Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjsp20

Methods to determine saddle height in cycling and implications of changes in saddle height in performance and injury risk: A systematic review

Rodrigo Bini & Jose Priego-Quesada

To cite this article: Rodrigo Bini & Jose Priego-Quesada (2021): Methods to determine saddle height in cycling and implications of changes in saddle height in performance and injury risk: A systematic review, Journal of Sports Sciences, DOI: 10.1080/02640414.2021.1994727

To link to this article: https://doi.org/10.1080/02640414.2021.1994727

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2021.1994727

Methods to determine saddle height in cycling and implications of changes in saddle height in performance and injury risk: A systematic review

Rodrigo Bini[a,b] and Jose Priego-Quesada[c]

[a]La Trobe Rural Health School, La Trobe University, Bendigo, Australia; [b]Sports Performance Research Institute New Zealand, AUT University, Auckland, New Zealand; [c]Research Group in Sports Biomechanics (Gibd), Department of Physical Education and Sports, University of Valencia, Valencia, Spain

ABSTRACT

The objective of this systematic review was to assess the methods to determine bicycle saddle height and the effects of saddle height on cycling performance and injury risk outcomes. The key motivator of this review was to update and expand the finding reported by a previous narrative review published in 2011. The literature search included all documents from the following databases: Medline, Scopus, CINAHL, OVID and Google Scholar. Studies were screened against the Appraisal tool for Cross-sectional Studies to assess methodological quality and risk of bias. After screening the initial 29,398 articles identified, full-text screening was performed on 66 studies with 41 of these included in the systematic review. Strong evidence suggests that saddle height should be configured using dynamic measurements of the knee angle, and limb kinematics is influenced by changes in saddle height. However, moderate evidence suggests that changes in saddle height less than 4% of the leg length results in trivial to small changes in lower limb loads, and no effect on oxygen uptake and efficiency. It is also possible to state that there is limited evidence on the effects from changes in saddle height on supramaximal cycling performance or injury risk.

ARTICLE HISTORY
Accepted 13 October 2021

KEYWORDS
Bicycle; bike fit; injury prevention; seat position

1 Introduction

Cycling is a popular form of physical activity used for transportation, recreation and structured exercise (Decock et al., 2016; Priego Quesada et al., 2019). Cycling has numerous health benefits such as improved muscular, cardiovascular, and psychological function (Priego Quesada et al., 2019; Springer 2013) but, it is also associated with a large percentage of injuries (28–49% for acute and 52–65% for overuse) (Bernardo et al., 2012; Decock et al., 2016). Different from acute injuries, which usually related to accidents (Decock et al., 2016), overuse injuries are multi-factorial and have been associated with elements such as incorrect bicycle configuration (Callaghan, 2005; Priego Quesada et al., 2019; Silberman et al., 2005).

Among the different bicycle configuration parameters, the saddle height has been one of the most studied. One of the reasons for the large interest in changes in saddle height possibly relates to the magnitude of changes in body position resulting from its modification (Bini, Hume, Croft et al., 2011a). In comparison to other elements of bicycle components, such as the crank length that commonly requires changing the crank set and limited sizes are available, the saddle height can be changed to accommodate a range of leg lengths. In this sense, a correct configuration of the saddle height was suggested to improve cycling performance, reduce injury risk and improve comfort (Bini, Hume, Croft et al., 2011a; Priego Quesada, Pérez-Soriano et al., 2016). Sub-optimal configuration of the saddle height has been associated with knee pain (Callaghan, 2005; Priego Quesada, Pérez-Soriano et al., 2016), higher knee joint forces (Bini, Hume, Croft et al., 2011a; Ericson & Nisell, 1987), elevated oxygen uptake (Bini, Hume, Croft et al., 2011a; Peveler, 2008) and reduced cycling economy (Price & Donne, 1997). The rationale for these changes in biomechanical and physiological outcomes involves influences in joint angular motion, which have implications in muscles' force-length-velocity relationship (Connick & Li, 2013).

In 2011, a narrative review summarised the main methods used to determine saddle height for road cyclists and the implications from changes in saddle height in terms of injury risk and performance (Bini, Hume, Croft et al., 2011a). This narrative review illustrated that most studies had a focus on improving cycling performance through changes in saddle height, but there was limited evidence about the effect of saddle height on injury risk (Bini, Hume, Croft et al., 2011a). Moreover, this review suggested that the saddle height should be configured to obtain a 25–30° of knee flexion at the 6 o'clock crank position whilst cyclists sustain a static position. However, despite this recommendation for using the assessment of body position on the bicycle to inform changes in saddle height, the use of anthropometric methods are still largely used in practice (Bini, Hume, Croft et al., 2011a).

In the last 10 years, further research has been conducted in this topic and more affordable methods have been made available for the assessment of cyclists' body position on the bicycle. As an example, other methods of kinematic analysis have also been utilised which allow for motion analysis to be a part of the decision-making when determining saddle height (Evans et al.,

CONTACT Rodrigo Bini r.bini@latrobe.edu.au La Trobe Rural Health School, La Trobe University, Flora Hill Campus, Bendigo 3550, Australia

2020; Swart & Holliday, 2019). Engineering and computational methods have also been incorporated in the assessment of cyclists' position on the bicycle (Blocken et al., 2018), which highlights that an update of the review paper published in 2011 (Bini, Hume, Croft et al., 2011a) is needed.

Therefore, this study utilised a systematic review of the literature to assess the methods for determining bicycle saddle height and the effects of saddle height on cycling performance and injury risk published since 2010. The rationale for using a systematic search was to ensure a broad search of high-quality data and a fair assessment of papers. In addition, the limitation to studies published after 2010 was to ensure no overlap with the data presented by Bini et al. (Bini, Hume, Croft et al., 2011a).

2 Methods

2.1 Protocol

This systematic review was performed and reported in accordance to the guidelines described by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher, 2009). This review has been registered in the Open Science Foundation (OSF) website: https://osf.io/gsz5k/.

2.2 Inclusion criteria

Studies were included if they tested human participants (i.e. experimental studies rather than computer models), presented a full text published in English, original research or peer-reviewed, assessed a method to determine saddle height or the implications of changes in saddle height on performance or injury risk, and were published after the 1st of January of 2010. The reason for not including studies prior to January 2010 was because they were likely to have been included in a narrative review published later in 2011 (Bini, Hume, Croft et al., 2011a).

2.3 Search strategy

The search strategy was based on three of the PICO elements, participants were cyclists, intervention was saddle height and outcomes were methods to determine saddle height and implications from changes in saddle height in performance and injury risk. Based on that, the constructs presented in Table 1 were used with Boolean operators (i.e. AND/OR).

The literature search included all documents from 1st of January 2010 to 31st of August 2021. Four online databases were searched initially (Medline, Scopus, CINAHL and OVID), followed by a supplementary search that included Google Scholar. The reference lists of all included articles were also examined to determine if all relevant articles had been found.

Table 1. Main construct terms and synonyms utilised in database searches combined with the terms "bicycle OR cycling" and "saddle height OR seat height".

Constructs	Methods	Performance	Injuries
Synonyms	Kinematic* Joint angl*	Energy expenditure Energy cost Oxygen Uptake VO_2 Power output Pedal forc* Efficiency Economy	Injur* Joint forc* Moment*

2.4 Study selection

All references were exported to Covidence (www.covidence.org) and duplicates removed automatically. Two reviewers (RB and JPQ) screened titles and abstracts as per the inclusion criteria and retrieved full text for further analysis. Disagreements were resolved by consensus between reviewers.

2.5 Data extraction

Data extracted included demographic information, study design, method to determine saddle height, outcome measures and key findings.

2.6 Risk of bias and quality of evidence assessment

Studies were screened against the Appraisal tool for Cross-sectional Studies (AXIS tool) to assess methodological quality and risk of bias. The AXIS tool was developed by Downes et al (Downes et al., 2016) and has been proposed to appraise cross-sectional studies. The AXIS tool consists of 20 components to examine the quality of studies, study design and potential risk of bias in cross-sectional studies (Downes et al., 2016). Each question is answered either yes or no unless not applicable or undetermined and scores one point ("yes" = 1, "no" = 0, "unable to determine" = 0, "not applicable" = 0), however, questions 7 and 14 are reversed in their answers ("no" = 1, "yes" = 0). An overall rating of quality is not provided by the AXIS tool due to quality being compromised in different studies due to unfulfilled criteria (Giménez-Legarre et al., 2020). Therefore, we opted for calculating the number of "yes" to determine the percentage of the criteria that was attained by each study.

2.7 Data synthesis for evidence based recommendations

Outcome variables were qualitatively synthesised with varying levels of evidence of each study being established using an alternative model of the van Tulder criteria (Van Tulder et al., 2003):

- *Strong evidence*: findings are constant in at least three studies, two of which are high quality.
- *Moderate evidence*: findings are constant in at least two studies, with one being high-quality.
- *Limited evidence*: findings are constant in one high quality or two low or moderate-quality studies.
- *Very limited evidence*: findings are constant in one moderate or low-quality study.
- *Inconsistent evidence*: findings are inconsistent across multiple studies.
- *Conflicting evidence*: findings are contradictory across multiple studies.

- *No evidence*: findings were insignificant regardless of study quality.

3 Results

3.1 *Study selection*

The initial search identified 29,398 articles from database searches. After screening of papers, full-text screening was performed on 66 studies with 41 of these included in the systematic review (Figure 1).

3.2 *Quality and risk of bias assessment*

The analysis of quality and risk of bias indicated that 18 studies presented very high quality (82–94%), 11 studies presented high quality (71–76%), one study presented moderate quality (65%), five studies presented low quality (53–59%) and five studies presented very low quality (6–47%). Areas of weakness in study design included justification of sample size (only six studies), representativeness of sample size in relation to the target population (only eight studies) and selection process coherent to the target population (only one study). These results are presented in Table 2.

