Do biomechanical foot-based interventions reduce patellofemoral joint loads in adults with and without patellofemoral pain or osteoarthritis? A systematic review and meta-analysis

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► Additional supplemental material is published online only. To view, please visit the journal online (http://dx.doi.org/10.1136/bjsports-2022-106542).

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Accepted 28 February 2023
Published Online First 10 March 2023

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To cite: Kayll SA, Hinman RS, Bryant AL, *et al. Br J Sports Med* 2023;**57**:872–881.

ABSTRACT

Objective To evaluate the effects of biomechanical foot-based interventions (eg, footwear, insoles, taping and bracing on the foot) on patellofemoral loads during walking, running or walking and running combined in adults with and without patellofemoral pain or osteoarthritis.

Design Systematic review with meta-analysis.

Data sources MEDLINE, CINAHL, SPORTdiscus, Embase and CENTRAL.

Eligibility criteria for selecting studies English-language studies that assessed effects of biomechanical foot-based interventions on peak patellofemoral joint loads, quantified by patellofemoral joint pressure, reaction force or knee flexion moment during gait, in people with or without patellofemoral pain or osteoarthritis.

Results We identified 22 footwear and 11 insole studies (participant n=578). Pooled analyses indicated low-certainty evidence that minimalist footwear leads to a small reduction in peak patellofemoral joint loads compared with conventional footwear during running only (standardised mean difference (SMD) (95% CI) = –0.40 (–0.68 to –0.11)). Low-certainty evidence indicated that medial support insoles do not alter patellofemoral joint loads during walking (SMD (95% CI) = –0.08 (–0.42 to 0.27)) or running (SMD (95% CI) = 0.11 (–0.17 to 0.39)). Very low-certainty evidence indicated rocker-soled shoes have no effect on patellofemoral joint loads during walking and running combined (SMD (95% CI) = 0.37) (–0.06 to 0.79)).

Conclusion Minimalist footwear may reduce peak patellofemoral joint loads slightly compared with conventional footwear during running only. Medial support insoles may not alter patellofemoral joint loads during walking or running and the evidence is very uncertain about the effect of rocker-soled shoes during walking and running combined. Clinicians aiming to reduce patellofemoral joint loads during running in people with patellofemoral pain or osteoarthritis may consider minimalist footwear.

WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Patellofemoral pain and patellofemoral osteoarthritis are conditions characterised by retro/peripatellar pain during activities that load the patellofemoral joint, such as running.
⇒ Clinicians commonly use biomechanical foot-based interventions (footwear, insoles, taping or bracing placed on the foot) to treat these conditions due to their potential to reduce patellofemoral joint load.

WHAT THIS STUDY ADDS

⇒ Minimalist footwear may reduce patellofemoral joint loads slightly compared with conventional footwear in people with and without patellofemoral pain during running only.
⇒ Medial support insoles may not alter patellofemoral joint loads during walking or running in people with patellofemoral pain or osteoarthritis and the evidence is very uncertain about the effect of rocker-soled shoes during walking and running combined.

HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY

⇒ Clinicians managing people with patellofemoral pain or osteoarthritis may consider minimalist footwear instead of medial support insoles to reduce patellofemoral joint loads during running.
⇒ Future research is needed to determine whether minimalist footwear can also reduce patellofemoral pain or osteoarthritis symptoms.
⇒ Minimalist footwear may be recommended for the management of patellofemoral pain or osteoarthritis with more research into these populations.

INTRODUCTION

Patellofemoral pain is a highly prevalent condition affecting young people through to older adults, including both active and sedentary populations.[1] Clinical guidelines recommend exercise, and education on load, self-management strategies and the nature of patellofemoral pain, as the cornerstones of patellofemoral pain treatment.[2–4] However, 57% of people still report symptoms 5–8 years following diagnosis,[5] showing that current treatment is suboptimal for this non-self-limiting condition. The persistent nature of patellofemoral pain symptoms, the poor long-term prognosis and limited evidence on effective treatment options, means patients may also be at an increased risk of developing patellofemoral osteoarthritis compared with the general population, although this is yet to be confirmed by prospective studies.[6 7]

