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REVIEW ARTICLE

Influence of muscle fatigue on the pedaling kinetic and kinematics in different cycling protocols: a scoping review

Influência da fadiga muscular sobre a cinética e cinemática de pedalada em diferentes protocolos de ciclismo: uma revisão de escopo

Influencia de la fatiga muscular en la cinética y cinemática de pedaleo en diferentes protocolos de ciclismo: una revisión del alcance

Fábio J. Lanferdini[a,b], Marco A. Vaz[a]

Keywords:
Cycling;
Fatigue;
Crank forces;
Kinematics.

ABSTRACT
The aim of this study was to review the literature on the effects of muscle fatigue generated by different cycling protocols, on the kinetics and kinematics of the crank cycle. Twenty-two studies were included in the review. The establishment of the fatigue processes caused an increase in the resulting and effective forces (all tests), together with the pedaling efficiency (incremental and constant tests). In addition, fatigue caused joint changes in the lower limbs (increased range of motion in the ankle and reduced contribution to total torque) in different cycling tests. Therefore, these pedaling strategies may be related to the maintenance of muscle work to postpone the cyclists' exhaustion.

Palavras-chave:
Ciclismo;
Fadiga;
Forças na pedalada;
Cinemática.

RESUMO
O objetivo deste estudo foi revisar a literatura sobre os efeitos da fadiga muscular gerada por diferentes protocolos de ciclismo, sobre a cinética e cinemática do ciclo de pedalada. Vinte e dois estudos foram incluídos na revisão. A instauração dos processos de fadiga provocou aumento das forças resultante e efetiva (todos os testes), em conjunto com a eficiência de pedalada (testes incremental e constante). Além disso, a fadiga provocou mudanças articulares dos membros inferiores (aumento da amplitude articular do tornozelo e redução da sua contribuição para o torque total), em diferentes testes de ciclismo. Estas estratégias de pedalada podem estar relacionadas à manutenção do trabalho muscular para postergar a exaustão dos ciclistas.

Palabras clave:
Ciclismo;
Fatiga;
Fuerzas en pedalear;
Cinemática.

RESUMEN
El objetivo de este estudio fue revisar la literatura sobre los efectos de la fatiga muscular generada por diferentes protocolos de ciclismo, sobre la cinética y cinemática del ciclo de pedaleo. Veintidós estudios se incluyeron en la revisión. El establecimiento de los procesos de fatiga provocó un aumento de las fuerzas resultantes y efectivas (todas las pruebas), junto con la eficiencia del pedaleo (prueba incremental y constante). Además, la fatiga provocó cambios articulares en los miembros inferiores (mayor rango de movimiento en el tobillo y menor contribución al torque total) en diferentes pruebas de ciclismo. Estas estrategias de pedaleo pueden estar relacionadas con el mantenimiento del trabajo muscular para posponer el agotamiento de los ciclistas.

[a]Universidade Federal do Rio Grande do Sul, Laboratório de Pesquisa do Exercício. Porto Alegre, RS, Brasil.
[b]Universidade Federal de Santa Catarina, Laboratório de Biomecânica. Florianópolis, SC, Brasil.

***Corresponding author:**
Fábio J. Lanferdini
E-mail: fabiolanferdini@gmail.com

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INTRODUCTION

Fatigue can be defined as the inability to maintain strength or power output (PO) for the crank cycle (Rattey et al., 2006). Currently, two types of fatigue have been evidenced in the practice of endurance sports, peripheral fatigue [Catastrophic Model (Amann et al., 2013)] and central fatigue [Central Governor Model (Noakes, 2007)]. Central fatigue is related to a reduction of muscle activation (reduction in firing frequency and/or number of activated motor units) for the same force demand (Bigland-Ritchie and Woods, 1984). The main factors of central fatigue origin are related to muscle inhibition (reduction in the ability to activate all motor units and consequent reduction in the muscle strength production), which imposes an exercise intensity reduction by the central nervous system in order to avoid musculoskeletal injuries. Peripheral fatigue is observed both by maintaining the force produced with a concomitant muscle activation increase, or by reducing the force generated with a reduction in muscle activation during time-to-exhaustion (TTE) protocols (Amann et al., 2013; Millet and Lepers, 2004). In addition, Ulmer (1996) proposed a theoretical model of a control system for optimization of performance during heavy exercise (e.g., cycling). The model is based on a standard feedback control loop, in which the efferent signals contain information on motion, force or PO, time, and muscular metabolism, which determine muscle metabolic rate and exercise intensity. Afferent signals send feedback information from chemoreceptors and mechanoreceptors, which may be used to alter or modify movement and force of PO to optimize performance (Lambert et al., 2005). Furthermore, afferent information include biomechanical feedback for optimizing the 'somatosensory' control, beyond the metabolic feedback parameters, for optimizing the metabolic control (optimal adjustment of energy consumption), and cyclists need such feedback, assuming that they possessed an extracellular feedback control system for optimal adjustment of metabolic rate (Ulmer, 1996); Figure 1.