3.3 *Study characteristics*

Of the 41 studies included for review, 15 assessed methods to determine saddle height (Baino, 2011; Bini & Hume, 2016; Encarnación-Martínez et al., 2021; Ferrer-Roca et al., 2012; Fonda et al., 2014; Grainger et al., 2017; Holliday et al., 2017; Macedo et al., 2015; Millour & Bertucci, 2017; Millour et al., 2019, 2021; Peveler et al., 2012) and 28 compared the influence from changes in saddle height in terms of performance and/or injury risk outcomes (Bae et al., 2014; Bini, 2021; Bini & Hume, 2014; Bini, Hume, Crofta et al., 2011b; Bini et al., 2014; Braeckevelt et al., 2019; Chabroux et al., 2012; Chiu et al., 2013; Connick & Li, 2013; Damm et al., 2017; Diefenthaeler et al., 2016; Evens & Danoff, 2019; Ferrer-Roca et al., 2014; Korff et al., 2011; Kruschewsky et al., 2018; Kutzner et al., 2012; Lamba et al., 2011; De Moura et al., 2017; Priego Quesada, Carpes et al., 2016; Priego Quesada et al., 2017; RR. Bini, 2020; Verma et al., 2016; Vrints et al., 2011; Wang et al., 2019), as illustrated in Table 3.

3.4 *Methods to determine saddle height*

As illustrated in Table 4, most studies (nine) opted for assessing of a form of lower limb joint angular-based methods to determine changes in saddle height.

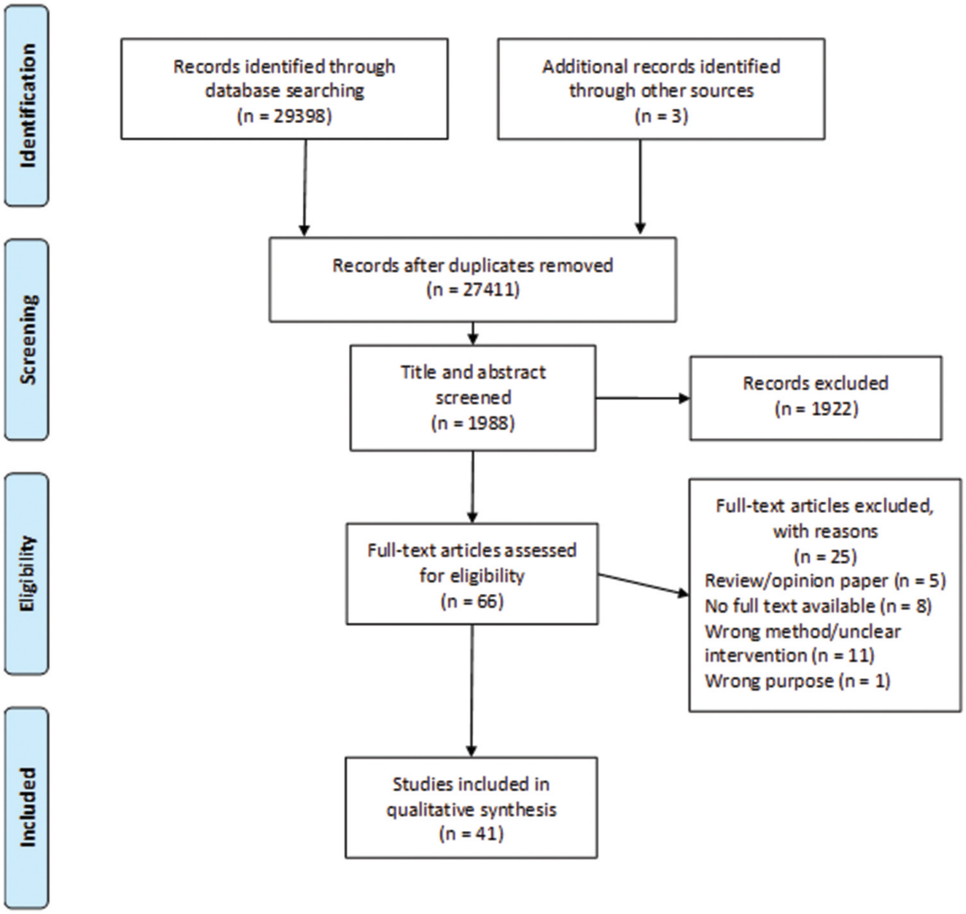

Figure 1. Preferred Reporting Items for Systematic reviews and Meta Analyses (PRISMA) flow chart of included studies.

Table 2. Methodological quality assessment with the AXIS scale. Y = criterion fulfilled, N = criterion not fulfilled. Final score = sum of Y's and the N in the case of the criteria 19 (with the value in percentage inside of the parenthesis). Some criteria were excluded from the analysis because they were not related to the studies assessed (criterion 7, 13 and 14), thus 17 criteria contributed to the final score.

Included studies	(1)	(2)	(3)	(4)	(5)	(6)	(8)	(9)	(10)	(11)	(12)	(15)	(16)	(17)	(18)	(19)	(20)	Final Score (%)	Qualitative score
(Bae et al. 2014)	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	N	N	Y	12 (71)	High
(Baino, 2011)	Y	Y	N	Y	Y	N	N	N	N	Y	Y	Y	Y	N	N	N	N	9 (53)	Low
(Bini, Hume, Crofta et al., 2011b)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	13 (76)	High
(Bini et al., 2014)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	14 (82)	Very High
(Bini & Hume, 2014)	Y	Y	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	15 (88)	Very High
(Bini & Hume, 2016)	Y	Y	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	15 (88)	Very High
(Bini, 2020)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	16 (94)	Very High
(Bini, 2021)	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	15 (88)	Very High
(Braeckevelt et al., 2019)	N	Y	N	N	N	N	N	N	N	N	N	Y	N	Y	N	N	N	4 (23)	Very Low
(Chabroux et al., 2012)	Y	Y	N	Y	N	N	Y	Y	Y	Y	N	Y	Y	Y	N	N	Y	12 (71)	High
(Chiu et al., 2013)	Y	Y	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	N	N	Y	11 (65)	Moderate
(Connick & Li, 2013)	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	13 (76)	High
(Damm et al., 2017)	Y	Y	N	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	12 (71)	High
(De Moura et al., 2017)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	14 (82)	Very High
(Diefenthaeler et al., 2016)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	13 (76)	High
(Dedieu et al., 2020)	N	N	N	Y	Y	N	N	Y	N	N	Y	N	N	N	N	N	Y	6 (35)	Very Low
(Encarnación-Martínez et al., 2021)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	13 (76)	High
(Evans et al., 2021)	Y	Y	N	N	N	N	Y	Y	Y	Y	N	Y	N	Y	N	N	Y	10 (59)	Low
(Evens & Danoff, 2019)	Y	Y	N	N	N	N	N	N	Y	N	Y	Y	Y	Y	N	N	N	8 (47)	Very Low
(Ferrer-Roca et al., 2012)	Y	N	N	Y	N	N	Y	Y	Y	N	Y	Y	Y	N	N	N	Y	10 (59)	Low
(Ferrer-Roca et al., 2014)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	13 (76)	High
(Fonda et al., 2014)	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	15 (88)	Very High
(Gatti et al., 2021)	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	16 (94)	Very High
(Grainger et al., 2017)	Y	Y	N	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	15 (88)	Very High
(Holliday et al., 2017)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	14 (82)	Very High
(Hummer et al., 2021)	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	15 (88)	Very High
(Korff et al., 2011)	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	N	N	Y	12 (71)	High
(Kruschewsky et al., 2018)	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	14 (82)	Very High
(Kutzner et al., 2012)	Y	Y	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	12 (71)	High
(Lamba et al., 2011)	Y	Y	N	N	N	N	Y	N	Y	Y	Y	Y	N	Y	N	N	N	10 (59)	Low
(Macedo et al., 2015)	Y	N	N	Y	N	N	N	Y	Y	N	N	Y	N	Y	N	N	N	7 (41)	Very Low
(Manigandan et al., 2021)	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	1 (6)	Very Low
(Millour & Bertucci, 2017)	Y	Y	N	Y	N	N	N	Y	N	N	Y	Y	Y	Y	N	N	N	10 (59)	Low
(Millour et al., 2019)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	13 (76)	High
(Millour et al., 2021)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	14 (82)	Very High
(Peveler et al., 2012)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	14 (82)	Very High
(Priego Quesada, Carpes et al., 2016)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	14 (82)	Very High
(Priego Quesada et al., 2017)	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	14 (82)	Very High
(Verma et al., 2016)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	14 (82)	Very High
(Vrints et al., 2011)	Y	Y	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y	N	N	Y	12 (71)	High
(Wang et al., 2019)	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	14 (82)	Very High+

Scoring: 1–13, 15–18, 20: "yes" = 1, "no" = 0, "unable to determine" = U (scored as 0), "not applicable" = N (scored as 0). 7 and 14: "no" = 1, "yes" = 0.

Criteria: (1) Was the aims/objectives of the study clear, (2) was the study design appropriate for the stated aims, (3) was the sample size justified, (4) was the target/reference population clearly defined, (5) was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation, (6) was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation, (8) were the risk factor and outcome variables measured appropriate to the aims of the study, (9) were the risk factor and outcome variables measured correctly using instruments/measurements that had been trialled, piloted or published previously, (10) is it clear what was used to determine statistical significance (e.g., p values, CIs), (11) were the methods sufficiently described to enable them to be repeated, (12) Were the basic data adequately described, (15) were the results internally consistent, (16) were the results for the analyses described in the methods presented, (17) were the authors' discussions and conclusions justified by the results, (18) were the limitations of the study discussed, (19) were there any funding sources or conflicts of interest that may affect the authors' interpretation of the results and (20) was ethical approval or consent of participants attained.

Six studies utilised cross-sectional observational designs, where participants were assessed in a single session with the intention to draw correlations between outcome measures. The remaining studies used cross-sectional randomised controlled trials, where participants were assessed multiple times within one or more sessions. Thirteen studies utilised dynamically taken joint angles, proposing that the knee angle measured at the 6 o'clock crank position whilst cycling should be 30–40° (Encarnación-Martínez et al., 2021; Ferrer-Roca et al., 2012) or 33–43° (Millour et al., 2019). Using measurements taken whilst cyclists were static, the knee angle at the 6 o'clock crank position was recommended to be 25–35° (Millour et al., 2019) or 25–30° (Macedo et al., 2015). Differences between static and dynamically taken angles have been associated with differences in ankle angle whilst cycling and with the absence of moment of inertia when cyclists are static (Bini & Hume, 2016). Equations have been proposed, but not validated using a separate dataset, to optimise the saddle height for males (Ferrer-Roca et al., 2012), females (Encarnación-Martínez et al., 2021) and a mixed group (Gatti et al., 2021). In addition, the 3 o'clock crank position has been shown to produce knee flexion angles similar to dynamic measured angles (Bini & Hume, 2016). It was also noted that, given measurements have been taken using two-dimensional video technology, a difference of 2.2° is expected in relation to three-dimensional technology (i.e. gold-standard) (Fonda et al., 2014).

