Sports Med (2015) 45:411–422
DOI 10.1007/s40279-014-0283-6

SYSTEMATIC REVIEW

The Effect of Footwear on Running Performance and Running Economy in Distance Runners

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Abstract

Background The effect of footwear on running economy has been investigated in numerous studies. However, no systematic review and meta-analysis has synthesised the available literature and the effect of footwear on running performance is not known.

Objective The aim of this systematic review and meta-analysis was to investigate the effect of footwear on running performance and running economy in distance runners, by reviewing controlled trials that compare different footwear conditions or compare footwear with barefoot.

Methods The Web of Science, Scopus, MEDLINE, CENTRAL (Cochrane Central Register of Controlled Trials), EMBASE, AMED (Allied and Complementary Medicine), CINAHL and SPORTDiscus databases were searched from inception up until April 2014. Included articles reported on controlled trials that examined the effects of footwear or footwear characteristics (including shoe mass, cushioning, motion control, longitudinal bending stiffness, midsole viscoelasticity, drop height and comfort) on running performance or running economy and were published in a peer-reviewed journal.

Results Of the 1,044 records retrieved, 19 studies were included in the systematic review and 14 studies were included in the meta-analysis. No studies were identified that reported effects on running performance. Individual studies reported significant, but trivial, beneficial effects on running economy for comfortable and stiff-soled shoes [standardised mean difference (SMD) <0.12; $P < 0.05$), a significant small beneficial effect on running economy for cushioned shoes (SMD $= 0.37$; $P < 0.05$) and a significant moderate beneficial effect on running economy for training in minimalist shoes (SMD $= 0.79$; $P < 0.05$). Meta-analysis found significant small beneficial effects on running economy for light shoes and barefoot compared with heavy shoes (SMD < 0.34; $P < 0.01$) and for minimalist shoes compared with conventional shoes (SMD $= 0.29$; $P < 0.01$). A significant positive association between shoe mass and metabolic cost of running was identified ($P < 0.01$). Footwear with a combined shoe mass less than 440 g per pair had no detrimental effect on running economy.

Conclusions Certain models of footwear and footwear characteristics can improve running economy. Future research in footwear performance should include measures of running performance.

Key Points

- Running shoes with greater shoe cushioning, greater longitudinal shoe stiffness and greater shoe comfort were associated with improved running economy.
- Running in light shoes or running barefoot reduced metabolic cost compared with running in heavy shoes but there was no difference in metabolic cost between running in light shoes and running barefoot.
- No studies have investigated the effect of footwear on running performance measured using a time-trial or time-to-exhaustion test.

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1 Introduction

Selection of appropriate footwear (or lack of footwear, i.e. barefoot) is often advocated as an essential requirement for distance running [1] and as a means for improving running performance [2]. Performance enhancement is also a primary motivating reason that runners try new footwear [3]. However, a systematic search conducted in 2007 found no studies that had investigated the effect of footwear on running performance [4] and there is a lack of consensus amongst the literature on what should be considered appropriate footwear for distance running [4–6]. Despite the lack of research investigating the effects of footwear on running performance, several studies have investigated the effect of footwear on running economy, a surrogate measure of running performance [5, 7]. Running economy is determined from the oxygen demand at a given velocity of submaximal running and is a good predictor of distance running performance [8].

Several different footwear characteristics such as shoe mass, cushioning, motion control, longitudinal bending stiffness, midsole viscoelasticity, drop height and comfort have been proposed to influence running economy and in turn influence running performance [2, 6, 9–14]. Shoe mass has been shown to be important for determining running economy, with additional shoe mass predictably increasing metabolic cost at a given workload [9]. The effect of shoe cushioning on running economy is less clear [13, 15]. Increased shoe cushioning does not always reduce metabolic cost [13] and running barefoot or in minimalist shoes with no cushioning has been shown to be more economical than some cushioned shoes [2, 6]. Indeed, running barefoot or in minimalist shoes that have a flat shoe sole with no cushioning can cause runners to make acute, short-term changes in running gait from a rearfoot strike to a forefoot strike, increase cadence and reduce vertical oscillation of the centre of mass, which can contribute to improved running economy [2, 6].

A review of the current available literature concerning the effects of footwear on distance running performance and running economy is important given the increasing amount of research being published in the area and the need for synthesis of this information to provide direction for ongoing research. There is also an increasing desire on the part of athletes to understand the effects of different footwear [3] and a systematic review could help determine the optimal footwear for distance running. As a result, the aim of this review was to investigate the effect of different types of footwear (heavy, light or minimalist) and footwear characteristics (shoe mass, cushioning, motion control, longitudinal bending stiffness, midsole viscoelasticity, drop height and comfort) on running performance and running economy in distance runners, by reviewing controlled trials that compare different footwear conditions or compare footwear with barefoot.

2 Methods

This review followed the PRISMA statement for improved reporting of systematic reviews [16].

2.1 Information Sources

A literature search was conducted on 5 April 2014. The following databases were searched: Web of Science, Scopus, MEDLINE, EMBASE, AMED (Allied and Complementary Medicine), CINAHL (Cumulative Index to Nursing and Allied Health), SPORTDiscus and CENTRAL (Cochrane Central Register of Controlled Trials). Databases were searched from inception up until April 2014. Searches were supplemented by forward citation searching and hand searching the reference lists of eligible studies.