Looking in more detail at cycling, the PO produced during pedaling is the most used measure to represent the fatigue processes' onset in TTE (Abbiss and Laursen, 2005). PO is directly related to two factors: the speed of contraction and the maximum generated force. Therefore, muscle fatigue determines a reduction in force when large, fast-twitch and rapidly fatigable motor units can no longer be recruited (reducing the maximum capacity to generate force quickly), while the units still activated have a slowness in their contractility (reducing

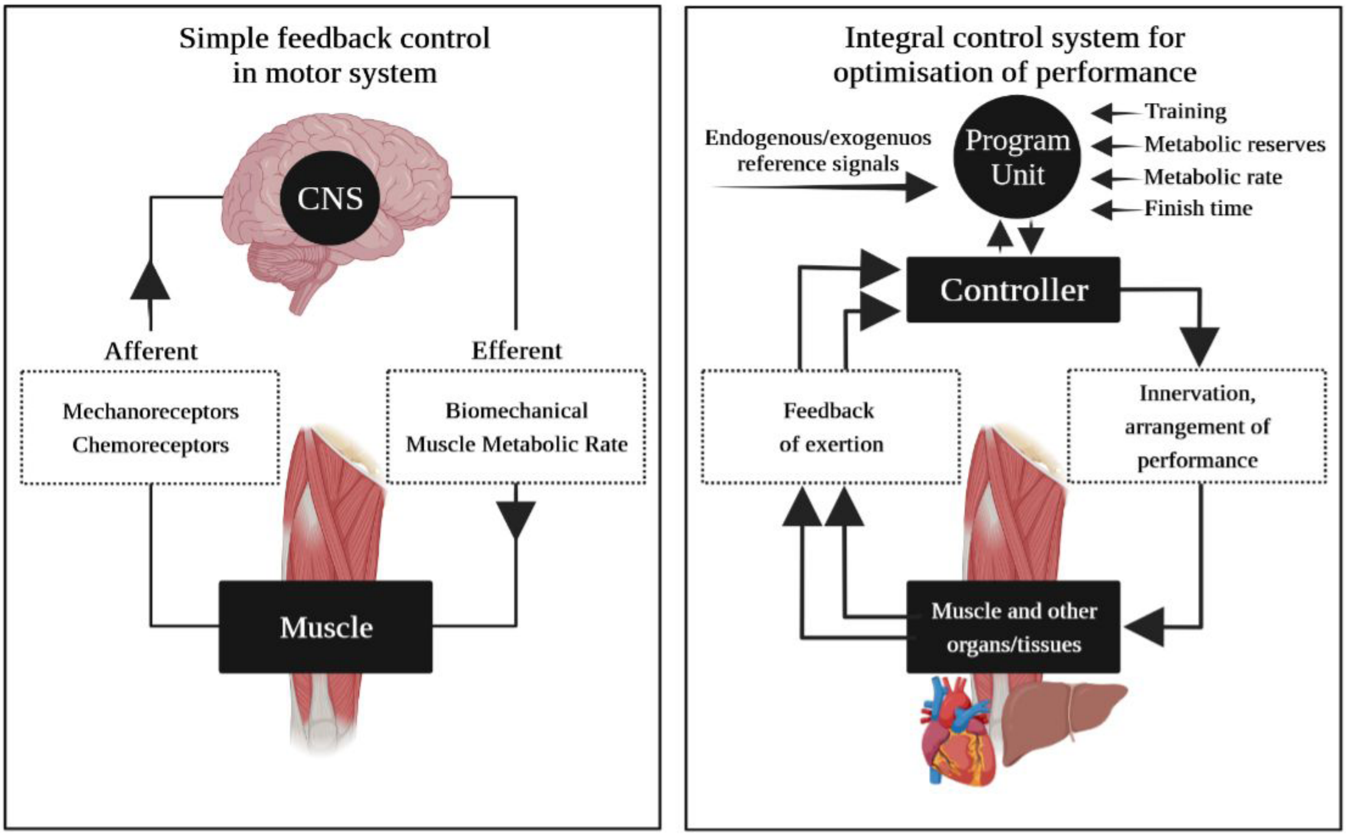

Figure 1. Ulmer's hypothetical model of a control system for optimization of performance during exercise (e.g., cycling). The left panel shows simple feedback control of the motor system by the central nervous system (CNS). The right panel shows an integrative control system for optimization of performance where there are a number of different levels of control in the CNS and peripheral physiological systems (Adapted from Lambert et al., 2005; and Ulmer, 1996).

the maximum speed of muscle shortening and joint movement), as described in Abbiss and Laursen (2005).

