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Review

Influence of Footwear Features on Oxygen Consumption and Running Economy: A Review

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Abstract: It has been reported that the new technology applied to current racing shoes has increased the performance of runners who use this kind of footwear. This improvement has been proven in the scientific literature in relation to oxygen consumption. Nevertheless, as it is a novel topic, there is a lack of knowledge about which specific features achieve a decrease in oxygen consumption during running. Thus, the purpose of this study was to determine the influence of the features of footwear, specifically the shoe mass, the cushioning system, the longitudinal bending stiffness and the comfort feeling on running economy. This review was carried out from the bibliographic search in the main databases such as PubMed, Cochrane Plus and Medline and considering the PRISMA statement as a reference so that an analysis of the results has been obtained together with the methodological quality and risk of bias of the studies. Nineteen articles met the inclusion criteria, which presented a moderate/high methodological quality, and an analysis of their results was carried out. Footwear features such as the shoe mass, the cushioning system and the longitudinal bending stiffness produce advantages compared to other footwear that does not include this technology. Due to the lack of evidence, the influence of comfort feeling on oxygen consumption has not been proved.

Keywords: oxygen consumption; shoe mass; cushioning system; longitudinal stiffness; comfort feeling

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Citation: Melero-Lozano, M.Á.; San-Antolín, M.; Vicente-Campos, D.; Chicharro, J.L.; Becerro-de-Bengoa-Vallejo, R.; Losa-Iglesias, M.E.; Rodríguez-Sanz, D.; Calvo-Lobo, C. Influence of Footwear Features on Oxygen Consumption and Running Economy: A Review. *Appl. Sci.* **2023**, *13*, 23. https://doi.org/10.3390/app13010023

Academic Editors: Rita M. Kiss and Alon Wolf

Received: 28 November 2022
Revised: 13 December 2022
Accepted: 15 December 2022
Published: 20 December 2022

1. Introduction

Worldwide, running may be considered one of the most practiced sports activities, particularly when considering it as a natural task that has always been part of human existence [1]. In addition, this sport modality presents a low-cost activity from an economic point of view as it does not require much more specialized equipment than footwear and may be performed outdoors. Numerous health benefits have been reported for those who practice running, as it can reduce the prevalence of vascular and neurological diseases [2] and even different types of cancer like colorectal or lung cancer [3,4], as well as other diseases related to a sedentary lifestyle such as cardiovascular function or increased adiposity [5,6]. Nevertheless, running may cause injuries, mainly on the lower limb [7,8] (i.e., medial tibial stress syndrome, Achilles tendinopathy, or plantar fasciitis). The incidence of injuries associated with running has risen with the increased popularity of the sport among those middle/long-distance runners who practice it [9]. Nowadays there are studies that set the incidence of injuries in the lower limb at between 19.4 and 79.3% [9]. It is known that the origin of these injuries is multifactorial (i.e., factors such as age, history of previous injury, or perception of risk should be considered) [10] and there are diverse risk factors that may predispose to injury in the lower limb. These risk factors may be classified into three areas, namely (1) personal factors (i.e., age, sex, or height), (2) running/training factors (i.e., weekly running days, distance, or running shoes), and (3) health and lifestyle-related factors (i.e., smoking, a history of comorbidity and previous injuries). Among the characteristics of training, footwear plays an important role [11]. Coinciding with the increase in popularity of running races from 1970 onward, research on sports shoes started in two different directions, the prevention of injuries and the improvement in performance during the race. Despite the investment that has been made in these two areas, the injury rate has barely decreased and the improvement in sports performance has not undergone a marked change until recent years [12,13].

The present review aimed to analyze the scientific literature on the influence of footwear on running economy at a medium/long distance. In order to understand how this improvement in running performance is quantified, it is important to know the following concepts. Three physiological parameters are usually studied to predict the speed that an athlete can maintain in competitive events greater than 3000 m, the maximal rate of oxygen consumption (VO_{2max}), the blood lactate threshold and the energy cost of running [14,15]. From these data, we can obtain the oxygen cost of running at a given speed, which is known as running economy and is measured in ml O_2/kg/min [15]. This is the parameter that has traditionally been used to measure the performance of athletes and even today many studies continue to assess improvement in running by measuring oxygen consumption [16,17]. At the same time, it should be noted that there has recently been a proposal to express running economy in terms of metabolic cost measured in kJ/kg/min since this value would have greater sensitivity than oxygen consumption [18]. So, if an athlete has a greater running economy, that is, a lower oxygen cost/metabolic cost, he or she will be able to run at the same speed with less physiological effort, which will translate into an improvement and greater distance traveled in less time [19]. Therefore, in this review, running economy may be considered as the metabolic cost measured in kJ/kg/min whenever possible because, although this measurement may be more reliable, this fact has only been confirmed in recent years and the vast majority of previous studies [15–17] use running economy as a reference in relation to oxygen consumption in ml O_2/kg/min. There are several factors that affect running economy [20] and that may be improved or modified in the life of an athlete, such as strength training, altitude training, or the environment where they practice sports [21]. It is interesting to note that there are other variables that we could qualify as extrinsic factors since they do not depend directly on the athlete, which provides the possibility to improve running economy. These are the surface on which the race takes place [22] and footwear [23–25]. Since the podiatrist is considered the specialist in the anatomy and biomechanics of the foot and the lower limb, whether in walking or running, his/her role in the research and development of sports footwear acquires great importance in order to prevent injuries or increase running economy [11–13].

