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REVIEW

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Increased footwear comfort is associated with improved running economy – a systematic review and meta-analysis

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ABSTRACT

Footwear with or without custom foot orthotics have the potential to improve comfort, but the link with running performance needs further investigation. We systematically reviewed the association of footwear comfort on running economy in recreational runners. Nine electronic databases were searched from inception to March 2020. Eligible studies investigated both direct outcome measures of running performance (e.g. running speed) and/or physiological measures (e.g. running economy (RE)) alongside comfort for each footwear condition tested. Methodological quality was assessed using the "Effective Public Health Practice Project" (EPHPP). RE during submaximal running was the most common physiological outcome reported in 4 of the 6 eligible studies. The absolute difference in RE between the most and least comfortable footwear condition was computed, and meta-analysis was conducted using a random effect model. The most comfortable footwear is associated with a reduction in oxygen consumption (MD: -2.06 mL.kg^{-1}.min^{-1}, 95%CI: -3.71, -0.42, $P = 0.01$) while running at a set submaximal speed. There was no significant heterogeneity ($I^2 = 0\%$, $P = 0.82$). EPHPP quality assessment demonstrated weak quality of the studies, due to reporting bias and failing to disclose the psychometric properties of the outcome measures. It can be concluded with moderate certainty that improved RE in recreational athletes is associated with wearing more comfortable footwear compared to less comfortable footwear.

KEYWORDS
Footwear comfort; running economy; recreational athletes

Highlights

- This systematic review reports on the association of footwear comfort with running economy in recreational runners.
- Running economy during constant submaximal running is likely improved in recreational runners wearing more comfortable compared to less comfortable footwear.
- This finding is based on a meta-analysis, including four studies, showing a small but statistically significant decreased oxygen consumption at steady state speeds while wearing the most comfortable footwear.

Introduction

Optimizing running performance is crucial for competitive runners of all levels. Running performance can be improved by maximizing key physiological determinants such as running economy (RE), maximal oxygen uptake and lactate threshold (Moore, Jones, & Dixon, 2014). Theoretically, runners with better RE exercise with the same physiological strain at a faster speed over a set distance, or with less physiological exertion for a longer time at a set speed. Various intrinsic biomechanical parameters such as stride length, leg stiffness and leg extension at toe-off have been shown to improve RE when optimized (Moore, 2016).

The use of running footwear to reduce injuries and improve performance has become a focus in both sport industries and academia (Sun, Lam, Zhang, Wang, & Fu, 2020). Running footwear can be partially tailored for the athlete by replacing the insole with a custom foot orthosis. Footwear with or without custom foot orthotics have the potential to minimize soft tissue vibration, reduce muscle activity, minimize fatigue, and increase perceived comfort (Nigg, 2001; Wakeling, Von Tscharner, Nigg, & Stergiou, 2001). On the other hand, compared to barefoot running, footwear with or without orthotics are considered detrimental for RE due to their extra weight. However, based on a strong

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linear correlation ($R = 0.85$, $P < 0.01$) between shoe mass and oxygen consumption (VO_2) relative to barefoot running, Fuller, Bellenger, Thewlis, Tsiros, and Buckley (2015) suggested that footwear not exceeding 440 g per pair does not negatively affect RE. Further, technological advances in light weight footwear, incorporating special engineered resilient foams and stiff carbon plates, improved RE by ~4% in competitive male runners when compared to more traditional sport shoes (Hoogkamer et al., 2018; Hoogkamer, Kipp, & Kram, 2019). The limited evidence base provided by Crago, Bishop, and Arnold (2019) investigating the effect of foot orthotics on RE shows small improvements in RE for elite athletes when designed to manipulate longitudinal bending stiffness. The effectiveness of these orthotics features needs to be further investigated and tested in recreational athletes.

Footwear comfort perception encompasses the overall footwear experience, which is highly influenced by individual preference (Mundermann, Nigg, Humble, & Stefanyshyn, 2003). Several objective and subjective footwear characteristics such as fit (Hurst, Branthwaite, Greenhalgh, & Chockalingam, 2017; Witana, Goonetilleke, Au, Xiong, & Lu, 2009), cushioning (Dinato et al., 2015; Zhang et al., 2019), weight and even appearance (Williams & Nester, 2006) alongside perception of ride (Agresta et al., 2020), pain (Stevens, Mauger, Hassmèn, & Taylor, 2018), fatigue and running speed (Hintzy, Cavagna, & Horvais, 2015) can influence individual overall comfort perception. Partially tailoring footwear with custom foot orthoses could potentially improve comfort perception (Mills, Blanch, & Vicenzino, 2011). Albeit custom foot orthoses usually are introduced as a component of a treatment plan after a sustained injury (Hirschmuller et al., 2011), many athletes prefer to keep using them after gradually returning back to sport, during which time they are performing at or above their preinjury level (Ardern et al., 2016). From a biomechanical point of view, increased comfort of footwear including foot orthotics can improve performance because of improved fit, reduced muscle activity and lowered fatigue (Nigg, Nurse, & Stefanyshyn, 1999). Further, the "footwear comfort filter" paradigm, where running footwear selection is based on the athletes' own comfort filter, has been associated with a reduction of lower limb injuries (Nigg, Baltich, Hoerzer, & Enders, 2015) A few studies have explored the association between footwear comfort and RE (Lindorfer, Kroll, & Schwameder, 2020; Luo, Worobets, Nigg, & Stefanyshyn, 2009; Sinclair, McGrath, Brook, Taylor, & Dillon, 2016; Sinclair, Shore, & Dillon, 2016) but there is currently a lack of synthesis of the current evidence with regard to this link.

