristoffersen et al., 2014; Kristoffersen et al., 2019; Marquet et al., 2016; Mikkelsen et al., 2019; Passfield & Doust, 2000; Płoszczyca et al., 2021; Rodríguez-Marroyo et al., 2009; Ronnestad et al., 2015; Stebbins et al., 2014; Sunde et al., 2010; Taylor et al., 2021; Tebeck et al., 2020; Williams et al., 2009).

The criteria created to give an overall judgement to the studies were the following: the studies that had 2 or more of the “no blinding” domains, which were blinding to participants (domain 4, D4), blinding to those delivering the treatment (domain 5, D5) and blinding to the outcome assessors (domain 7, D7), classified as “High” were ranked as “High” risk of bias. For this reason, 16 studies were classified as “High” risk of bias (Almquist et al., 2022; Almquist et al., 2020b; Bastiaans et al., 2001; Evans et al., 2018; Harnish et al., 2007; Karlsen et al., 2015; Kristoffersen et al., 2014; Kristoffersen et al., 2019; Marquet et al., 2016; Mikkelsen et al., 2019; Płoszczyca et al., 2021; Rodríguez-Marroyo et al., 2009; Sunde et al., 2010; Taylor et al., 2021; Tebeck et al., 2020; Williams et al., 2009). The other 9 studies (Almquist et al., 2020a; Christensen et al., 2013; Cole et al., 2014; Cole et al., 2018; Dumke et al., 2009; Fröhlich et al., 2014; Passfield & Doust, 2000; Ronnestad et al., 2015; Stebbins et al., 2014) had an overall assessment of “High” risk of bias since there was too much missing information to be ranked only has “Some concerns”. The 2 studies (Clark et al., 2007; Ramonas et al., 2023) classified as “Some concerns”, had missing information about allocation to groups or about outcome assessors blinding, despite having most of the domains ranked as “Low”. The 8 studies that remain had an overall judgement of “Low” risk of bias had 0 of the 13 domains classified as “High” (Cardinale et al., 2019; Carlsson et al., 2024; Dumke et al., 2007; Garnacho-Castaño et al., 2018; Mumford et al., 2018; Rokkedal-Lausch et al., 2021; Voskamp et al., 2020; Whitty et al., 2016).

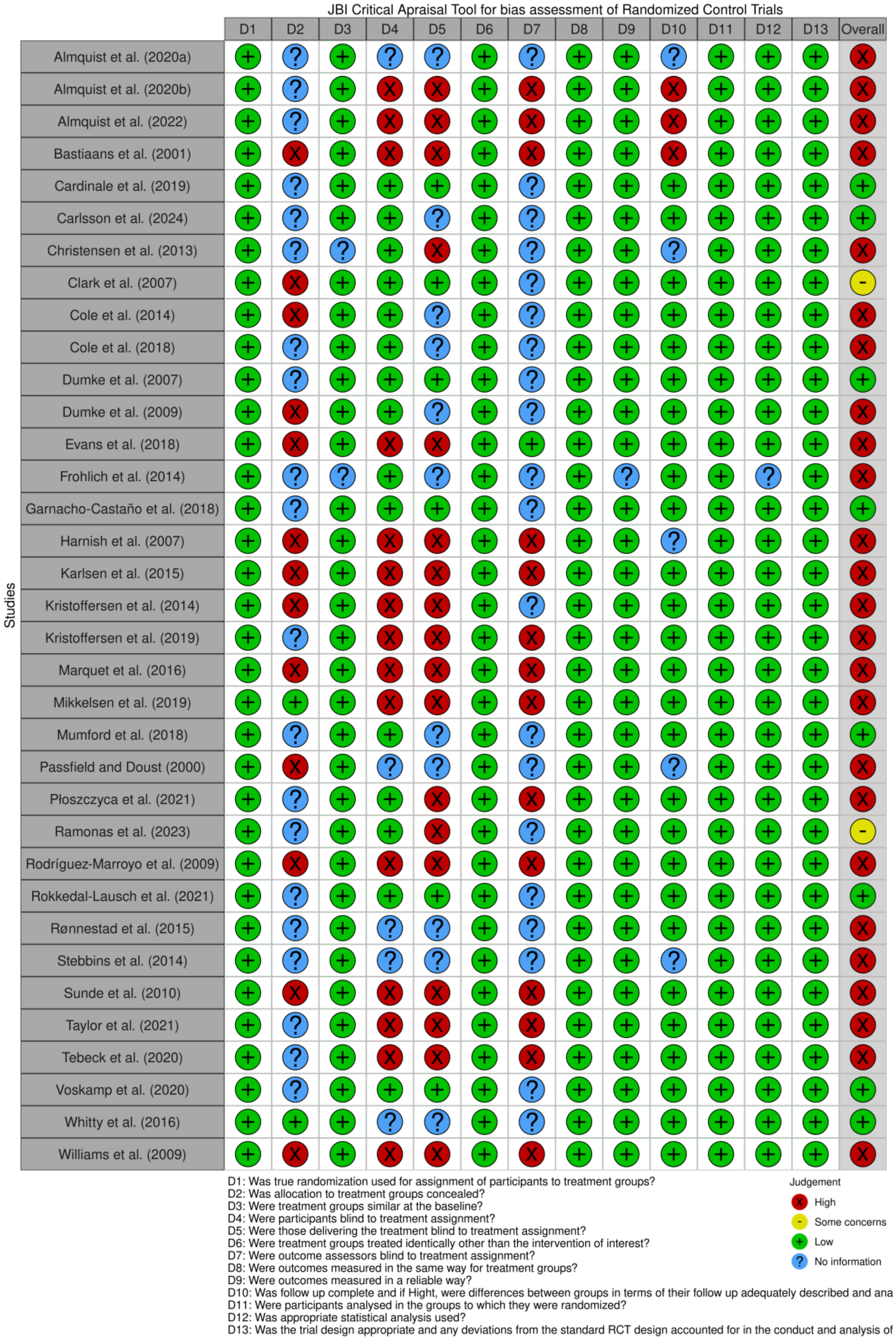

Figure 2. Individual assessment of risk of bias for each included study

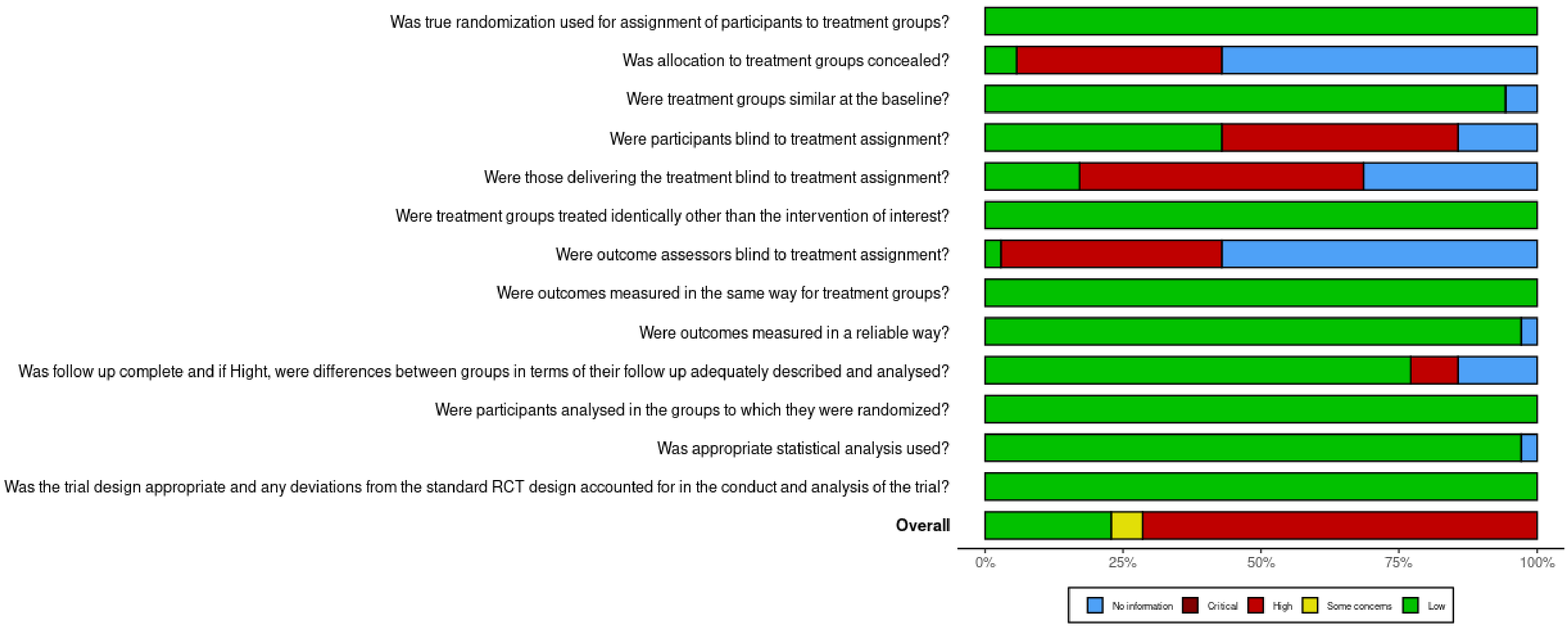

Figure 3. Summary plot of the assessed risk of bias.

3.4. Results of individual studies

The results of the included studies in this study are presented in Table 2. From the 35 studies included in this review, 7 (Dumke et al., 2007; Dumke et al., 2009; Garnacho-Castaño et al., 2018; Karlsen et al., 2015; Mumford et al., 2018; Voskamp et al., 2020; Whitty et al., 2016) reported their data on plots and so, for this reason, *Web Plot Digitizer*, an online software, was used to extract the graphs and estimate values. On the other 28 articles, values of the results are presented in mean and standard deviation (SD).

Table 2. Individual results of the included studies.