Currently, three aerobic models are frequently used to investigate the mechanisms of muscle fatigue installation in cycling: (A) incremental test (IT), which consists of gradually increasing the workload until the cyclist becomes exhausted (Bini et al., 2012; Black et al., 1994); (B) constant test (CT) and sustained until exhaustion test (Diefenthaeler et al., 2012b); (C) time-trial (TT), which aims to assess the implications of muscle fatigue when the cyclist has the freedom to determine the workload in order to cover a pre-determined distance in the shortest possible time (Albertus et al., 2005). These protocols (IT and CT) have a voluntary exhaustion criteria (Abbiss and Laursen, 2005). However, TT despite generating muscle fatigue, does not necessarily generate exhaustion, as it depends on the athlete's own perception of effort during its performance. Regardless of the experimental model of workload choice, an increase in different physiological variables related to performance (oxygen consumption, heart rate, and subjective perceived exertion) were observed after a prolonged period of cycling (Carpes et al., 2005; Liedl et al., 1999). During the TT model, it is possible to observe a voluntary PO increase at end of the test (Albertus et al., 2005; Bini et al., 2008; Carpes et al., 2007). The comparison of physiological responses between different cycling protocols (e.g., IT versus TT) for the generation of muscle fatigue is difficult, because the fatigue installation process is related to the exercise type performed, increased workload, or a combination of these factors.

However, the evaluation of pedaling kinetic and kinematic parameters still needs further clarification, especially in relation to the effects of muscle fatigue on changes in pedal forces, forces acting on joints, and changes in lower limb kinematics. Nevertheless, to date, no studies have been found in the literature that reviewed the implications arising from muscle fatigue processes in the behavior of kinetic and kinematic variables during different cycling tests. Therefore, the aim of this study was to review the literature on the effects of muscle fatigue generated by different cycling protocols (IT; CT; and TT), on the kinetics (forces) and kinematics (articular angles) of crank cycling.

METHODS

ELIGIBILITY CRITERIA

The present study is characterized by a literature scoping review (Munn et al., 2018), developed based on the quantitative and qualitative analysis of published cross-sectional experimental design articles (IT, CT and TT). Studies evaluating cyclists and triathletes, competitive or recreational, aged between 18 and 45 years, were included in this review (Ansley and Cangley, 2009).

SEARCH STRATEGY

The search for scientific articles was carried out in the PubMed, Scopus, and Google Scholar databases between 1970 and 2021. The following keywords were used to search for articles: Fatigue; Cycling; Kinematics; Kinetics; Forces; and their respective terms in Portuguese: Fadiga; Ciclismo, Cinemática, Cinética, Forças. The combination of three keywords was performed in all searches (e.g., Cycling and Fatigue and Kinematics; Cycling and Fatigue and Kinetics; Cycling and Fatigue and Forces).

SELECTION OF STUDIES AND DATA EXTRACTION

Initially, the titles of the articles found with the reviewer search strategy were read. From the first selection, after reading the titles, the abstracts were read in order to obtain information about the relationship or not of the article with the topic of interest. Original articles related to the kinematics and/or kinetics (forces) of cycling during IT, CT, or TT, written in English and/or Portuguese, were included in the study, and review articles were excluded. After analyzing the abstracts and excluding those that did not fit the inclusion criteria, the other articles were fully read to be included in the present work, which should be in accordance with the pre-established eligibility criteria. Using a standardized form, information was extracted from the included studies: (1) Author and year of study; (2) Study design; (3) Participants; (4) Joanna Briggs Institute (JBI); (5) Proposed methodology; (6) Main results.

DATA ANALYSIS

The studies were qualitatively analyzed, described, and tabulated according to pre-established criteria. In addition, the methodological quality classification was determined through the JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies instruments (Aromataris and Munn, 2020).

RESULTS

A total of 1019 studies were identified in the databases. After applying the exclusion criteria and eliminating duplicated studies, twenty-two studies were included in this scoping review (see the literature flow diagram on Figure 2). The studies included in this analysis are shown in Tables 1, 2, and 3, which summarize the main findings of these studies. Supplementary material (Tables 1S, 2S and 3S) demonstrated that the studies' methodological quality was low. The main weaknesses were related to the inclusion criteria, identification and strategies to deal with confounding factors and valid and reliable outcomes measured.

The thorough analysis of the included studies revealed that seven of these studies assessed pedaling kinetics and/or kinematics during IT (Table 1). Eight