Although most runners use sports footwear for their daily activity, running barefoot or with minimal foot protection (minimalist footwear) has been described in humans for about 2 million years [1] and it was not until the beginning of the 19th century that footwear began to be used in order to protect the foot from the surface on which the wearer was walking. Nevertheless, modern sports footwear is a relatively recent development and it's only in the last 40 years that most of the running shoe companies have been founded and most of the scientific advances in this field have been made [26]. Simultaneously, more technology and sophistication have been added to running shoes. In 2005, the first modern minimalist footwear (Nike Free) was developed by the sneaker brand Nike. In 2006, it was proposed that a style of footwear used by yacht crews, the Vibram brand FiveFingers, could be the ideal footwear to imitate barefoot racing [26]. However, the turning point that popularized minimalist footwear was the publication of Christopher McDougall's book "Born To Run". Many of the people who have read the book are convinced that this type of footwear could be the solution for injuries and could even increase their performance [26]. These affirmations have been widely discussed in the scientific literature and there is great controversy. Indeed, there is no evidence that running in minimalist footwear causes a significant decrease in injury rate [27]. In addition, we must keep in mind that minimalist running has certain risks, from skin injuries caused by minimal foot protection to muscle-tendon injuries associated with poor adaptation to minimalist footwear [28]. Taking this latter fact into account, the adaptation to minimalist footwear must be progressive and controlled by a specialist who will guide wearers in this process [27,28]. Regarding the improvement in running economy thanks to minimalist footwear, there are studies that support this hypothesis but these studies present a limitation in that the tests are carried out on subjects experienced in minimalist running [29,30]. This fact must be taken into account, as a person used to a given activity seems to have lower physiological demands to perform that activity than someone who performs the same activity for the first time. In fact, in a study with 15 subjects without previous experience with minimalist footwear, a 4-week adaptation to minimalist footwear was carried out and running economy tests were performed before and after adaptation, comparing them with tests with standard footwear. In the tests prior to adaptation, no differences were found in oxygen consumption between barefoot running and standard footwear. Conversely, after adaptation, the results supported the theory that minimalist footwear reduces oxygen consumption [31].

This improvement in running economy with minimalist footwear is based on the weight of the shoe, as, for every 100 g added to the shoe, there is a loss of approximately 1% in running economy [32,33]. Nevertheless, when we use a light shoe (approximately 220 g per pair of shoes) with a good cushioning system, no differences are found between running barefoot and with shoes due to what is known as the cushioning cost that must be carried out by the muscles to cushion the impact when we run wearing minimalist footwear [32]. In order to study running economy in terms of the parameters mentioned above and continue with the trend of looking for footwear that improves performance in a race, a review of the features of the shoe with regard to the consumption of oxygen and running economy was carried out in this review. These features are the weight of the shoe [32], the cushioning system [17], increased dorsiflexion stiffness [34] and the comfort feeling [35].

Among the features that may explain this phenomenon, previous studies suggest that different changes in these shoe properties result in an improved running economy [16,36]. The addition of carbon fiber plates into the midsole increases the longitudinal bending stiffness, reducing the energy cost of running; however, it depends on the plate design (flat or curved and length) [36]. If the plate design is correct, it may result in a force during push-off that acts at the right location, time and frequency, improving running economy [37]. The combination of this plate with the right cushioning system and the light weight of the shoes cause an improved running economy [25]. This improved running economy may be interesting for long-distance performance, as a better running economy is directly translated into less physiological effort at the same speed [19], although the same improvements have not been shown in previous research [16,25]. These controversial findings highlight the necessity to carry out this review.

The development of a new type of shoe by sports shoe companies that provides a clear benefit compared to previous shoes [16] has caused repercussions in recent years necessitating the modifying of the regulations regarding its use [38]. Due to the scarce evidence on this subject and the interest that it arouses in the sports community and at the research level by different professionals, it is considered necessary to review the available bibliography in relation to the improvement in performance in long-distance races due to the characteristics of the footwear that decrease the metabolic cost [17,32,34,35] in an attempt to know the true impact of the new sports footwear. Consequently, the effect of different characteristics of footwear in improving running performance has been investigated by reviewing observational studies, clinical trials and randomized controlled trials. In order to reach a conclusion about the subject to study, two hypotheses have been established. We hypothesized that the features of the footwear such as the shoe mass, the cushioning system, the longitudinal bending stiffness and the comfort feeling produce a positive influence on running economy in trained athletes. The main purpose was to determine the influence of the characteristics of the footwear on the running economy in trained athletes and the secondary aim was to detail the shoe mass, the cushioning system, the longitudinal bending stiffness and the comfort feeling influence on running economy in trained athletes.

2. Methods

2.1. Study Design

This review followed the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) criteria [39]. A bibliographic search of scientific literature was carried out from December 2020 to December 2022. Most of the studies used for this work have been published in the last ten years. Nevertheless, certain articles which have not been published in the last decade were included in order to be able to perform a complete review regarding the study purposes. From these studies, the most relevant information was collected to carry out each section of the work. Observational studies, clinical trials and randomized clinical trials were included.

2.2. Selection Criteria

Studies were included in this review if [24,40]: (1) the studies presented running economy data (measured in kJ/kg/min or mL O_2/kg/min) on at least one of the characteristics of interest for this work (shoe mass, cushioning system, longitudinal bending stiffness and comfort feeling); (2) running economy should be evaluated on a treadmill or a running track; and (3) studies that were indexed at scientific journals that presented an impact factor as a hallmark for international citations. The exclusion criteria were [23,24]: (1) articles that were not written in English or Spanish; (2) articles that included in their sample patients with some type of musculoskeletal or neurological disorder that could affect their performance; (3) investigations carried out in some unusual environment that affects performance (on the beach, in water or on steep slopes); and (4) articles that do not study running economy in the units mentioned above.

2.3. Search Strategy

The databases used to carry out this bibliographic review were PubMed, Cochrane Plus and Medline offered by the services of the library of the Complutense University of Madrid. The search terms were based on the following keywords combined with Boolean operators "VO_2" OR "running economy" OR "metabolic cost" OR "oxygen consumption" AND "shoe mass" OR "cushioning running shoes" OR "soft soled shoes" OR "longitudinal bending stiffness" "shoe bending stiffness" OR "footwear comfort". Table 1 shows the results of this search strategy for each database.

2.4. Methodological Quality Assessment

The methodological quality of the studies was assessed using the Spanish Critical Reading Skills Program (CASPe Criteria) which allowed evaluation of observational studies and clinical trials [41]. This program is one of the most widely used tools to carry out this type of assessment being an effective system currently used by many authors in the article selection process [42–44]. As it is a scale that allows the evaluation of a wide variety of types of articles, there is no perfectly defined ranking, so in this work, a score of 0–5 was considered as a low methodological quality and a score greater than or equal to 6 was considered as moderate/high methodological quality.

2.5. Impact Factor Assessment

The impact factor of the articles was obtained using the Journal Citations Report (JCR) tool. This quality indicator, which can be found on the Web of Science platform, measures the impact factor of each journal using a formula that takes into account the number of citations received by the articles published in the previous two years divided by the total number of articles published in those two years [45]. Although the impact factor is the main quality indicator, the position and quartile (Q) in the range of journals of the same category were also provided.

Table 1. Search strategy results.