Author	Studied variables	Condition Studied						P - values
Almquist et al. (2020a)		E & S		E				
		PRE	POST	PRE	POST			
	GE (%)	19.0±0.2	18.1±0.2	19.1±0.2	18,1±0,2			p=0.001
Almquist et al. (2020b)		SPR			CON			*p<0.05 (significant difference between fresh and semi-fatigued state)
		PRE	POST	DIF	PRE	POST	DIF	
	GE Fresh (%)	19.9±1.0	19.5±1.0	-0.4±1.0	19.1±1.0	19.2±1.0	0.1±1.0	
	GE Semi-fatigued (%)	18.9±1.0	18.9±1.0	0.1±1.0	19.1±1.0	19.3±1.0	-0.2±1.1	
	GE Fresh vs. Semi-fatigued (%)	-1.0±1.2*	-0.6±1.1	-0.4±1.2	0.0±1.3	0.0±1.1	0.0±1.2	
Almquist et al. (2022)		TP		BP				*p<0.05 (Indicates a significant change from Pre to Post12)
		PRE	POST12	PRE	POST12			
	GE Fresh (%)	19.4±1.9	19.2±1.6	18.5±2.2	18.7±2.3			
	GE Semi-fatigued (%)	18.5±2.1	18.8±1.6*	18.0±1.4	18.6±2.0*			
	GE Fresh vs. Semi-fatigued (%)	-0.9±0.9	-0.3±0.8*	-0.5±1.1	-0.1±1.0*			
Bastiaans et al. (2001)		EXP			CON			
		PRE	POST4	POST9	PRE	POST4	POST9	
	GE(%)	21.17±0.78	21.92±0.32	22.29±1.13	21.97±0.87	21.86±0.79	22.36±0.72	N.S.
	DE(%)	24.63±1.41	26.95±4.71	26.22±4.37	24.99±1.32	23.27±2.49	24.13±2.28	p<0.05
Cardinale et al. (2019)		NORM		HYPER				N.A.
		PRE	POST	PRE	POST			
	GE(%)	19.0±0.9	19.3±1.1	19.7±0.1	20.0±1.3			
	WE at 150W (%)	24.2±1.0	24.9±0.5	25.0±1.3	25.7±1.7			
Carlsson et al. (2024)		SEA	RTSS	STA				
	GE(%)	21.3 ± 1.2	21.0 ± 1.1	21.3 ± 1.1				p=0.21

Table 2. Individual results of the included studies. (cont.)

Author	Studied variables	Condition Studied				P - values
Christensen et al. (2013)		PLA	BJ			* p<0.01 ** p<0.001
	GE(%) at S1	20.3±0.9	20.7±1.5			
	GE(%) at S2	19.8±0.7	20.3±1.6*			
	GE(%) at S3	19.9±0.7	20.4±1.7*			
	GE(%) at S4	19.7±0.6	20.0±1.6**			
Clark et al. (2007)		ALTITUDE				
		SL(200M)	1200M	2200M	3200M	
	Maximal GE (%)	18.6±0.82	18.9±0.77	19.1± 0.59	19.0 ± 1.20	p=0.47
		ALTITUDE				N.A.
		SL(200M)	1200M	2200M	3200M	
	Subaximal GE at 50 W (%)	~13.22	~13.45	~13.27	~13.12	
	Subaximal GE at 100 W (%)	~16.87	~17.15	~16.67	~16.49	
	Subaximal GE at 150 W (%)	~18.38	~18.41	~18.03	~17.83	
	Subaximal GE at 200 W (%)	~18.94	~18.92	~18.61	~18.31	
	Subaximal GE at 250 W (%)	~18.99	~18.92	~18.55	~18.14	
Cole et al. (2014)		HCHO	LCHO	MCHO		*Significantly higher in High CHO condition vs. other conditions (p ≤ 0.05)
	GE (%) at 25–30min	21.20±1.72*	20.72±1.91	20.34±1.32		
	GE (%) at 55–60min	20.35±1.55	20.28±2.26	20.00±1.71		
	GE (%) at 85–90min	20.13±1.88*	19.64±1.52	19.33±1.78		
	GE (%) at 115–120min	20.01±2.14	18.99±1.86	19.01±1.14		
Cole et al. (2018)		W+W	W+CHO	CAF+W	CAF+CHO	*Significant difference from W + W (p < 0.05). p=0.008 (W+CHO) p=0.023 (CAF+W) p=0.077 (CAF+CHO)
	Mean GE (%)	20.43±0.36	19.91±0.27*	20.12±0.35*	20.24±0.34	
	Mean GE (%) over 2h	-1.78±0.31	-0.70 ± 0.25	-1.12±0.24	-0.63 ± 0.27	

Table 2. Individual results of the included studies. (cont.)

Author	Studied variables	Condition Studied						P - values
Dumke et al. (2007)		PLA	CHO					N.A.
	GE(%) at 20min	~100.0	~100.0					
	GE(%) at 40min	~97.6	~102.6					
	GE(%) at 60min	~97.6	~97.0					
	GE(%) at 80min	~96.6	~97.9					
	GE(%) at 100min	~94.7	~97.9					
	GE(%) at 120min	~98.1	~98.4					
	GE(%) at 140min	~91.3	~101.6					
Dumke et al. (2009)		PLA	QUE					N.A.
	GE(%) at 30min	~19.8	~19.6					
	GE(%) at 60min	~19.6	~19.4					
	GE(%) at 90min	~19.5	~19.3					
	GE(%) at 120min	~19.4	~19.1					
	GE(%) at 150min	~19.5	~19.2					
	GE(%) at 180min	~19.3	~19.1					
Evans et al. (2018)		30% V02máx	40% V02máx	50% V02máx	60% V02máx	70% V02máx	80% V02máx	INTEN; COND; INTER
	GE KET (%)	10.4±3.6	15.0±2.3	16.9±1.9	18.2±1.7	18.8±1.6	19.1±1.9	p<0.001; p=0.789; p=0.992
	DE KET (%)	N.A.	27.0±4.7	23.1±3.4	23.1±3.4	21.6±3.0	19.9±6.8	
	GE CON(%)	10.7±3.6	15.2±2.0	16.9±1.7	18.2±1.1	18.8±1.0	19.2±1.0	p<0.001; p=0.737; p=0.830
	DE CON(%)	N.A.	28.2±9.6	22.7±3.9	24.2±5.2	20.9±5.9	21.8±7.0	
Frohlich et al. (2014)		Standard Sole	Carbon Sole					
	DE (280W)	11.5 ± 10.3	11.7 ± 11.3					p > 0.05
	DE (20sec)	4.2 ± 4.1	4.6 ± 3.7					p > 0.05
Garnacho-Castaño et al. (2018)		BJ			PLA			N.A.
		VT1	VT2	VT1+VT2	VT1	VT2	VT1+VT2	
	GE(%)	~22.38	~23.27	~22.79	~22.93	~24.08	~23.47	

Table 2. Individual results of the included studies. (cont.)

Author	Studied variables	Condition Studied						P - values
Harnish et al. (2007)		LOW INTENSITY		MEDIUM INTENSITY		HIGH INTENSITY		
		SEA	STA	SEA	STA	SEA	STA	
	NE	24.2±1.7	25.1 ±3.7	25.2 ±1.4	25.7 ±2.2	26.0 ±1.7	26.7 ±2.3	p > 0.05
		Final Maximal uphill trial						N.A.
	Mean NE		31.2±2.3					
Karlsen et al. (2015)		CON		HA				
		PRE	POST	PRE	POST			
	GE at 100 W	~15.49	~14.87	~15.88	~16.19			N.A.
	GE at 200 W	~19.37	~18.59	~19.64	~19.76			
	DE	~25.81	~25.15	~25.89	~25.31			
Kristoffersen et al. (2014)		Lactate Threshold Test						
			LCTG			FCCG		
		PRE	POST	%C	PRE	POST	%C	
	GE (%)	20.5±1.5	20.2 ± 1.3	-0.3 ± 1.6	20.6 ± 0.6	20.2 ± 0.7	-0.4 ± 0.6	p > 0.05
		30-min Performance Test						
			LCTG			FCCG		
		PRE	POST	%C	PRE	POST	%C	
	GE (%)	20.0±0.6	19.8 ± 0.7	-0.2 ± 0.9	20.1 ± 1.2	20.2±1.1	0.1 ± 0.8	p > 0.05
Kristoffersen et al. (2019)			SST			HST		
		PRE	POST	%C	PRE	POST	%C	
	GE Fresh State (%)	20.3±1.3	20.0±1.1	-0.3±0.9p	20.5±1.0	20.2±1.1	-0.3±0.5p	p > 0.05
	GE Prolonged Cycling (%)	19.7±0.6	19.7±0.8	0.1±0.7p	19.5±1.0	19.5±0.7	0.0±0.7p	p > 0.05
Marquet et al. (2016)		CON		SL				*p<0.05 as compared with PRE values.
		PRE	POST	PRE	POST			
	DE(%) at 100W	26.3±2.5	26.5±2.4	26.5±4.5	29.6±8.0*			

Table 2. Individual results of the included studies. (cont.)

Author	Studied variables	Condition Studied						P - values
Mikkelsen et al. (2019)		CON		HA				
		PRE	POST	PRE	POST			
	GE(%) at 100W	14.8±0.5	15.2±0.4	15.4±0.3	15.2±0.2			$p > 0.05$
	GE(%) at 175W	19.3±0.5	19.8±0.5	19.7±0.3	19.4±0.2			$p > 0.05$
Mumford et al. (2018)		PLA	BLN					N.A.
	Efficiency (W/$\dot{V}O_2$) at 5'min	~4.98	~4.98					
	Efficiency (W/$\dot{V}O_2$) at 10'min	~4.81	~5.02					
	Efficiency (W/$\dot{V}O_2$) at 15'min	~4.61	~4.82					
	Efficiency (W/$\dot{V}O_2$) at 20'min	~4.45	~4.53					
	Efficiency (W/$\dot{V}O_2$) at 25'min	~4.41	~4.69					
	Efficiency (W/$\dot{V}O_2$) at 30'min	~6.23	~7.63					
PassField and Doust (2000)		30-min Performance Test						**p<0.01 as compared with PRE values.
		COM			EXERCISE			
		PRE	POST	%C	PRE	POST	%C	
	GE (%)	22.2±1.6	21.6±1.6	-0.6±0.5	22.6±0.9	20.7±1.1	-1.8±0.8**	
		30 Seconds Sprint Test						**p<0.01 as compared with PRE values.
		CON			EXERCISE			
		PRE	POST	%C	PRE	POST	%C	
	GE (%)	21.8±0.7	21.7±0.9	-0.1±0.5	21.8±0.8	20.8±1.4	-1.0±0.8**	

Table 2. Individual results of the included studies. (cont.)