Table 3. Number of studies and percentage of these studies using different methods to determine saddle height and outcomes assessed.

Methods for determining setting saddle height	Percentage of all studies	
Type	**N**	**(%)**
Anthropometrical	20	46
Lower limb joint angles (dynamic and static)	7	17
Lower limb joint angles (only static)	7	17
Lower limb joint angles (only dynamic)	6	12
Changes related to preferred position	4	10
Undetermined or unspecific	2	5
Outcome measures		
Type	**N**	**(%)**
Linear and angular kinematics	22	54
Comfort/pain or fatigue perception	8	20
Joint forces/internal moments	7	17
Pedal force/torque	7	17
Muscle activation	7	17
Bike measures/anthropometrical/equations	6	15
Oxygen uptake/gross efficiency/heart rate/lactate	4	10
Tests performance/peak power output	3	7
Handlebar/saddle pressure/forces	2	5
Aerodynamics outcomes	1	5
Skin temperature	1	2

3.5 *Influence from changes in saddle height*

One case study (pre- vs. post-intervention) and 27 cross-sectional (acute responses) randomised controlled trials were assessed. Key outcomes related to implications from changes in saddle height were linear and/or angular kinematics (20 studies), comfort/pain (8 studies), pedal forces and torque (6 studies), muscle activation (6 studies), oxygen uptake, efficiency, perceived exertion and performance (5 studies) and joint forces/internal loads (7 studies), as shown in Table 5.

3.5.1 *Kinematics*

Reductions in saddle height were associated with increased ankle ROM (Bini & Hume, 2014; Bini et al., 2014) and dorsiflexion (Evens & Danoff, 2019; Ferrer-Roca et al., 2012), increased knee flexion (Bini & Hume, 2014; Bini et al., 2014; Evens & Danoff, 2019; Ferrer-Roca et al., 2012; RR. Bini, 2020; Wang et al., 2019) and abduction (Wang et al., 2019), increase hip flexion (Bini & Hume, 2014; Bini et al., 2014; Ferrer-Roca et al., 2012), reduced abduction-adduction ROM (Chiu et al., 2013; Hummer et al., 2021), less trunk flexion and reduced wrist deviation (Chiu et al., 2013). Increased craniovertebral angle was also observed when cycling with a low saddle height (Lamba et al., 2011). Adjusting saddle height to a recommended position reduced mean trunk acceleration (Evans et al., 2021).

3.5.2 *Comfort/pain*

Two studies observed increased comfort when cyclists were assessed at their preferred saddle height compared to a higher and lower height (Bini, 2020; Verma et al., 2016). Along with that, a saddle height eliciting 30° at the 6 o'clock crank position (measured dynamically) resulted in increased comfort compared to a lower saddle height (Priego Quesada et al., 2017). A case study though reported that a cyclist with anterior knee pain that opted for a low saddle height (45° of knee flexion at the 6 o'clock crank position) presented improvements in pain when the saddle was increased by 2.5 cm (25° at the 6 o'clock crank position) (Evens & Danoff, 2019). Differently, another study only observed reduced comfort when cyclists opted for a low saddle height (2.5% lower than a reference position) (Kruschewsky et al., 2018).

3.5.3 *Kinetics*

Trivial to moderate increases in pedal forces were observed when cycling with a low saddle height, which led to a reduced force effectiveness (Bini, Hume, Crofta et al., 2011b; Bini et al., 2014) but no differences were observed in another study (Verma et al., 2016). Peak crank torque and interlimb asymmetries were not affected by changes in saddle height but the preferred limb seems to produce consistently more torque (Diefenthaeler et al., 2016; Kruschewsky et al., 2018). Force at the handlebars increased at higher saddle height, whilst saddle CoP displacement increased (Chiu et al., 2013; Verma et al., 2016).

Knee and hip mechanical work were not affected by changes in saddle height in one study (Bini et al., 2014). Likewise, patellofemoral (Bini & Hume, 2014) and tibiofemoral compressive forces were not affected by changes in saddle height (Bini & Hume, 2014; Kutzner et al., 2012). Increases in saddle height from 40º to both 30º and 20º reduced the knee extension moment (Hummer et al., 2021) but no effect was observed in the internal knee abductor moment (Bini, 2021; Hummer et al., 2021). Differently, increased external knee adduction moment was observed at a lower saddle height (Wang et al., 2019). Assessment of temporal patterns indicated differences in patellofemoral force mostly when low force magnitudes were being transmitted between the femur and the patella (Bini, 2021). In contrary, calculated anterior tibiofemoral shear force was larger at a higher saddle height (Bini & Hume, 2014) and increased *in vivo* posterior shear force was observed for a lower saddle height (Kutzner et al., 2012). *In vivo* hip forces were larger when using a lower saddle height (Damm et al., 2017).

3.5.4 *Muscle activation*

Activation of Biceps Femoris and the combined activation from Vastus Lateralis and Biceps Femoris were increased using a high saddle height (Bae et al., 2014). This is in line with another study that showed greater activation for the Rectus Femoris and Biceps Femoris at higher saddle heights and lower activation of Vastus Lateralis and Gastrocnemius Medialis at the preferred height (De Moura et al., 2017). Reduced activation for the Gastrocnemius Medials (Verma et al., 2016) and duration of eccentric contraction for the Gastrocnemius Medials and Vastus Lateralis were observed along with increased eccentric contraction for the Biceps Femoris when using a high saddle height (Connick & Li, 2013).

3.5.5 *Oxygen uptake, efficiency, perceived exertion and performance*

One study (Ferrer-Roca et al., 2014) reported reduced oxygen uptake and improved efficiency when cycling with 2% lower saddle height compared to a 2% higher saddle height (i.e. 4% change in saddle height) whilst two studies did not find differences when a similar range of saddle heights was compared

Table 4. Summary of experimental studies examining methods to determine saddle height.

Study	No. of participants and study design	Method for setting saddle height	Outcome measures	Main results and recommendations for setting saddle height
(Baino, 2011)	– 120 (60 male and 60 female) commuter cyclists - Cross-sectional observational	Anthropometrical	- Optimal saddle-to-pedal distance - Optimal saddle-to-handlebars distance - Optimal saddle width	- Reasonable linear correlation between standing height and inseam leg length with saddle-to-pedal distance - Weak correlation between saddle-to-handlebars distance and saddle width with anthropometric measures - No method was proposed to optimise saddle height
(Bini & Hume, 2016)	– 30 ranging from recreational to competitive - Cross-sectional observational	Lower limb joint angles (dynamic and static)	Hip, knee and ankle angles taken statically (3 and 6 o'clock crank positions) and dynamically	- Angles taken statically replicated measures obtained dynamically only at the 3 o'clock crank position - Saddle height should be determined using dynamically taken angles or statically measured angles at the 3 o'clock crank position
(Encarnación-Martínez et al., 2018,2021)	– 30 indoor-cyclists (15 male and 15 female) - Cross-sectional randomised controlled trial	- Lower limb joint angles (dynamic and static) - Anthropometrical	- Saddle height - Hip, knee and ankle angles taken dynamically - Knee flexion angle taken statically	- Female cyclists presented less often with a knee flexion angle between 30–40° (proposed recommended range for optimal saddle height) - An equation was presented, but not tested, to determine optimal saddle height
(Ferrer-Roca et al., 2012)	– 23 competitive cyclists - Cross-sectional randomised controlled trial	- Lower limb joint angles (dynamic and static) - Anthropometrical	- Saddle height - Hip, knee and ankle angles taken dynamically - Hamstrings flexibility	– 56% of cyclists presented with a saddle height different from recommended (i.e. 106–109% of inseam leg length) - 26% of cyclists did not present a knee flexion angle between 30–40° (proposed recommended range for optimal saddle height) - An equation was presented, but not tested, to determine optimal saddle height
(Fonda et al., 2014)	– 11 cyclists (six elite and five recreational) - Cross-sectional randomised controlled trial	Knee joint angles dynamic using two- and three-dimensional methods	Knee angles taken statically (6 o'clock crank positions) and dynamically	- Two-dimensional assessment of the knee flexion angle underestimated this outcome by ~2.2° compared to three-dimensional measurements - No method was proposed to optimise saddle height
(Gatti et al., 2021)	– 41 recreational cyclists - Cross-sectional randomised controlled trial	–18 Randomized modifications of saddle position	-Anthropometrics: Height, inseam, lateral malleolar height, greater trochanter height, and foot length. -Minimum and maximum knee and hip flexion angles dynamically	-An equation to predict saddle height using minimum knee flexion angle was provided: Saddle height (cm) = 7.41 + 0.82 (inseam cm) – 0.1(minimum knee flexion °) + 0.003 (inseam cm)(seat tube angle °). -An equation to predict saddle height using maximum knee flexion was provided: Saddle height (cm) = 41.63 + 0.78(inseam cm) – 0.25 (maximum knee flexion °) + 0.002 (inseam cm)(seat tube angle °)
(Grainger et al., 2017)	– 142 non-cyclists (7–16 years of age) - Cross-sectional randomised controlled trial	Anthropometrical	Comfort and angles (trunk and knee flexions)	- Saddle height was predictable using inseam leg length (equation proposed) - Arm and torso length enabled predicting saddle-to-handlebars distance - 50% of the variance in the predictive models was unaccounted for (i.e. could not be explained by the independent variables)
(Holliday et al., 2017)	– 19 road cyclists - Cross-sectional observational	Lower limb joint angles (dynamic and static)	Elbow, shoulder, hip, knee and ankle angles taken statically (using an inclinometer and a goniometer) and dynamically using three-dimensional measurements	- Moderate to good reproducibility was obtained for all methods - Only the knee, shoulder and elbow joints presented statistical moderate correlations (r^2 = 0.44–0.49) with the three-dimensional measurements (criterion) - No method was proposed to optimise saddle height

(*Continued*)

Table 4. (Continued).