	Search Terms	Selection Criteria	Results	Selection
PubMed	VO_2 OR running economy OR metabolic cost OR oxygen consumption AND shoe mass	10 years English and Spanish	62	6
	VO_2 OR running economy OR metabolic cost OR oxygen consumption AND cushioning running shoes OR soft soled shoes	10 years English and Spanish	22	2
	VO_2 OR running economy OR metabolic cost OR oxygen consumption AND longitudinal bending stiffness OR shoe bending stiffness	10 years English and Spanish	6	1
	VO_2 OR running economy OR metabolic cost OR oxygen consumption AND footwear confort	10 years English and Spanish	16	1
Cochrane Plus	VO_2 OR running economy OR metabolic cost OR oxygen consumption AND shoe mass	10 years English and Spanish	113	1
	VO_2 OR running economy OR metabolic cost OR oxygen consumption AND cushioning running shoes OR soft soled shoes	10 years English and Spanish	70	1
	VO_2 OR running economy OR metabolic cost OR oxygen consumption AND longitudinal bending stiffness OR shoe bending stiffness	10 years English and Spanish	66	1
	VO_2 OR running economy OR metabolic cost OR oxygen consumption AND shoe mass	10 years English and Spanish	156	1
Medline	VO_2 OR running economy OR metabolic cost OR oxygen consumption AND longitudinal bending stiffness OR shoe bending stiffness	10 years English and Spanish	65	1

2.6. Risk of Bias Assessment

The recommendations of the Cochrane Handbook of Systematic Reviews of Interventions were followed to assess the risk of bias in the included articles. The evaluation of the risk of bias was carried out through a domain-based assessment, since, as stated in this manual, assessing the risk of bias using scales is not recommended, since these assessments included considerations that could be difficult to support. The most practical way to perform an assessment of this type was to use criteria that may be specified objectively. Therefore, six domains were evaluated classifying them as "low risk", "high risk" or "unclear risk" in order to obtain a summary of the risk of bias that was included in the results section [40].

2.7. Data Extraction

As mentioned above, although this work is not a systematic review or a meta-analysis and given that the PRISMA criteria [39] were followed, a synthesis of results was not carried out. Nevertheless, we have tried to adapt this section on the synthesis of results included in the criteria already mentioned and an analysis of the results was performed.

This analysis was collected in the results section including Tables 1–4 according to the studied outcome measurements. These tables collected the information extracted from each article including: the title of the article, author, year of publication, the sample of subjects, age and sex of each person included in the studies, method of evaluation for the race, running experience that each person reported, adjustment of the mass between the different footwear investigated, race protocol to measure the economy of the race, and characteristics of the control footwear and shoe with which they are compared; finally, oxygen consumption with each shoe and the *p*-value were included to know if the difference was statistically significant or not.

Table 2. Shoe Mass.

Study	Year and Author	Sample M:W	Age	Race Assessment	Barefoot Running Experience	Mass Correction	Race Protocol	Footwear Characteristics	VO_2 (mL O_2/kg/min)	*p*-Value
Barefoot-Shod Running Differences: Shoe or Mass Effect?	2008. Divert, C	12 trained subjects. 12:0	24 ± 5	Treadmill	Do not provide information	Yes	6 four-minute trials 13 km/h. 2 min break between trials	Barefoot Sock 50 g Sock 150 g Sock 350 g Footwear 150 g Footwear 350 g	40.7 ± 2.9 40.4 ± 2.8 40.8 ± 2.5 41.6 ± 2.5 40.6 ± 3.1 42.1 ± 2.3	$p < 0.01$
Biomechanical and physiological comparsion of barefoot and two shod conditions in experienced barefoot runners	2009. Squadrone, R	8 subjects with barefoot running experience. 8:0	32 ± 5	Treadmill	Yes	No	3 six-minute trials 12 km/h. 4 min break between trials	Barefoot FiveFingers 148 g Normal Footwear 341 g	45.7 ± 2 45 ± 2 46.3 ± 2	$p < 0.05$
Oxygen cost of running barefoot vs. running shod	2011. Hanson, N.J	10 recreational runners. 5:5	23.8 ± 3.39	Treadmill/Athletics Track	2 subjects	No	4 six-minute trials at 70% of their vo2max. Rest until HR < 110 ppm	Barefoot Footwear 350 g	35.67 ± 8 36.40 ± 8	$p < 0.034$
Metabolic cost of running barefoot vs shos. Is lighter better?	2012. Franz, J.R	12 trained athletes. 12:0	29.8 ± 7.3	Treadmill	Yes	Yes	7 five-minute trials 3.35 ms. 4 min break between trials	Barefoot/ +150 g/ +300 g/+450 g Footwear/ +150 g/+300 g	40.28 ± 0.88 40.83 ± 0.96 41.46 ± 0.76 41.86 ± 1.00 39.43 ± 0.75 39.82 ± 0.72 40.77 ± 0.80	$p < 0.001$ barefoot $p < 0.001$ in shoes
Mechanical and Physiological Examination of Barefoot and Shod Conditions in Female Runners	2014. Paulson, S	8 trained women. 0:8	20.1 ± 1.4	Treadmill	Yes	No	3 seven-minute trials 3.13 ms. 5 min break between trials	Barefoot Fivefingers 142 g Normal Footwear 268.7 g	36.29 ± 1.92 37.22 ± 1.61 38.41 ± 1.49	$p = 0.04$
Four-week habituation to simulated barefoot running improves running economy when compared with shod running	2014. Warne, J.p	15 trained runners. 15:0	24 ± 5	Treadmill	No	No	8 six-minute trials 11 and 13 km/h. 4 trials pre and 4 post familiarization	Fivefingers 150 g Normal Footwear 400 g	43.61 ± 0.99 51.44 ± 1.23 42.53 ± 0.82 50.33 ± 0.94 42.99 ± 1.15 50.99 ± 1.34 39.55 ± 1.04 46.92 ± 1.35	$p < 0.05$

Table 2. *Cont.*

Study	Year and Author	Sample M:W	Age	Race Assessment	Barefoot Running Experience	Mass Correction	Race Protocol	Footwear Characteristics	VO_2 (mL O_2/kg/min)	*p*-Value
Barefoot Running Reduces the Submaximal Oxygen Cost in Female Distance Runners	2016. Berrones, A.J	14 recreational athletes. 0:14	27.6 ± 1.6	Treadmill	No	No	6 five-minute trials at 65, 75 and 85% of their vo2max barefoot/in shoes. 2 min break	Barefoot Footwear 590 g	2.03% 2.82% 4.27%	$p < 0.05$
Influence of Shoe Mass on Performance and Running Economy in Trained Runners	2020. Rodrigo-Carranza, V	11 trained athletes. 6:5	20.64 ± 1.60 22.12 ± 1.03	Treadmill	No	No	3 five-minute trials at 75, 85 and 95% of their vo2max in shoes	Control Control + 50 g Control + 100 g	222.04 ± 12.43 214.16 ± 11.54 205.50 ± 10.87 223.79 ± 17.13 217.44 ± 15.91 213.50 ± 16.71 229.92 ± 13.89 225.17 ± 13.02 217.13 ± 15.67	$p < 0.021$

Table 3. Cushioning System.