Author	Studied variables	Condition Studied						P - values
Płoszczyca et al. (2021)		LT1						N.A.
		SP		PLA				
		PRE	POST	PRE	POST			
	GE (%)	18.73±0.47	18.96±0.45	19.06±0.50	19.00±0.48			
		LT2						N.A.
		SP		PLA				
		PRE	POST	PRE	POST			
	GE (%)	20.20±0.43	20.05±0.41	20.54±0.45	20.39±0.43			
Ramonas et al. (2023)		STEADY STATE TESTS						N.A.
		CHO			PLA			
		50% PPO	55% PPO	60% PPO	50% PPO	55% PPO	60% PPO	
	GE (%)	19.8±1.6	20.1±1.6	20.7±1.0	20.0±1.6	20.6±2.0	21.2±1.8	
		60% PPO						N.A.
		CHO		PLA				
		GDT	SS	GDT	SS			
	GE (%)	22.06±1.91	20.15±1.77	20.15±1.77	21.22±1.78			
Rodríguez-Marroyo et al. (2009)		CON	ROT-1	ROT-2	ROT-3	ROT-4	ROT+	N.A.
	GE (%)	20.7±0.8	20.5±0.8	20.5±0.9	20.9±1.0	21.1±0.9	21.6±1.0	
Rokkedal-Lausch et al. (2021)		NPL	NBJ	HPL	HBJ			SUPP: p = 0.333; COND: p = 0.112; INTER: p = 0.656;
	GE (%)	18.0 ± 0.4	18.2 ± 0.4	17.6 ± 0.4	17.9 ± 0.4			
Rønnestad et al. (2015)		125W	175W	225W				N.A.
	GE (%)	16.7±1.2	18.4 ± 1.2	19.2 ± 0.8				
Stebbins et al. (2014)		80 RPM		100 RPM				*p <0.05 vs.65%$\dot{V}O_2$max; †p<0.05 vs.80RPM
		65% $\dot{V}O_2$max	80% $\dot{V}O_{2max}$	65% $\dot{V}O_{2max}$	80% $\dot{V}O_{2max}$			
	GE (%)	22.8±1.0	23.1±0.7	21.3±4.5 †	22.1±0.9 *†			
Sunde et al. (2010)		INT			CON			* p<0.05
		PRE	POST	DIF	PRE	POST	DIF	
	NE (%)	21.1±0.7	22.1±1.2	1.0±1.0*	21.5±0.9	21.8±0.7	0.3±0.3*	

Table 2. Individual results of the included studies. (cont.)

Author	Studied variables	Condition Studied								P - values
Taylor et al. (2021)		SPR		COM						N.A.
		COMP	PREP	COMP	PREP					
	GE (%) rested	20.0 ± 1.3	19.7 ± 0.9	19.9 ± 0.5	20.7 ± 1.4					
	GE (%) fatigued	20.4 ± 1.9	19.7 ± 1.5	20.1 ± 0.3	19.7 ± 0.8					
Tebeck et al. (2020)		DRY			HUMID					N.A.
		PRE	POST	DIF	PRE	POST	DIF			
	GE (%) at 200W	19.8 ± 0.9	19.8 ± 0.8	0.08	19.4 ± 1.3	20.2 ± 1.0	0.55			
Voskamp et al. (2020)		NaHCO3				PLA				N.A.
		PRE	extrap	POST1	POST2	PRE	extrap	POST1	POST2	
	GE (%)	23.31	21.99	21.72	21.83	23.53	22.06	21.93	22.13	
Whitty et al. (2016)		HCPRET	HCPOSTT	LCPRET	LCPOSTT					N.A.
	GE (%) at 50rpm	~24.81	~24.90	~24.02	~24.00					
	GE (%) at 70rpm	~24.41	~24.51	~23.41	~23.71					
	GE (%) at 90rpm	~22.71	~23.61	~21.79	~22.69					
	GE (%) at 110rpm	~20.00	~20.92	~19.89	~20.00					
	GE (%) at FCC	~22.81	~23.22	~21.79	~22.41					
Williams et al. (2009)		UC		TC						p(Group x Time)
		PRE	POST	PRE	POST					
	GE (%) at 70% $\dot{V}O_{2max}$	19.7±0.4	20.9±0.4	19.8±0.4	20.3±0.4					p=0.250;
	GE (%) at 200W	20.8±0.4	20.4±0.4	20.0±0.4	20.8±0.4					p=0.260;

Abbreviations:
%C - %Change; BJ - Beetroot juice; BLN - Betalain-rich beetroot concentrate; BP - Block Periodized Training; CHO - Carbohydrate supplementation; COMP - Competitive period; CON - Control group; COND - Condition; DE - Delta Efficiency; DIF - Difference; E - Exercise without sprints; E&S - Exercise with 9 x 30s sprints; EXP - Experimental group; FCCG - Freely chosen cadence group; GDT - Glycogen Depletion Test; GE - Gross Efficiency; HA - Heat acclimatization group; HBJ - Hypoxia Beetroot juice; HCHO - High carbohydrate diet; HCPOSTT - High cadence post-test; HCPRET - High cadence pre-test; HPL - Hypoxia Placebo; HST - heavy strength training; HYPER - Hyperoxia; INT - Intervention group; INTEN - Intensity; INTER - Interaction; KET - Ketones (βHB salts); LCHO - Low carbohydrate diet; LCPOSTT - High cadence post-test; LCPRET - Low cadence pre-test; LCTG - Low cadence training group; LT 2,LT 1 - Absolute workload corresponding to one and two workloads below lactate threshold (LT); MCHO - Moderate carbohydrate diet; N.A - Not available; N.S - Not significant; NBJ - Normoxia Beetroot juice; NE - Net Efficiency; NORM - Normoxia; NPL - Normoxia Placebo; PLA - Placebo; PREP - Preparatory period; QUE - Quercetin; ROT - Crank angle of maximum crank arm length [116º (ROT-1), 122º (ROT-2), 128º (ROT-3) and 134º (ROT-4)]; RPM - Revolutions per minute; RTSS - Repeated transitions between seated and standing cycling; S1 (0-20min), S2 (30-50min), S3 (60-80min), S4 (90-110min) - Stable load periods (50% iPPO); SEA- Seated position; SL - Sea level; SPR - Sprints; SS - Steady State ; SST - short-sprint training; STA - Standing position; SUPP - Supplement; TC - Traditional Cranks; TP - Traditional Periodized Training; UC - Uncoupled Cranks; W - Watts; WE - Work Efficiency; p - Percentage point change;

3.5. Syntheses of results

The outcomes investigated in the 35 included studies are presented and approached in 4 main clusters created to group together studies that dealt with the same topic. The 4 clusters were named as “Physiological and Biomechanical factors”, “Training factors”, “Nutritional factors” and “Environmental and External factors”. In the “Physiological and Biomechanical factors” cluster 6 studies were grouped (Carlsson et al., 2024; Harnish et al., 2007; Kristoffersen et al., 2014; Passfield & Doust, 2000; Stebbins et al., 2014; Whitty et al., 2016), in the “Training factors” cluster 8 studies were included (Almquist et al., 2022; Almquist et al., 2020a; Almquist et al., 2020b; Bastiaans et al., 2001; Kristoffersen et al., 2019; Ronnestad et al., 2015; Sunde et al., 2010; Taylor et al., 2021), the “Nutritional factors” cluster incorporated 13 studies (Christensen et al., 2013; Cole et al., 2014; Cole et al., 2018; Dumke et al., 2007; Dumke et al., 2009; Evans et al., 2018; Garnacho-Castaño et al., 2018; Marquet et al., 2016; Mumford et al., 2018; Płoszczyca et al., 2021; Ramonas et al., 2023; Rokkedal-Lausch et al., 2021; Voskamp et al., 2020) and the “Environmental and External factors” cluster featured 8 studies (Cardinale et al., 2019; Clark et al., 2007; Fröhlich et al., 2014; Karlsen et al., 2015; Mikkelsen et al., 2019; Rodríguez-Marroyo et al., 2009; Tebeck et al., 2020; Williams et al., 2009).

3.5.1. Physiological and Biomechanical factors

Studying whether endurance exercise would cause changes in CE, after a warm up and a 5-min performance test or a 30 seconds sprint test, Passfield & Doust (2000) showed that a decline in GE was significantly greater for the exercise group, which completed ~60 min of endurance cycling, compared with the control (CON) group, that rested for the same amount of time. In the 5-min performance test protocol the CON group GE changed -0.6±0.5% (pre-test 22.2±1.6% and post-test 21.6±1.6%, $p > 0.05$) while the exercise group impaired -1.8±0.8 (pre-test 22.6±0.9% and post-test 20.7±1.1%, $p < 0.01$). In the 30 seconds sprint test trial the CON group GE changed -0.1±0.5% (pre-test 21.8±0.7 and post-test 21.7±0.9%, $p > 0.05$) while the exercise group impaired -1.0±0.8% (pre-test 21.8±0.8% and post-test 20.8±1.4%, $p < 0.01$).

Stebbins et al. (2014) investigated the effects of cadence showing that, when cycling at 80 revolutions per minute (rpm), GE was stable between low and high intensity (GE65%$\dot{V}O_{2max}$-80rpm 22.8±1.0%, GE80%$\dot{V}O_{2max}$-80rpm 23.1±0.7%, $p > 0.05$). However, when riding at 100rpm, GE increased from the low to the high intensity (GE65%$\dot{V}O_{2max}$-100rpm 21.3±4.5%, GE80%$\dot{V}O_{2max}$-100rpm 22.1±0.9%, $p < 0.05$). It is also relevant that when comparisons are made by power output, GE at low intensity was similar between 80 and 100-rpm tests (GE65%$\dot{V}O_{2max}$-80rpm 22.8±1.0%, GE65%$\dot{V}O_{2max}$-100rpm 21.3±4.5%, $p > 0.05$). However, for the high intensity, GE decreased from the 80rpm to the 100rpm trial (GE80%$\dot{V}O_{2max}$-80rpm 23.1±0.7%, GE80%$\dot{V}O_{2max}$-100rpm 22.1±0.9%, $p < 0.05$). At both low and high exercise intensities GE was 4 to 7% less at 100rpm vs. 80rpm.

Also focused on studying the effects of pedaling rate, Kristoffersen et al. (2014) implemented a 12-week training plan, where a low cadence (LC) group and a freely chosen cadence (FCC) group were created to undertake, pre- and post-intervention, a lactate threshold (LT) test and a 30-min performance test. No changes within groups were observed in GE for the LT tests (ES = 0.21 for the LC group and ES = 0.61 for the FCC group, $p > 0.05$) nor from pre- to post-test on the 30-min performance test, for neither one of the two groups (ES = 0.31 for the LC group and ES = 0.09 for the FCC group, $p > 0.05$).

Whitty et al. (2016) made their sample undertake tests at 5 different cadences, 50rpm, 70rpm, 90rpm, 110rpm and FCC. A high cadence group (HC) pedaled at 20% above their individual FCC, while a LC group pedaled at 20% below their FCC, over 6 weeks. At the end of the intervention, cadences tests were repeated. GE decreased as cadence increased for both the LC group (p = 0.01) and the HC group (p = 0.01). The authors also revealed that an increase, from pre- to post-test, in GE at 90 rpm (pre - ~22.7%, post- ~23.6%, p = 0.05) and 110 rpm (pre- ~20.0%, post- ~20.9%, p = 0.05) was displayed for the HC group. There were no marked changes in GE for both groups at the FCC from pre- (HC - ~22.8%, LC - ~21,8%) to post-training (HC - ~23.2%, LC - ~22.4%).