2.2 Search Strategy

In each database the title, abstract and keyword search fields were searched using the following search strategy:

> run* AND shoe* OR footwear OR shod AND performance OR race* OR racing OR marathon* OR time OR distance OR speed OR endurance OR economy OR efficiency OR oxygen OR VO_2 NOT orthotic OR pain OR injury

Where possible, limits were placed on searches according to publication type so that only controlled trials, which provide the highest quality of scientific evidence, were included. Additionally, searches were limited to human participant and English language only publications. Eligibility criteria are shown in Table 1.

2.3 Study Selection

Eligibility and risk of bias assessment were performed independently by two reviewers (JTF and CRB) with disagreement settled by consensus. All records were examined by title and abstract in order to exclude obviously irrelevant records. Full-text articles for the remaining records were retrieved and assessed for eligibility. Data including the publication details, study design, participant characteristics, randomisation, allocation, blinding, testing procedures, description of intervention and results of any analysis of running performance or running economy outcomes were extracted from all eligible studies. If insufficient information was reported (e.g. shoe mass not

Table 1 Eligibility criteria

Criterion	Description
Type of participant	Healthy adult distance runners (aged >18 years). Eligible studies had to describe participants as runners
Type of intervention	Running shoe
Type of comparison	A comparative running shoe condition or barefoot but not running shoe plus orthotic
Type of outcome measure	
Running performance	Race time, time-trial or time-to-exhaustion test for distances $\geq$1,500 m or respective running speeds
Running economy	Measured using steady-state oxygen consumption or energy expenditure calculated using indirect calorimetry
Type of study	Controlled studies
Publication status	Peer-reviewed journal publication
Publication date	Publication date did not form part of the eligibility criteria
Language of publication	English language publication

reported) authors were contacted to seek clarification or additional information about the included studies.

2.4 Risk of Bias Assessment

This review used the Cochrane Collaboration's tool for assessing risk of bias in controlled trials [17]. Additionally, as all studies identified by the search were of crossover design, the appraisal of bias also considered the appropriateness of using a crossover design and whether appropriate statistical analysis had been performed on the paired data.

2.5 Statistical Considerations

No studies concerning the effect of footwear on distance running performance were identified. As a result, statistical analysis was confined to the effect of footwear on running economy. For each running economy study outcome, standardised mean differences (SMDs) were calculated. Mean differences were standardised using the pooled between-subject standard deviation for the two footwear conditions being compared. Effects were quantified as trivial (<0.2), small (0.2–0.6), moderate (0.61–1.2), large (1.21–2.0) and very large (>2.0) [18].

To investigate the effect of shoe mass on running economy, the SMD for all studies comparing shod (heavy, light or minimalist shoe) and barefoot conditions were plotted against the respective shoe mass, calculated as the combined mass of both shoes per pair. Studies that controlled for shoe mass in the comparison between shod and barefoot were not included because they had controlled for the shoe mass that was the focus of this analysis. The association between running economy and shoe mass was explored using bivariate correlation analysis and linear regression.

Meta-analysis was undertaken for studies that compared running economy between heavy shoes, light shoes and barefoot without controlling for shoe mass across conditions. It was not possible to control for other footwear characteristics (e.g. cushioning, motion control, longitudinal bending stiffness, etc.) when comparing between heavy and light shoes. As a result, statistical analysis considered only the average effect of a heavy or light shoe. Meta-analysis also compared running economy between minimalist and conventional running shoes in studies that controlled for difference in shoe mass and between soft and hard cushioned heavy running shoes. Statistical significance was set at $P < 0.05$.

Random-effects meta-analysis was performed in Review Manager (RevMan) software (version 5.2, Cochrane Collaboration, Oxford, UK) using the inverse-variance method. Where not reported, the standard error of mean difference and correlations between treatment outcomes were estimated from P values using the equivalent T-statistic or F-statistic. When this was not possible, standard error of mean difference was estimated according to the methods described by Elbourne et al. [19], using the lowest correlation estimate among other studies. Presence of statistical heterogeneity was determined using the I^2 and Cochran's Q statistics [20].

3 Results

After removal of duplicates, the initial search identified 634 records. An additional six records were identified through hand searching of the reference lists of articles identified in the electronic search. A summary of the search, including number of studies suitable for meta-analysis and reasons for exclusion, is shown in Fig. 1. All 19 studies included in the review were of crossover design and are summarised in Table 2 [2, 5–7, 9–15, 21–28].

3.1 Reasons for Exclusion

Five studies were excluded for not using a study sample of distance runners only [29–33], one study was excluded for