Systematically reviewing the link between footwear comfort and RE will allow practitioners to provide better evidence-based footwear advice and scope for the use of custom foot orthotics when returning to sport. For the purpose of this review, "footwear" relates to all footwear features in general with or without any type of insole. Therefore, the aim of this systematic review was to determine if there was an association of footwear comfort with performance and/or running economy in recreational runners.

Methods

This review complied with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses. The PRISMA Statement (Moher, Liberati, Tetzlaff, Altman, & Group, 2009) was submitted to the International prospective register (PROSPERO) (see supplementary file 1) but was rejected as the outcome measures (Footwear comfort and performance) were not of direct patient or clinical relevance.

Inclusion criteria

Studies were included if the population was described as adult (18+) healthy athletes of any level (including athletes returning to sport after injury). Studies needed to report on different footwear conditions (any type of sport shoe, with or without (custom) foot orthoses that might change cushioning, position or contouring of the foot) or shoes versus barefoot with clear intent to measure the change in running performance or physiological factors linked to running performance and perceived running comfort. To be included in the review, studies required to report both direct outcome measures of running performance (e.g. race time) and/or physiological measures (e.g. RE) and comfort recorded for each footwear condition. Any type of observational or experimental studies, published as a full article in a peer-reviewed journal was eligible for inclusion.

Search method

A comprehensive search strategy was undertaken to identify all possible studies for inclusion. The following electronic databases were interrogated: Cochrane Library, Web of Science Core Collection (1900 – today), Scopus, EBSCOhost (including CINAHL, Medline and SPORTDiscus), LILACS and PEDro. Searches were also applied to grey literature through ProQuest dissertations and theses Open and Proquest Central. All searches were completed by KVA in March 2020. Search terms included MeSH and keywords for the (a) population (e.g. Athlete*, Sportsm*, Sportswom*, Runner*, Competitor*, Racer*, Recreational, Elite), (b) Footwear (e.g. trainers, Sport shoes, spikes, Barefoot, Foot Orthoses, Foot Orthosis, Foot Ortho*, Insole*), (c) performance (e.g. Running Performance, Race Running, Marathon, Running Distance, Running Economy, Running Energy cost, VO_2, Physiological Cost Index, Total Heartbeat Index) and (d) comfort (e.g. Comfort*, Discomfort*, Pain*, Relief, Alleviation, Well-being, fit, perceived exertion) (See supplementary file 2 for the complete search syntax specific for each database). The reference lists of the included studies were manually searched for potential studies not identified. Prior to manuscript submission (April 2021), database searches were checked again for any new eligible publications, and no new studies could be retrieved.

Screening

All identified references were imported to the Rayyan app (https://rayyan.qcri.org/) and duplicates were automatically removed. Articles were screened for eligibility based on the title and abstract by three independent reviewers (KVA, MvdL and DS). KVA screened the complete list while MvdL and DS each screened 50%. Full-text articles were retrieved for all remaining records and further screened to identify the final set of articles for inclusion. All discrepancies in assessment for eligibility at any stage (title, abstract or full-text screening) were resolved by consensus. In case a consensus between two reviewers could not be reached, MvdL or DS acted as independent third reviewers.

Data extraction and study quality

A data extraction table was developed, tested and refined by two researchers (KVA and MvdL). Five main categories were identified relating to participants (sex, age and athletic level), footwear (selection, aim of selection, wear-in time, mass compensation, randomization), running task characteristics, results (comfort and running-related outcome measures and association between the two) and study limitations.

Several study quality assessment tools were trialled (Downs and Black, CASP and SIGN), and a consensus was reached on the use of the Effective Public Health Practice Project tool (EPHPP) (Effective Public Health Practice Project, 2009). This tool presents a fair interrater reliability for the individual domains and excellent agreement for the final grade. It is also recommended by the Cochrane Public Health Review Group and is applicable to a range of study designs (Armijo-Olivo, Stiles, Hagen, Biondo, & Cummings, 2012; Jackson & Waters, 2005; Thomas, Ciliska, Dobbins, & Micucci, 2004). The tool covers six components (14 questions) to assess selection bias, study design, confounding factors, blinding, data collection methods and withdrawals or drop-outs. Each component receives a rating between 1 (strong) and 3 (weak) which results in a global rating of strong (in case of no weak ratings), moderate (in case of one weak rating) or weak (in case of two or more weak ratings). Evaluation criteria were agreed in advance for the confounders section of the EPHPP. If only one group was tested multiple times, the answer would be "no" for question 1 ("Were there important differences between groups prior to the intervention?") and "80-100% (most)" for question 2 ("Indicate the percentage of relevant confounders that were controlled") resulting in a "strong" rating for the confounders section. For the data collection methods section of the EPHPP, the study needed to state explicitly that the data collection tools were reliable and valid with references supporting this. If not, option 3: "cannot tell" for both questions 1 ("Were the data collection tools shown to be valid") and 2 ("Were the data collection tools shown to be reliable") was selected, resulting in a "weak" rating. The study quality was assessed independently by three reviewers. KVA screened all final studies where MvdL and DS each screened 50%. Deliberation occurred until consensus was reached for all components.