Study	No. of participants and study design	Method for setting saddle height	Outcome measures	Main results and recommendations for setting saddle height
(Macedo et al., 2015)	– 35 professional triathletes - Cross-sectional randomised controlled trial	- Lower limb joint angles (dynamic and static) - Anthropometrical	- Activation of lumbar erector, thoracic erector and quadrates lumborum - Pain (pre vs. post unclear intervention)	- Less muscle activation was observed when using the knee flexion angle method (Holmes et al. 1994) - Pain was reduced after five months from the pre-intervention - Using a saddle height that elicited 25–30° of knee flexion at the bottom dead centre (statically) was recommended
(Millour & Bertucci, 2017)	– 27 recreational cyclists - Cross-sectional observational	Anthropometrical	- Predicted saddle height determined by two anthropometrical measurements	- Methods were very similar in terms of mean bias - No single method was recommended as a unique option to determine saddle height
(Millour et al., 2019)	– 26 cyclists ranging from recreational to competitive - Cross-sectional observational	Lower limb joint angles (dynamic and static)	Hip, knee and ankle angles taken statically (6 o'clock crank positions) and dynamically	- Knee flexion angle was 8° greater taken dynamically than statically - The ranges of 25–35° for knee flexion at the bottom dead centre, statically, and 30–40°, dynamically, resulted in identical saddle heights - A range of 33–43° was proposed for the knee angle but not tested
(Millour et al., 2021)	– 26 cyclists ranging from recreational to competitive - Cross-sectional randomised controlled trial	Anthropometrical	- Knee flexion angle (maximum) - Comfort	- Cyclists with medium and long inseam leg length presented with 30–40° of maximum knee flexion angle but others with shorter leg length opted for lower saddle height (i.e. greater knee flexion) - Cyclists with short or long inseam leg length differed in terms of saddle height between Genzling and Hamley-Thomas methods - Cyclists with short inseam leg length (<0.80 m) should use the Hamley-Thomas whilst cyclists with long inseam leg length (>0.88 m) should use the Genzling method
(Millour & Bertucci, 2017)	– 34 cyclists ranging from recreational to competitive - Cross-sectional observational	- Lower limb joint angles (dynamic and static) - Anthropometrical	Knee and ankle angles taken dynamically at the 6 o'clock crank position	- Less knee flexion and plantar flexion at greater exercise intensities and in relation to static positions on the bicycle - Measurement of joint angles should be undertaken dynamically during bicycle fitting

(Connick & Li, 2013; Korff et al., 2011). Heart rate was also unaffected by changes of similar magnitude in saddle height in two studies (Ferrer-Roca et al., 2014; Kruschewsky et al., 2018). Differently, RPE was increased in one study when cyclists pedalled at a 2.5% lower saddle height (Kruschewsky et al., 2018), no changes in RPE were observed in two studies (Ferrer-Roca et al., 2014; Bini, 2020) and reduced RPE was observed in another study at the recommended position compared with the preferred height (Evans et al., 2021).

Only two studies assessed changes in saddle height during anaerobic cycling trials. One study reported reduced peak power for cyclists' preferred height compared to a 2.5% higher and a 2.5% lower height during 30-s Wingate tests (De Moura et al., 2017) while the other demonstrated reduced peak power during 5-s sprints using a 2 cm lower saddle height (Vrints et al., 2011).

3.5.6 *Other outcomes*

One study reported increased drag force when cycling with a high saddle height without differences to the preferred height and no differences were observed between saddle heights in terms of frontal area or drag coefficient (Chabroux et al., 2012).

Skin temperature was also observed to be greater using a high saddle height at the popliteus area with larger changes in temperature for the Tibialis Anterior area (Priego Quesada, Carpes et al., 2016).

4 Discussion

This systematic review analysed methods to determine saddle height proposed by experimental studies and assessed the implications of changes in saddle height in performance and injury risk during cycling. The key motivator of this review was to update and expand the finding reported by Bini et al. (Bini, Hume, Croft et al., 2011a), who observed that methods to determine saddle height were varied. This current review observed that there was still a number of studies (20 in total) utilising anthropometric methods to change saddle height. Differently, 13 studies introduced dynamic methods to assess joint angles and use this information to inform changes in saddle height, in line with most recent recommendations (Bini & Hume, 2016; Ferrer-Roca et al., 2012; Fonda et al., 2014;

Table 5. Summary of experimental studies examining effects from changes in saddle height.

Study	No. of participants and study design	Method for setting saddle height	Outcome measures	Main results
(Bae et al., 2014)	- Seven trained cyclists - Cross-sectional randomised controlled trial	Knee joint angles taken statically at the 6 o'clock crank position	- Integrated EMG from the Vastus Lateralis and Biceps Femoris - Hip, knee and ankle angles at the 6 o'clock crank position	- No apparent significant differences in joint angles from changes in saddle height. - Lower saddle height resulted in greater activation of the Biceps Femoris and less combined activation for the Vastus Lateralis and Biceps Femoris.
(Bini, Hume, Crofta et al., 2011b)	– 11 cyclists and 11 triathletes - Cross-sectional randomised controlled trial	Knee joint angles taken statically at the 6 o'clock crank position	Mean resultant pedal force and pedal force effectiveness calculated throughout the crank cycle	- Trivial to moderate differences in resultant force (larger at lower saddle heights) - Small to moderate differences in pedal force effectiveness (larger at higher saddle heights)
(Bini et al., 2014)	– 12 cyclists and 12 triathletes - Cross-sectional randomised controlled trial	Knee joint angles taken statically at the 6 o'clock crank position	Mean resultant pedal force and pedal force effectiveness, mean and ROM of the hip, knee and ankle joints, and joint mechanical work calculated throughout the crank cycle	- Trivial to small differences in resultant force (larger at lower saddle heights) - Small to moderate differences in pedal force effectiveness (larger at higher saddle heights) - Large decreases in ankle ROM and mechanical work at low saddle heights for triathletes. Greater knee and less hip angles at low saddle heights. No differences in knee or hip mechanical work.
(Bini & Hume, 2014)	– 16 recreational cyclists without pain and eight cyclists with knee pain - Cross-sectional randomised controlled trial	Knee joint angles taken statically at the 6 o'clock crank position	- Knee flexion angle at the 3 o'clock and 6 o'clock crank positions - Patellofemoral and tibiofemoral forces	- Large increases in knee angle for the lower saddle heights - No differences in patellofemoral or tibiofemoral compressive forces. Larger anterior tibiofemoral force at higher saddle heights.
(Bini, 2020)	– 10 commuter cyclists - Cross-sectional randomised controlled trial	Minimum knee joint angle measured dynamically	- Perceived comfort and RPE - Knee flexion angles at the 3 o'clock and 6 o'clock crank positions	- Greater comfort in the preferred saddle height compared to low height without differences in RPE - Increased knee flexion at both crank positions for the low saddle height
(Bini, 2020)	– 10 commuter cyclists - Cross-sectional randomised controlled trial	Minimum knee joint angle measured dynamically	- Patellofemoral and tibiofemoral forces - Knee flexion angles - Extensor and abductor internal moments	Large differences in temporal patterns for knee flexion due to changes in saddle height were followed by differences in patellofemoral force mostly when low force magnitudes were being transmitted between the femur and the patella
(Braeckevelt et al., 2019)	- Three cyclists of unspecified levels of training - Cross-sectional randomised controlled trial	Undetermined	- Handlebars drop and reach - Saddle height and setback - Knee-over-pedal-spindle - Maximum knee angle	- Large differences (3 cm) in body position on the bicycle observed in each cyclist after undertaken different bicycle fittings.
(Chabroux et al., 2012)	- Nine professional cyclists - Cross-sectional randomised controlled trial	10 mm increase and decrease in relation to preferred saddle height	Drag force, frontal area and drag coefficient measured during wind tunnel testing	-Increase in drag force when cycling with a high saddle height without differences to the preferred height using a time trial bicycle. -No differences between saddle heights in terms of frontal area or drag coefficient.
(Chiu et al., 2013)	– 20 non-cyclists - Cross-sectional randomised controlled trial	10% increase and decrease in relation to preferred saddle height	Force at the handlebars, saddle force and CoP, wrist, trunk, hip and knee ROM	- Wrist deviation and flex-ext, trunk flexion and hip abd-add larger at higher saddle height. - Force at the handlebars increased at higher saddle height - Saddle CoP range increased at higher saddle height

(*Continued*)

Table 5. (Continued).