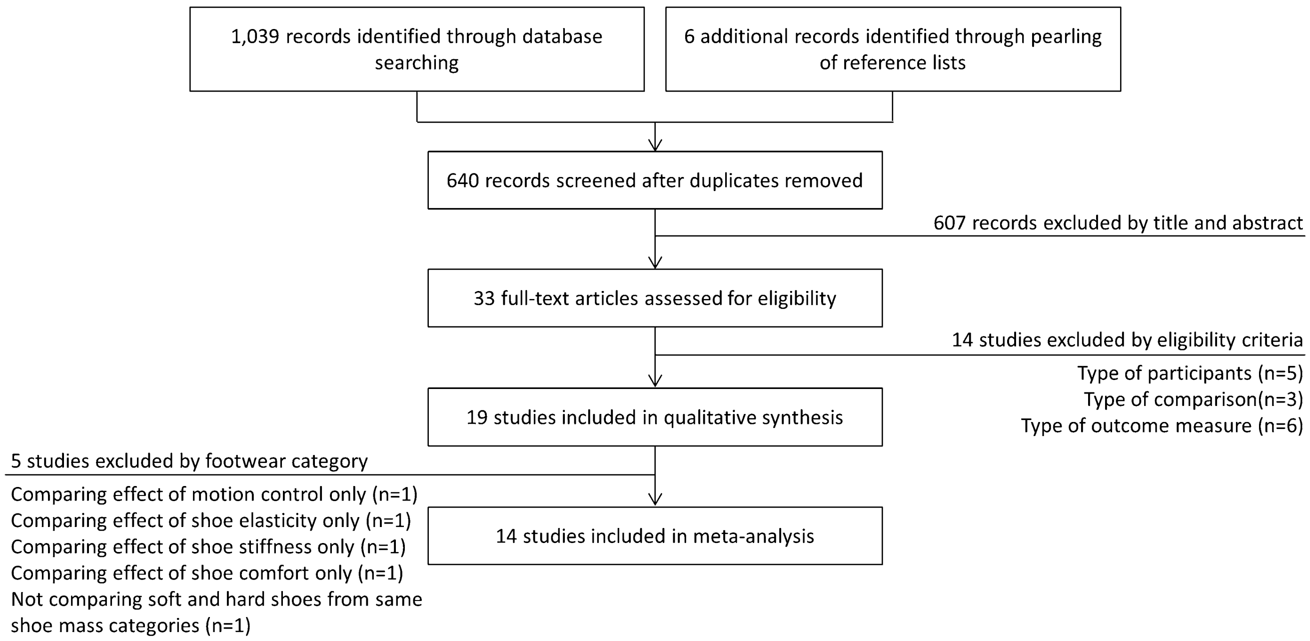

Fig. 1 Literature search flow chart. *n* number of studies

only comparing running shoe with running shoe plus orthotic [34], two studies were excluded for comparing running shoe with military boots [35] or spring boots [36], three studies were excluded for using short-distance running tests (18, 20 and 60 m) that were not considered representative of distance running performance [37–39], two studies were excluded for measuring running economy while running on an underwater treadmill [40, 41] and one study was excluded for not reporting running performance or economy data [42].

3.2 Risk of Bias

All eligible studies used a crossover design and produced paired data. Only one study [13] did not report use of appropriate pairwise analysis. Thomson et al. [13] reported use of a two-sample *t* test for analysis of data obtained from repeated measures on the same participants and was at a high risk of detection bias. No studies reported sufficient information regarding randomisation or allocation concealment. No studies provided information regarding blinding of participants, personnel or outcome assessors, and it is unclear what influence lack of blinding would have had on running performance and running economy outcomes. Four studies [9, 23, 24, 26] did not provide sufficient information regarding the number of participants assessed and analysed and were at an unclear risk of attrition bias. Two studies [11, 21] excluded participants from analysis and were at a high risk of detection bias. Nigg et al. [11] excluded one participant from analysis due to unreliable oxygen consumption measurement and Burkett et al. [21] excluded two participants from analysis without providing a reason. It is unclear what effect selective reporting may have had on the results of this review.

3.3 Participants

In all, 243 distance runners had running economy compared between differing footwear conditions. Eleven studies [6, 9–11, 13, 15, 21, 22, 25–27] included male participants only, two studies [2, 23] included female participants only, three studies [5, 7, 28] included both male and female participants, and three studies [12, 14, 24] did not report participant sex. Of the seven studies that considered barefoot running economy, three studies [22, 27, 28] included only participants who were experienced barefoot runners, one study [2] excluded participants with barefoot running experience and in three studies [7, 9, 21] participant experience with barefoot running was unclear.

3.4 Footwear

A variety of footwear conditions and footwear characteristics were compared (Table 2). Five studies [2, 9, 22, 27, 28] compared a light shoe with barefoot, five studies [2, 7, 9, 21, 27] compared a heavy shoe with barefoot, eight studies [2, 5, 6, 9, 23, 25–27] compared a heavy shoe with a light shoe, five studies [2, 5, 6, 25, 27] compared minimalist shoes with conventional shoes, four studies [13, 15, 24, 26] assessed the effect of sole cushioning, one study [14] compared a heavy cushioned shoe with a motion