Meta-analysis and GRADE assessment

Revman 5.4.1 Meta-analysis software (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) was used for meta-analysis. A random effects model with inverse variance weighting was applied to estimate the pooled effect for RE. This was identified as a common outcome measure in five of six studies when running at a fixed speed, using the same unit ($mL.kg^{-1}.min^{-1}$). However, four studies reported these data for each footwear condition. To investigate changes in RE when wearing the most comfortable footwear compared to the least comfortable footwear condition, the absolute difference between the mean scores (MD) with their 95% confidence interval (95% CI) in both footwear conditions was presented for each study. The MD approach gives studies with small SDs relatively higher weight compared to studies with larger SDs (Deeks, Higgins, & Altman, 2020). To measure heterogeneity, I-squared (I^2) was calculated. I^2 can be understood as the overlap of confidence intervals explaining the total variance attributed to the covariates (Deeks et al., 2020). I^2 Interpretation can be as follows: 0% to 40%, heterogeneity might not be important; 30% to 60%, moderate heterogeneity; 50% to 90%, substantial heterogeneity; 75% to 100%, considerable heterogeneity (Higgins et al., 2020). The GRADEpro app (https://gradepro.org/) from the Grading of Recommendations, Assessment, Development and Evaluation (GRADE) working group was used to assess the quality of evidence and the strength of recommendations based on the outcome described by the meta-analysis. GRADE has four levels of evidence or certainty in evidence ranging from: very low (little confidence in the effect estimate) over low (limited confidence in the effect estimate) to moderate (moderately confident in effect estimate) and high (very confident in the effect estimate) (Balshem et al., 2011).

Results

Description of studies

The initial search strategy identified 8512 potential references after duplicate exclusion ($n = 883$). Following title and abstract screening, 16 references remained for a full-text review. Six articles were included in the final review (see Figure 1).

Table 1 outlines the study characteristics of the six remaining articles. All articles were published between 2012 and 2020 with a total sample size of 71 with individual sample sizes ranging from 6 to 15. Sex was reported in five out of six articles including 95% of male ($n = 53$) and 5% of female ($n = 3$) participants. Average age of the participants was 26 ± 3.7 years and all were classified as "recreational" or "proficient" runners. Three studies described their training status of their population using their weekly running distance which ranged from 15 km/week to 35 km/week (Lindorfer et al., 2020; Sinclair, McGrath, et al., 2016; Souza et al., 2018). Two studies stated running at ~16–19 km.h^{-1} (pace of 5-6 min per mile) and ~14 km.h^{-1} (7 min per mile) for men and ~12 km.h^{-1} (8 min per mile) for female runners (Burke & Papuga, 2012; Souza et al., 2018). Two studies did not report any training history to describe their population (Luo et al., 2009; Sinclair, Shore, et al., 2016). In one study the authors have declared receiving funding from an orthotics manufacturer (Burke & Papuga, 2012) and out of the 6 studies 1/3 is from the same research group (Sinclair, McGrath, et al., 2016; Sinclair, Shore, et al., 2016).

Submaximal treadmill running was the common exercise task in all six articles. A range of speeds were used in the testing protocol by Burke and Papuga (2012). Other included studies used one submaximal speed based on individual lactate concentration (Lindorfer et al., 2020; Luo et al., 2009) or arbitrarily set (e.g. 12 km.h^{-1}) for all participants (Sinclair, McGrath, et al., 2016; Sinclair, Shore, et al., 2016; Souza et al., 2018). Souza et al. (2018) reported a submaximal treadmill trial at 8 km.h^{-1} for 6 min, but did not collect breath by breath gas analysis data required to calculate RE. Two studies validated the treadmill speed prior to data collection, which is necessary for reliable RE calculation (Sinclair, McGrath, et al., 2016; Sinclair, Shore, et al., 2016). Out of the five studies comparing RE in the different footwear conditions, four studies controlled for the difference in footwear mass by adding lead beads on the heel counter (Lindorfer et al., 2020; Luo et al., 2009) or by equally distributing them over the shoe of the lighter footwear conditions (Sinclair, McGrath, et al., 2016; Sinclair, Shore, et al., 2016). Four studies found a statistically significant mean reduction of RE when running with the most comfortable footwear condition compared to the least during steady state running (Burke & Papuga, 2012; Luo et al., 2009; Sinclair, McGrath, et al., 2016; Sinclair, Shore, et al., 2016). One found a low effect size ($d_z = 0.36$, $P = 0.20$) of comfort on RE (Lindorfer et al., 2020). Souza et al. (2018) found a significant reduction in pain and perceived exertion ($P = 0.036$ and $P = 0.027$, respectively) for a 15 min Balke test while running faster in cushioned shoes compared to barefoot while running on a synthetic track.