Study	Year and Author	Sample M:W	Age	Race Assessment	Mass Correction	Race Protocol	Footwear Characteristics	VO_2 (mL O_2/kg/min)	*p*-Value
Lower oxygen demands of running in soft-soled shoes	1986. Frederick, E.C	10 trained athletes. 10:0	Do not provide information	Traedmill	No	3 twelve-minute trials 3.65–4.55 ms. 5 min break between trials	Control shoe, EVA midsole	205.5–204.6	$p < 0.05$
							PU midsole	201.6–199.8	$p < 0.05$
Running shoe cushioning properties can influence oxygen consumption	2013. Worobets, J	12 fit athletes. 12:0	Do not provide information	Traedmill/Athletics Track	Yes	2 five-minute trials at a speed below their anaerobic threshold	EVA midsole PU midsole	44.7–40.7 44.3–40.3	$p = 0.01$
A test of the metabolic cost of cushioning hypothesis during unshod and shod running	2014. Tung, K.D	12 healthy subjects. 10:2	30.2 ± 9.1	Treadmill	Not needed	4 five-minute trials 3.35 ms. 3 min break between trials	Barefoot 0/10/20 mm Cushioned Footwear 211 g	39.17 ± 3.68 38.58 ± 3.27 38.99 ± 2.88 39.36 ± 3.09	$p = 0.034$
Softer and more resilient running shoe cushioning properties enhance running economy	2014. Worobets, J	12 recreational runners. No information	26.4	Treadmill	Yes	2 five-minute trials with each shoe. 5 min break between trials	EVA midsole 305 g TPU midsole 335 g	44.7 44.3	$p = 0.044$
		12 recreational runners. No information	29.2	Athletics Track	Yes	2 five-minute trials with each shoe. 5 min break between trials	EVA midsole 250 g TPU midsole 280 g	40.7 40.3	$p = 0.028$
Metabolic cost of running is greater on a treadmill with a stiffer running platform	2017. Smith, J.A	12 trained athletes. 8:4	18–45	Treadmill	Not needed	4 four-minute trials on each surface	Treadmill Stiffness Cosmos 3030 kNm Quinton 1354 kNm	224 ± 23 vs. 237 ± 23 221 ± 17 vs. 239 ± 21 221 ± 15 vs. 237 ± 14 221 ± 13 vs. 235 ± 13	$p < 0.05$

Table 4. Longitudinal Bending Stiffness.

Study	Year and Author	Sampple M:W	Age	Race Assessment	Mass Correction	Race Protocol	Footwear Characteristics	VO_2 (mL O_2/kg/min)	*p*-Value
Forefoot bending stiffness, running economy and kinematics during overground running	2016. Madden, R	18 recreational athletes. 18:0	28 ± 5	Athletics Track	No	2 five-minute trials at a speed below their anaerobic threshold	Control shoe 135 g Rigid shoe 162 g	37.7 38.1	$p > 0.05$
Does an increase in energy return and/or longitudinal bending stiffness shoe features reduce the energetic cost of running?	2019. Flores, N	19 recreational athletes. 19:0	24 ± 6	Athletics Track	No	4 eight-minute trials at 90% their vo2max	4 midsole combinations: high/low energy and high/low stiffness	Not significant difference on RE	$p > 0.05$
Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG	2006. Roy, J. P	13 subjects. 13:0	27.0 ± 5.1	Treadmill	No	6-min trial on each shoe	Control shoe 241.6 g Medium stiffness 236.6 g High stiffness 240.2 g	45.323 44.960 45.246	$p = 0.014$
The bending stiffness of shoes is beneficial to running energetics if it does not disturb the natural MTP joint flexion	2017. Oh, K	19 subjects. 19:0	24.7 ± 3.8	Treadmill	No	5 five-minute trials	Control shoe 4 Shoes of different stiffness	See Tables	$p < 0.05$

3. Results

3.1. Flow Diagram

As the flow diagram of the PRISMA criteria [39] included in Figure 1 shows, in a first search, 580 articles were obtained. After removing duplicate records and articles which did not meet the requirements, 54 studies were selected for eligibility. Finally, 35 studies were eliminated as they did not meet the inclusion criteria. Therefore, a total of 19 articles remained for the analysis of results.