Table 2 Summary of included studies

Study	Year	*n*	Washout period	Running economy		Study comparisons		SMD (A–B)
				Unit of measure	Speed	Footwear condition A	Footwear condition B	
Moore et al. [2]	2014	F: 15	10 min	mL·kg^{-1}·min^{-1}	2.78 m·s^{-1}	Barefoot	Light minimalist shoe	−0.33*[a]
						Barefoot	Heavy shoe	−0.52*[b]
						Light minimalist shoe	Heavy shoe	−0.26*[a]
Tung et al. [28]	2014	M: 10	3 min	mL·kg^{-1}·min^{-1}	3.35 m·s^{-1}	Barefoot	Lightweight shoe	−0.06
		F: 2		W·kg^{-1}				
Lussiana et al. [25]	2013	M: 14	5 min	mL·kg^{-1}·m^{-1}	2.78 m·s^{-1}	Light minimalist shoe	Heavy shoe	−0.33*
Sinclair et al. [26]	2013	M: 12	HR <110 bpm	mL·kg^{-1}·min^{-1}	4.0 m·s^{-1}	Light hard shoe[c]	Heavy soft shoe	−0.01
Franz et al. [22]	2012	M: 12	4 min	W·kg^{-1}	3.35 m·s^{-1}	Barefoot	Light shoe	0.28
						Barefoot[c]	Light shoe	0.45*
Perl et al. [5]	2012	M: 13	Same day	mL·kg^{-1}·m^{-1}	3.0 m·s^{-1}	Light minimalist shoe[c]	Heavy shoe	−0.34*
		F: 2						
Warne and Warrington [6]	2012	M: 15	24 h	mL·kg^{-1}·min^{-1}	3.06 m·s^{-1}	Light minimalist shoe	Heavy shoe	−0.12
					3.61 m·s^{-1}	Light minimalist shoe	Heavy shoe	−0.79*[d]
Hanson et al. [7]	2011	M: 5	HR <110 bpm	mL·kg^{-1}·min^{-1}	70 % v$VO_{2\max}$	Barefoot	Heavy shoe	−0.09
		F: 5				Barefoot	Heavy shoe	−0.29[e]
Luo et al. [10]	2009	M: 10	3 min	mL·kg^{-1}·min^{-1}	0.23 m·s^{-1}	Most comfortable heavy shoe[c]	Least comfortable heavy shoe[c]	−0.09*[f]
					>vaT			
Rubin et al. [14]	2009	14	2–7 days	mL·kg^{-1}·min^{-1}	65 % v$VO_{2\max}$	Heavy cushioned shoe	Heavy motion control shoe	−0.30
Squadrone and Gallozzi [27]	2009	M: 8	4 min	mL·kg^{-1}·min^{-1}	3.33 m·s^{-1}	Barefoot	Light minimalist shoe	0.35
						Barefoot	Heavy shoe	−0.3
						Light minimalist shoe	Heavy shoe	−0.65*
Divert et al. [9]	2008	M: 12	2 min	mL·kg^{-1}·min^{-1}	3.61 m·s^{-1}	Barefoot	Light shoe	0.03
						Barefoot	Heavy shoe	−0.54
						Light shoe	Heavy shoe	−0.56*
						Barefoot[c]	Light shoe	0.07
						Barefoot[c]	Heavy shoe	−0.21
Roy and Stefanyshyn [12]	2006	13	5 min	mL·kg^{-1}·min^{-1}	0.22 m·s^{-1}	Heavy stiff (38 N·mm) shoe	Heavy control (18 N·mm) shoe	−0.12*
					<vLT	Heavy stiffest (45 N·mm) shoe	Heavy control (18 N·mm) shoe	−0.03
						Heavy stiffest (45 N·mm) shoe	Heavy stiff (38 N·mm) shoe	0.09
Hardin et al. [24]	2004	12	HR <120 bpm	mL·kg^{-1}·min^{-1}	3.40 m·s^{-1}	Soft shoe[g]	Hard shoe[g]	0.12[h]
					>vaT			
Nigg et al. [11]	2003	M: 18	3 min	mL·kg^{-1}·min^{-1}	"Slightly above" vaT	Heavy viscous shoe	Heavy elastic shoe	0.0
Thomson et al. [13]	1999	M: 14	Separate days	mL·kg^{-1}·min^{-1}	3.14 m·s^{-1}	Heavy soft shoe	Heavy hard shoe	−0.04
					4.02 m·s^{-1}			
Hamill et al. [23]	1988	F: 8	Unclear	mL·kg^{-1}·min^{-1}	90 % v$VO_{2\max}$	Lightweight shoe	Heavy shoe	−0.12

Table 2 continued

Study	Year	n	Washout period	Running economy		Study comparisons		SMD (A–B)
				Unit of measure	Speed	Footwear condition A	Footwear condition B	
Frederick et al. [15]	1986	M: 10	Same day	$\text{mL}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$	$3.65–4.55\ \text{m}\cdot\text{s}^{-1}$	Soft shoe[g]	Hard shoe[g]	−0.37*
Burkett et al. [21]	1985	M: 19	5 min	$\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$	$3.35\ \text{m}\cdot\text{s}^{-1}$	Barefoot	Heavy shoe[i]	−0.18

bpm beats per minute, *F* female, *HR* heart rate, *M* male, *n* sample size, *SMD* standardised mean difference, *vaT* velocity at aerobic threshold, *vLT* velocity at lactate threshold, vVO_{2max} velocity at maximal oxygen consumption

* $P < 0.05$

[a] Adjusted for shoe mass and stride length

[b] Adjusted for shoe mass

[c] External mass added to footwear conditions to balance mass difference between conditions

[d] Comparison after 4-week familiarisation in lightweight shoe

[e] Oxygen uptake measured during overground running

[f] Calculated relative to pooled standard deviation across all studies because information not available

[g] Shoe mass not reported but the mass of the compared shoes reported to be within 0–31 g

[h] Effect size estimated based on graphical data

[i] Mass of heavy shoe estimated from the body mass-normalised shoe mass reported by authors

control shoe, one study [10] assessed the effect of shoe comfort, one study [12] assessed the effect of longitudinal bending stiffness and one study [11] assessed the effect of shoe sole viscoelasticity.

3.5 Study Outcomes

No studies provided information concerning the effect of footwear on running performance. All eligible studies provided information concerning the effect of footwear on running economy. All studies expressed oxygen uptake (VO_2) relative to body mass. Fifteen studies [2, 6, 7, 9–14, 21, 23, 24, 26–28] expressed VO_2 relative to time, three studies [5, 15, 25] expressed VO_2 relative to distance and two studies [22, 28] converted VO_2 to caloric expenditure. The unit of measure chosen to assess running economy did not appear to affect study findings (Table 2).