Comfort related to footwear was measured in a variety of ways. Outcome measures included the 9-item Footwear Comfort Assessment Tool (FCAT) (Mundermann et al., 2003), ranking of footwear from least to most comfortable, a six-point Likert scale, and Multidimensional Pain Evaluation Scale (EMADOR) (Souza et al., 2018) and a 150 mm VAS scale. Physical exertion was measured using the Borg scale (Borg, 1982) and the omnibus scale for perceived exertion (OMNI) (Utter et al., 2004).

Table 2 exhibits the study quality assessment for all included studies. The overall "weak" ($n = 5$) and "moderate" ($n = 1$) quality of the studies was primarily linked to "participant blinding" and "data collection" when using the EPHPP scale. There was also an underreporting of assessor blinding to the intervention to avoid detection bias. Furthermore, none of the studies reported whether or not participants were aware of the research question to avoid reporting bias. Four out of the six articles did not report the validity or reliability of their data collection methods, tools or outcome measures (Burke & Papuga, 2012; Lindorfer et al., 2020; Luo et al., 2009; Souza et al., 2018).

Meta-analysis

RE measures were reported in five out of six articles. However, the results of four studies could be included in the meta-analysis. Luo, Berglund, and An (1998) stated that higher footwear comfort was associated

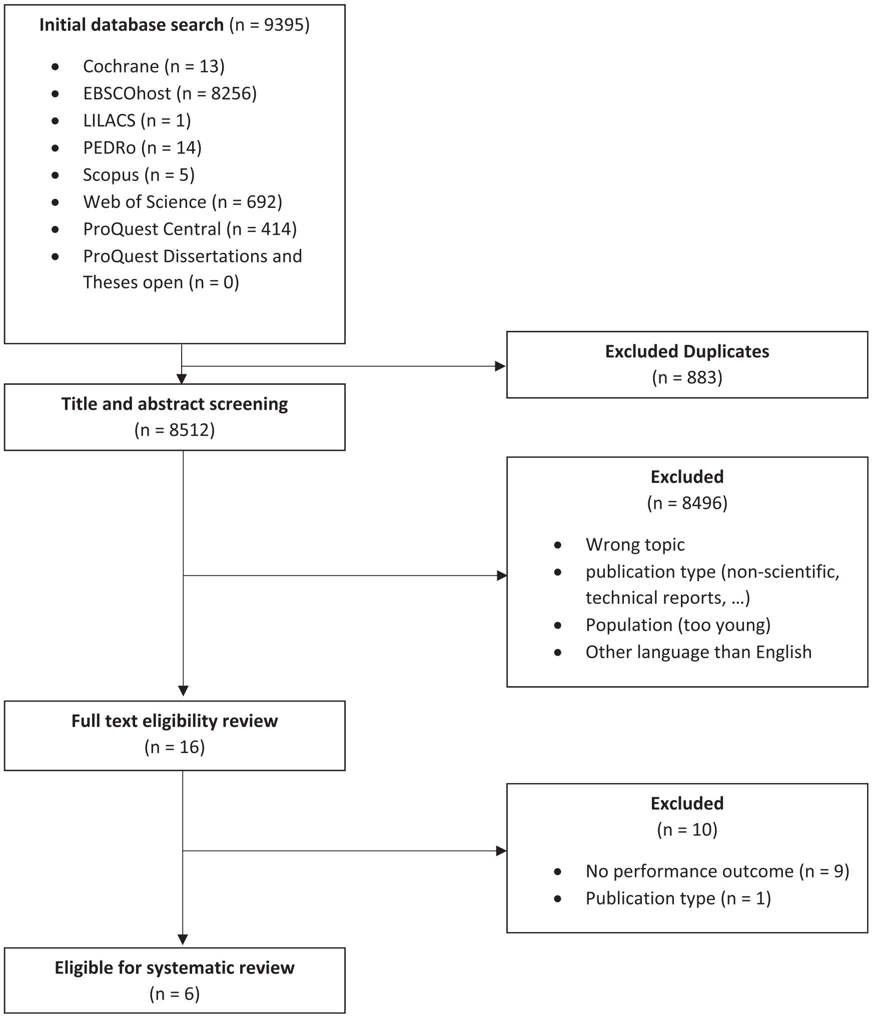

Figure 1. PRISMA flow diagram of included and excluded studies.

with a decreased VO_2 of up to 1.9% but failed to report the actual values for each condition. The differences in RE between the least and most comfortable footwear conditions are reported in Figure 2. The estimated association of footwear comfort on RE favoured higher footwear comfort with a reduction in VO_2 (MD: −2.06 mL.kg^{-1}.min^{-1}, 95%CI: −3.71, −0.42, $P = 0.01$) while running at a set submaximal speed. There was no significant heterogeneity (I^2 = 0%, P=0.82). Based on the GRADE assessment, the certainty of the evidence was established as "Moderate", meaning that the authors are moderately confident in the association: The true association is likely to be close to the estimate, but there is a possibility that it is substantially different (see supplementary file 3).

Discussion

Our systematic review reports on the association of footwear comfort on RE in recreational runners. The meta-analysis, including four studies, showed a small but statistically significant decreased VO_2 (MD: −2.06 mL.kg^{-1}.min^{-1}, 95% CI: −3.71, −0.42, $P = 0.01$) when running at steady state speed while wearing most comfortable footwear. Based on the current evidence available, a systematically modifiable, cause–effect relationship between footwear comfort and RE cannot be established. Therefore, it can be concluded with moderate certainty that wearing more comfortable compared to less comfortable footwear is associated with improved RE during constant submaximal running in recreational runners.