Harnish et al. (2007) mainly focused on the cyclist's position on the bicycle and found no differences in NE between seated and standing positions, at all tested intensities ($p > 0.05$). The impacts of cycling position were also studied by Carlsson et al. (2024), to determine whether transitioning repeatedly between a seated and a standing position, in the bicycle, could have an impact in important cycling performance indicators. There were no differences in GE between tested positions ($p = 0.21$), when cycling at an inclination ~7% and at an intensity close to the aerobic threshold.

3.5.2. Training factors

Addressing the topic of strength training (ST) and how it could affect performance, Bastiaans et al. (2001) reported that, after 9-weeks of an explosive ST program, there was no significant change in DE in the experimental (EXP) group (pre- 24.63±1.41%, post4- 26.95±4.71%, post9- 26.22±4.37%) and a decrease in the CON group (pre- 24.99±1.32%, post4- 23.27±2.49%, post9- 24.13±2.28%). The group-by-training interaction wasn't significant ($p > 0.05$) but an increase tended to be greater for the EXP group (pre- 21.17±0.78%, post4- 21.92±0.32%, post9- 22.29±1.13%) when compared to the CON group (pre- 21.97±0.87%, post4- 21.86±0.79%, post9- 22.36±0.72%).

Instead of a 9-week program, Sunde et al. (2010) used an 8-week intervention to evaluate the effects of maximal ST on work efficiency, calculated as NE. A significant 4.7% improvement in NE for the EXP group was found (pre- 21.1±0.7% and post- 22.1±1.2%, $p < 0.05$). Despite having a smaller improvement (1.4%), it was also significant (pre- 21.5±0.9% and post- 21.8±0.7%, $p < 0.05$) for the CON group. Ronnestad et al. (2015) studied ST impact on cyclists noting that during a 25-week plan there weren't any significant GE changes in the athletes at any of the tested power outputs - 125 watts (W), 175W and 225W (GE at 125W, 175W, 225W, was 16.7±1.2%, 18.4±1.2% and 19.2±0.8%, respectively).

ST was also used in the study of Kristoffersen et al. (2019), but this time for comparing with sprint training (SPT) in a 6-week intervention. The athletes were tested at a fresh state (FS) and at a fatigued state (FGS), both pre- and post-intervention. In both states and in both groups (ST and SPT groups), no differences were observed from pre- to post-test ($p > 0.158$) neither between groups, at both FS (p = 0.685, ES = 0.15) and FGS (p = 0.891, ES = 0.05). The effects of sprinting on GE were also the focus of the investigations of Almquist et al. (2020a) and Almquist et al. (2020b).

In the study of Almquist et al. (2020a) involving a 4-hour cycling trial, at low intensity, where the EXP group had to perform, in the first 3 hours, short bouts of 30 seconds sprints, GE decreased in both groups from the beginning to the end of the test. In the pre-test GE was 19.0±0.2% for the EXP and 19.1±0.2% for the CON group. In post-test GE values of 18.1±0.2% and 18.1±0.2% were found for the EXP and CON group, respectively. Despite GE being lower in the EXP group (p = 0.02), no time-condition interaction was evident (p = 0.6). Almquist et al. (2020b) also reported that being fresh (p = 0.18) or being semi-fatigued (p = 0.63) did not change GE between groups from pre- to post-test. Moreover, the change from fresh to a semi-fatigued state (SFF) at pre-test (p = 0.13) or at post-test (p = 0.26) was not different between groups, despite a decrease in GE had occurred in the EXP group from FS to SFF (p = 0.02).

Taylor et al. (2021) also presented data about sprinting experiments made in the transition (TRAN) period of a season, to examine effects on the shift between competitive (COMP) and preparatory (PREP) periods. The GE at FS and at FGS was maintained in both groups in the PREP even after the inclusion of 30 seconds maximal sprints in low intensity sessions during a 3-week TRAN period. In COMP, GE at FS values were of 20.0±1.3% for EXP group and of 19.9±0.5% for CON group, while GE at FGS values were of 20.4±1.9% for EXP group and of 20.1±0.3% for CON group. In PREP, GE at FS values were of 19.7±0.9% for EXP group and of 20.7±1.4% for CON group, while GE at FGS values were of 19.7±1.5% for EXP group and of 19.7±0.8% for CON group. No differences between groups and within-group were found (p > 0.05).

Periodization was examined by Almquist et al. (2022) in a study where the effects of implementing a traditional periodization (TP) endurance training plan were compared to a block periodization (BP) one. Measurements were made initially (pre) and 12 weeks after (post12) and no differences in FS were noticed from pre to post12 in both groups. However, for FGS, GE significantly changed (p < 0.05) from pre to post12 in TP (pre- 18,5±2,1% and post12- 18,8±1,6%) and in BP (pre- 18,0±1,4% and post12- 18,6±2,0). Moreover, training reduces GE decay by 0.5±1.1% from pre to post12 (p = 0.026).

3.5.3. Nutritional factors

Dumke et al. (2007) investigated how 2½ hours of cycling with and without carbohydrate (CHO) supplementation could affect GE. There was a 10% reduction in GE for the placebo (PLA) group in the end compared to baseline. The most discrepant results are observed at minute 40 and 140 where, compared with the first measurement, at minute 20, GE increased in the CHO group (GE at min20 - ~100; GE at min40 - ~102.6; GE at min140 - ~101.6), but decreased in the PLA group (GE at min20 - ~100; GE at min40 - ~97.6; GE at min140 - ~91.3). Compared with PLA, GE was higher ($p < 0.05$) in the CHO group at minute 40 and 140.

The studies of Cole et al. (2014), Cole et al. (2018), Marquet et al. (2016) and Ramonas et al. (2023) also studied the effects of CHO intake on CE. In the experiment of Cole et al. (2014) the participants were assigned to one of the three following CHO diets: high in CHO (HCHO - 70% CHO), low in CHO (LCHO - 20% CHO) or containing a moderate amount of CHO (MCHO - 45% CHO). Across all trials, a decrease in GE with time ($p < 0.01$) was evident and no differences were found between LCHO and MCHO at any timepoint ($p > 0.05$). However, at 25-30min and at 85-90min, HCHO (GE of 21.20±1.72% at 25-30min and GE of 20.13±1.88% at 85-90min) was higher ($p < 0.05$) than LCHO (GE of 20.72±1.91% at 25-30min and GE of 19.64±1.52% at 85-90min) and MCHO (GE of 20.34±1.32% at 25-30min and GE of 19.33±1.78% at 85-90min).

In the other investigation of Cole et al. (2018), both CHO (6% CHO drink) and caffeine ([CAF], a water drink with 5 milligrams of caffeine per kilogram of body weight) were studied, being constituted four groups, one of only water (WA), WA+WA, one of WA+CHO, one of WA+CAF and one of CHO+CAF. Despite mean GE being greater during the WA+WA trial than in both WA+CHO (p = 0.010) and WA+CAF (p = 0.030), mean GE decreased in all conditions throughout time ($p < 0.01$). Additionally, only at the 20 to 30-min interval were marked differences seen with WA+WA having higher GE measures than WA+CHO ($p = 0.002$) and WA+CAF ($p = 0.038$).

Marquet et al. (2016) examined if a 3-week ‘‘Sleep Low’’ (SL) strategy related to CHO intake could affect CE. The SL group had a CHO restricted recovery with an overnight fast while the CON had no CHO restrictions. The results show that from pre-test (DE at 100W of 26.3±2.5% and 26.5±4.5 for the CON and SL group, respectively) to post-test (DE at 100W of 26.5±2.4% and 29.6±8.0 for the CON and SL group, respectively) there was an improvement in DE only for the SL group ($p < 0.05$).

Ramonas et al. (2023) evaluated the effect of a CHO drink at a steady state (SS) condition and at a glycogen depletion (GD) condition. On the SS the CHO drink had no effect on GE, being registered values of 19.8±1.6% at 50% of peak power output (PPO), 20.1±1.6% at 55%PPO and 20.7±1.0% at 60%PPO for the CHO group and of 20.0±1.6% at 50%PPO, 20.6±2.0% at 55%PPO and 21.2±1.8% at 60%PPO for the PLA ($p = 0.14$ for main drink effect and $p = 0.37$ for main intensity effect). In the GD condition, GE at 60%PPO was higher than GE at 60%PPO during SS intervals in CHO (22.06±1.91% vs 20.15±1.77%, $d = 1.03$, $p < 0.01$) and revealed a trend to be higher in PLA as well (22.45±0.99% vs 21.22±1.78%, $d = 0.79$, $p = 0.07$).

Dumke et al. (2009) examined the effects of Quercetin (QUE) on CE. A 3-week supplementation of QUE or PLA were given to participants in the groups of this experiment, QUE and PLA groups. The results reveal that GE decreased over time ($p = 0.03$) and that GE was different at 2h (QUE GE of ~19.1% and PLA GE of ~19.4%) and 3h (QUE GE of ~19.1% and PLA GE of ~19.3%) for both groups, when compared to the first measurement, at ½h (QUE GE of ~19.6% and PLA GE of ~19.8%), even though no effects of day, group or interaction was found.

Christensen et al. (2013), Garnacho-Castaño et al. (2018), Mumford et al. (2018) and Rokkedal-Lausch et al. (2021) studied the effects of beetroot (BR) derivates consumption on CE. Christensen et al. (2013) studied this subject on a 2-hour test, where GE was measured at individual stable PPO (50%) periods of

20 minutes (S1- 0 to 20min; S2- 30 to 50min; S3- 60 to 80min and S4- 90 to 110min). For both BR and PLA groups, all evaluated periods were different ($p < 0.01$) from S1, having GE a decreasingly tendency. Between groups, no differences were found during the 2h test ($p > 0.05$).

Garnacho-Castaño et al. (2018) investigated the effects of ingesting a dose of BR juice, on CE, at different intensities, the first and second ventilatory thresholds (VT1 and VT2, respectively). No effect of supplement neither of the interaction between supplement and intensity on GE ($p > 0.05$) was discovered (GE at VT1 of ~22,38% and ~22,93 for BR and PLA, respectively; GE at VT2 of ~23,27% and ~24,08 for BR and PLA, respectively) for both groups (PLA and BR).

Mumford et al. (2018) made their participants take one week of betalain-rich BR concentrate supplementation. A time interaction was found for both groups, PLA and BR, ($p < 0.01$), as well as an interaction between time and condition ($p = 0.045$) at the 30-min time trial tests performed. The only timepoint where a moderate effect ($d = 0.45$) difference in CE was noticed, between groups, was at minute 30, with BR group having a higher CE than PLA group ($p = 0.029$).

Rokkedal-Lausch et al. (2021) used a 7-day supplementation period to examine if a high-dose of BR juice could improve performance in both normoxia (NORM) and hypoxia (HYPO). No effects of condition ($p = 0.112$), supplementation ($p = 0.333$) nor supplementation-by-condition interactions ($p = 0.656$) were found on GE for both PLA and BR groups. In NORM were found GE values of 18.0±0.4% and 18.2±0.4% and in HYPO of 17.6±0.4 and 17.9±0.4, for PLA and BR groups, respectively.