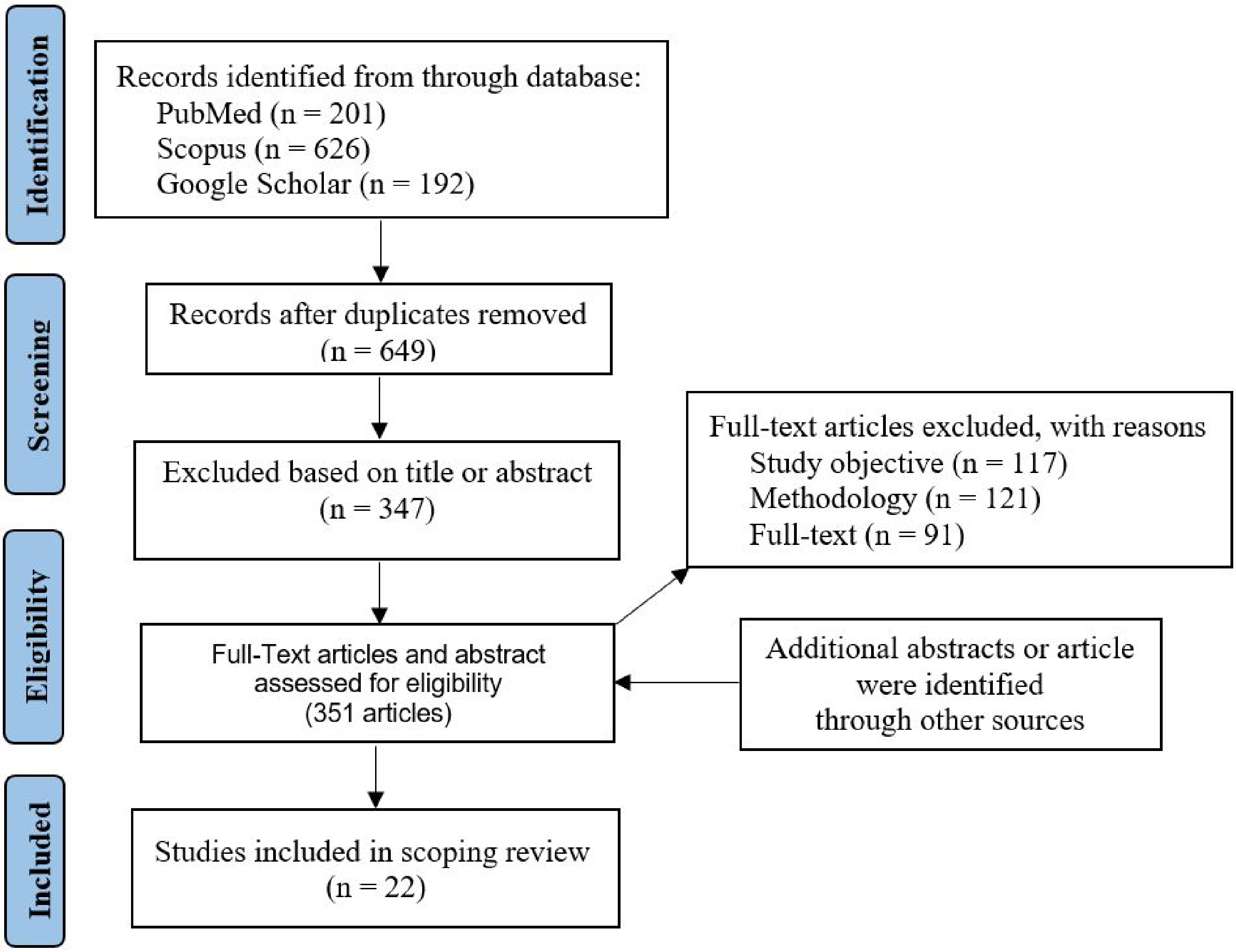

Figure 2. Flow diagram of study selection.

studies (Table 2) evaluated kinetic and/or kinematic parameters in cycling exhaustion tests with CT. Another experimental model commonly used for evaluating mechanical aspects of cycling fatigue is the races' simulation in the laboratory with TT, and its results are shown in Table 3.

DISCUSSION

The present review analysis of the studies showed that muscle fatigue reduces the PO capacity and the lower limbs' torque output during cycling. Furthermore, outcomes of this review demonstrated changes in hip, knee, and ankle joints' excursion (such as increased range of motion and reduced ankle contribution to the joint total torque), associated with changes in the direction of the forces applied to the pedal (improved pedaling technique).

During IT, Black et al. (1994) observed an increase in the effective force (EF) applied to the pedal, with a concomitant increase in the resultant force (RF) due to the workload increase during IT. An increase in the ankle dorsiflexion angle indicated a kinematics change due to increased workload and the occurrence of fatigue (Black et al., 1994). Corroborating previous studies, Bini and Diefenthaeler (2010) found a torque increase at the plantar flexors, knee flexors, and hip flexors, without changes on the dorsiflexors and knee extensors torque during IT. In addition, the authors also found a range of motion increase at the ankle and hip joints, without changes at the knee joint with increased workload. Moreover, they evaluated the lower limb resultant joints' torques with the aim of understanding the coordination pattern with the progressive workload increase (Black et al., 1994). Kautz et al. (1991) described a sensitivity joint kinematics with the increased cycling workload (e.g., during IT). Moreover, kinematic changes were linked to the exigence of force application used by cyclists to maintain the given performance standard (Sanderson and Black, 2003).

However, Zameziati et al. (2006) observed an increased index of effectiveness (IE) with the workload increase until voluntary exhaustion (end of test),

Table 1. Summary of sample, training experience, characteristics and results from studies investigating the effects of muscle fatigue on the maximal incremental cycling test.