Although synthesizing the current best evidence, the result of this review should be interpreted relative to the small number of studies available, the small sample sizes and several limitations. Effect sizes reported in meta-analyses may be negatively correlated with study sample size. Systematic reviews including studies with relatively small sample sizes tend to have larger positive effect size (Slavin, 2009). To begin with, the overall

Table 1. Details of included studies.

h	*n* (M/F); age (y ± SD)	Athlete level; Performance history	Footwear condition Study aim	Wear-in time; Mass compensation	Random Footwear order; Randomization described	Task	Comfort measure	Running related outcome measure	Correlation comfort-running related response; main effect	Limitations
Burke and Papuga (2012)	6(3/3); 32.3 ± 10.07	Recreational Pace: ≤8min/mile (females) ≤7min/mile (males) for ≥30 min.	Own footwear + 1 = custom orthotics 2 = shoe fitted support Aim: to compare VO_2 and vVO_2 and comfort between the two conditions	NR; No	Yes; No	Submaximal treadmill running at 5 different speeds (10.7–13.8 km.h^{-1}) 5 x 5 min steady state runs No individual speeds Different speeds for men and women	9 item FCAT Results: all in favour of condition 1 - Overall (*P* = 0.027). - Heel cushioning (*P* = 0.002), - Forefoot cushioning (*P* = 0.036), - Heel cup fit (*P* = 0.011), - Heel width (*P* = 0.024), - Length (*P* = 0.038). Others comfort measures not significant	Submaximal VO_2 (ml.min^{-1}.kg^{-1}): 1 = 37.7 ± 3.3 2 = 40.7 ± 1.6 (*P* = 0.023) VO_{2max} (ml.min^{-1}.kg^{-1}): 1 = 53.3 ± 6.5 2 = 53.3 ± 6.1 (NS) (*P* = 0.962) vV02(mph): 1 = 10.94 ± 0.64 2 = 9.81 ± 0.98 (*P* = 0.008)	Submaximal VO_2 and - overall comfort ($r = 0.64$) - heel cushioning ($r = 0.64$) - heel cup fit ($r = 0.60$) - medial-lateral stability ($r = 0.31$) - arch height support ($r = 0.33$) Submaximal VO_2 and - overall fit (r ≥ 0.70) - heel width ($r = 0.89$) - forefoot width ($r = 0.86$) - length ($r = 0.71$) No effect measures calculated	- Small Sample size, - Condition 1 preferred condition - Partly funded by orthotic lab
Lindorfer et al. (2020)	15(15/0); 26 ± 4	Recreational Distance: ≥20km/wk	5 standardized footwear conditions with varying in mechanical properties reduced to 1 = most preferred shoe (MC) 2 = least preferred shoe (LC) Aim 1: to determine potential differences in VO_2 and biomechanical variables to explain changes in metabolic demand between the two conditions Aim 2: to determine potential differences in coordination variability associated with LE injuries in previous studies between the two conditions.	NR; Yes	Yes; Yes	Submaximal treadmill running at fixed speed (11.3 ± 1.7 km.h^{-1}) 4 x 6 min steady state runs Individual set speed	Ranking least-most comfortable to reduce 5 pairs to 2. In addition, a 100mm VAS scale used to rate comfort for each pair Absolute difference between MC and LC in rating on the VAS was 57±25 mm. Relative difference between the two conditions was 4±2 times the SMD.	Submaximal VO_2(ml.min^{-1}.kg^{-1}): 1 = 44.4 ± 8.9 2 = 44.2 ± 9.0 (*P* = 0.20)	No correlation was calculated Low effect of footwear comfort on VO_2 ($d_z = 0.36$; $P = 0.20$)	- All male group
Luo et al. (2009)	13 (13/0); 23.8 ± 3.4	Proficient Performance history: NR	5 standardized footwear conditions: A = a standard neutral running shoe B = neutral + carbon fiberplate inserted to increase the longitudinal bending stiffness. C = neutral + thin leather insole and an exaggerated arch support. D = flat cross-trainer	NR; Yes	Yes; Yes	Submaximal treadmill running (Speed NR) 4 x 6 min steady state runs Individual set speed	7 and 6 items 5 point Likert scale: 1 is "just right", 3 acceptable, 5 unacceptable <u>Static Comfort:</u> - shoe length, - toe box height, - forefoot width,	Submaximal VO_2 (ml.min^{-1}.kg^{-1}): LC – MC = 0.28 (*P* = 0.036) 8/10 participants ≤1.9% in VO_2 for MC AVG VO_2 = 0.28	No correlation was calculated A significant effect of footwear comfort on VO_2 (*P* = 0.036) with AVG 0.28 ml.min^{-1}.kg^{-1} reduction for MC vs LC	- Analysis done on 10 out of 13 participants - No description of participant running level - Speeds not mentioned - In methods mentioning of paired t test to compare AVG oxygen consumption between least and most comfortable shoe condition, but