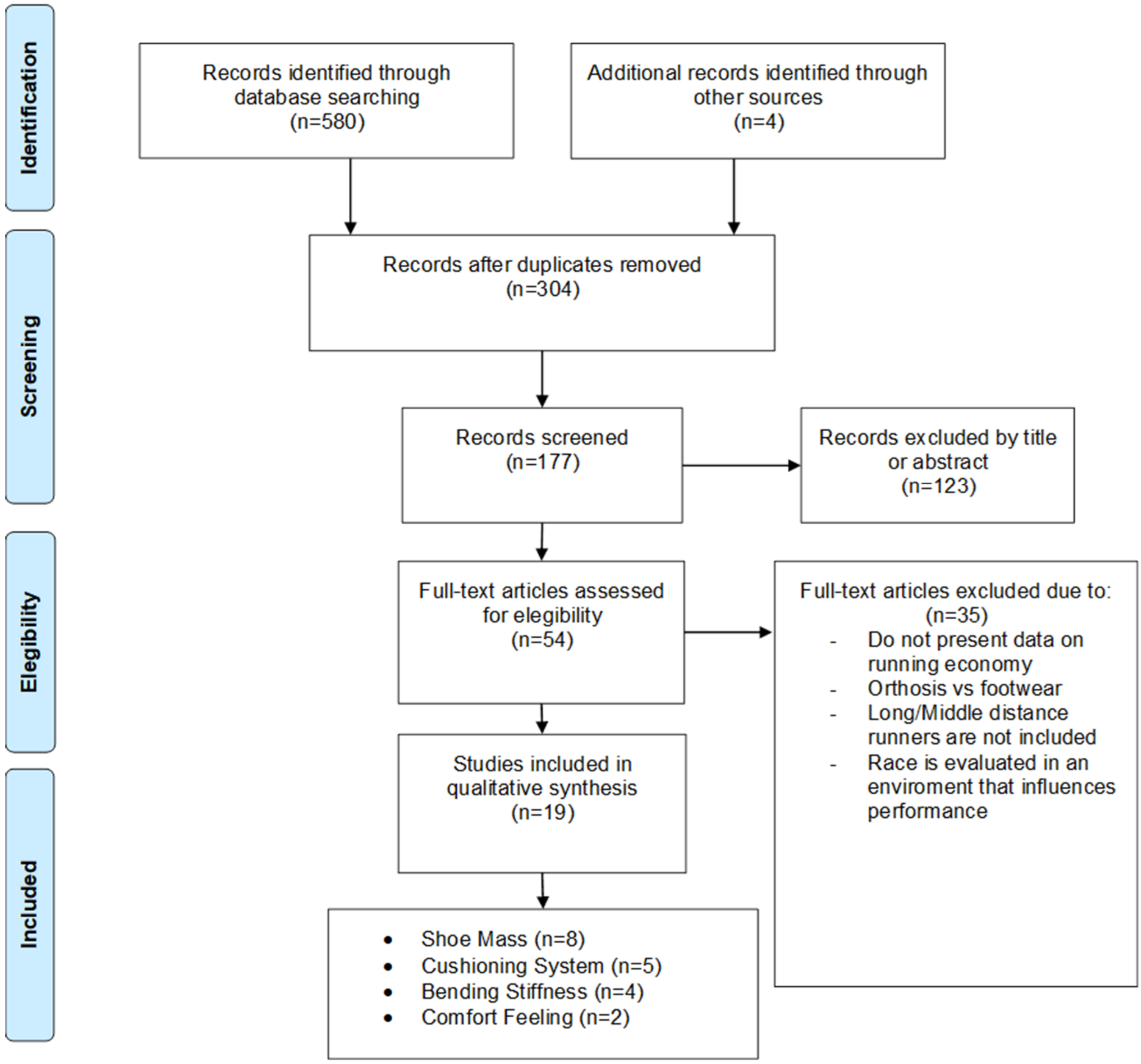

Figure 1. Flow diagram of the narrative review.

3.2. Study Outcomes

A summary of the data from each article is presented in Tables 2 and 3. Table 2 shows data on shoe mass. Eight articles were included that comprised a total of 90 subjects of which 27 were women with a mean age between 20–32 years. These subjects performed between one and four visits depending on the study and the race was evaluated mainly on a treadmill. Finally, the oxygen consumption values may be observed as reflected in Table 3. In all cases, the p-value was less than 0.05. In one of the columns, the characteristics of the shoes were compared. The data analysis corresponding to the cushioning system is shown in Table 3. In this case, five studies were analyzed. They included a total of 70 subjects, of which at least 6 were women (one article did not specify the sex of the participants) and they were between 18–45 years old. Regarding this variable, the range of visits to the laboratory by the participants was between one and three with an evaluation of the race mainly on a treadmill, although in this case two of the studies also performed measurements on a running track. Finally, the oxygen consumption and the *p*-value were reflected, which favored shoes with polyurethane (PU). Information on the shoes to be compared was also included. Regarding longitudinal bending stiffness, Table 4 shows 4 articles with 69 subjects, none of whom are women. The average age was 26 years and all of the studies evaluated the race on a treadmill, except for one, which has a *p*-value above 0.05. One of the columns shows the different footwear conditions that were tested. Regarding the comfort feeling, Table 5 is presented, including 2 articles and 28 subjects, none of whom are women. The evaluation of the race was carried out on a treadmill after evaluating the comfort of the shoes they used. In the results column, a *p*-value less than 0.05 was shown in one of these articles, which found differences in favor of more comfortable footwear, while the other studies did not.

Table 5. Comfort Feeling.

Study	Year and Author	Sample M:W	Age	Race Assessment	Mass Correction	Comfort Assessment	Race Protocol	VO_2 (mL O_2/kg/min)	*p*-Value
Does enhanced footwear comfort affect oxygen consumption and running biomechanics?	2020. Lindorfer, J	15 trained runners. 15:0	26 ± 4	Treadmill	Yes	Static no items evaluatedDynamic no items evaluated	2 six-minute trials. 2 min break between trials	Comfortable shoe 44.4 ± 8.9 Uncomfortable shoe 44.2 ± 9.0	$p = 0.200$
Improved footwear comfort reduces oxygen consumption during running	2009. Luo, G	13 trained athletes. 13:0	23.8 ± 3.4	Treadmill	Yes	Static 7 items evaluatedDynamic 6 items evaluated	4 six-minute trials.3 min break between trials	See Tables	$p = 0.036$

3.3. Methodological Quality Assessment

The methodological quality of clinical trials and observational studies was evaluated with the CASPe tool and is summarized in Tables 6 and 7, respectively. The responses to each of the questions are shown, obtaining a score corresponding to a moderate/high methodological quality in all studies. An average score of 7.3 out of 11 has been obtained in clinical trials and 6.3 out of 11 in observational studies.

Table 6. Methodological Quality (clinical trials). ND. Not Detailed.