Studies	Participants			Methods	Main Results
	Sample	Training	Characteristics	Maximal Incremental Test	
Black et al. (1994)	5♂ Competitive Road Cyclists	---	---	25 W/min to exhaustion; Cadence of ~80 rpm	↑ Ankle dorsiflexion; and ~100% of ↑ RF, EF with exhaustion
Carpes et al. (2006)	5♂ (Age: 22 years; Body mass: 78 kg) Competitive Road Cyclists and MTB	6 years' experience 200 km/week	VO_{2MAX}: 58 ml.kg^{-1}.min^{-1} PO_{MAX}: 350 W	50 W/5 min to exhaustion; Cadence between 75 and 100 rpm	↑ 60% of the lateral displacement of the knee (NDLL) with exhaustion
Zameziati et al. (2006)	10♂ (Age: 26 years; Body mass: 69 kg) Healthy Subjects	---	VO_{2MAX}: 58 ml.kg^{-1}.min^{-1} PO_{MAX}: 273 W	30 W/min to exhaustion; Cadence 80 rpm	↑ TF and IE
Bini et al. (2007)	11♂ (Age: 31 years; Body mass: 74 kg) Road Cyclists	---	VO_{2MAX}: 61 ml.kg^{-1}.min^{-1} PO_{MAX}: 407 W	Initial workload at 60% of predicted maximum for 4 min; After every 2 min increase to 75, 90 and 100%; Cadence between 80 and 100 rpm	↑ PO and torque applied to the pedals
Bini and Diefenthaeler (2010)	11♂ (Age: 31 years; Body mass: 74 kg) Competitive Road Cyclists	---	VO_{2MAX}: 61 ml.kg^{-1}.min^{-1} PO_{MAX}: 407 W	Initial workload at 60% of predicted maximum for 4 min; After every 2 min increase to 75, 90 and 100%, respectively; Cadence between 70 and 110rpm.	↑ 42% at the time of plantar flexors; ↑ 38% for knee flexors; and ↑ 39% for hip flexors; Without changes in the moment in the dorsi flexors, knee and hip extensor. ↑ ankle and hip joint range, without changes in the knee joint.
Bini et al. (2012)	15♂ (Age: 29 years; Body mass: 76 kg) Competitive Cyclists and Triathletes; and 14♂ (Age: 25 years; Body mass: 71 kg) non-athletes	5 years' experience 316 km/week	Athletes: VO_{2MAX}: 61 ml.kg^{-1}.min^{-1} PO_{MAX}: 375 W Non-Athletes VO_{2MAX}: 49 ml.kg^{-1}.min^{-1} PO_{MAX}: 283 W	25 W/min to exhaustion; Cadence of ~90 rpm	↑ ankle joint range: athletes (17%) and non-athletes (25%), without changes in hip and knee joints
Pouliquen et al. (2021)	12♂ (Age: 26 years; Body mass: 73 kg) Continental Road Cyclists	---	VO_{2MAX}: 75 ml.kg^{-1}.min^{-1} PO_{MAX}: 350 W	50 W/2 min to exhaustion; Self-select cadence	↓ hip flexion/extension and internal/external rotation as well knee abduction/adduction ranges of motion, without changes ankle joint

MTB = Mountain Bike; PO = Power output; RF = Resultant force; EF = Effective force; IE = Index of effectiveness; TF = Total force; NDLL = Non-dominant lower limb; VO_{2MAX} = Maximal Oxygen Uptake; $PO_{MAX:}$ Maximal power output.

which is explained by an improvement in the pedaling technique during the recovery phase (180-360º) of the crank cycle. These findings are explained by the better use of the muscle forces produced and the consequent improvement in the pedaling technique with the increased workload during IT. Bini and Hume (2013) complement that the progressive workload increase results in the increase of normal and anteroposterior forces applied on the pedals. Therefore, improvement in pedaling technique may be associated with an increase in the strength demand during IT (Bini and Diefenthaeler, 2010). In addition, increased ankle joint range motion with the workload increase in both groups (cyclists and non-athletes) is due to the attempt to support the mechanical work with the increase in workload during IT (Figure 3). This increased ankle joint range motion, in

Table 2. Summary of sample, training experience, characteristics and results from studies investigating the effects of muscle fatigue on the constant test.