Evans et al. (2018) investigated if an acute ingestion (1 hour prior to each exercise test) of β-hydroxybutyrate (βHB) salts could have a positive impact in cyclist's efficiency. GE and DE were measured at 30%, 40%, 50%, 60%, 70% and 80% of maximal oxygen consumption ($\dot{V}O_{2max}$). No differences were seen in condition ($p = 0.789$ and $p = 0.737$ for βHB and CON groups, respectively) and in interaction between conditions ($p = 0.992$ and $p = 0.830$ for βHB and CON groups, respectively), but differences were observed between intensities ($p <$

0.01) for both groups, since GE tended to increase with the increment of intensity and DE had the opposite effect, decreased with the increment of intensity.

Voskamp et al. (2020) investigated if sodium bicarbonate (SB) affected GE. In this study a SB and PLA groups were created to perform a 2000-meter time trial, where GE was calculated at pre-trial, at post1 (4 to 7 minutes after the trial) and at post2 (7½ to 10½ minutes after the trial). There was a timepoint, halfway between pre and post1, where GE was extrapolated (extrap). A decline in GE was clear for both groups during the trial, even though it was only significant between pre and extrap. The effect of SB supplementation was unclear between males and females (males: ES = 0,7; ±1.8%; females: ES = 0.6; ±2.1%).

Płoszczyca et al. (2021) researched the effects of tri-sodium phosphate (SP) supplementation on the GE during exercise under HYPO. Tests were conducted at two different intensities, individual lactate threshold 1 and 2 (LT1, LT2, respectively). No changes in GE were found, from pre- to post-test, for both groups, SP and PLA, at both evaluated intensities, LT1 (18.73±0.47% and 19.06±0.50% at pre-test for SP and PLA, respectively; 18.96±0.45% and 19.00±0.48% at post-test for SP and PLA, respectively) and LT2 (20.20±0.43% and 20.54±0.45% at pre-test for SP and PLA, respectively; 20.05±0.41% and 20.39±0.43% at post-test for SP and PLA, respectively).

3.5.4. Environmental and External factors

Clark et al. (2007) simulated an acute exposure at several different altitudes to examine the impact it could have on GE. GE did not differ (p = 0.47) at sea level (200m, 18.6±0.82%) compared with the 1200m (18.9±0.77%), 2200m (19.1±0.59%) and 3200m (19.0±1.2%). GE was also not different among the four above-mentioned altitudes at a 5-min time trial test (p = 0.61). Submaximal GE decreased at 3200m (16.8±2.2%) in comparison with 200m (17.3±2.4%) and 1200m (17.3±2.4%), respectively (p = 0.0013). Comparing by power output, at 50W (13.2±1.3%) and 100W (16.8±1.3%) GE was lower than at 150W (18.2±1.1%), 200W (18.7±0.9%) and 250W (18.6±0.8%), respectively (p < 0.0001).

Rodríguez-Marroyo et al. (2009) studied the impact that a rotor pedaling system (ROT) could have on professional cyclist's performance. None of the utilized versions of ROT (ROT-1, ROT-2, ROT-3, ROT-4 and ROT+) increased GE when compared to the CON group (CON: 20.7±0.8%, ROT-1: 20.5±0.8%, ROT-2: 20.5±0.9%, ROT-3: 20.9±1.0%, ROT-4: 21.1±0.9% and ROT+: 21.6±1.0%), given that no differences were found between ROT and CON groups ($p > 0.05$).

Williams et al. (2009) used a 6-week intervention to study the cranks system. No differences were seen between uncoupled cranks (UC) and traditional cranks (TC) among both groups (GE at 70%$\dot{V}O_{2max}$, $p = 0.962$; GE at 200W; $p = 0.183$, respectively). Additionally, no between-group changes on GE at either 70%$\dot{V}O_{2max}$ ($p = 0.250$) or GE at 200W ($p = 0.260$) were noticed. However, the intervention revealed an effect on GE at 70%$\dot{V}O_{2max}$ ($p = 0.011$), that didn´t occur in GE at 200W ($p = 0.671$).

Fröhlich et al. (2014) tested different types of cycling shoe insoles (standard vs carbon). DE was calculated at 280W and in a 20 seconds test. No improvement in CE was found between carbon insoles and regular insoles at both DE at 280W ($p > 0.05$, $d = 0.02$) and DE at the 20 seconds test ($p > 0.05$, $d = 0.21$).

Heat acclimatization was studied by Karlsen et al. (2015), Mikkelsen et al. (2019) and Tebeck et al. (2020). Karlsen et al. (2015) tested whether time (p = 0.17-0.56), the intervention (p = 0.14-0.87), or their interaction (p = 0.08-0.92), affected exercise efficiency and no differences were found. DE decreased in both groups, CON (pre- ~25.81% and post- ~25.15%) and Heat Acclimation (HA) group (pre- ~25.89% and post- ~25.31%), despite not being significant ($p > 0.05$). In terms of GE, for HA group increased for both 100W (pre- ~15.88% and post- ~16.19%) and 200W (pre- ~19.64% and post- ~19.76%), but for the CON group GE decreased at both 100W (pre- ~15.49% and post- ~14.87%) and 200W (pre- ~19.37% and post- ~18.59%).

Mikkelsen et al. (2019) used a 5½-week period and the results showed that HA had no effect on GE ($p > 0.05$). In this study it was the CON group who showed an increase in GE at 100W (pre- 14.8±0.5% and post- 15.2±0.4%) and at 175W (pre- 19.3±0.5% and post- 19.8±0.5%), while GE in the HA group decreased at 100W (pre- 15.4±0.3% and post- 15.2±0.2%) and at 175W (pre- 19.7±0.3% and post- 19.4±0.2%). Tebeck et al. (2020) examined adaptations induced by dry and humid short-term HA (a 5-day block for each condition) during a 48-day study period. A decrease in GE was found, with an ES of -0.6±0.5 when comparing the dry group to the humid one.

Cardinale et al. (2019) approached if an increment in oxygen availability had an impact on CE. A Hyperoxia (HYPER) group and a NORM group were established. From pre- to post-intervention no changes in GE and WE at 150W were observed (HYPER GE from 19.7±0.1% to 20.0±1.3% and NORM GE from 19.0±0.9% to 19.3±1.1%; HYPER WE from 25.0±1.3% to 25.7±1.7% and NORM WE from 24.2±1.0% to 24.9±0.5%) neither between group differences were evident.

3.6. Evidence certainty

The certainty of the evidence for each outcome was evaluated using the GRADE approach and is summarized in Table 3. For GE, the certainty was downgraded to low due to serious risk of bias, with 18 out of the 26 included RCTs presenting methodological issues related to randomization, allocation concealment, or lack of blinding. The DE and NE was also rated as low. These outcomes were each supported by two RCTs, which led to downgrading due to imprecision. Only the outcome combining GE & DE was rated as moderate certainty, based on three RCTs with no serious concerns identified in any domain.

Table 3. GRADE assessments. Summary of findings on cycling efficiency type

Efficiency type	Number of RCTs	Certainty assessment					Certainty of evidence
		Risk of Bias	Inconsistency	Indirectness	Imprecision	Other considerations	
Gross Efficiency (GE)	26	Serious (18 High)	Not serious	Not serious	Not serious	None	⊕⊕◯◯ LOW
Gross Efficiency (GE) & Delta Efficiency (DE)	3	Not serious	Not serious	Not serious	Not serious	None	⊕⊕⊕◯ MODERATE
Delta Efficiency (DE)	2	Not serious	Not serious	Not serious	Serious (2 studies)	None	⊕⊕◯◯ LOW
Net Efficiency (NE)	2	Not serious	Not serious	Not serious	Serious (2 studies)	None	⊕⊕◯◯ LOW

Abbreviations: Randomized Controlled Trials (RCTs)

Notes:

- GE: Risk of bias (RoB) downgraded due to 18 studies (Almquist et al., 2022; Almquist et al., 2020a; Almquist et al., 2020b; Christensen et al., 2013; Cole et al., 2014; Cole et al., 2018; Dumke et al., 2009; Kristoffersen et al., 2014; Kristoffersen et al., 2019; Mikkelsen et al., 2019; Passfield & Doust, 2000; Płoszczyca et al., 2021; Rodríguez-Marroyo et al., 2009; Ronnestad et al., 2015; Stebbins et al., 2014; Taylor et al., 2021; Tebeck et al., 2020; Williams et al., 2009) presented in figure 2.
- DE: Two studies (Fröhlich et al., 2014; Marquet et al., 2016) presented in figure 2.
- NE: Two studies (Harnish et al., 2007; Sunde et al., 2010) presented in figure 2.

4. Discussion

4.1. Summary of evidence

In this review, which identified and synthesized the current available evidence of CE determinants in road cyclists and triathletes, 35 studies (589 participants) were included. Some CE related variables presented in the included studies were investigated (e.g., DE, GE, NE, WE). Heterogeneity regarding sample, age, performance level and conditions evaluated was evident among studies. Consequently, caution should be taken when generalizing or interpreting results of individual studies.

4.2. Physiological and Biomechanical factors

Bouts of acute moderate-intensity endurance exercise (~60 minutes) tend to result in a decrease in GE. Hagan et al. (1992) reported that CE decreased over a 45-min test. Faria et al. (2005a) reported that prolonged cycling may reduce the efficiency of contraction in muscles, and that this may be explained by fatigue. Hopker et al. (2017) also reported that a significant decrease in GE was evident after two hours of cycling at a constant load. Therefore, from older to recent studies, there is a consensus in the literature that prolonged cycling decreases efficiency (Almquist et al., 2021; Noordhof et al., 2015).

Cadence increments may lead to GE decrements, as evident in the studies of Stebbins et al. (2014) and Whitty et al. (2016). Despite Lucia et al. (2004) reporting that low cadences are less efficient, our analysis is in line with the most of the literature that reports a decrease effect of cadence on GE (Arkesteijn et al., 2013; Chavarren & Calbet, 1999; Dumke et al., 2007; Foss & Hallén, 2005; Hopker et al., 2009; Jacobs et al., 2013; Leirdal & Ettema, 2011; Takaishi et al., 1998). Nimmerichter et al. (2015) report high cadences to be above 80 rpm and the most efficient cadence to be around 50 rpm. Other studies also show that lower cadences are associated with a higher efficiency (Foss & Hallén, 2005; Jacobs et al., 2013; Leirdal & Ettema, 2009).