Study	CASPe1	CASPe2	CASPe3	CASPe4	CASPe5	CASPe6	CASPe7	CASPe8	CASPe9	CASPe10	CASPe11	Score
Oxygen cost of running barefoot vs running shod	Yes	Yes	Yes	No	Yes	Yes	ND	ND	Yes	ND	Yes	7/11
Metabolic cost of running barefoot vs shos. Is lighter better?	Yes	Yes	Yes	Yes	Yes	Yes	ND	ND	Yes	ND	Yes	8/11
Mechanical and Physiological Examination of Barefoot and Shod Conditions in Female Runners	Yes	Yes	Yes	No	Yes	Yes	ND	ND	Yes	ND	Yes	7/11
Four-week habituation to simulated barefoot running improves running economy when compared with shod running	Yes	Yes	Yes	No	Yes	Yes	ND	ND	Yes	ND	Yes	7/11

Table 6. *Cont.*

Study	CASPe1	CASPe2	CASPe3	CASPe4	CASPe5	CASPe6	CASPe7	CASPe8	CASPe9	CASPe10	CASPe11	Score
Barefoot Running Reduces the Submaximal Oxygen Cost in Female Distance Runners	Yes	Yes	Yes	No	Yes	Yes	ND	ND	Yes	ND	Yes	7/11
Influence of Shoe Mass on Performance and Running Economy in Trained Runners	Yes	Yes	Yes	Yes	Yes	Yes	ND	ND	Yes	ND	Yes	8/11
Lower oxigen demands of running in soft-soled shoes	Yes	No	Yes	Yes	Yes	Yes	ND	ND	Yes	ND	Yes	7/11
Running shoe cushioning properties can influence oxygen consumption	Yes	Yes	Yes	Yes	Yes	Yes	ND	ND	Yes	ND	Yes	8/11
A test of the metabolic cost of cushioning hypothesis during unshod and shod running	Yes	Yes	Yes	No	Yes	Yes	ND	ND	Yes	ND	Yes	7/11
Softer and more resilient running shoe cushioning properties enhance running economy	Yes	Yes	Yes	Yes	Yes	Yes	ND	ND	Yes	ND	Yes	8/11
Metabolic cost of running is greater on a treadmill with a stiffer running platform	Yes	Yes	Yes	Yes	Yes	Yes	ND	ND	No	ND	Yes	7/11
Forefoot bending stiffness, running economy and kinematics during overground running	Yes	Yes	Yes	Yes	Yes	Yes	ND	ND	Yes	ND	Yes	8/11
Does an increase in energy return and/or longitudinal bending stiffness shoe features reduce the energetic cost of running?	Yes	Yes	Yes	Yes	Yes	Yes	ND	ND	Yes	ND	No	7/11
The bending stiffness of shoes is beneficial to running energetics if it does not disturb the natural MTP joint flexion	Yes	Yes	Yes	No	Yes	Yes	ND	ND	Yes	ND	Yes	7/11
Does enhanced footwear comfort affect oxygen consumption and running biomechanics?	Yes	Yes	Yes	Yes	Yes	Yes	ND	ND	No	ND	Yes	7/11
Improved footwear comfort reduces oxygen consumption during running	Yes	Yes	Yes	Yes	Yes	Yes	ND	ND	No	ND	Yes	7/11

Table 7. Methodological Quality (observational studies). ND. Not Detailed.

Study	CASPe1	CASPe2	CASPe3	CASPe4	CASPe5	CASPe6	CASPe7	CASPe8	CASPe9	CASPe10	CASPe11	Score
Barefoot-Shod Running Differences: Shoe or Mass Effect?	Yes	Yes	Yes	No	Yes	Yes	ND	ND	ND	Yes	Yes	7/11
Biomechanical and physiological comparsion of barefoot and two shod conditions in experienced barefoot runners	Yes	Yes	No	No	Yes	Yes	ND	ND	ND	Yes	Yes	6/11
Shoe midsole longitudinal bending stiffness and running economy, joint energy, and EMG	Yes	Yes	No	No	Yes	Yes	ND	ND	ND	Yes	Yes	6/11

3.4. Impact Factor Assessment

The articles included in this work were published in journals with impact factors between 1.432 and 4.029 according to the JCR tool. Since it is also important to pay attention to the position of the journal in the rank of its category, information on the quartile was included, obtaining that eight of the articles were in Q1 journals, four were in Q2 journals and two were in Q3 journals. All these data are compiled in Table 8.

Table 8. Impact Factor. JIF. Journal Impact Factor.

Study	Year and Author	Journal	JIF 2019	RANK	Quartile	Participant Variable
Influence of shoe mass on performance and RE in trained runners	2020. Rodrigo-Carranza, V	Frontiers in Physiology	3367	20/81	Q1	Shoe Mass
Barefoot running reduces the submaximal oxygen cost in female distance runners	2016. Berrones, A	Journal of strength and codition research	2973	28/81	Q2	Shoe Mass
Four-week habituation to simulated barefoot running improves RE when compared with shod running	2014. Warne, J.P	Scandinavian Jorunal of medicine and science in sport	3255	11/81	Q1	Shoe Mass
Mechanical and physiological examination of barefoot and shod conditions in female runners	2014. Paulsons, S	International Journal of Sports Medicine	2556	24/81	Q2	Shoe Mass
Metabolic cost of running barefoot vs shod: is lighter better?	2012. Franz, J.R	Medicine and Science in Sports and Excercise	4029	4/84	Q1	Shoe Mass
Oxygen cost of running barefoot vs running shod	2011. Hanson, N.J	International Journal of Sports Medicine	2556	14/85	Q1	Shoe Mass
Biomechanical and physiological comparsion of barefoot and two shod conditions in experienced barefoot runners	2009. Squadrone, R	Journal of Sports Medicine and Physical Fitness	1432	51/73	Q3	Shoe Mass
Barefoot-shod running diferences shoe or mass effect?	2008. Divert, C	International Journal of Sports Medicine	2556	27/71	Q2	Shoe Mass
Metabolic cost of running is greater on a treadmile with a stiffter running platform	2017. Smith, J	Journal of Sports Sciences	2597	19/81	Q1	Cushioning System
A test of the metabolic cost of cushioning hypothesis during unshod and shod running	2014. Tung, K	Medicine and Science in Sports and Excercise	4029	6/81	Q1	Cushioning System
Softer and more resilent running shoe cushioning properties enhance RE	2014. Worobets, J	Footwear Science	Not indexed in JCR	—	—	Cushioning System
Running shoe cushioning properties con influence oxygen consumption	2013. Worobets, J	Footwear Science	Not indexed in JCR	—	—	Cushioning System
Lower oxygen demands of running in soft soled shoes	1986. Frederick, E.C	Research Quarterly for excercise and sport	1883	—	—	Cushioning System
Does an increase in energy return and/or longitudinal bending stiffness shoes feature reduce the energetics of running	2019. Flores, N	European Journal of Applied Physiology	3044	18/85	Q1	Stiffness
The bending stiffness of shoes is beneficial to running energetics if it does not disturb the natural MTP joint flexión	2017. Oh, K	Journal of Biomechanics	2,32	39/72	Q3	Stiffness

Table 8. *Cont.*

Study	Year and Author	Journal	JIF 2019	RANK	Quartile	Participant Variable
Forefoot bending stiffness RE and kinematics during overground running	2016. Madden, R	Footwear Science	Not indexed in JCR	—	—	Stiffness
Shoe midsole longitudinal stiffness and running economy, joint energy and EMG	2006. Roy, J.P	Medicine and Science in Sports and Excercise	4029	5/73	Q1	Stiffness
Does enhanced footwear confort affect oxygen consumption and running biomechanics?	2020. Lindorfer, J	European Jornal of Sport Science	2781	24/85	Q2	Comfort
Improved footwear confort reduces oxygen consumption during running	2009. Luo, G	Footwear Science	Not indexed in JCR	—	—	Comfort

3.5. Risk of Bias Assessment

The risk of bias in the articles was evaluated using the Cochrane Manual summarized in Figure 2. As the figure shows, the risk of bias in the included articles was low, revealing a common characteristic in all studies showing that the risk of bias was unclear in the domains of performance bias and detection bias.