The washout period between assessments in different footwear conditions ranged from 2 min to 7 days (Table 2). The length of the washout period was unclear in two studies [13, 23]. All studies, except one [7], assessed running economy during submaximal running bouts on a treadmill. Hanson et al. [7] compared running economy between barefoot and heavy shoe conditions during submaximal running bouts on a treadmill and overground. The authors reported an SMD in running economy for barefoot compared with heavy shoes during overground running that was three times that reported for treadmill running (Table 2). This suggests that footwear might affect running economy differently for treadmill compared with overground running. However, the overground running results reported by Hanson et al. [7] have been challenged in the literature, with concerns about the presence of systematic error in the experimental procedures used to assess overground running economy [43, 44]. Due to the potential difference in running economy outcomes tested on treadmill and overground, only study outcomes assessed on a treadmill were included in the meta-analysis.

SMD in running economy ranged from 0 to 0.79 (Table 2). Two studies [6, 27] reported SMDs for light minimalist shoe compared with heavy shoe that were of moderate effect (0.65–0.79). Two other studies reported SMDs for light shoe [9] and barefoot [2, 9] compared with heavy shoe that were close to moderate effect (0.52–0.56). The remaining studies reported SMDs that were of trivial to small effect.

3.6 Regression Analysis

There was a strong correlation between the combined mass of a shoe pair and change in VO_2 relative to running barefoot ($R = 0.85$, $P < 0.01$) [7, 9, 21, 22, 27, 28]. The metabolic cost of running increased linearly with

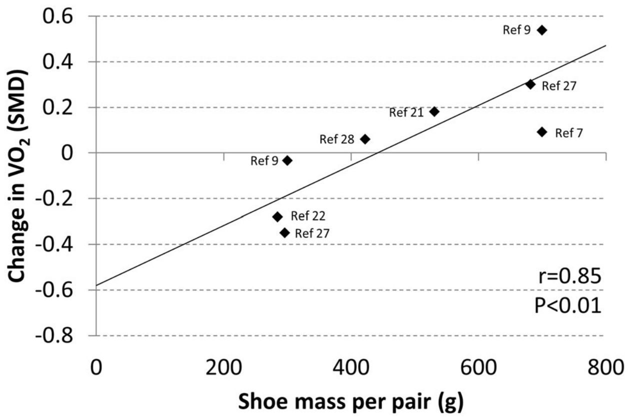

Fig. 2 Change in oxygen uptake for shod running in shoes of different mass compared with barefoot. Shoe mass values are the combined mass of a shoe pair [7, 9, 21, 22, 27, 28]. *SMD* standardised mean difference, VO_2 oxygen uptake

increasing shoe mass (Fig. 2). The linear relationship predicted that there would be no difference in VO_2 between shod and barefoot running for footwear with a combined shoe mass of 440 g per pair (Fig. 2). Extrapolation of this linear relationship to the hypothetical situation where shoe mass was zero indicated that shoe characteristics other than shoe mass had a theoretical combined small beneficial effect on running economy (SMD = 0.58; Fig. 2).

3.7 Meta-Analysis

A summary of within-study comparisons and methods used to calculate the individual study standard error of mean difference is shown in Table 3. Results of meta-analysis are shown in Fig. 3. Shoe conditions were grouped into two categories based on shoe mass:

- Light shoe (combined shoe mass per pair >0 to ≤440 g);
- Heavy shoe (combined shoe mass per pair >440 g).

The shoe mass of 440 g was selected as the demarcation between heavy and light shoes based on the results of the linear regression analysis, which predicted that footwear

Table 3 Available data and results for 18 outcomes across 14 studies included in meta-analysis

Study	Year	*n*	Information available	Footwear comparison		SMD (A–B)	SE (A–B)	Correlation used
				Condition A	Condition B			
Moore et al. [2]	2014	15	Treatment-specific summaries, *P* values (*t* test)	Minimalist	Conventional	−0.26	0.09	0.94
Tung et al. [28]	2014	12	Treatment-specific summaries, *P* values (*t* test)	Barefoot	Light	−0.06	0.09	0.97
Lussiana et al. [25]	2013	14	Treatment-specific summaries, correlation assumed	Light	Heavy	−0.33	0.19	0.77
Franz et al. [22]	2012	12	Treatment-specific summaries, *P* values (*t* test)	Barefoot	Light	0.28	0.17	0.84
Perl et al. [5]	2012	15	Individual-specific data	Minimalist	Conventional	−0.34	0.11	0.91
Warne and Warrington [6]	2012	15	Treatment-specific summaries, 95 % CI provided by authors	Light	Heavy	−0.12	0.17	0.81
Hanson et al. [7]	2011	10	Treatment-specific summaries, correlation assumed	Barefoot	Heavy	−0.09	0.21	0.77
Squadrone and Gallozzi [27]	2009	8	Treatment-specific summaries, correlation assumed	Barefoot	Heavy	−0.30	0.24	0.77
				Barefoot	Light	0.35	0.24	0.77
				Light	Heavy	−0.65	0.24	0.77
Divert et al. [9]	2008	12	Treatment-specific summaries, correlation assumed	Barefoot	Heavy	−0.54	0.21	0.77
				Barefoot	Light	0.03	0.20	0.77
				Light	Heavy	−0.56	0.21	0.77
Hardin et al. [24]	2004	12	Treatment-specific summaries, correlation assumed	Soft	Hard	0.12	0.20	0.77
Thomson et al. [13]	1999	14	Treatment-specific summaries, 95 % CI provided by authors	Soft	Hard	−0.04	0.18	0.77
Hamill et al. [23]	1988	8	Treatment-specific summaries, correlation assumed	Light	Heavy	−0.12	0.24	0.77
Frederick et al. [15]	1986	10	Individual-specific data	Soft	Hard	−0.37	0.09	0.96
Burkett et al. [21]	1985	19	Treatment-specific summaries, F-statistic (repeated measures ANOVA)	Barefoot	Heavy	−0.18	0.11	0.90