It appears at the same cadence, GE increases with an intensity increment (65 to 80% $\dot{V}O_{2max}$), but that this is only significant at high cadences (100 rpm). The study of Sidossis et al. (1992) contradicts this assertion by reporting a stability in GE when cycling between 60 and 100 rpm at WR of 80 to 90% of $\dot{V}O_{2max}$. However, in this study higher intensities were used. Between 60 and 80 rpm, no differences were found in GE at any of the workloads tested and cadence increments (from 80 to 120 rpm) led to GE decrements (Foss & Hallén, 2005). Stebbins et al. (2014) report that during low to moderate WR (where the 65 to 80% $\dot{V}O_{2max}$ interval used fits), the use of a HC is not economical and can potentially compromise endurance cycling performance.

Kristoffersen et al. (2014) reported that when individuals used a FCC (which can be considered a HC, since mean was above 90 rpm), GE from the FCC training group didn't differ from the training group that completed a LC intervention. Leirdal & Ettema (2009) disagreed by showing a negative relationship between employed FCC and GE. Whitty et al. (2016) support the notion that FCC is more comfortable to the riders, can be altered with HC training, and that the personal choice of using a HC is more related to endurance riding instead of an efficient riding. Although demanding a greater energy expenditure, HC riding reduces the force applied per pedal stroke, reducing muscle fatigue and stress, allowing the riders to keep on riding for more time, increasing their endurance performance (Faria et al., 2005a; Whitty et al., 2016).

During uphill cycling, when the gradient starts to increase, a cyclist tends to regularly alter from a seated to a standing position (Bouillod & Grappe, 2018). Our review found no differences in efficiency when cycling seated, standing or when transitioning repeatedly from one of these positions to the other (Carlsson et al., 2024; Harnish et al., 2007). Millet et al. (2002) also reported that level-seated, uphill-seated or standing cycling display similar CE and stated that gradient might not be a factor affecting CE. Arkesteijn et al. (2016) reported that standing reduces cycling economy, compared with a seated position, and that this reduction is more evident at low intensities when compared to high ones. However, this study, for the calculation of economy, accounts for the volume of oxygen consumed, instead of energy expended, and care must be taken when comparing these two concepts.

4.3. Training factors

Although within-group changes were similar, the overall trend found by Bastiaans et al. (2001) indicates that the group that performed a ST protocol improved DE while the CON group declined. It wasn't clear if ST improves CE. Earlier studies observed improvements in economy, in other sports, using maximal ST protocols, based on training at high intensities, but with few repetitions, that emphasize explosive concentric movements (Østerås et al., 2002). This type of ST differed from the one used by Bastiaans et al. (2001) that focus on traditional ST, using many more repetitions. After traditional bouts of ST, Devantier-Thomas et al. (2024) reported improvements in NE, but also found partial levels of exercise-induced muscle damage, that elicited an increase in delayed onset muscle soreness (DOMS), which may reduce the quality of sessions in cycling. Sunde et al. (2010), implemented a maximal ST intervention of 8 weeks with marked improvements in NE, in both groups, CON and EXP, despite this improvement being higher in the latter. These findings are in agreement with Barrett-O'Keefe et al. (2012) who concluded that maximal ST improves efficiency. However, Ronnestad et al. (2015) and Kristoffersen et al. (2019) didn't record any significant changes in GE, in both groups, after implementing their ST protocols, which varied from a 6-week to a 25-week intervention. In summary, there is no clear consensus in literature about ST improving CE. It should also be pointed that the results found vary among time intervention and efficiency index used, which doesn't ease comparisons and conclusions. However, there is an agreement that concurrent endurance training and ST training may improve cycling performance (Rønnestad & Mujika, 2014), which, after all, is the main purpose of athletes and coaches.

In terms of SPT, even though, in the study of Almquist et al. (2020a), mean GE values ended up slightly lower in SPT group, compared to the CON group, this decline likely reflects the effect of fatigue generated by prolonged low-intensity cycling. When comparing GE values of the SPT group in a FS with a FGS, Almquist et al. (2020b) reported a significant decrease, evidence that the EXP condition itself was sensitive enough to reveal a decline in GE under fatigue. Noordhof et al. (2015) outline that GE reductions during both submaximal and maximal efforts appear consistent, regardless of the specific exercise protocol or the modality used, which agrees with our analysis. However, the results of Taylor et al. (2021) contradict this, showing that incorporating short, maximal sprints into low-intensity sessions during the TRAN period does not compromise GE in either COMP or PREP periods. Although GE at both the FS and FGS remained stable across groups, GE was similar from the COMP to the PREP period. Almquist et al. (2022) compared the effects of TP and BP endurance training over 12 weeks and showed that only in a FGS significantly differences were found, since GE increased in both groups. Sassi et al. (2008) reveal that, in highly trained cyclists, GE was stable and that changes and increments in this performance metric should not always be expected throughout a season. Hopker et al. (2009) showed increases in GE in cycling, revealing that it happens mostly when training at high intensities. Hopker et al. (2010) and Clark et al. (2014) also agree and suggested incorporating high-intensity training prior to the main competitive moment of a season to enhance GE. Despite this, Noordhof et al. (2015) points that lower GE is seen after high-intensity exercise, such as the sprints used in the TRAN period. Solli et al. (2025) found no differences in GE between groups after a 6-day microcycle of high intensity interval training.

The literature is not conclusive in this regard and many methodological factors contributed to the variability found in study results (e.g., measuring methods, efficiency indices used, duration of the intervention, athletes training status, type of training performed).

4.4. Nutritional factors

Science is constantly evolving and research for new ways of supplements enhancing performance is continuously growing. The interaction between nutrition and exercise is essential to an athlete’s sports success. Nutrition plays a key role in addressing limiting factors that may lead to a decrease in performance, which can potentially be avoided by periodizing feeding strategies (Burke, 2015). In endurance sports, there has been an increasing interest in alternative fueling strategies, using, not only but also, CHO and ketogenic diets, through exogenous supplementation (Evans et al., 2018).

The study of Cole et al. (2014) reported that all CHO supplemented groups became less efficient over time, despite the HCHO group showing slightly higher GE values than LCHO and MHCO. The study of Cole et al. (2018) showed that GE significantly decreased in time within all conditions and that neither CHO nor CAF ingestion could improve GE. Both these substances, CHO or CAF, reduced GE at certain timepoints after their ingestion, showing a trend for a decrement in efficiency or an increment in energy expenditure. However, Dumke et al. (2007) revealed that CHO supplementation taken by the EXP group helped preserve or enhance CE during prolonged exercise, while in the PLA group a steady decline was noticed. This difference was most pronounced from the mid-point on, suggesting an important role of CHO supplementation in sustaining efficiency under fatigue conditions. The results seen from SL CHO intake of Marquet et al. (2016) pointed that this strategy can enhance exercise efficiency. Ramonas et al. (2023) showed that a CHO drink had no effect on GE at a SS condition, but that it was able to improve GE at a GD state in both groups, despite only significantly in the CHO group. Benefits of CHO intake to perform better are supported in the literature (Currell & Jeukendrup, 2008; Davis et al., 1988; Wright et al., 1991). Bourdas et al. (2021) also corroborate a positive effect of CHO in efficiency, reporting increased endurance exercise efficiency and concluding that in prolonged exercise, performance is favored by CHO solutions intake. The literature is in favor of supplying athletes with supplements that mainly contain this macronutrient, given that CHO supplementation can potentially enhance performance and delay fatigue (Ramonas et al., 2023).

In the last decade, the trend of using BR supplements to improve athletic performance has increased. BR juice was classified as a supplement that guarantees high scientific evidence in improving performance in sports (Garnacho-Castaño et al., 2018). BR is usually linked to a better oxygen utilization by the body, due to its important role in the regulation of delivering oxygen to the muscles (Christensen et al., 2013). BR derivates elevate nitric oxide body levels, which may lead to enhanced gas exchange, blood flow, mitochondrial biogenesis, mitochondrial efficiency and muscle contraction strengthening (Domínguez et al., 2017). Christensen et al. (2013) results reveal a decrease in GE in both PLA and BR groups, indicating that BR supplementation didn't even attenuate a reduction in efficiency compared to the PLA group. Garnacho-Castaño et al. (2018) results suggest that an acute ingestion of this kind of supplementation doesn't improve CE, regardless of exercise intensity. Rokkedal-Lausch et al. (2021) revealed that a high-dose BR juice didn't improve CE under neither oxygen conditions (NORM and HYPO), which is in agreement with the study of Hennis et al. (2022). Mumford et al. (2018) found benefits of supplementing with BR. However, a significant difference in CE was only observed at the 30-min mark, suggesting that BR only provides benefits during sustained or prolonged exercise, rather than immediately or at the start. The literature reports that chronic supplementation of BR may increase time to exhaustion, improve efficiency and cardiorespiratory performance, mostly at high intensities (Domínguez et al., 2017). Our analysis isn't in agreement with this. The differences may come from the supplementation strategies used, once most benefits seem to come from long exposure to this substance and the protocols used in our included studies used acute exposures. Valiño-Marques et al. (2024), reported that BR supplementation effectiveness in enhancing cycling performance it's mostly trivial, whether using short-distance and high-intensity tests or moderate-intensity and long-duration tests. Supplementation duration (acute or chronic), regular dietary and dose of nitrate intake, duration and intensity of exercise tests, athlete's status and training level may all impact the outcomes of BR supplementation (Garnacho-Castaño et al., 2018).

In the last few years, another supplement, ketone bodies, such as the βHB salts used in the study of Evans et al. (2018), have emerged and gained a bigger significance in sports nutrition, mostly in endurance sports such as cycling (Sitko, 2024). Ketones are organic molecules that during periods of low glucose availability are produced in the liver (Evans et al., 2018) and that are used to provide up until 10% of energy during exercise in the fasted state, like in a low CHO availability situation (Sitko, 2024). Evans et al. (2018) results demonstrated that this kind of supplements has no effect on CE, indicating that these substances may not be as good ergogenic aids as it was postulated. Dearlove et al. (2021) contradicts concluding that elevated blood βHB concentrations led to an exercise efficiency enhancement, when compared to a CON condition. As literature regarding the effects of these molecules in sports performance it's still limited, caution should be taken when approaching ketones supplementation (Dearlove et al., 2021; Sitko, 2024).

Dumke et al. (2009) showed that after 3 weeks of QUE supplementation GE declined over a 3-hour period of cycling, but that QUE had no effect on these results. QUE, which can be found in many foods, reveals to be related to many anti-inflammatories, antioxidant, anticarcinogenic and cardioprotective properties and can directly affect the skeletal muscle and cardiac mitochondria (Dumke et al., 2009). Although existing few information about this substance in cycling, Cureton et al. (2009) revealed that short duration (7 days) of QUE supplementation didn't improve determinants of performance, and performance itself, in untrained subjects. The fact that the sample was composed by untrained man and that a much shorter intervention was used doesn't allow reliable comparisons. The study of MacRae & Mefferd (2006) showed that a 6-week intervention of supplementing elite male cyclists with a substance containing QUE improved cycling time trial performance at high intensities. Here, an intervention twice as long was used and the substance supplemented was mixed with antioxidants, which also doesn't easy comparisons. After all, more information and research in this topic must be presented, to the scientific community, for conclusions to be made about whether QUE supplementation enhances CE and, therefore, cycling performance.