Study	D1	D2	D3	D4	D5	D6
Paulson, S 2014[46]	+	–	?	?	+	+
Rodrigo-Carranza, V 2020[47]	+	+	?	?	+	+
Squadrone, R 2009[29]	+	–	?	?	+	+
Berrones, Adam J 2016[48]	+	–	?	?	+	+
Franz, Jason R 2012[32]	+	+	?	?	+	+
Hanson, NJ 2011[30]	+	–	?	?	+	+
Warne, J. P 2014[31]	+	–	?	?	+	+
Divert, C 2008[33]	+	+	?	?	+	+
Worobets, J 2013[49]	+	+	?	?	+	+
Frederick,E. C 1986[50]	–	+	?	?	+	+
Worobets, J 2014[51]	+	+	?	?	+	+
Smith, J. A. H 2017[52]	+	+	?	?	+	+
Tung, K 2014[17]	+	–	?	?	+	+
Madden, R 2013[53]	+	+	?	?	+	+
Flores, N 2016[54]	+	+	?	?	+	–
Roy, J. P. R 2006[55]	+	–	?	?	+	+
Oh, K 2017[34]	+	–	?	?	+	–
Lindorfer, J 2020[56]	+	+	+	?	+	+
Luo, G 2009[35]	+	+	+	?	+	–

Figure 2. Risk of Bias of analyzed papers [17,29–35,46–56]. D1, Random sequence generation (selection bias); D2, Allocation concealment (selection bias); D3, Blinding of participants and personnel (performance bias); D4, Blinding of outcome assessment (detection bias); D5, Incomplete outcome data (attrition bias); D6, Selective reporting (reporting bias). (−) high risk; (+) low risk; (?) unclear risk.

4. Discussion

This review summarizes the articles that study the influence of different tools of footwear on the economy of running and oxygen consumption. Overall, it has been observed that shoe mass [29,33], the material of the midsole [49,50] and the longitudinal bending stiffness of the shoe [27,43] decreased oxygen consumption during the race. While comfort feeling was a less researched characteristic. Only two articles have been found discussing the latter [35,56], which obtained opposite results.

4.1. Shoe Mass

The weight of the shoe was one of the most studied features by the scientific community, as the large number of articles found regarding this characteristic shows. In order to study this feature, two types of studies may be differentiated. One type of study compared barefoot running and/or minimalist footwear with running with standard footwear [29–31,46,48]. A second type compared barefoot running with standard footwear and also added weights in barefoot running and footwear to observe the difference that existed in this type of running when the mass was modified [32,33,47].

In the studies that compared barefoot running and/or minimalist footwear with running in standard footwear, there was a consensus that lower weight led to lower oxygen consumption. Hanson et al. compared barefoot running with 350 g footwear and found that there was a 3.8% greater chance of injury with the shoes (p = 0.034) [30]. Conversely, Squadrone et al. found differences in favor of minimalist footwear of 148 g when compared with standard footwear of 341 g ($p < 0.05$) [29]. Likewise, Paulson et al. found differences (p = 0.04) between barefoot running and standard shoes [46]. At the same time, although they found a difference between barefoot running and minimalist footwear, the difference was not significant (p = 0.15). Berrones et al. compared barefoot running with a 590 g shoe at different speeds and they found differences (p = 0.018) only when the subjects ran at 85% VO_{2max} [48]. Warne et al. were also able to find differences in favor of minimalist footwear after 4 weeks of familiarization with this footwear (p = 0.016) [31].

Considering the studies that compared barefoot running with standard footwear and added weight to both conditions, the increase in mass influenced oxygen consumption [32,33,47]. At this time, it is worth highlighting the study by Franz et al. who used a material in the midsole that was different from the one used in footwear in the rest of the studies [32]. Franz et al. also found differences according to the weight gain of the shoe. Nevertheless, when the shoe weight was less than 220 g and was provided with a material in the midsole to provide the necessary cushioning, there were no differences between this condition and barefoot running.

4.2. Cushioning System

Continuing with the hypothesis confirmed by Franz et al. [32], some studies suggested that appropriate characteristics of the midsole could represent an economic advantage compared to other shoes that were not provided with these materials. In this way, studies with two different approaches were found. One type of study compared shoes identical in appearance but differing in the material of the midsole [49–51]; the second did not use a shoe in order to avoid the influence of weight and modification of the rigidity of the treadmill [17,52].

Studies comparing different materials in the midsole observed that there was a difference in favor of the use of PU as a cushioning system. Frederick et al. observed an improvement of 2.4% in favor of the PU sole ($p < 0.05$) [50]. In 2013, Worobets et al. compared running in both footwear conditions [49], finding a benefit in favor of the shoe with a PU sole (p = 0.01). Later, Worobets et al. selected two groups of 12 subjects [51]. One group performed their running tests on a treadmill and the other on a running track. In this case, Worobets et al. found differences in both cases, p = 0.044 and p = 0.028, respectively. The study carried out by Tung et al. also confirmed the hypothesis of the cushioning system [17]. In his study, four running conditions were compared on the same treadmill: light and cushioned shoe, barefoot running but with the treadmill covered with 10 mm thick foam strips of the same material used in the sole of the treadmill and running barefoot with foam strips of the same material but in this case, the thickness was 20 mm. The results showed a benefit of 1.47% ($p = 0.015$) in favor of running barefoot with the 10 mm strips compared to the treadmill without cushioning. In the case of the 20 mm strips, they did not find difference compared to the treadmill without cushioning.