ANOVA analysis of variance, *CI* confidence interval, *n* sample size, *SE* standard error of mean difference, *SMD* standardised mean difference

Study	Year	n	SMD	SE	Weight (%)	SMD (95% CI)
Light shoe vs heavy shoe						
Lussiana et al. [25]	2013	14	-0.33	0.19	23.6	-0.33 (-0.69, 0.04)
Warne et al. [6]	2012	15	-0.12	0.17	26.0	-0.12 (-0.46, 0.22)
Squadrone et al. [27]	2009	8	-0.65	0.24	15.7	-0.65 (-1.12, -0.18)
Divert et al. [9]	2008	12	-0.56	0.21	19.2	-0.56 (-0.97, -0.14)
Hamill et al. [23]	1988	8	-0.12	0.24	15.5	-0.12 (-0.60, 0.35)
Total (95% CI)					100	-0.34 (-0.54, -0.13)
Heterogeneity: Chi^2 = 5.07, df = 4 (P = 0.28); I^2 = 21%						
Test for overall effect: Z = 3.25 (P<0.01)						
Barefoot vs heavy shoe						
Hanson et al. [7]	2011	10	-0.09	0.21	14.4	-0.09 (-0.51, 0.33)
Squadrone et al. [27]	2009	8	-0.30	0.24	11.5	-0.30 (-0.77, 0.17)
Divert et al. [9]	2008	12	-0.54	0.21	15.7	-0.54 (-0.94, -0.14)
Burkett et al. [21]	1985	19	-0.18	0.11	58.4	-0.18 (-0.38, 0.03)
Total (95% CI)					100	-0.24 (-0.39, -0.08)
Heterogeneity: Chi^2 = 3.01, df = 3 (P = 0.39); I^2 = 0%						
Test for overall effect: Z = 2.89 (P<0.01)						
Barefoot vs light shoe						
Tung et al. [28]	2014	12	-0.06	0.09	43.1	-0.06 (-0.23, 0.11)
Franz et al. [22]	2012	12	0.28	0.17	23.6	0.28 (-0.04, 0.61)
Squadrone et al. [27]	2009	8	0.35	0.24	14.2	0.35 (-0.12, 0.82)
Divert et al. [9]	2008	12	0.03	0.20	19.1	0.03 (-0.35, 0.42)
Total (95% CI)					100	0.10 (-0.10, 0.30)
Heterogeneity: Chi^2 = 5.00, df = 3 (P = 0.17); I^2 = 40%						
Test for overall effect: Z = 0.96 (P=0.34)						
Soft shoe vs hard shoe						
Hardin et al. [24]	2004	12	0.12	0.20	28.2	0.12 (-0.27, 0.50)
Thomson et al. [13]	1999	14	-0.04	0.18	29.9	-0.04 (-0.40, 0.32)
Frederick et al. [15]	1986	10	-0.37	0.09	41.9	-0.37 (-0.55, -0.18)
Total (95% CI)					100	-0.13 (-0.45, 0.18)
Heterogeneity: Chi^2 = 6.37, df = 2 (P = 0.04); I^2 = 69%						
Test for overall effect: Z = 0.83 (P=0.40)						
Minimalist vs minus conventional shoe						
Moore et al. [2]	2014	15	-0.26	0.09	59.5	-0.26 (-0.44, -0.09)
Perl et al. [5]	2012	15	-0.34	0.11	40.5	-0.34 (-0.55, -0.13)
Total (95% CI)					100	-0.29 (-0.43, -0.16)
Heterogeneity: Chi^2 = 0.27, df = 1 (P = 0.60); I^2 = 0%						
Test for overall effect: Z = 4.29 (P<0.01)						

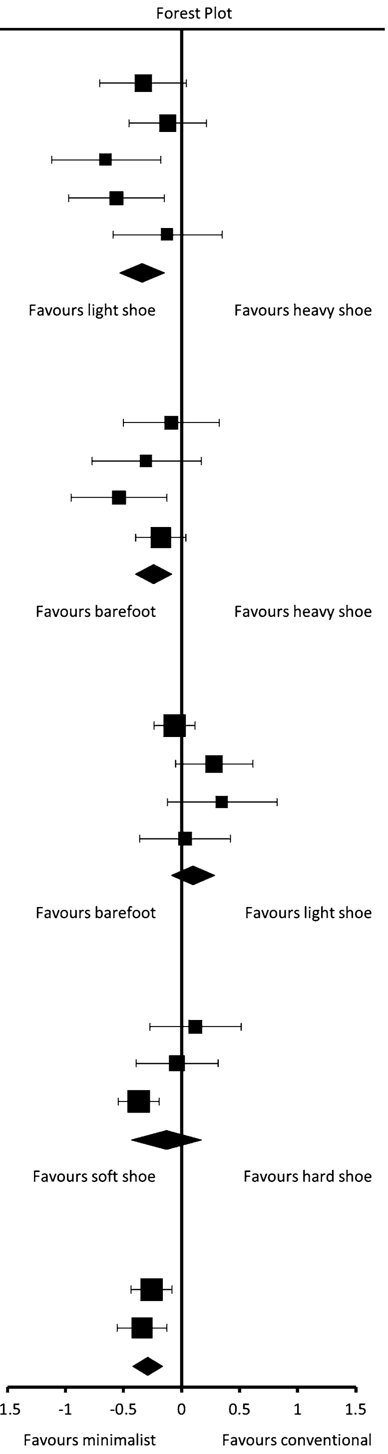

Fig. 3 Results of meta-analysis. *CI* confidence interval, *n* number of participants, *SE* standard error, *SMD* standardised mean difference