In terms of sodium supplements, Voskamp et al. (2020) demonstrated that SB doesn't increase GE. Płoszczyca et al. (2021) showed that SP didn't impact GE at any of the intensities tested (low or moderate) but that, in a hypoxic environment, it improved the efficiency of the cardiorespiratory system at the exercise intensities abovementioned. Although being different substances, both SB and SP come from the same base, sodium, and both reveal no significant impact on enhancing CE. Nevertheless, Valiño-Marques et al. (2024) reported a tendency of positive effects on cyclist's athletic performance after SB supplementation and de Oliveira et al. (2022) showed that SB was the most effective supplement for improving outcomes in performance tests, time-to-exhaustion tests and protocols to resist fatigue. For these reasons, it is recommended a further investigation of these kinds of supplements. An individual and informed usage of these supplements, to enhance performance, may vary according to the athlete’s needs and requirements.

4.5. Environmental and External factors

Karlsen et al. (2015) indicated that 2 weeks of HA didn’t significantly improved CE in temperate conditions. Mikkelsen et al. (2019) showed that 5 weeks of HA did not enhance CE, concluding that in cool conditions benefits weren’t found. Tebeck et al. (2020) result’s follow the same line. After a short term (5 days) HA protocol, in a dry and in a humid condition, GE remained stable revealing that it isn’t clear an endurance performance improvement in temperate conditions. These three studies reveal a trend supporting that HA doesn’t positively impact CE in temperate temperatures.

Although HA being related to enhanced exercise performance in hot environments, and despite seeming to be a good strategy to adopt when competitions are happening in hot environments (Corbett et al., 2014; Mikkelsen et al., 2019; Tebeck et al., 2020), the transfer of these benefits to cool conditions are not very consensual in the literature, as some studies report benefits, while others report no effects (Mikkelsen et al., 2019; Tebeck et al., 2020). Chalmers et al. (2014) reported potential performance enhancements following short term HA and Corbett et al. (2014) refers that HA adaptive responses may lead to an increased exercise performance in cool conditions, despite no CE data was presented in these manuscripts. Hettinga et al. (2007) highlighted that a deteriorated exercise performance is usually observed in heat circumstances, when compared to thermo-neutral ones, and that the same happens with GE. In a case study, Bell et al. (2017) demonstrated that, in hot conditions, GE at lower intensities was higher, but when intensity rises, GE tends to become similar despite the temperature. Consecutive bouts of cycling at increasing submaximal intensities also don’t make GE differ in the heat (Waldron, 2014). Once again literature doesn’t fully agree on the impacts that HA has on CE and on other cycling performance determinants. For these reasons, further research is advised to withdraw more reliable and solid conclusions.

Altitude training has been around for years when it comes to use it to pursue endurance performance enhancements (Girard et al., 2017). Variations related to oxygen availability (OA) happen with changes in altitude. The higher we get, the lower is the air density. This means that decreases in OA occur with increasing altitudes (Clark et al., 2007), and that's why altitude training is also referred as hypoxic training.

Clark et al. (2007) results indicate that endurance efforts at submaximal intensities may feel more demanding and lead to reduced performance as elevation get higher. Despite no differences being found in GE during maximal exercise, their results showed that at submaximal intensities GE values decreased with increasing altitude. Gore et al. (2001) contradicts this by reporting a higher exercise efficiency with HYPO. However, in this study a living high and training low protocol was used, which doesn't allow reliable comparisons between results. More recently published studies agree with Clark et al. (2007) that lower GE values at high altitudes are registered, when compared with the sea level (Noordhof et al., 2013; van Erck et al., 2019). The study of Schiffer et al. (2014), which made their well accustomed to cycling sample breathe a gas with approximately 16% of oxygen (5% less than the air in the atmosphere), simulating HYPO or altitude, also revealed decreases on whole body efficiency.

Manselin et al. (2017) report that reductions in CE, seen in environments with lower OA, might be positive body adaptations, to allow higher power productions by individuals, according to the optimal efficiency for maximum power (OEMP) principle. In this principle an optimal efficiency level exists for a maximized power production. It defends that at efficiencies lower than the OEMP, higher power production occurs due to increases in efficiency and that at efficiencies higher than the OEMP, increases in efficiency happen due to power production, while decreases in efficiency lead to higher power production (Schiffer et al., 2014).

Cardinale et al. (2019) studied the effects of HYPER training, where, contrary to altitude training, an increased OA exists. Their results showed that no significant improvements were found in GE and WE in the EXP group. This agrees with the findings of Manselin et al. (2017) that, after submitting one group to inhaling a gas with approximately 30% of oxygen (9% more than the air in the atmosphere), obtained a significant decrease in GE compared to a normoxia condition. It was also reported that HYPER may be more impactful in subjects with a higher efficiency than in subjects with lower efficiency.

Rodríguez-Marroyo et al. (2009) showed that the ROT system did not improve GE in professional cyclists under the tested conditions, which indicates that switching to a noncircular chainring like ROT may not provide measurable performance benefits in terms of CE. This in agreement with the literature. Lucía et al. (2004) found no differences in GE and DE in trained cyclists using the ROT system and Jobson et al. (2009) also reported no differences in GE. The findings of Santalla et al. (2002) showed no improvements in GE but revealed higher DE values when using a ROT system. However, in this study the sample was composed by physical education students, not cyclists, which may influence results and difficult comparisons. For these reasons, using a ROT system, which allows an independently motion of the pedals, doesn't seem to play an important role on CE.

Williams et al. (2009) showed that training with an UC system did not allow any benefits regarding CE, compared with training with a TC system, once no between-group changes in GE were noticed. The findings of Burns et al. (2012) are in line, reporting no differences in CE after a 5-week intervention of training with UC. This suggests that no significant advantages in CE may come from training with UC, compared to the TC system.

In this review it was also analyzed that cycling with carbon insoles provides no advantages in CE and cycling performance, when compared with regular standard insoles (Fröhlich et al., 2014). Despite literature being very scarce and no other manuscripts, studying CE, in this domain, have been found, Koch et al. (2013) reported that no effects of carbon insoles in several performance measurements. This agrees with our analysis and lead us to conclude that CE may not be altered by this type of product.

4.6. Caveats when interpreting the findings, limitations, and future perspectives

One limitation that can be attributed to this study is related to the heterogeneity found in its sample. In our included studies, the corresponding samples showed a high degree of heterogeneity in terms of the age and performance level (De Pauw et al., 2013) of the subjects. This leads us to advise caution in interpreting the results, since the literature reveals that the age (Martin et al., 2002; Peiffer et al., 2016) and the level of the athletes (Sallet et al., 2006) are factors that may impact their degree of efficiency.

Despite most of our results being presented as GE index, as previously mentioned, the use of different CE indices along the included studies, and therefore in our review, might also be a confounding factor. As explained before, these measurements rely on different methods of calculation and protocols, and comparing them might not be as accurate as it should be.

The fact that this review only includes results from randomized controlled trials may allow for the loss of essential information related to the topic under study and may also be indicated as another limitation. However, when it comes to experimental research and interventions efficacy assessment, this kind of study design chosen is a gold standard (Hariton & Locascio, 2018) and for this reason it was the study design chosen for this manuscript.

Additionally, risk of bias among included studies was high and GRADE judgments revealed low evidence certainty. This means that a fragile basis foundation is supporting the results showed and that reliably strong conclusions should be avoided.

Finally, further studies in this field of knowledge are recommended to better clarify the effects that some of the above-mentioned factors may have, specifically in CE, and generally in cycling performance.

5. Conclusions

This study showed that prolonged cycling decreases efficiency, and that at lower cadences, higher CE values are expected. Moreover, the adoption of different positions on the bike reveals similar efficiency, even when transitioning between positions is done repeatedly. It appears that GE is usually stable, that substantial variations in GE over time should not always be expected. Analysis of the literature indicates that a consensus can't be found on SPT training improving CE. Hypoxia and hyperoxia tend to reduce CE, rotor pedaling systems, uncoupled crank systems and carbon insoles show no advantages in enhancing CE. Despite more information being needed in terms of these factors related to CE, carbohydrate, beetroot and sodium-based supplements and strength training seemed to impact cycling performance positively. There are many similarities between endurance road cycling and the cycling segment of triathlons. For these reasons, most of these conclusions can be generalized to triathlon cycling, despite coming from results of studies that mostly used road cyclists as sample. In this work there's considerable heterogeneity among studies, the risk of bias was mostly high, and evidence certainty was judged as low. Given these limitations, further studies in this field are needed to better clarify the effects of the studied determinants in CE.

6. Other Information

6.1. Funding

The authors have no funding to declare.

6.2. Conflicts of interest

The authors have no conflict of interest to declare.

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Appendix 1: Search Strategies by databases

Databases	Date	Search Strategy
Pubmed	09/01/2025	((((("road cycling"[Title/Abstract]) OR (bicycling[Title/Abstract])) OR (cyclist*[Title/Abstract])) OR (triathlon[Title/Abstract])) OR (triathlete*[Title/Abstract])) AND (efficiency[Title/Abstract])
Scopus	09/01/2025	("Road Cycling" OR "Bicycling" OR "Cyclist" OR "Cyclists" OR "triathlon" OR "triathlete" OR "triathletes") AND "efficiency"
Web of Science	09/01/2025	AB=(roadcycling OR bicycling OR cyclist* OR triathlon OR triathlete* AND efficiency) AND TI=(roadcycling OR bicycling OR cyclist* OR triathlon OR triathlete* AND efficiency)

Appendix 2: Criteria for participant level classification according to the Guidelines to classify subject groups in sport-science research (De Pauw et al., 2013)

Author	Title	Performance Level (PL) (De Pauw et al. 2013)	Premise for sample PL assessment (De Pauw et al., 2013)
Almquist et al. (2020)	The effect of 30-s sprints during prolonged exercise on gross efficiency, electromyography and pedaling technique in elite cyclists	PL5	cycling experience (years)
Almquist et al. (2020)	Effects of Including Sprints in One Weekly Low-Intensity Training Session During the Transition Period of Elite Cyclists	PL5	1° relative $\dot{V}O_{2max}$
Almquist et al. (2022)	No Differences Between 12 Weeks of Block- vs. Traditional-Periodized Training in Performance Adaptations in Trained Cyclists	PL2 and PL3	1° relative $\dot{V}O_{2max}$
Bastiaans et al. (2001)	The effects of replacing a portion of endurance training by explosive strength training on performance in trained cyclists	PL5	training h/wk
Cardinale et al. (2019)	Influence of Hyperoxic-Supplemented High-Intensity Interval Training on Hemotological and Muscle Mitochondrial Adaptations in Trained Cyclists	PL3	absolute $\dot{V}O_{2max}$