			E = inexpensive shoe (no protective features) reduced to 1 = Most comfortable shoe (MC) 2 = Least comfortable shoe (LC) Aim: to determine if running footwear comfort can influence running economy				- midfoot height, - arch support, - ankle collar height, - heel hold Dynamic comfort: - forefoot cushioning, - Rearfoot cushioning - forefoot flexibility, - stability, - heel-to-toe transition, - shoe weight Dynamic comfort assessed during 5 min preferred speed running Result: Most comfortable: shoe A (*n* = 10) Least comfortable: shoe B (*n* = 3), C (*n* = 4), D (*n* = 2), E (*n* = 1)	ml.min^{-1}.kg^{-1} (−0.7%) for MC compared to LC		missing in the results - No *P* values for comfort measures
Souza et al. (2018)	15 (NR/NR); 28.1 ± 5.8	Recreational Frequency: ≥3x/wk, Distance: 15–20 km/wk Pace: 5–6 min/km	1 = Cushioned shoes 2 = Barefoot Aim: to evaluate the effect of various ground conditions and barefoot vs regular running shoes in race performance, in rating of perceived exertion and in pain perception.	No, No	Yes; No	1 = 15-minute Balke synthetic track test	A = OMNI scale (RPE) B = EMADOR (Pain) Balke test OMNIscale 1 = 6.40 ± 1.42 2 = 4.90 ± 1.52 (*P* = 0.036) EMADOR 1 = 0.50 ± 1.58 2 = 3.30 ± 3.33 (*P* = 0.027)	Balke test Speed (m/s): 1 = 2.58 ± 0.19 2 = 2.46 ± 0.36 (*P* = 0.345)	No correlation was calculated Effect of footwear during Balke test on RPE (*d* = 0.10; *P* = 0.036) Pain (*d* = 1.07; *P* = 0.027) Speed (*d* = 0.41; *P* = 0.345)	- No mentioning of sex participant group - No VO_2 data gathered during submaximal treadmill run
						2 = 3000 m beach run	Beach run OMNIscale 1 = 8.10 ± 1.05 2 = 7.60 ± 1.07 (*P* = 0.237) EMADOR 1 = 3.20 ± 3.19 2 = 1.30 ± 2.40 (*P* = 0.150)	Beach run Speed (m/s): 1 = 1.85 ± 0.17 2 = 1.96 ± 0.13 (*P* = 0.128)	Effect of footwear during Beach run on RPE (d = 0.04; *P* = 0.237) Pain (d = 0.08; *P* = 0.150) Speed (d = 0.72; *P* = 0.128)	
						3 = Submaximal treadmill running (8 km.h^{-1}) 2 x 6 min steady state runs No individual speeds	Treadmill run No OMNI or EMADOR Results	Treadmill Stride frequency (Hz): 1 = 165.00 ± 10.96 2 = 165.20 ± 9.62 (*P* = 0.966) Stride amplitude: 1 = 57.23 ± 6.72 2= 54.17 ± 6.17 (*P* = 0.303)	Effect of footwear during Treadmill on Stride frequency (*d* = 0.01; *P* = 0.966) Stride amplitude (*d* = 0.47; *P* = 0.303) Angle (d = 0.07; *P* = 0.119)	

								Angle (deg): 1 = 172.50 ± 6.73 2 = 168.10 ± 5.17 (P = 0.119)		
Sinclair, McGrath, et al. (2016)	12(12/0); 22.4 ± 2.2	Active Frequency: ≥3/wk Distance: ≥35km/wk	1 = Saucony PGGII (conventional) 2 = Adidas Energy Boost (energy return claim) Aim: to comparatively explore the effects of energy return footwear on the oxygen cost of steady-state running in relation to conventional running shoes	Yes; Yes	Yes; No	Submaximal treadmill running (12 km.h^{-1}) 2 x 6 min steady state runs No individual speeds	Borgscale (6-20 point) 150mm VAS Comfort extreme left side = "not comfortable at all" and extreme right = "most comfortable condition imaginable" RPE: 1 = 11.0 ± 1.9 VS 2 = 10.5 ± 1.3 VS (P > 0.008) VAS: 1 = 10.1 ± 2.9 VS 2 = 12.0 ± 1.9 VS (P = 0.006)	VO_2 (ml.min^{-1}.kg^{-1}): 1 = 43.6 ± 3.7 2 = 41.8 ± 3.2 [1] (P = 0.008) RER: 1 = 0.99 ± 0.06 2 = 0.98 ± 0.08 (P = 0.007) HR no significant differences	No correlation calculated, The majority had a lower VO_2 for the energy return shoe, the overall preference was 50/50% for either shoe Footwear main effect on comfort favouring condition 2 (n^2 = 0.49; P = 0.006) Footwear main effect on VO_2 favouring condition 2 (n^2 = 0.48; P = 0.008)	- Bonferroni <0.008 but 0.006 and 0.007 regarded as statistically significant.
Sinclair, Shore, et al. (2016)	10 (10/0); 23.4 ± 2.1	Recreational Performance history: NR	1 = minimalist shoe 2 = maximalist shoe 3 = energy return shoe Aim: to explore the effects of minimalist, maximalist and energy return footwear of equal mass on economy and substrate utilization during steady state running.	Yes; Yes	Yes; No	Submaximal treadmill running (13 km.h^{-1}) 3 x 6 min steady state runs No individual speeds	Borgscale (6–20 point) 150 mm VAS Comfort extreme left side = "not comfortable at all" and extreme right = "most comfortable condition imaginable" RPE: 1 = 11.6 ± 2.0 2 = 10.4 ± 1.2 3 = 10.3 ± 0.8 (P > 0.05) VAS: 1 = 7.0 ± 2.9 2 = 9.7 ± 1.8 3 = 10.0 ± 2.4 ($P \leq$ 0.05)	VO_2 (ml.min^{-1}.kg^{-1}): 1 = 37.8 ± 5.2 VS 2 = 37.8 ± 4.9 VS 3 = 35.9 ± 3.4 ($P \leq$ 0.05)	No correlation calculated, however, on average lowest VO_2 measure in energy return shoe Overall preference was 1 = 20% 2 = 30% 3 = 50% Footwear Comfort main effect favouring condition 3 (pn^2 = 0.30) ($P \leq$ 0.05)	- No information on level of recreational runners