with a combined shoe mass greater than 440 g per pair would increase the metabolic cost of running (Fig. 2).

Light shoes (>0 to ≤440 g per pair) and barefoot significantly reduced the metabolic cost of running compared with heavy shoes (>440 g per pair) ($P < 0.01$), but there was no significant difference between light shoes (>0 to ≤440 g per pair) and barefoot ($P = 0.34$). When shoe mass was controlled for, minimalist shoes were significantly more economical for running than conventional running shoes ($P < 0.01$). There was no significant difference between running economy in soft shoes and running economy in hard shoes of the same shoe mass ($P = 0.40$). However, this result was significantly affected by statistical heterogeneity ($P = 0.04$, $I^2 = 69$ %).

4 Discussion

The effect of footwear on running performance is an area of increasing interest, with almost half of the 19 studies identified by the search published in the last 3 years (Table 2). However, despite the increased interest, no studies identified by the search determined the effect of footwear on time or distance measures of running performance. Instead, all studies identified used running economy measured at submaximal running speeds as a measure of running performance. This choice has logical validity given that running performance is dependent to some extent on running economy [8] and running economy is likely to be affected by footwear. Indeed, several authors have previously observed a strong association between running economy and running performance [45, 46]. However, a strong association between running economy and running performance has not always been found [47, 48] and time or distance measures should be considered the reference standard for assessment of running performance.

All studies included in this review used crossover designs and only one study [6] included a longer-term follow-up of 4 weeks. To the authors' knowledge, there have been no studies investigating what the appropriate washout period for footwear intervention studies is and it is unclear whether the washout periods of several minutes to several days used by studies included in this review were appropriate (Table 2). Additionally, all but one study [6] focused on only the acute, short-term effects of footwear on running economy. Focusing on acute effects ignores potential long-term effects on running economy that may be associated with running in certain footwear over time. This possibility has not been thoroughly tested, but it would seem reasonable to expect that, over time, learning and training effects would occur in response to running in footwear. Indeed, a study measuring running economy in a novel shoe condition with and without a 4-week familiarisation found significant differences between the effect of the novel footwear when tested with and without the familiarisation [6]. Knowledge of these possible learning and training effects would be valuable information for runners who spend extensive time running in different footwear.

A variety of different footwear characteristics were investigated across the studies included in this review (Table 2). The effect of motion control characteristics [14], midsole longitudinal bending stiffness [12], heel viscoelasticity [11] and shoe comfort [10] was trivial to small (SMD = 0.0–0.30) and each was only investigated by an individual study so could not be pooled for meta-analysis. Despite the small effects observed for these characteristics, improvements in running economy were significant for shoes with stiff midsole components (38–45 N·mm) [12] and comfortable shoes [10]. These significant effects were of a magnitude that was classified as trivial (SMD = 0.08–0.12) [10, 12]. However, even these small effects on running economy may be important for high-performance athletes for whom relatively small improvements in performance can have large effects on the outcome of major competitive events [49].

The largest individual study effect sizes were reported by studies investigating the effect of light shoes, minimalist shoes or barefoot on running economy [2, 6, 9, 27]. This suggests that shoe mass is a critical consideration for designing and selecting shoes for use in distance running competition. The importance of shoe mass in determining running economy is intuitive. If one were to consider the simple inertial differences between a heavy and light shoe that must be accelerated with and against gravity with each step taken, it is logical that the reduced muscular effort will lead to improved running economy. Indeed, a positive association between shoe mass and the oxygen cost of running has been previously reported [22] and our linear regression model found a similar positive association (Fig. 2). However, interestingly, our model suggested that the detrimental effect on running economy for shoe mass compared with barefoot was only evident for shoes weighing greater than 440 g per pair and shoes weighing less than this would have a beneficial effect on running economy.

When using 440 g as the demarcation between light and heavy shoes, meta-analysis found light shoes and barefoot to be significantly more economical than heavy shoes (SMD = 0.24–0.34), but found no difference between light shoes and barefoot. The reason that the mass of a light shoe (<440 g per pair) does not have detrimental effects on running economy relative to barefoot, and may even improve running economy, remains untested. It would seem likely that, for footwear weighing less than 440 g per pair, any disadvantage due to having to repeatedly accelerate and decelerate the shoe against gravity might be balanced by the beneficial effects on running economy derived from the shoe cushioning [15], stiffness [12] and comfort [10]. Indeed, our linear regression model predicted that if shoe mass could be zero, then the combined effect of other shoe characteristics would have close to a moderate beneficial effect on running economy (Fig. 2).