Studies	Participants			Methods	Main Results
	Sample	Training	Characteristics	Constant Workload Test	
Amoroso et al. (1993)	11♂ Competitive Road Cyclists	---	---	Workload at 300 W; Cadence 80 rpm	↑ 1.5º at the hip joint extension angle; ↑ 4.1º at ankle joint dorsiflexion; Without changes in the RF, EF and IE.
Sanderson and Black, (2003)	12♂ (Age: 28 years; Body mass: 75 kg) Competitive Road Cyclists	---	VO_{2MAX}: 67 ml.kg^{-1}.min^{-1} PO_{MAX}: 413 W	Workload at 80% of maximal power output. Cadence 90 rpm	↑ 18% at hip joint extension angle; ↑ 12% at knee joint flexion; ↑ 17% at ankle joint plantar flexion; ↑ 11% of EF; Without changes of IE.
Dingwell et al. (2008)	10♂ (Age: 30 years; Body mass: 75 kg) Competitive Road Cyclists	10 years' experience 12-16 hours/ week	VO_{2MAX}: 61 ml.kg^{-1}.min^{-1}	Workload at 100% of maximal power output; Cadence 90 rpm	↑ at ankle joint plantar flexion; Without changes of hip and knee joints.
Dorel et al. (2009)	10♂ (Age: 21 years; Body mass: 69 kg) Competitive Road Cyclists	9 years' experience 14000 km/year	VO_{2MAX}: 65 ml.kg^{-1}.min^{-1} PO_{MAX}: 412 W	Workload at 80% of maximal power output; Cadence ~95 rpm	↑ 7% of EF; Without changes of IE.
Wiest et al. (2009)	4♂ (Age: 21 years; Body mass: 78 kg) Competitive MTB	---	VO_{2MAX}: 71 ml.kg^{-1}.min^{-1}	1 hour with workload at 80% of VO_{2MAX}; Cadence between 90 and 100 rpm	↑ 75% at ankle joint range of motion throughout the test; Without changes in hip and knee joint.
Bini et al. (2010)	10♂ (Age: 31 years; Body mass: 74 kg) Competitive Road Cyclists	---	VO_{2MAX}: 60 ml.kg^{-1}.min^{-1} PO_{MAX}: 408 W	Workload at 100% maximal power output; Preferred cadence	↓ 13% at ankle joint torque; ↑ ~50% at hip and knee joints torque; ↓ ~7% at the hip range of motion, and ↑ ~35% at the ankle joint.
Diefenthaeler et al. (2012a)	8♂ (Age: 31 years; Body mass: 73 kg) Competitive Road Cyclists	2 years' experience 350-600 km/ week	VO_{2MAX}: 60 ml.kg^{-1}.min^{-1} PO_{MAX}: 408 W	Workload at 100% maximal power output; Preferred cadence	↑ 35% of EF; Without changes in the RF and IE; ↑ 47% at ankle joint range.
Diefenthaeler et al. (2012b)	14♂ (Age: 21 years; Body mass: 77 kg) Competitive Triathletes	4 years' experience	VO_{2MAX}: 62 ml.kg^{-1}.min^{-1} PO_{MAX}: 355 W	Workload at 100% maximal power output; Preferred cadence	↑ 18% of RF

MTB = Mountain Bike; RF = Resultant force; EF = Effective force; IE = Index of effectiveness; VO_{2MAX} = Maximal Oxygen Uptake; $PO_{MAX:}$ Maximal power output.

turn, is necessary to increase the plantar flexor muscles' workload and shortening speed, which are related to the muscle power increase needed (Bini et al., 2012).

In order to better understand the effects of fatigue on the muscles that act on the different joints of the lower limb during crank cycle in this model, it is important to evaluate the contribution of each joint to the absolute sum of joint moments. Mornieux et al. (2007) suggest that there seems to be no change in the contribution of each joint to the absolute sum of joint moments as an effect

Table 3. Summary of sample, training experience, characteristics and results from studies investigating the effects of muscle fatigue on the variable workload test.

Studies	Participants			Methods	Main Results
	Sample	Training	Characteristics	Variable Workload Test (Time-Trial)	
Albertus et al. (2005)	15♂ (Age: 25 years; Body mass: 69 kg) Competitive Road Cyclists	---	PO_{MAX}: 397 W	Time-trial of 20 Km	↑ 30% of PO in the end of teste
Carpes et al. (2005)	1♂ (Age: 25 years) Competitive Triathlete	10 years' experience	---	Time-trial of 40 Km	↑ ~40% of PO and ↑ EF of end test
Duc et al. (2005)	9♂ (Age: 21 years; Body mass: 66 kg) Competitive Road Cyclists	2-11 years' experience	VO_{2MAX}: 74 ml.kg^{-1}.min^{-1} PO_{MAX}: 388 W	Time-trial of 30 Min	No changes in torque applied at cranks
Carpes et al. (2007)	6♂ (Age: 20 years; Body mass: 72 kg) Recreational Road Cyclists	5 years' experience	VO_{2MAX}: 56 ml.kg^{-1}.min^{-1} PO_{MAX}: 400 W	Time-trial of 40 Km	↑ 16% in torque applied at cranks in the end of test
Bini et al. (2008)	8♂ (Age: 32 years; Body mass: 77 kg) Competitive Triathletes	6 years' experience	VO_{2MAX}: 61 ml.kg^{-1}.min^{-1} PO_{MAX}: 414 W	Time-trial of 40 Km	↑ 16% of PO in the end of test
Sayers et al. (2012)	10♂ (Age: 36 years; Body mass: 80 kg) Competitive Road Cyclists	5 years' experience	---	Time-trial of 60 Min	↑ 5% in the range of motion at hip joint, and ↓ 12% at ankle joint; Without changes at knee joint
Bini e Hume (2015)	10♂ (Age: 32 years; Body mass: 71 kg) Competitive Road Cyclists and Triathletes	---	VO_{2MAX}: 62 ml.kg^{-1}.min^{-1} PO_{MAX}: 377 W	Time-trial of 4 Km	↑ ~10% in PO during test

PO = Power output; EF = Effective force; VO_{2MAX} = Maximal Oxygen Uptake; $PO_{MAX:}$ Maximal power output.