Study	No. of participants and study design	Method for setting saddle height	Outcome measures	Main results
(Connick & Li, 2013)	- Ten recreational cyclists - Cross-sectional randomised controlled trial	96%, 98% and 100% of the trochanteric height	-Timing of concentric and eccentric contractions calculated from kinematics and EMG for the medial Gastrocnemius, Vastus Lateralis and Biceps Femoris - Oxygen uptake	- Duration of medial Gastrocnemius and Vastus Lateralis eccentric contractions decreased with increasing saddle height - Duration of Biceps Femoris eccentric contractions significantly increased with saddle height - No difference was observed for oxygen uptake
(Damm et al., 2017)	- Five male non-cyclists - Cross-sectional randomised controlled trial	Knee joint angles taken statically at the 6 o'clock crank position	*In vivo* hip joint forces measured using instrumented implants	Hip forces were increased by 7–15% at the lower saddle height (i.e. 9 cm)
(De Moura et al., 2017)	– 12 competitive cyclists - Cross-sectional randomised controlled trial	Inseam leg length	- Wingate cycling performance - Muscle activation for the Vastus Lateralis, Rectus Femoris, Biceps Femoris and Gastrocnemius Lateralis	- Reduced peak power at the preferred saddle height compared to a higher and a lower height, without difference between low and high saddle heights. - Less activation of the Vastus Lateralis and Gastrocnemius Medialis at the preferred compared to the higher and lower heights. Increased activation of Rectus Femoris and Biceps Femoris for the higher compared to the lower saddle height.
(Dedieu et al., 2020)	–18 competitive cyclists - Cross-sectional randomised controlled trial	Saddle height determined by a standard method (Bini, Hume, Croft et al., 2011a) vs. saddle height at fully extended lower limb, and saddle height minus the distance modified at the fully extended lower limb.	-Muscle activation for Rectus Femoris, Vastus Lateralis, Vastus Medialis, Gluteus Medius, Biceps Femoris, Gastrocnemius Medialis, Gastrocnemius Lateralis and Tibialis Anterior. -Hip, knee and ankle angles (mean angle and ROM)	For the higher and lower saddle height compared with the usual saddle height, duration of the neuromuscular activation was longer, and the offset was delayed for Vastus, Rectus Femoris, Gastrocnemius and Soleus. For Biceps Femoris, the start of activation was ahead, and duration was longer for the higher saddle height than the others experimental conditions
(Diefenthaeler et al., 2016)	– 12 competitive cyclists - Cross-sectional randomised controlled trial	Inseam leg length	-Peak crank torque during constant submaximal and Wingate tests -Asymmetry index for peak torques	- Peak torque was larger for the preferred limb, regardless of saddle height - Asymmetry indices were similar between saddle heights
(Evans et al., 2021)	– 7 recreational triathletes	-Preferred position and saddle height adjusted using an anthropometrical equation (Ferrer-Roca et al., 2012).	Trunk mean acceleration and RPE in 20 km circuit protocol	Adjusted saddle height reduced trunk mean acceleration and RPE
(Evens & Danoff, 2019)	- One female cyclist with bilateral knee pain - Case study	Saddle increased by 2.5 cm	-Pain (VAS), LEFS, KOOS -Knee flexion angles at 6 o'clock and 12 o'clock crank positions -Ankle angle at the 3 o'clock crank position	-Reduction in pain (40% in VAS), improvements in LEFS (65 before vs 79 after intervention) and KOOS (81.1 before vs 93.5 after intervention) -Reduction in knee flexion and increase in plantar flexion
(Ferrer-Roca et al., 2014)	– 14 competitive cyclists and triathletes - Cross-sectional randomised controlled trial	Saddle increased and decreased by 2%	- Oxygen uptake, gross efficiency, heart rate, lactate and RPE - Hip, knee and ankle angles	- Oxygen uptake decreased, and efficiency increased at the 2% lower saddle height compared to the 2% higher saddle height without differences in heart rate, lactate or RPE - Increased hip and knee flexions and larger ankle dorsiflexion at the lower saddle height

(*Continued*)

Table 5. (Continued).

Study	No. of participants and study design	Method for setting saddle height	Outcome measures	Main results
(Hummer et al., 2021)	– 47 recreational cyclists - Cross-sectional randomised controlled trial	Knee joint angles taken statically at the 6 o'clock crank position	-Kinematic: knee ROM (sagittal and abduction) -Kinetic: peak knee moments (extension, flexion, and abduction) - EMG from Biceps Femoris, Semitendinosus, Vastus Lateralis, and Vastus Medialis.	- Knee adduction ROM was greater at 20º compared with 30º - Saddle height did not affect internal knee abduction moment - Increases in saddle height from 40º to both 30º and 20º reduced the knee extension moment - The EMG of Semitendinosus was greater as saddle height increased
(Korff et al., 2011)	– 18 recreational cyclists - Cross-sectional randomised controlled trial	Heel method (see Bini et al. 2011 for details)	- Gross efficiency - Averaged normalised positive non-muscular power - index of force effectiveness - relative joint power contributions to pedal power, and hip transfer power	- Due to combination of changes in bicycle configuration (including a reduced saddle height) and coaching sessions, small change in pedalling mechanics without influence in gross efficiency were observed
(Kruschewsky et al., 2018)	- Nine recreational cyclists - Cross-sectional randomised controlled trial	Inseam leg length	- Affective response (comfort) - Peak crank torque - Heart rate and RPE	- Less comfort using a lower saddle height - No differences in peak torque or heart rate between saddle heights - Increase RPE at lower saddle heights
(Kutzner et al., 2012)	- Nine male non-cyclists - Cross-sectional randomised controlled trial	Heel method (see Bini et al. 2011 for details)	*In vivo* tibiofemoral joint forces measured using instrumented implants	A lower seat height (i.e. 7.5 cm from a reference height) did not increase tibiofemoral resultant force but increased posterior shear forces.
(Lamba et al., 2011)	– 60 non-cyclists - Cross-sectional randomised controlled trial	Inseam leg length	Craniovertebral angle	Increased craniovertebral angle when cycling with a low saddle height
(Manigandan et al., 2021)	– 1 participant with unspecified cycling category	Saddle height increased and reduced by 10 mm	Power metre data	Higher saddle height (+10 mm than recommended position) reduced power output (9%) and increased the average pace. However, no clear differences were observed on energy output and energy expenditure
(Priego Quesada, Carpes et al., 2016)	–16 club cyclists - Cross-sectional randomised controlled trial	Knee joint angles taken dynamically at the 6 o'clock crank position	Skin temperature of different body regions	-Immediately after the cycling test, knee flexion at 20° (when the pedal was at the 6 o'clock crank position) produced higher skin temperature in popliteus than knee flexion at 40°. -Knee flexion at 30° produced higher skin temperature variation (difference between 10 min post cycling and pre-measurements) in the tibialis anterior than knee flexion at 20°.
(Priego Quesada et al., 2017)	–20 club cyclists - Cross-sectional randomised controlled trial	Knee joint angles taken dynamically at the 6 o'clock crank position	-Comfort -Pain perception -Fatigue perception	-Knee flexion of 30° (when the pedal was at the 6 o'clock crank position) was considered the most comfortable posture. -Knee flexion of 40° was the most uncomfortable with higher rating of fatigue and pain in the anterior thigh and knee.
(Verma et al., 2016)	– 28 commuter cyclists - Cross-sectional randomised controlled trial	Inseam leg length	- Comfort - Pedal forces - Saddle CoP - EMG from Vastus Medialis, Tibialis Anterior and Gastrocnemius	- Greater discomfort at higher and lower saddle heights compared to the reference height - No differences in pedal forces from changes in saddle height - Increased displacement for the saddle CoP at the lower and higher saddle heights - Reduced activation of Gastrocnemius at lower saddle height

(*Continued*)

Table 5. (Continued).

Study	No. of participants and study design	Method for setting saddle height	Outcome measures	Main results
(Vrints et al., 2011)	– 10 trained cyclists - Cross-sectional randomised controlled trial	Inseam leg length	- Peak power output - Moment generating capacity	- Reduced peak power at lower saddle heights - Reduced moment generating capacity for the Biceps Femoris, Rectus Femoris and Vastus Lateralis
(Wang et al., 2019)	– 20 recreational/ commuter cyclists - Cross-sectional randomised controlled trial	Knee joint angles taken statically at the 6 o'clock crank position	-Sagittal and coronal plane knee angles - Adduction external moment	- Increased knee flexion and abduction at the lower saddle height - Increased knee adduction moment at the lower saddle height

EMG: Electromyography; CoP: centre of pressure; RPE: rating of perceived exertion; ROM: range of motion; VAS: Visual Analog Scale; LEFS: Lower extremity functional scale; KOOS: knee injury and osteoarthritis outcome scale

Millour et al., 2019). Even though, Bini et al. (Bini, Hume, Croft et al., 2011a) observed that there was need for studies looking at optimisation of saddle height to improve performance and reduce the risk of injuries, conflicting evidence on the optimal saddle height still exist. Moreover, no prospective studies on the longer-term implications of different saddle heights or randomised controlled trials using control groups were found to determine chronic effects from changes in saddle height.

4.1 Methods to determine saddle height

Since 2010, there was a clear increase in the number of studies utilising knee joint angles measured dynamically to determine the most appropriate saddle height. The rationale for the change in the preferred method for determining saddle height is two-fold. When compared to anthropometrical methods, knee angles are preferred because they allow movement patterns to be consistent between cyclists. This is critical to ensure that muscles' force-length-velocity relationships are more similar between cyclists, which increases the likelihood of improving overall function and performance (Bini, Hume, Croft et al., 2011a). However, studies utilising statically measured angles, observed that they not always reproduce angles measured during motion (Bini & Hume, 2016; Fonda et al., 2014; Peveler et al., 2012). This creates a barrier because bicycle fitters need access to real-time technology to measure angles, which is not always possible. The most used methods to measure joint angles statically is a handheld goniometer, which involves measuring cyclists statically. Goniometers have shown though to accurately reproduce angles from motion when cyclists are measured at the 3 o'clock crank position but not at the 6 o'clock position (Bini & Hume, 2016), which deviates from the most accepted position in the crank cycle for measuring knee angles (Bini, Hume, Croft et al., 2011a). It is unclear though if saddle height measured using the static 3 o'clock position is similar to those from a dynamic 6 o'clock position. This comparison can potentially inform alternative methods for bicycle fitting that do not depend on dynamic movement analysis. Moreover, alternative methods using electronic goniometers (Fonda et al., 2014) and manual inclinometer (Holliday et al., 2017) indicate that further work is needed given these methods did not achieve high levels of validity compared to the gold-standard motion capture analysis. Therefore, we can state that there is strong evidence that saddle height should be configured using dynamic measurements of the knee flexion angle rather than angles taken statically. Moreover, the use of dynamic measurements should be used as much as possible instead of anthropometric methods as dynamic methods provide appropriate validity in replicating the movement of cyclists, which is not achievable using static methods (Bini & Hume, 2016; Ferrer-Roca et al., 2012; Holliday et al., 2017; Peveler et al., 2012).

There has been an attempt to propose an ideal method to determine saddle height in some studies. Three studies (Encarnacion-Martinez et al., 2018; Ferrer-Roca et al., 2012; Gatti et al., 2021) presented equations based on dynamically taken joint angles and anthropometric measurements, but none of them were tested to determine their accuracy. This is particularly important given one study observed that female cyclists are less likely to meet the recommended saddle height (Encarnación-Martínez et al., 2021), which suggests further work needed to support women cycling. In addition, exclusive anthropometric-based methods were limited to determine only 50% of the variance in saddle height (Grainger et al., 2017), which likely relates to between-cyclists differences in joint angles. Therefore, if new equations are to be proposed, they should be tested in a large group of cyclists to provide data on accuracy of the derived saddle heights. Therefore, there is limited evidence that predictive equations can be used to optimise saddle height.