Although still considered a light shoe, minimalist shoes differ from conventional running shoes in regards to drop height, sole thickness and toe box structure. Two studies [2, 5] compared the effect of these differences on running economy by controlling for the effect of shoe mass. Meta-analysis of these two studies found a significant small improvement (SMD = 0.29) in running economy for minimalist shoes compared with conventional running shoes (Fig. 3). It has been suggested that the flat, thin-soled minimalist shoes cause runners to increase cadence and adopt a forefoot strike, which in turn improves running economy [6]. However, both studies included in the meta-analysis of minimalist shoes found significant improvements in running economy for minimalist shoes compared with conventional running shoes even when controlling for changes in foot strike and cadence [2, 5]. As a result, there must be further reason for the observed difference in running economy. Perl et al. [5] suggested that flat, thin-soled shoes increase the storage and release of elastic energy in the Achilles tendon and longitudinal arch of the foot. However, to date, this hypothesis has not been thoroughly tested. Nonetheless, when controlling for shoe mass, running in minimalist shoes has a beneficial effect on running economy.

When shoe mass and running gait were not controlled for between minimalist shoes and conventional running shoes, the beneficial effect of minimalist shoes on running economy increased (SMD = 0.12–0.79) [6, 25, 27] (Table 2). This larger beneficial effect could be partly explained by the reduction in shoe mass associated with minimalist shoes compared with conventional shoes but could also be due to changes in foot strike and cadence that have previously been associated with running in a minimalist shoe [6, 27, 50]. It is thought that the heightened somatosensory feedback associated with running in minimalist shoes, which lack cushioning, prompts runners to increase cadence and land with a more anterior foot strike [2]. Indeed, Squadrone and Gallozzi [27] and Warne and Warrington [6] observed SMD improvements in running economy of 0.65 and 0.79 for the minimalist shoe when runners also adopted a forefoot strike [6, 27] and increased cadence [6]. The participants were either experienced barefoot runners [27] or were given 4 weeks to familiarise themselves with the minimalist shoes [6]. Given the size of these effects, future research should further explore the long-term effects of running in minimalist shoes on running economy and biomechanics.

Although running in minimalist shoes may be associated with large improvements in running economy [6, 27], running in these shoes may have negative effects on injury risk [51] and this effect on injury should not be ignored. Running in minimalist shoes is associated with increased peak tibial acceleration [26], which is known to be significantly greater in runners who have sustained a recent tibial stress fracture than in healthy controls [52]. Additionally, changing from a rearfoot strike to a forefoot strike is associated with increased ankle joint contact forces and increased plantar flexor muscle forces [53]. These unaccustomed high forces could increase the risk of injury until the associated muscular and articular tissue has had time to adapt [53]. The long-term safety of minimalist shoes should be investigated before they are advocated as a means for runners to improve running economy.

Meta-analysis was also possible for studies that compared running economy between soft- and hard-soled shoes (Table 3) [13, 15, 24]. Meta-analysis found no significant difference in running economy between soft- and hard-soled shoes of similar mass (Fig. 3). However, this result was significantly affected by statistical heterogeneity and should be interpreted with caution (Fig. 3). It is likely that the heterogeneity in results was due to differences in the extent of cushioning provided by each of the shoe conditions considered across the different studies. Tung et al. [28] showed that while 10 mm of surface cushioning significantly improved barefoot running economy on a treadmill, 20 mm of surface cushioning had no significant effect. The authors hypothesised that there may be an optimum amount of surface cushioning for each individual, which minimises the metabolic cost of running [28]. Future research should investigate this hypothesis to determine if it is possible to predict the amount of shoe cushioning needed to optimise running economy based on the characteristics of a runner (e.g. body size, body composition, etc.).

In addition to the aforementioned limitations associated with use of short washout periods between testing in different shoe conditions and lack of long-term follow-up, two additional limitations should be considered when interpreting the findings of this review. Firstly, all study findings were based on running economy measurements at submaximal running speeds and assume that the response to footwear will be the same at the faster speeds that may be used in competition. Secondly, all results were based on running economy assessed on a treadmill and different levels of treadmill cushioning between laboratories may have influenced the findings [28]. Additionally, the single study [7] that compared overground running with treadmill running found significant differences in economy which favoured overground running. Although the accuracy of this finding has been debated in the literature [43, 44], overground running has the greatest external validity for investigating the effect of footwear on running performance and future research should further explore the validity and reliability of overground running economy assessment.

5 Conclusion

This review found trivial and small effects on running economy, such that greater longitudinal shoe stiffness, greater shoe cushioning and greater shoe comfort were associated with improved running economy. Light shoes and barefoot also had a small effect on running economy when compared with heavy shoes. Shoe mass was positively associated with metabolic cost of running. However, for footwear with a combined shoe mass of less than 440 g per pair, there was no detrimental effect on running economy. When controlling for differences in shoe mass, foot strike and cadence, minimalist shoes had a small beneficial effect on running economy compared with conventional running shoes. This beneficial effect appeared to increase further in response to gait adaptations resulting from training in minimalist shoes. However, further research is required to confirm this finding and any long-term beneficial effects on running economy associated with running in these shoes must be considered against the potential to affect injury risk. Future research in footwear performance should include time or distance measures of running performance and include a long-term follow-up.

Acknowledgments No sources of funding were used to assist in the preparation of this review. Dr. Dominic Thewlis has been a recipient of funding from ASICS Oceania (ASICS Oceania Pty Ltd, Eastern Creek, NSW, Australia) to undertake separate research. All other authors declare no potential conflicts of interest and have no financial relationships with any organisations that might have an interest in the submitted work.

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