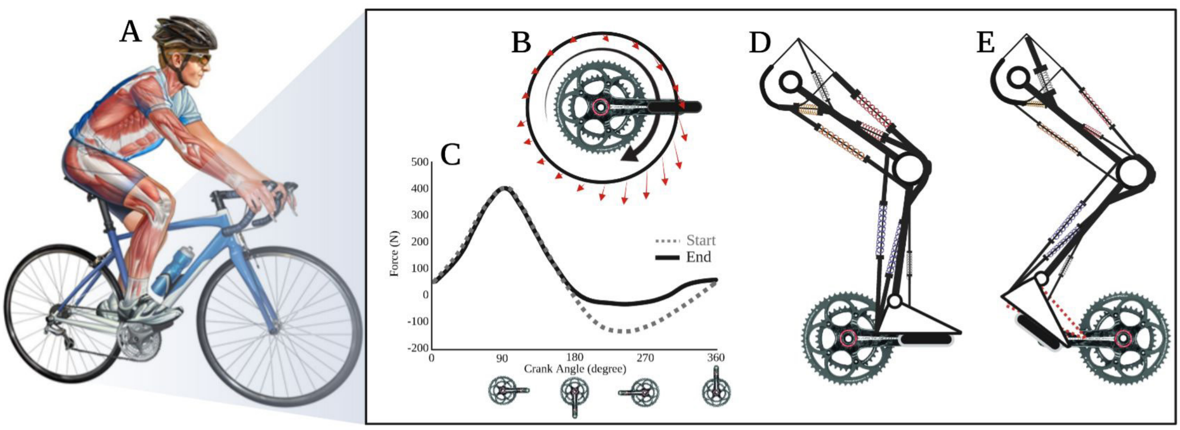

Figure 3. (A) Illustration of a cyclist on the bicycle; (B) Illustration of real force vectors and magnitudes (red arrows), where it can be observed that a large part of the propulsive forces and/or output power is generated at the middle propulsion-phase (30-150°) of the crank cycle (Turpin and Watier, 2020); (C) Effective force (EF) during 360° of crank cycle at the start (grey) and end (black), with a decline in negative EF at the recovery-phase of the crank cycle at the end of the time-to-exhaustion or time-trial tests (Sanderson and Black, 2003; Carpes et al., 2005); (D) Schematic of lower limb kinematic and muscle activation in the middle propulsion-phase of a 90° crank cycle (Turpin and Watier, 2020); (E) Schematic of lower limb kinematic and muscle activation in the middle recovery-phase of 270º crank cycle (Turpin and Watier, 2020), showing changes in lower limb kinematics {especially increased ankle plantarflexion and/or range of motion [illustrated by the change from the original foot position (dashed red line) to the solid black line (representing increased plantar flexion of the ankle)]} at the end of incremental (Bini and Diefenthaeler, 2010) and constant workload tests (Dingwell et al., 2008).

of the fatigue installation process in TTE. The behavior of the resulting joint torques during TTE was investigated by Sanderson and Black (2003), who found changes in the ankle (greater plantar flexor torque), knee (greater flexor torque), and hip (greater extensor torque) joints peak torques. The only assessment made so far of the coordination pattern during cycling, through the analysis of joint torques, was described by Mornieux et al. (2007), who, when re-analyzing the results of Sanderson and Black (2003), observed maintenance of the coordination pattern (torques contribution of each joint for the total lower limb torque) during the fatigue protocol. Similarly, only one analysis was made in relation to the behavior of joint forces, with the aim of understanding how these are influenced by the fatigue installation process. Bini et al. (2010) found a decline of the ankle joint contribution on CT end, which may be related to the joint muscles' difficulty (e.g., triceps surae) in transferring force to the pedal with fatigue. There was also an increase in torque resulting from the hip and knee joints at the end of the test, as a cyclists' strategy to maintain performance. Furthermore, Diefenthaeler et al. (2012a) observed that IE did not show significant pedal force changes, indicating a pedaling technical maintenance of the applied pedal force, possibly as a strategy to maintain the workload during high intensity cycling. Changes in muscle recruitment caused by the onset of fatigue processes may generate changes in the capacity to produce force during crank cycle, possibly explaining these results (Dorel et al., 2009).

However, Sanderson and Black (2003) observed an increased EF after CT until exhaustion (80% of maximal oxygen uptake), as well as a reduction in the negative EF during the recovery phase of crank cycle (Figure 3), in addition to increased hip and knee joints' extension angles. These changes may be the result of intrinsic muscle strategies for exercise maintenance (Sanderson and Black, 2003). Dingwell et al. (2008) found an association between joint range changes with muscle recruitment (assessed by means of median frequency analysis of the electromyographic signals) with the fatigue processes' onset on lower limb muscles. Dingwell et al. (2008) found an increase on the ankle plantarflexion angles, without changes at knee and hip joint angles, with a median frequency reduction on the medial gastrocnemius activation (Figure 3), which is indicative of muscle fatigue (probably related to a reduction in the motor units' action potential conduction velocity).