There seems to be some differences in the proposed optimal knee flexion angle to determine saddle height via dynamic methods. Two studies suggested 30–40° (Encarnación-Martínez et al., 2021; Ferrer-Roca et al., 2012) whilst another proposed 33–43° (Millour et al., 2019) when the crank is at the 6 o'clock position. Bini (RR. Bini, 2020) observed that to elicit a change of 10° of difference in knee flexion angle 3 ± 0.9 cm of change in saddle height were required. Three elements are important to discuss in this discrepancy. The first is related to an additional error of 2.2° in relation to three-dimensional technology (i.e. gold-standard) given these angles were obtained using two-dimensional video-analysis, which is prone to parallax error (Fonda et al., 2014). The second element is that it seems that implications of changes in knee angles smaller than 10° of flexion, deriving from changes in saddle height, are minimum in terms of pedal and joint forces (Bini, 2021; Bini & Hume, 2014; Bini et al., 2014), which will be discussed next. Finally, some studies used absolute angles (Bini et al., 2014; Ferrer-Roca et al., 2014), while others (Peveler et al., 2012; Quesada et al., 2016) used angles relatives to an offset (considering a full knee extension = 0º). A mean discrepancy of 11º was observed between absolute and relative angles, with an individual variability between 5° and 19º (Quesada et al., 2016), which can also explain the discrepancies observed in the recommended angles between studies. Therefore, although limited evidence exists about the benefits from using recommended angles, it is important to consider the methods employed to obtain those angles (e.g., offsets in knee extension).

4.2 Influence from changes in saddle height

Overall, there is a clear effect in joint angles when saddle height is changed. Increases in ROM were observed in several studies (Bini & Hume, 2014; Bini et al., 2014; Evens & Danoff, 2019; Ferrer-Roca et al., 2012; RR. Bini, 2020; Wang et al., 2019), which provides further support for guiding changes in bicycle fitting using motion analysis. Although a 20% higher saddle height seems to increase range of motion for the trunk compared to a lower height (Chiu et al., 2013), most studies have been limited to the assessment of lower limb angles. Moreover, this effect could be higher if saddle height is modified without adjusting handlebar height and depending on seat tube angles, which should be considered for future studies.

The implications of changes in saddle height are somehow consistent when looking at perceived comfort, with two studies suggesting that cyclists' self-selected saddle height is the most comfortable (Kruschewsky et al., 2018; Priego Quesada et al., 2017). However, it is unknown whether this greater comfort in the self-selected saddle height is due to habituation to that posture. Therefore, future studies should analyse whether comfort changes after long exposure to a different posture. Lower saddle heights were generally associated with reduced comfort (Kruschewsky et al., 2018; Priego Quesada, Pérez-Soriano et al., 2016), but higher saddle heights were not always different from the preferred or reference height. Therefore, there is strong evidence that changes in saddle height affect lower limb kinematics and cyclist's comfort.

When taking a following step to explore the implications of changes in forces, data suggests conflicting results in terms of pedal forces and force effectiveness (i.e., ratio between tangential and radial crank forces) when saddle height is changed. Two studies though observed that higher saddle heights seem to increase the displacement of the CoP, which could increase pressure in wider areas of cyclists' buttocks (Chiu et al., 2013; Verma et al., 2016). Further studies are needed though to ascertain on how this change in CoP affects injury risk. Knee and hip work, patellofemoral and tibiofemoral forces were not affected by changes in saddle height (Bini & Hume, 2014; Bini et al., 2014; Kutzner et al., 2012), which suggest that implications for injury risk are less than what is normally anticipated when looking at movement patterns. This lack of agreement between kinematics and kinetics has been suggested to relate with the distribution of load across the hip, knee and ankle, which minimises the impact in a single joint when saddle height is changed (Bini et al., 2014). It is important to note though, that whenever saddle height was changed more than 3–4% of the leg length, prior studies observed influences in knee loads (Ericson et al., 1986; Ericson & Nisell, 1987, 1986). Therefore, within a range of saddle heights, the musculoskeletal system can acutely mitigate changes in moment-arms and loads from changes in saddle heights. However, no data is available on the chronic responses from changes in saddle height. It is also important to state that a systematic review indicated that, the overload model proposed to explain knee injuries in cyclists still needs further evidence because cyclists with and without pain do not present differences in knee loads (Bini & Flores Bini, 2018). Moreover, the observation that hip forces increase when large reductions in saddle height are prescribed (Damm et al., 2017) needs further research in terms of potential risk of hip injuries. Therefore, there is moderate evidence that changes in saddle height less than 4% of the leg length will result in trivial to small changes in lower limb loads. In addition, in line with a prior systematic review (Bini & Flores Bini, 2018), it seems that there is no evidence that changes in saddle height less than 4% of the leg length affect risk of injuries in cycling as no data is available in this topic.

In line with the summary of findings presented by Bini et al. (Bini, Hume, Croft et al., 2011a), activation of Biceps Femoris, Rectus Femoris and Gastrocnemius was increased at higher saddle heights and less activation of Vastus Lateralis was found at cyclists' preferred saddle height (Bae et al., 2014; De Moura et al., 2017; Verma et al., 2016). These findings suggest that bi-articular muscles crossing the lower limb joints may be further required when cycling at a higher saddle height. However, based on findings from this review and from Bini et al. (Bini, Hume, Croft et al., 2011a), it is not possible to determine an optimal saddle height based on muscle activations. No study though assessed if a summation of activations of various muscles would be sensitive to changes in saddle height. Given activations from multiple muscle should contribute to energy expenditure and oxygen uptake, it seems possible that implications would be observed for these outcomes. However, evidence in terms of efficiency is conflicting with two studies reporting no change in this outcome when saddle height is changed by 4% (Connick & Li, 2013; Korff et al., 2011) and one study showing greater efficiency at lower saddle heights (Ferrer-Roca et al., 2014). It is possible though that the changes in internal loads are limited when saddle height is changed less than 4% of the leg length, which do not largely influence energy expenditure, in line with a summary from Bini et al. (Bini, Hume, Croft et al., 2011a). Further to this, heart rate was unaffected in two studies (Encarnación-Martínez et al., 2021; Ferrer-Roca et al., 2014) and RPE did not change in two studies (Ferrer-Roca et al., 2014; RR. Bini, 2020). Therefore, it seems that, when a range of saddle heights close to the cyclist's self-selected height is used, no changes in efficiency or energy expenditure are expected. Implications in terms of skin temperature, when saddle height is changed, still needs further investigation because only one study assessed these outcomes

(Priego Quesada, Carpes et al., 2016). Therefore, there is strong evidence that muscle activity is affected by changes in saddle height but moderate evidence suggesting that oxygen uptake and efficiency are not affected by changes in saddle height of less than 4% of the leg length.

Two studies further explored if more intense cycling would be sensitive to changes in saddle height. One study observed better performance at higher and lower saddle heights, compared to cyclists' preferred height during 30-s Wingate tests (De Moura et al., 2017), which is initially counterintuitive. Moreover, a study using 5-s maximum sprints observed reduced performance when saddle height was lowered by 2 cm (Vrints et al., 2011). These findings suggest that further research is needed exploring a range of supramaximal intensities to determine implications of saddle heights in cycling performance. This is particularly important for disciplines of cycling that involve greater intensities than road cycling (e.g., track cycling). In this regard, only one study assessed effects from changes in saddle height on aerodynamics of cycling with a time trial bicycle, demonstrating that higher saddle heights increase drag forces and potentially limits on road performance (Chabroux et al., 2012). Therefore, there is limited evidence on the effects from changes in saddle height on supramaximal cycling performance.

4.3 Limitations of studies and future directions

In the current review, it was possible to quantitatively assess papers using the AXIS tool, which demonstrated that ~73% of the studies presented high/very high quality for a cross-sectional design (i.e. acute responses). However, only one case study presented data from a pre-post intervention (chronic response) changing saddle height to improve knee pain (Evens & Danoff, 2019). This preliminary study demonstrated that, when cyclists present knee pain and a low saddle height, there is potential benefit from increasing saddle height as a form of treatment of pain. However, further studies are needed with a larger cohort of cyclists with knee pain and altered saddle height to explore the true effectiveness of saddle height fitting in reducing pain in cyclists. This design should include a placebo-control group because cyclists are not always sensitive to changes in saddle height (Bini, 2020), which suggest a prior expectation of benefits from the intervention (i.e. placebo effect (Scoz et al., 2021)).

It was observed that most studies failed though to justify their sample size and to explain how they recruited cyclists. This information is important to ensure that cyclists assessed in these studies truly represent the population of interest. However, there is a clearer attempt to assess cyclists rather than non-cyclists in more recent studies, which is an improvement compared to the review published by Bini et al. (Bini, Hume, Croft et al., 2011a). In addition, further data on intra and inter-session reliability could have been provided by studies as this information allows clinicians and bike fitters to determine the smallest worthwhile effect from changes in saddle heights in the intended outcomes. Recent studies demonstrated that reproducibility in knee flexion angles can be ~1° intra-session (Bini & Hume, 2020; Fonda et al., 2014) and 1–6° inter-sessions (R Bini & Hume, 2020), which should be taken into account when deciding on changes in saddle height based on joint angles. Overall though, studies seem to have improved in quality since the outcomes reported by Bini et al. (Bini, Hume, Croft et al., 2011a). It is important to note though that, most studies assessing injury-related outcomes, concentrated on knee injuries (Bini, 2021; Bini & Hume, 2014), with no attempt to explore other body sites of injuries in cyclists. As an example, it is unclear if lower back pain could be associated with lower or higher saddle heights, which warrants further studies in this topic. Finally, although the body of literature is suggesting that kinematics is the best method to configure saddle height, future studies could explore the use of different data (kinematics, kinetics, neuromuscular activation, comfort, etc.) to improve the individualization of this adjustment.