Notes: NR = Not reported; FCAT = Footwear Comfort Assessment Tool; AVG = average; VAS = Visual Analogue Scale; OMNI = omnibus scale for perceived exertion; EMADOR = Multidimensional Pain Evaluation Scale; LC = least comfortable; MC = most comfortable; RPE = rating of perceived exertion; VO_2= steady-state oxygen consumption; RER= respiratory exchange ratio; HR = heart rate; P = significance level; n^2 = effect size eta^2; pn^2 = effect size using partial eta^2; d = effect size using Cohens d.

Table 2. Study quality assessment using the effective public health practice project (EPHPP).

Reference	Component rating						Global rating
	Selection bias	Study design	Confounders	Blinding	Data collection	Withdrawals/ drop-outs	Overall study quality
Burke and Papuga (2012)	Weak	Moderate	Strong	Weak	Weak	Strong	**Weak**
Lindorfer et al. (2020)	Moderate	Strong	Strong	Weak	Weak	Weak	**Weak**
Luo et al. (2009)	Moderate	Moderate	Strong	Weak	Weak	Moderate	**Weak**
Souza et al. (2018)	Moderate	Moderate	strong	Weak	Weak	Weak	**Weak**
Sinclair, McGrath, et al. (2016)	Moderate	Moderate	Strong	Weak	Moderate	Strong	**Moderate**
Sinclair, Shore, et al. (2016)	Moderate	Moderate	Strong	Weak	Moderate	Weak	**Weak**

quality of the included studies was "weak" except for one where this was "moderate". However, the weak rating can mainly be attributed to either underreporting or lack of blinding (who was blinded and how) and the lack of reporting psychometric properties of the outcome measures. In general, effective blinding is difficult and often underreported in studies involving physical interventions (Armijo-Olivo et al., 2017). As a solution, assessors and participants could be blinded by covering the footwear with overshoes or full gaiters to minimize detection bias, as long as they do not affect running comfort (Luo et al., 2009). If participants cannot be blinded to their footwear condition, performance or reporting bias can be minimized by blinding participants to the study hypotheses. All six studies, included for quality assessment, failed to mention the psychometric properties of the metabolic carts and comfort measures. However, all metabolic carts used for gas analysis and self-reported scales used to assess footwear comfort have shown to be reliable and/or valid (Guidetti et al., 2018; Hodges, Brodie, & Bromley, 2005; Meyer, Georg, Becker, & Kindermann, 2001; Mundermann, Nigg, Stefanyshyn, & Humble, 2002; Perkins, Pivarnik, & Green, 2004; Sousa, Pereira, Cardoso, & Hortense, 2010; Utter et al., 2004; Yusof et al., 2019). The overall study quality for all studies would be moderate to strong on the EPHPP scale if authors had described their blinding strategy and psychometric properties of their outcome measures.

Secondly, recreational runners recruited in selected studies were mostly young, recreational male runners (average: 26 ± 3.4 years; range: ∼22.4–32.3 years). Honert, Mohr, Lam, and Nigg (2020) have shown that, based on their proposed definitions of three categories of runners, improved footwear comfort is the most important criteria for novice and recreational runners when selecting footwear and slightly less important for high-caliber runners when selecting shoes. With regards to the applicability of these findings to a wider population, the increasing average age of the recreational running community would also need to be considered. Globally, the average age of runners increased from 35.2–39.3 years between 1986 and 2018, indicating a gap of about 10 years between the participants reported in the literature and the recreational athletes average age participating in running events. Furthermore, the female running community is growing steadily with 60% participation in 5-km runs in 2018 and rising from under 20% in 1986 to just above 50% in 2018 over all running events and distances worldwide (Andersen, 2020 https://runrepeat.com/state-of-running). Perceived comfort may differ between males and females so generalization of findings from studies with predominantly male participants (95% in this systematic review) may not be appropriate.