Therefore, fatigue mechanisms may be associated with these changes: (1) increase in the workload during IT; or (2) arrival at the end of the TTE (CT). In both tests, gastrocnemius, vasti and/or hamstrings muscles were sensitive to workload (Silva et al., 2016; Pouliquen et al., 2021) or exhaustion (Dingwell et al., 2008; Dorel et al., 2009; von Tscharner, 2009), especially causing an increase of the ankle joint plantarflexion range of motion (Dingwell et al., 2008; Bini and Diefenthaeler, 2010; Bini et al., 2012) and pedaling forces efficiency (Zameziati et al., 2006), probably postponing exhaustion in both tests (Figure 3).

Another experimental model commonly used to assess neurophysiological aspects of cycling fatigue is the simulation of tests in the laboratory, or TT (Albertus et al., 2005; Bini and Hume, 2015). This model has as an advantage in relation to the IT and CT, related to the fact that the cyclist chooses the effort intensity, enabling the investigation of the factors that determine the race pace choice (Liedl et al., 1999). Duc et al. (2005) did not find changes in lower limb muscle activation and torque during TT, suggesting that there was no central and/or peripheral fatigue in the participants evaluated. In addition, Bini et al. (2008) observed that triathletes increased the PO and oxygen uptake at the end of TT. In addition, an increase in the vastus lateralis activation was observed throughout the test, without change of the other lower limbs muscles' activation, indicating a type of selective activation aimed at improving performance and minimizing muscle fatigue (Bini et al., 2008).

However, five studies found an increase in PO, RF, EF, IE, and torque at the end of the TT (Albertus et al., 2005; Bini and Hume, 2015; Bini et al., 2008; Carpes et al., 2007; Carpes et al., 2005). These studies suggest that there are improvements in pedaling technique, and that this may be associated with better use of the generated force (e.g., RF) to generate the bicycle's propulsion. The improvement in the pedaling technique can be associated with the control of effort intensity during the test, which is increased towards the end of the test, and may be associated with greater neuromuscular efficiency (Bini et al., 2008).

Nevertheless, Sayers et al. (2012) found an increase in hip joint extension and ankle joint dorsiflexion at the start compared to the end of the TT. Changes in the hip joint might be related to rotational changes of the pelvis. However, the authors comment that, when compared to TTE tests' studies, there is approximately a 10º variation with a reduction in the ankle range of motion for the TT. These changes that occurred at the ankle joint appear to be related to the increased use of the stretching-shortening cycle. This mechanism may be related to the increase in the muscle shortening velocity, or even to the increased storage of elastic energy absorbed by the ankle muscles during the eccentric-phase of the crank cycle (Bini and Diefenthaeler, 2010), providing an increase in PO by the plantar flexors' stretching-shortening cycle (Connick and Li, 2013).

CRITICAL LITERATURE ANALYSIS

The attempt to understand the fatigue installation process using the IT and CT seems to provide relevant information about the repercussions of fatigue on cycling kinetics and kinematics. However, there are few studies that sought to relate the implications of fatigue with coordination in cycling (Bini et al., 2008; Mornieux et al., 2007), which indicates a gap in the literature about the effects of fatigue on motor control during cycling. The advantage of IT and CT experimental models in relation to the TT model lies in the control of effort intensity and in the possibility of leading the evaluated cyclist, which often does not happen in the TT model (Bini et al., 2008; Duc et al., 2005). Nevertheless, the TT model makes it possible to evaluate cycling performance in ecological real situation (e.g., cycling race). Therefore, based on our review, the outcomes of muscle fatigue effects on kinematics and pedaling kinetics are still inconclusive, despite some consistent evidence discussed in this review. Therefore, we suggest that further studies should be carried out with the three different cycling tests (e.g., comparing the IT, CT and TT in the same sample), and with greater methodological rigor to strengthen the knowledge about the influence of muscle fatigue on the crank cycle's kinetics and kinematics in cyclists.

Assessing cycling kinetics and kinematics is relatively straightforward in a laboratory set up. Miniaturization of electromyography sensors, force sensors embodied in the pedals, and increasingly accessible cameras or inertial sensors, allow researchers to provide information about the biomechanics of pedaling in real time. However, it must be emphasized that most kinetics and kinematics of cycling are difficult to interpret directly in terms of performance due to fatigue and several other conditions (e.g., muscle mechanics, discomfort, history of injuries, cyclist morphology) and nature of the effort, such as cycling race (Turpin and Watier, 2020).

CONCLUSION

Understanding the motor strategies adopted during the fatigue installation process in cycling involves understanding physiological, neural, and biomechanical aspects. In summary, knowing the kinetic and kinematic changes caused by fatigue processes during cycling, allows the development of strategies to optimize the transfer of mechanical energy from the segment to the crank and, therefore, delay the onset of muscle fatigue, postponing exhaustion and improving cycling performance. Outcomes of the reviewed studies demonstrated that instauration of fatigue process during cycling tests provoked increase of RF, EF and efficiency during end of tests, postponing exhaustion. Additionally, outcomes showed changes in hip, knee, and ankle joints (such as increased range of motion and reduced ankle contribution to the joint torque total) during aerobic cycling tests.

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CONFLICTS OF INTEREST

We wish to confirm that there are no known conflicts of interest associated with this publication.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: 10.6084/m9.figshare.16888528