5 Conclusions

It is possible to conclude that, strong evidence suggests that saddle height should be configured using dynamic measurements of the knee angle but limited evidence on how this outcome should be embedded into predictive equations or the optimal ranges of knee angle have been noted. There is strong evidence though that lower limb kinematics is influenced by changes in saddle height, but moderate evidence suggests that changes in saddle height less than 4% of the leg length results in trivial to small changes in lower limb loads. Even though muscle activity is affected by changes in saddle height, moderate evidence suggests that oxygen uptake and efficiency are not affected by changes in saddle height of less than 4% of the leg length. In regards to the effect of saddle height on injury risk, more prospective with follow-up measurements are necessary. It is also possible to state that there is limited evidence on the effects from changes in saddle height on supramaximal cycling performance and injury risk. Finally, there is a lack of studies assessing differences from gender on bicycle fitting, which also highlights the necessity to explore if saddle height adjustments should be different between males and females.

Acknowledgements

Authors acknowledge La Trobe University for providing access to Covidence, EndNote and databases, which enabled this review to be conducted.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported there is no funding associated with the work featured in this article.

ORCID

Rodrigo Bini http://orcid.org/0000-0002-2138-7350
Jose Priego-Quesada http://orcid.org/0000-0002-0375-1454

Availability of data and material

Data will be made available through the OSF link: https://osf.io/gsz5k/.

Authors’ contributions

RB registered the review at OSF and conducted the databases search. RB and JQ contributed to screening and analysis of papers, drafted the manuscript and approved its final version for submission.

References

Bae, J. H., Choi, J. S., Kang, D. W., Shin, Y. H., Lee, J. H., & Tack, G. R. (2014). A study on lower limb joint angles and muscle activities during maximal and sub-maximal pedaling by saddle heights. *43*(2014), 748–751.

Baino, F. (2011). Evaluation of the relationship between the body positioning and the postural comfort of non-professional cyclists: A new approach. *Journal of Sports Medicine & Physical Fitness*, *51*(1), 59–65. https://www.minervamedica.it/en/journals/sports-med-physical-fitness/article.php?cod=R40Y2011N01A0059

Bernardo, N., Barrios, C., Vera, P., Laíz, C., & Hadala, M. (2012, May). Incidence and risk for traumatic and overuse injuries in top-level road cyclists. *Journal of Sports Sciences*, *30*(10), 1047–1053. https://doi.org/10.1080/02640414.2012.687112

Bini, R. (2021). Influence of saddle height in 3D knee loads commuter cyclists: A statistical parametric mapping analysis. *Journal of Sports Sciences*, *39*(3), 275–288. https://doi.org/10.1080/02640414.2020.1816289

Bini, R., & Hume, P. (2020). Reproducibility of lower limb motion and forces during stationary submaximal pedalling using wearable motion tracking sensors. *Sports Biomechanics*, 1–22. https://doi.org/10.1080/14763141.2020.1776760

Bini, R. R. (2020). Acute effects from changes in saddle height in perceived comfort during cycling. *International Journal of Sports Science & Coaching*, *15*(3), 390–397. https://doi.org/10.1177/1747954120918965

Bini, R. R., & Flores Bini, A. (2018). Potential factors associated with knee pain in cyclists: A systematic review. *Open Access Journal of Sports Medicine*, *9*, 99–106. https://doi.org/10.2147/OAJSM.S136653

Bini, R. R., & Hume, P. (2016). A comparison of static and dynamic measures of lower limb joint angles in cycling: Application to bicycle fitting. *Human Movement*, *17*(1), 36–42. https://doi.org/10.1515/humo-2016-0005

Bini, R. R., & Hume, P. A. (2014). Effects of saddle height on knee forces of recreational cyclists with and without knee pain. *International SportMed Journal*, *15*(2), 188–199. https://www.researchgate.net/publication/263587378_Effects_of_saddle_height_on_knee_forces_of_recreational_cyclists_with_and_without_knee_pain

Bini, R. R., Hume, P. A., & Croft, J. L. (2011a). Effects of bicycle saddle height on knee injury risk and cycling performance. *Sports Medicine*, *41*(6), 463–476. https://doi.org/10.2165/11588740-000000000-00000

Bini, R. R., Hume, P. A., & Crofta, J. L. (2011b). Effects of saddle height on pedal force effectiveness. *Procedia Engineering*, *13*(1), 51–55. https://doi.org/10.1016/j.proeng.2011.05.050

Bini, R. R., Hume, P. A., & Kilding, A. E. (2014). Saddle height effects on pedal forces, joint mechanical work and kinematics of cyclists and triathletes. *European Journal of Sport Science*, *14*(1), 44–52. https://doi.org/10.1080/17461391.2012.725105

Blocken, B., van Druenen, T., Toparlar, Y., & Andrianne, T. (2018Oct01). Aerodynamic analysis of different cyclist hill descent positions. *Journal of Wind Engineering and Industrial Aerodynamics*, *181*, 27–45. https://doi.org/10.1016/j.jweia.2018.08.010

Braeckevelt, J., De Bock, J., Schuermans, J., Verstockt, S., Witvrouw, E., & Dierckx, J. (2019). The need for data-driven bike fitting: Data study of subjective expert fitting. In *Proceedings of the 7th International Conference on Sport Sciences Research and Technology Support - icSPORTS*, ISBN 978-989-758-383-4; ISSN 2184-3201, pages 181-189. https://doi.org/10.5220/0008344701810189Not StartedCompletedRejected

Callaghan, M. J. (2005). Lower body problems and injury in cycling. *Journal of Bodywork and Movement Therapies*, *9*(3), 226–236. https://doi.org/10.1016/j.jbmt.2005.01.007

Chabroux, V., Barelle, C., & Favier, D. (2012). Aerodynamics of cyclist posture, bicycle and helmet characteristics in time trial stage. *Journal of Applied Biomechanics*, *28*(3), 317–323. https://doi.org/10.1123/jab.28.3.317

Chiu, M. C., Wu, H. C., & Tsai, N. T. (2013). *The relationship between handlebar and saddle heights on cycling comfort*. 12–19. Springer

Connick, M. J., & Li, F. X. (2013). The impact of altered task mechanics on timing and duration of eccentric bi-articular muscle contractions during cycling. *Journal of Electromyography and Kinesiology*, *23*(1), 223–229. https://doi.org/10.1016/j.jelekin.2012.08.012

Damm, P., Dymke, J., Bender, A., Duda, G., & Bergmann, G. (2017). In vivo hip joint loads and pedal forces during ergometer cycling. *Journal of Biomechanics*, *60*, 197–202. https://doi.org/10.1016/j.jbiomech.2017.06.047

de Moura, B. M., Moro, V. L., Rossato, M., De Lucas, R. D., & Diefenthaeler, F. (2017). Effects of saddle height on performance and muscular activity during the Wingate test. *Journal of Physical Education (Maringa)*, *28*, 1. https://doi.org/10.4025/jphyseduc.v28i1.2838

Decock, M., De Wilde, L., Vanden Bossche, L., Steyaert, A., & Van Tongel, A. (2016). Incidence and aetiology of acute injuries during competitive road cycling. *British Journal of Sports Medicine*, *50*(11), 669. https://doi.org/10.1136/bjsports-2015-095612

Dedieu, P., Pelaez, M., Poirier, E., & Zanone, P. G. (2020). Effects of saddle height on muscular pattern and interlimb coordination in cycling. *Journal of Physical Education and Sport*, *20*(1), 222–228. https://hal.archives-ouvertes.fr/hal-03015668/document

Diefenthaeler, F., Berneira, J. O., Moro, V. L., & Carpes, F. P. (2016). Influence of saddle height and exercise intensity on pedalling asymmetries in cyclists. *Revista Brasileira De Cineantropometria E Desempenho Humano*, *18*(4), 411–418. https://doi.org/10.5007/1980-0037.2016v18n4p411

Downes, M. J., Brennan, M. L., Williams, H. C., & Dean, R. S. (2016). Development of a critical appraisal tool to assess the quality of cross-sectional studies (AXIS). *BMJ Open*, *6*(12), e011458. https://doi.org/10.1136/bmjopen-2016-011458

Encarnacion-Martinez, A., Ferrer-Roca, V., & Garcia-Lopez, J. (2018). Influence of sex on current methods of adjusting saddle height in indoor cycling. *Journal Of Strength And Conditioning Research / National Strength & Conditioning Association*.

Encarnación-Martínez, A., Ferrer-Roca, V., & García-López, J. (2021). Influence of sex on current methods of adjusting saddle height in indoor cycling. *Journal of Strength and Conditioning Research*, *35*(2), 519–526. https://doi.org/10.1519/JSC.0000000000002689

Ericson, M. O., Bratt, A., & Nisell, R. (1986). Load moments about the hip and knee joints during ergometer cycling. *Scandinavian Journal of Rehabilitation Medicine*, *18*(4), 165–172. http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A498418&dswid=-1386

Ericson, M. O., & Nisell, R. (1986). Tibiofemoral joint forces during ergometer cycling. *American Journal of Sports Medicine*, *14*(4), 285–290. https://doi.org/10.1177/036354658601400407

Ericson, M. O., & Nisell, R. (1987). Patellofemoral joint forces during ergometric cycling. *Physical Therapy*, *67*(9), 1365–1369. https://doi.org/10.1093/ptj/67.9.1365

Evans, S. A., James, D. A., Rowlands, D., & Lee, J. B. (2021). Evaluation of accelerometer-derived data in the context of cycling cadence and saddle height changes in triathlon. *Sensors*, *21*(3), 3. https://doi.org/10.3390/s21030871

Evans, S. A., Lee, J. B., Rowlands, D., & James, D. A. (2020). Using wearable technology to detect changes to trunk position and power in cycling. *ISBS proceedings archive*,

Evens, T., & Danoff, J. (2019). The effects of saddle alignment and pedal stroke training on a competitive cyclist with anterior knee pain: A case report. *Internet Journal of Allied Health Sciences & Practice*, *17*(3), 1–9. https://nsuworks.nova.edu/ijahsp/vol17/iss3/3/

Ferrer-Roca, V., Bescos, R., Roig, A., Galilea, P., Valero, O., & Garcia-Lopez, J. (2014). Acute effects of small changes in bicycle saddle height on gross efficiency and lower limb kinematics. *Journal Of Strength And Conditioning Research / National Strength & Conditioning Association*, *28*(3), 784–791. https://doi.org/10.1519/JSC.0b013e3182a1f1a9