Carlsson et al. (2024)	Steep uphill cycling using repeated transitions between seated and standing positions results in a lower blood-lactate concentration than continuous use of either seated or standing position	N.A.	N.A.
Christensen et al. (2013)	Influence of nitrate supplementation on VO_2 kinetics and endurance of elite cyclists	PL5	1° relative $\dot{V}O_{2max}$
Clark et al. (2007)	The effect of acute simulated moderate altitude on power, performance and pacing strategies in well-trained cyclists	PL4	1° relative $\dot{V}O_{2max}$
Cole et al. (2014)	Improved Gross Efficiency during Long Duration Submaximal Cycling Following a Short-term High Carbohydrate Diet	PL3	1° relative $\dot{V}O_{2max}$
Cole et al. (2018)	The effects of acute carbohydrate and caffeine feeding strategies on cycling efficiency	PL3	1° relative $\dot{V}O_{2max}$
Dumke et al. (2007)	Effect Of Duration And Exogenous Carbohydrate On Gross Efficiency During Cycling	PL2	1° relative $\dot{V}O_{2max}$
Dumke et al. (2009)	Quercetin's effect on cycling efficiency and substrate utilization	PL2	1° relative $\dot{V}O_{2max}$
Evans et al. (2018)	Effect of acute ingestion of β-hydroxybutyrate salts on the response to graded exercise in trained cyclists	PL3	1° relative $\dot{V}O_{2max}$
Frohlich et al. (2014)	The effect of carbon insole on left and right pedal forces cycling	N.A.	N.A.
Garnacho-Castaño et al. (2018)	Effects of a single dose of beetroot juice on cycling time trial performance at ventilatory thresholds intensity in male triathletes	PL2	1° relative $\dot{V}O_{2max}$
Harnish et al. (2007)	Effect of cycling position on oxygen uptake and preferred cadence in trained cyclists during hill climbing at various power outputs	PL4	1° relative $\dot{V}O_{2max}$
Karlsen et al. (2015)	Heat acclimatization does not improve VO max or cycling performance in a cool climate in trained cyclists	PL3	1° relative $\dot{V}O_{2max}$
Kristoffersen et al. (2014)	Low cadence interval training at moderate intensity does not improve cycling performance in highly trained veteran cyclists	PL3	1° relative $\dot{V}O_{2max}$
Kristoffersen et al. (2019)	Comparison of Short-Sprint and Heavy Strength Training on Cycling Performance	PL3	1° relative $\dot{V}O_{2max}$
Marquet et al. (2016)	Enhanced Endurance Performance by Periodization of Carbohydrate Intake: "Sleep Low" Strategy	PL3	1° relative $\dot{V}O_{2max}$
Mikkelsen et al. (2019)	Prolonged Heat Acclimation and Aerobic Performance in Endurance Trained Athletes	PL3	1° relative $\dot{V}O_{2max}$
Mumford et al. (2018)	Effect of 1-week betalain-rich beetroot concentrate supplementation on cycling performance and select physiological parameters	PL1	relative PPO
PassField and Doust (2000)	Changes in cycling efficiency and performance after endurance exercise	PL3	1° relative $\dot{V}O_{2max}$
Płoszczyca et al. (2021)	The Effects of Sodium Phosphate Supplementation on the Cardiorespiratory System and Gross Efficiency during Exercise under Hypoxia in Male Cyclists: A Randomized, Placebo-Controlled, Cross-Over Study	PL5	cycling experience (years)
Ramonas et al. (2023)	Carbohydrate intake before and during high intensity exercise with reduced muscle glycogen availability affects the speed of muscle reoxygenation and performance	PL3	1° relative $\dot{V}O_{2max}$
Rodríguez-Marroyo et al. (2009)	The rotor pedaling system improves anaerobic but not aerobic cycling performance in professional cyclists	N.A.	N.A.
Rokkedal-Lausch et al. (2021)	Multiple-day high-dose beetroot juice supplementation does not improve pulmonary or muscle deoxygenation kinetics of well-trained cyclists in normoxia and hypoxia	PL4	1° relative $\dot{V}O_{2max}$
Rønnestad et al. (2015)	Strength training improves performance and pedaling characteristics in elite cyclists	PL5	1° relative $\dot{V}O_{2max}$
Stebbins et al. (2014)	Effects of Cadence on Aerobic Capacity Following a Prolonged, Varied Intensity Cycling Trial	PL3	1° relative $\dot{V}O_{2max}$
Sunde et al. (2010)	Maximal Strength Training Improves Cycling Economy In Competitive Cyclists	PL5	1° relative $\dot{V}O_{2max}$
Taylor et al. (2021)	The Inclusion of Sprints in Low-Intensity Sessions During the Transition Period of Elite Cyclists Improves Endurance Performance 6 Weeks nto the Subsequent Preparatory Period	PL5	1° relative $\dot{V}O_{2max}$
Tebeck et al. (2020)	Differing Physiological Adaptations Induced by Dry and Humid Short-Term Heat Acclimation	PL5	1° relative $\dot{V}O_{2max}$

Voskamp et al. (2020)	The Effect of Sodium Bicarbonate Supplementation on the Decline in Gross Efficiency During a 2000-m Cycling Time Trial	PL3 (Males) and PL2 (Females)	1° relative $\dot{V}O_{2max}$
Whitty et al. (2016)	The effect of low vs high cadence interval training on the freely chosen cadence and performance in endurance trained cyclists.	PL3	absolute $\dot{V}O_{2max}$
Williams et al. (2009)	Cycling Efficiency and Performance Following Short-Term Training Using Uncoupled Cranks	PL3	1° relative $\dot{V}O_{2max}$

Chapter III – Final Considerations

3.1. General discussion of the main findings of this Academic Dissertation

The general aim of this Academic Dissertation was to identify and summarize the determinants and factors that influence CE. This included studies in this work showed that prolonged cycling decreases efficiency, which agrees with the literature (Faria et al., 2005a; Hopker et al., 2017), and that at lower cadences, higher CE values are expected (Foss & Hallén, 2005; Jacobs et al., 2013; Leirdal & Ettema, 2009).

This Academic Dissertation also reported that GE is usually stable and that substantial variations in GE over time should not always be expected (Sassi et al., 2008). Additionally, similar efficiency is expected when adopting different positions on the bike, even when transitioning between positions is done repeatedly (Arkesteijn et al., 2016; Millet et al., 2002), as found in our studies.

Hypoxia (Clark et al., 2007; Noordhof et al., 2013; van Erck et al., 2019) and hyperoxia (Manselin et al., 2017) tend to reduce CE, rotor pedaling systems (Lucía et al., 2004; Jobson et al., 2009), uncoupled crank systems (Burns et al., 2012; Williams et al., 2009) and carbon insoles show no advantages in enhancing CE (Koch et al., 2013).

Analysis of the current existing literature indicates that a consensus can't be found on SPT training improving CE. Despite seeming to impact cycling performance positively, carbohydrate, beetroot and sodium-based supplements and strength training lack conclusive information about being determinant factors to CE.

Many are the similarities between endurance road cycling and the cycling segment of triathlons, and for these reasons, most of these conclusions can be generalized to triathlon cycling, despite coming from results of studies that mostly used road cyclists.

3.2. Limitations

Some are the limitation that can be attributed to this study. In our included studies, the corresponding samples showed a high degree of heterogeneity in terms of the age and performance level (De Pauw et al., 2013) of the subjects. Hence, caution when interpreting the results should be taken, since the literature reveals that the age (Martin et al., 2002; Peiffer et al., 2016) and the level of the athletes (Sallet et al., 2006) are factors that may impact their degree of efficiency.

Additionally, and as mentioned in the manuscript that integrates this Academic Dissertation, the use of different CE indices along the included studies, and therefore in our review, can also be pointed as a confounding factor. The methods and calculations used for each one of the mentioned CE indices rely on different formulas, protocols and collected data, and for those reasons, comparing them might not be as accurate as it should be.

Despite randomized controlled trials being considered the gold standard when it comes to experimental research and interventions efficacy assessment (Hariton & Locascio, 2018), the use of only this type of study design may be pointed as another limitation to this work, since essential information related to the topic under study may be lost by restricting it to only one study design type.

Additionally, risk of bias among included studies was considered high and GRADE judgments revealed low evidence certainty. This means that a fragile basis foundation is supporting the results showed and that reliably strong conclusions should be avoided.

3.3. Futures avenues for research

Future research in this field of knowledge is recommended to better clarify the effects that some of the mentioned factors may have, specifically in CE, and generally in cycling performance. Researchers should focus on gathering more homogenous samples, by age, experience or even performance level. Future systematic reviews should focus on one specific CE index, once having results from many might bring some confusion to the readers. Upcoming studies should also be built on a foundation that provides high evidence certainty and a risk of bias as low as possible.

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Supplements

Supplementary Table 1. PRISMA 2020 Checklist - Efficiency in Cycling for Road and Triathlon Disciplines: Determinants and Insights from a Systematic Narrative Review

Section and Topic	**Item #**	**Checklist item**	**Location where item is reported**
		TITLE	
Title	1	Identify the report as a systematic review.	11
		ABSTRACT	
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	12
		INTRODUCTION	
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	13
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	15
		METHODS	
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	15
Information sources	6	Specify all databases, registers, websites, organizations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	16
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	16 + Appendix 1
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	16
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or	16

		confirming data from study investigators, and if applicable, details of automation tools used in the process.	
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g., for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	17
	10b	List and define all other variables for which data were sought (e.g., participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	17
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	17
Effect measures	12	Specify for each outcome the effect measure(s) (e.g., risk ratio, mean difference) used in the synthesis or presentation of results.	N.A.
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g., tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	17-18
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	N.A.
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	N.A.
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	N.A.
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g., subgroup analysis, meta-regression).	N.A.

	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	N.A.
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	N.A.
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	18
		RESULTS	
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	18-19 + Figure 1
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	18-19
Study characteristics	17	Cite each included study and present its characteristics.	20-21 + Table 1
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	22-23 + Figure 2 & 3
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g., confidence/credible interval), ideally using structured tables or plots.	26 + Table 2
Results of syntheses	20a	For each synthesis, briefly summarize the characteristics and risk of bias among contributing studies.	34
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g., confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	N.A.
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	N.A.
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	N.A.
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	N.A.

Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	43 + Table 3
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	45-54
	23b	Discuss any limitations of the evidence included in the review.	55
	23c	Discuss any limitations of the review processes used.	55
	23d	Discuss implications of the results for practice, policy, and future research.	55
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	15
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	15
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	N.A.
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	56
Competing interests	26	Declare any competing interests of review authors.	56
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	N.A.