In the most recent study that was included regarding the cushioning system, two treadmills that presented different stiffness were compared [52]. In this study, eight men and four women performed four tests on each treadmill while their oxygen consumption was analyzed. It was concluded that running on the stiffer treadmill at the same speed as on the softer treadmill caused an increase in oxygen consumption ($p < 0.05$). It can be assumed that running on a surface with some cushioning may present positive effects on oxygen consumption. Regarding the midsole material, PU was the most suitable for the sole of the shoe.

4.3. Longitudinal Bending Stiffness

The insertion of elements that increased the longitudinal bending stiffness making the midsole more rigid to flex was the latest tool added to modern running footwear that could have an influence on running economy [36]. This increased bending stiffness of the shoe can be carried out through a stiffer material in the midsole or by inserting a carbon plate.

In the study by Flores et al., the first method—providing greater rigidity to the midsole—was used [54]. In this study, tests on a running track with footwear were carried out by combining the following materials: material that returned a lot or little energy with another material that provided bending stiffness or not, creating four footwear conditions. After testing the different shoe conditions on 19 subjects, no significant differences were found for any combination of materials.

In a study published in 2017, a control shoe was compared with four shoes with carbon plates of different stiffness [34]. In order to provide a different stiffness to each sole, they took as a reference in this study what they called "critical stiffness" and defined it as the joint moment index of the first metatarsophalangeal joint to reach the maximum flexion of this joint. Thus, there were five levels of stiffness in the midsole: control shoe; a carbon plate with rigidity similar to critical stiffness; a plate stiffness between the control shoe value and critical stiffness; a carbon plate with a stiffness that was twice the critical stiffness; and shoes where the stiffness of the plate was between the values of the critical stiffness and the maximum stiffness. After carrying out a running test in each shoe condition, they obtained a favorable result in favor of the shoes that contained the carbon plate with a rigidity similar to the critical stiffness ($p < 0.05$). This comparative study assessed a control shoe with two shoes that included a carbon plate [55]. The shoe conditions presented in this study were: control shoe, stiff shoe and very stiff shoe. After performing the corresponding tests with each shoe, results were shown in a graph featuring a U-shaped curve where there was a lower oxygen consumption in 11 of the 13 subjects in the rigid shoe compared to the control shoe ($p = 0.014$). Madden et al. compared a control shoe with a bending stiffness of 8.1 N/mm with a shoe with a carbon plate in its midsole that provided a stiffness of 23.1 N/mm [53]. After testing the 18 participants on a 200 m athletic track, the authors did not obtain any difference between the two shoe conditions although 13 of the 18 subjects showed lower oxygen consumption on the rigid shoe. Thanks to the separation of the participants into two groups based on whether there was an improvement or not, the limit to consider a better running economy was established in a decrease in oxygen consumption of at least 0.5% for rigid shoes compared to control shoes. When the differences were studied by separating the groups, they found benefits in the group of 13 subjects who responded to the carbon plate.

There seems to be a consensus on the insertion of the carbon plate in the midsole of the shoe; however, it is important to note that no one stiffness was ideal and, instead, the value seemed to depend on each subject.

4.4. Comfort Feeling

The last feature to check was the influence on oxygen consumption of how comfortable the shoe felt. On this subject, two articles with opposite results were found. In a study carried out on 13 subjects [35], comfort was evaluated both in dynamics and in statics of five different shoe conditions. Of these five shoes, only those rated as the most comfortable and the least comfortable were selected for the race tests. After doing these tests and eliminating 3 subjects for different reasons, they found that, of the 10 remaining participants, 8 showed a decrease ($p = 0.036$) in oxygen consumption with the shoe rated as the most comfortable. However, a recently published study by Lindorfer et al. found the opposite result [56]. In this study, the participants also rated five different shoes. After making the evaluations, the race tests were carried out on the most and least preferred shoes. There were no differences in oxygen consumption found between these shoes ($p = 0.200$).

This is a lack of research regarding this feature, and it could be an interesting line of future research. Nevertheless, with only two articles related to this characteristic, a clear conclusion cannot be stated.

4.5. Future Research

In the development of this review and with the reading of the scientific bibliography that has been carried out during this period, we want to propose different lines in which possible studies related to the improvement of performance thanks to footwear could be focused. First, a more exhaustive study of the influence of the comfort feeling on oxygen consumption during the race is considered necessary since a small number of articles have been found to be able to obtain a conclusive result regarding this variable. During the development of this work and with the bibliographic search that has been carried out, it can be affirmed that there were no studies that assessed the influence of the geometry of the sole (rocker sole or toe-off) on oxygen consumption during the race; thus, this can be a future line to develop research studies.

4.6. Limitations

Given that the PRISMA criteria have been followed and some could not be met, they are presented below as limitations of this review: (1) the work has not been published in PROSPERO; (2) a synthesis of results has not been carried out and therefore the measures of consistency (i.e., I^2) has not been obtained; (3) due to the lack of appropriate and specific MeSH terms for the search, keywords were used; (4) no articles have been found that addressed the ICC in the measurement of the metabolic cost variable; (5) although Footwear Science journal was not specifically indexed in JCR, four articles published have been used since they were of great interest for the explanation; (6) four studies have been included that have not been published in the last 10 years; (7) It has not been possible to add years of barefoot running experience due to it not being stated in the searched papers.

5. Conclusions

After reading and analyzing the included studies, the recently developed new type of footwear produced improvements in running economy and oxygen consumption. Footwear features such as the shoe mass, cushioning system and increased longitudinal bending stiffness provided improvements in running economy. In relation to the comfort feeling, further investigations should be performed to reach firm conclusions.

Author Contributions: Conceptualization, M.Á.M.-L., M.S.-A., D.V.-C., J.L.C., R.B.-d.-B.-V., M.E.L.-I., D.R.-S. and C.C.-L.; methodology, M.Á.M.-L., M.S.-A., D.V.-C., J.L.C., R.B.-d.-B.-V., M.E.L.-I., D.R.-S. and C.C.-L.; resources, M.Á.M.-L. and C.C.-L.; data curation, M.Á.M.-L. and C.C.-L.; writing—original draft preparation, M.Á.M.-L. and C.C.-L.; writing—review and editing, M.Á.M.-L., M.S.-A., D.V.-C., J.L.C., R.B.-d.-B.-V., M.E.L.-I., D.R.-S. and C.C.-L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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