Ferrer-Roca, V., Roig, A., Galilea, P., & Garcia-Lopez, J. (2012). Influence of saddle height on lower limb kinematics in well-trained cyclists: Staticvs dynamic evaluation in bike fitting. *Journal of Strength and Conditioning Research*, *26*(11), 3025–3029. https://doi.org/10.1519/JSC.0b013e318245c09d

Fonda, B., Sarabon, N., & Li, F. X. (2014). Validity and reliability of different kinematics methods used for bike fitting. *Journal of Sports Sciences*, *32*(10), 940–946. https://doi.org/10.1080/02640414.2013.868919

Gatti, A. A., Keir, P. J., Noseworthy, M. D., Beauchamp, M. K., & Maly, M. R. (2021). Equations to prescribe bicycle saddle height based on desired joint kinematics and bicycle geometry. *European Journal of Sport Science*, 1–10. https://doi.org/10.1080/17461391.2021.1902570

Giménez-Legarre, N., Flores-Barrantes, P., Miguel-Berges, M. L., Moreno, L. A., & Santaliestra-Pasías, A. M. (2020). Breakfast characteristics and their association with energy, macronutrients, and food intake in children and adolescents: A systematic review and meta-analysis. *Nutrients*, *12*(8), 2460. https://doi.org/10.3390/nu12082460

Grainger, K., Dodson, Z., & Korff, T. (2017). Predicting bicycle setup for children based on anthropometrics and comfort. *Applied Ergonomics*, *59*(Pt A), 449–459. https://doi.org/10.1016/j.apergo.2016.09.015

Holliday, W., Fisher, J., Theo, R., & Swart, J. (2017). Static versus dynamic kinematics in cyclists: A comparison of goniometer, inclinometer and 3D motion capture. *European Journal of Sport Science*, *17*(9), 1129–1142. https://doi.org/10.1080/17461391.2017.1351580

Hummer, E., Thorsen, T., & Zhang, S. (2021). Does saddle height influence knee frontal-plane biomechanics during stationary cycling? *The Knee*, *29*, 233–240. https://doi.org/10.1016/j.knee.2021.01.026

Korff, T., Fletcher, G., Brown, D., & Romer, L. M. (2011). Effect of "pose" cycling on efficiency and pedaling mechanics. *European Journal of Applied Physiology*, *111*(6), 1177–1186. https://doi.org/10.1007/s00421-010-1745-7

Kruschewsky, A. B., Dellagrana, R. A., Rossato, M., Ribeiro, L. F. P., Lazzari, C. D., & Saddle Height, D. F. (2018). Cadence effects on the physiological, perceptual, and affective responses of recreational cyclists. *Perceptual and Motor Skills*, *125*(5), 923–938. https://doi.org/10.1177/0031512518786803

Kutzner, I., Heinlein, B., Graichen, F., Rohlmann, A., Halder, A. M., Beier, A., Georg, B. (2012). Loading of the knee joint during ergometer cycling: Telemetric in vivo data. *The Journal of Orthopaedic and Sports Physical Therapy*, *42*(12), 1032–1038. https://doi.org/10.2519/jospt.2012.4001

Lamba, D., Pant, S., & Chandra, G. (2011). Effect of saddle heights on craniovertebral angle during ergonomic cycling. *Indian Journal of Physiotherapy & Occupational Therapy*, *5*(3), 157–160. http://ijpot.com/scripts/IJPOT%20July-Sept%202011.pdf

Macedo, R. M. B., Ulbricht, L., Ripka, W., Stadnik, A. M. W., & Ricieri, D. V. (2015). *Ergonomics applied to the cycling with the utilization of two protocols for the saddle height adjust*. 241–244. Taylor and Francis Group.

Manigandan, S., Gunasekar, P., Praveen Kumar, T. R., Alahmadi, T. A., Subramanian, N., Pugazhendhi, A., & Brindhadevi, K. (2021). Influence of dynamic position, fluid intake, hydration, and energy expenditure on sustainable mobility transport. *Applied Acoustics*, 175. https://www.sciencedirect.com/science/article/abs/pii/S0003682X20309142

Millour, G., & Bertucci, W. (2017). Comparison of Genzling method vs Hamley method allowing a postural adjustment in cycling: Preliminary study. *Computer Methods in Biomechanics and Biomedical Engineering*, *20*(sup1), S135–6. https://doi.org/10.1080/10255842.2017.1382898

Millour, G., Duc, S., Puel, F., & Bertucci, W. (2019). Comparison of static and dynamic methods based on knee kinematics to determine optimal saddle height in cycling. *Acta Bioeng Biomech*, *21*(4), 93–99. https://doi.org/10.37190/ABB-01428-2019-02

Millour, G., Duc, S., Puel, F., & Bertucci, W. (2021). Comparison of two static methods of saddle height adjustment for cyclists of different morphologies. *Sports Biomechanics*, *20*(4), 391–406. https://doi.org/10.1080/14763141.2018.1556324

Moher, D. (2009). Preferred reporting items for systematic reviews and meta-analyses: The prisma statement. *Annals of Internal Medicine*, *151*(4), 264–269. https://doi.org/10.7326/0003-4819-151-4-200908180-00135

Peveler, W. W. (2008). Effects of saddle height on economy in cycling. *Journal of Strength and Conditioning Research*, *22*(4), 1355–1359. https://doi.org/10.1519/JSC.0b013e318173dac6

Peveler, W. W., Shew, B., Johnson, S., & Palmer, T. G. (2012). A kinematic comparison of alterations to knee and ankle angles from resting measures to active pedaling during a graded exercise protocol. *Journal Of Strength And Conditioning Research / National Strength & Conditioning Association*, *26*(11), 3004–3009. https://doi.org/10.1519/JSC.0b013e318243fdcb

Price, D., & Donne, B. (1997). Effect of variation in seat tube angle at different seat heights on submaximal cycling performance in man. *Journal of Sports Sciences*, *15*(4), 395–402. https://doi.org/10.1080/026404197367182

Priego Quesada, J. I., Carpes, F. P., Salvador Palmer, R., Perez-Soriano, P., & Cibrian Ortiz de Anda, R. M. (2016). Effect of saddle height on skin temperature measured in different days of cycling. *Springerplus*, *5*(1), 205. https://doi.org/10.1186/s40064-016-1843-z

Priego Quesada, J. I., Kerr, Z. Y., Bertucci, W. M., & Carpes, F. P. (2019). A retrospective international study on factors associated with injury, discomfort and pain perception among cyclists. *PLOS ONE*, *14*(1), e0211197. https://doi.org/10.1371/journal.pone.0211197

Priego Quesada, J. I., Perez-Soriano, P., Lucas-Cuevas, A. G., Salvador Palmer, R., & Cibrian Ortiz de Anda, R. M. (2017). Effect of bike-fit in the perception of comfort, fatigue and pain. *Journal of Sports Sciences*, *35*(14), 1459–1465. https://doi.org/10.1080/02640414.2016.1215496

Priego Quesada, J. I., Pérez-Soriano, P., Lucas-Cuevas, A. G., Salvador Palmer, R., & Cibrián Ortiz de Anda, R. M. (2016). Effect of bike-fit in the perception of comfort, fatigue and pain. *Journal of Sports Sciences*, *35*(14), 1459–1465. https://doi.org/10.1080/02640414.2016.1215496

Quesada, J. I. P., Jacques, T. C., Bini, R. R., & Carpes, F. P. (2016). Importance of static adjustment of knee angle to determine saddle height in cycling. *Journal of Science and Cycling*, *5*(1), 26–31. http://www.jsc-journal.com/js/index.php?journal=JSC&page=article&op=view&path%5B%5D=234

Scoz RD, Amorim CF, Espindola T, Santiago M, Mendes JJ, de Oliveira PR, Ferreira LM, Brito RN. (2021). Discomfort, pain and fatigue levels of 160 cyclists after a kinematic bike-fitting method: An experimental study. *BMJ Open Sport & Exercise Medicine*, *7*(3), e001096. https://doi.org/10.1136/bmjsem-2021-001096

Silberman, M. R., Webner, D., Collina, S., & Shiple, B. J. (2005). Road bicycle fit. *Clinical Journal of Sport Medicine*, *15*(4), 271–276. https://doi.org/10.1097/01.jsm.0000171255.70156.da

Springer, B. A. (2013). Ride 2 recovery's project HERO: Using cycling as part of rehabilitation. *Physical Therapy in Sport*, *14*(2), 77–86. https://doi.org/10.1016/j.ptsp.2012.11.001

Swart, J., & Holliday, W. (2019). Cycling biomechanics optimization—the (R) evolution of bicycle fitting. *Current Sports Medicine Reports*, *18*(12), 12. https://doi.org/10.1249/JSR.0000000000000665

Van Tulder, M., Furlan, A., Bombardier, C., & Bouter, L., & Group EBotCCBR. (2003). Updated method guidelines for systematic reviews in the Cochrane collaboration back review group. *Spine*, *28*(12), 1290–1299. https://doi.org/10.1097/01.BRS.0000065484.95996.AF

Verma, R., Hansen, E. A., De Zee, M., & Madeleine, P. (2016). Effect of seat positions on discomfort, muscle activation, pressure distribution and pedal force during cycling. *Journal of Electromyography and Kinesiology : Official Journal of the International Society of Electrophysiological Kinesiology*, *27*, 78–86. https://doi.org/10.1016/j.jelekin.2016.02.003

Vrints, J., Koninckx, E., Van Leemputte, M., & Jonkers, I. (2011). The effect of saddle position on maximal power output and moment generating capacity of lower limb muscles during isokinetic cycling. *Journal of Applied Biomechanics*, *27*(1), 1–7. https://doi.org/10.1123/jab.27.1.1

Wang, Y., Liang, L., Wang, D., Tang, Y., Wu, X., Li, L., & Liu, Y. (2019). Cycling with low saddle height is related to increased knee adduction moments in healthy recreational cyclists. *European Journal of Sport Science*, *20*(4), 1–7. https://doi.org/10.1080/17461391.2019.1635651