Thirdly, this review included a variety of outcomes used to assess self-reported comfort with no single outcome used in all six. Four out of six studies used a single item VAS scale to rate a complex construct such as footwear comfort either with or without ranking the footwear conditions from most to least comfortable (Lindorfer et al., 2020; Sinclair, McGrath, et al., 2016; Sinclair, Shore, et al., 2016; Souza et al., 2018). The need to identify and rate individual components of footwear such as the heel, arch and forefoot in different dimensions such as stability or cushioning is essential (Van Alsenoy, Ryu, & Girard, 2019). The nine-item comfort scale developed by Mundermann et al. (2002) is the

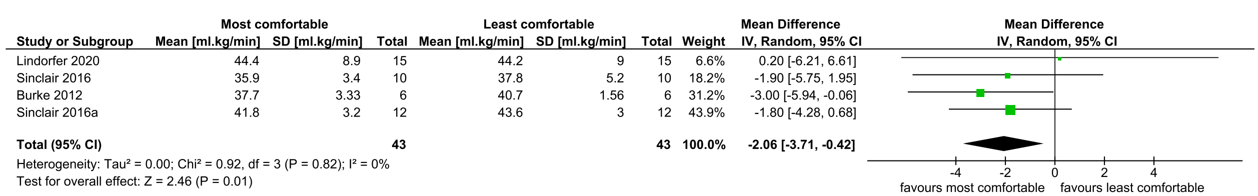

Figure 2. Forest plot representing the association of footwear comfort on running economy (most comfortable footwear vs least comfortable footwear) in order of weight.

only scale to date specifically assessing footwear including orthotics. More recently, a new five-item footwear comfort assessment tool was developed for the assessment of running footwear (RUN-CAT) (Bishop, Buckley, Esterman, & Arnold, 2020), but it does not state if this could include foot orthotics. Using composite scores, based on individual items would allow a more in-depth assessment to identify which specific aspects related to comfort might improve RE.

Fourthly, in all studies, recreational runners were asked to choose which footwear condition was more comfortable compared to others. Specifically, studies included two (Burke & Papuga, 2012; Sinclair, McGrath, et al., 2016; Souza et al., 2018), three (Sinclair, Shore, et al., 2016) and five (Lindorfer et al., 2020; Luo et al., 2009) footwear comparisons. In the aforementioned studies, runners chose the footwear condition that they perceived as being more comfortable between the different proposed options. Nonetheless, it is unknown if their preference was in fact the most comfortable shoe that would be available to them. When investigating the cause–effect of footwear comfort on RE, the magnitude of the effect might heavily depend on how extreme the most and least conditions are perceived. To date, it is unclear if the magnitude of difference in comfort rating influences the magnitude of difference in RE. Future studies should focus on investigating this individual comfort dose – RE response continuum. In doing so, using comfort scales ranging from the “least” to the “most” comfortable imaginable would increase the external validity of perceived comfort findings.

Finally, out of the six studies included in this review, the association of foot orthotics comfort on RE was specifically examined in one study by comparing custom foot orthotics and shoe fitted supports using the same shoes (Burke & Papuga, 2012). Specifically, while using their own preferred shoes including either a shoe fitted insole or a custom made orthotic in a randomized order, six participants ran at several submaximal speeds (10.7–13.8 $km.h^{-1}$). Meaningful reduction in cardiopulmonary responses of at least 3% (average range 5–12%) was observed, while wearing flexible custom-made orthotics. Luo et al. (1998) also incorporated a thin leather insole with an exaggerated arch support as one of five different footwear conditions used in their study. There is evidence that foot orthotics reduce foot and lower limb injuries of athletes (Kirby, 2017; Nigg et al., 1999) and improve overall footwear comfort (Mundermann, Stefanyshyn, & Nigg, 2001; Vicenzino, 2004). However, the link between comfort, measured for footwear including foot orthotics, and RE is still underreported and highlights a gap for potential future research. Measuring comfort has been shown to be reliable (Lindorfer, Kroll, & Schwameder, 2019) and is a key external modifiable factor affecting RE.

Some limitations related to the review process should be considered. Small deviations were made from the original PROSPERO registration document. Contrary to this document, systematic reviews were excluded to exclusively allow original data extraction for further meta-analysis. Also, while assessing the methodological quality using the Downs and Black assessment tool, several criteria in the checklist could not be answered, resulting in a heavily modified tool. Because this modified tool would no longer be considered valid and reliable, the EPHPP was used instead.

Several recommendations could be derived from observations made here to further our understanding and/or strengthen the design of future studies assessing the association of footwear comfort on RE. First, future research assessing footwear comfort in relation to RE should focus on the inclusion of foot orthotics. Second, participants should represent more female recreational athletes in their mid-to-late thirties and sample size should be determined based on a priori sample size calculations. Third, authors should be more vigilant in describing the blinding strategy and psychometric properties of outcome measures to improve methodological quality. Fourth, any footwear-related improvement in RE can be confounded by extra weight of the shoe and/or additional use of inserts. In order to avoid under/overestimation of the true effects of different footwear materials, the added weight of each condition must be carefully reported. Finally, because footwear comfort is a highly individual measure, reporting an association of footwear comfort on RE should be done on an individual basis rather than using group means.

Conclusion

In conclusion, our meta-analysis showed a small but statistically significant decreased VO_2 measured during running at the same speed, when wearing the most compared to the least comfortable footwear. With moderate confidence we can state that footwear comfort is an external modifiable factor that can be associated with RE. Nonetheless, this conclusion is based on a limited evidence base available of generally low methodological quality studies. More attention should be given to footwear conditions including custom foot orthotics given the widespread use of these devices throughout the return to sport continuum after injury.

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