Patellofemoral pain is defined as pain at or around the patella during activities that load the patellofemoral joint, such as running, squatting or descending stairs.[3 8] It is postulated that treatment strategies that reduce patellofemoral joint load may be efficacious for patellofemoral pain. Biomechanical foot-based interventions, such as footwear, insoles and foot/ankle taping or bracing, have been proposed as low-burden treatment approaches that may reduce patellofemoral joint loads and, therefore, improve symptoms. For example, minimalist footwear (ie, lightweight shoes with thin flexible soles that do not possess any motion control properties)[9] can reduce knee flexion and quadriceps muscle force, thereby reducing patellofemoral joint load.[10] Likewise, insoles with medial support, taping and bracing can reduce foot pronation,[11 12] a motion theoretically linked to an increase in patellofemoral joint load via tibial and femoral internal rotation.[13] As such, these interventions are commonly used in the clinical setting[14] and insoles are recommended as best practice in international guidelines for managing patellofemoral pain.[3 4]

Despite the biomechanical rationale and widespread use of these interventions, no study has systematically reviewed research investigating the effects of biomechanical foot-based interventions on patellofemoral joint loads. Although one recent systematic review included some studies that evaluated foot-based interventions,[15] its focus was on comparing patellofemoral joint reaction force across everyday activities, and it did not conduct a subgroup analysis of intervention effects. Thus, the specific effect(s) of biomechanical foot-based interventions on patellofemoral joint loads remains unclear.

Patellofemoral joint loads may be quantified using direct (reaction force and pressure)[16] or surrogate (external flexion or internal extension moment)[17] measures. Although three-dimensional models are considered more accurate,[18] the majority of researchers have estimated patellofemoral joint reaction force using sagittal plane two-dimensional (2D) models that combine the knee flexion angle and moment with mathematical representations of the extensor mechanism.[15 16] To calculate pressure, the reaction force is divided by the contact area obtained from previous studies.[16] Where there are high amounts of pressure during gait, the knee moment will also be high.[19 20] To fully understand the effects of interventions designed to reduce patellofemoral loads, it is thus important to consider research that has investigated each of these direct and surrogate estimates of patellofemoral joint loads.

Aim

This systematic review and meta-analysis aimed to evaluate the effect(s) of biomechanical foot-based interventions (eg, footwear, insoles, taping and bracing placed on the foot) on patellofemoral loads (as quantified by pressure, reaction force and external knee flexion moment) during walking, running or walking and running combined in adults with and without patellofemoral pain or osteoarthritis.

METHODS

This study was guided by the Methodological Expectations of Cochrane Intervention Reviews standards,[21] Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 checklist[22] (online supplemental file 2) and the implementing PRISMA in Exercise, Rehabilitation, Sport medicine and SporTs science (PERSiST) guidance.[23] The systematic review protocol was prospectively registered with the International Prospective Register of Systematic Reviews (PROSPERO) on 4 April 2022 (CRD42022315207) and has been published.[24] Deviations from the protocol are described in online supplemental file 1. We did not involve patients or the public in our research.

Inclusion and exclusion criteria

Study selection criteria were established a priori using the Population, Intervention, Comparison, Outcome framework.[25] Original published studies in the English-language were considered for inclusion. Study designs may have included but were not limited to: randomised cross-over, randomised controlled, cross-sectional and parallel group designs. We followed the recommendation of Adams *et al*[26] and excluded grey literature as the academic field is relatively mature. Editorials, comments, letters, abstracts, review articles, theses and dissertations were excluded. Studies that met the following criteria were included: (1) human participants who were either apparently healthy (ie, free from pathology that may affect gait) or diagnosed with patellofemoral pain or osteoarthritis, (2) used a biomechanical foot-based intervention (footwear, insertable shoe worn orthotic or insert (herein called insole) ankle brace or foot/ankle taping) with the stated objective of reducing patellofemoral joint loads, (3) had a control group which received either no intervention (excluding barefoot) or another eligible biomechanical foot-based intervention and (4) assessed peak patellofemoral loads during regular walking or running using data obtained from motion analysis. Patellofemoral joint loads had to be quantified by (1) peak patellofemoral joint pressure (patellofemoral joint reaction force divided by a unit of contact area), (2) peak patellofemoral joint reaction force (resultant compressive force from the pull of the quadriceps and patella tendon) or (3) peak external knee flexion moment (combination of the ground reaction force and the perpendicular distance of this force from the joint centre or the equivalent peak internal knee extension moment) during stance in the relevant unit of measurement. Full inclusion and exclusion criteria are outlined in our published protocol.[24]

Literature search strategy

With assistance from an academic librarian, one reviewer (SAK) conducted the search that combined relevant terms for population, intervention and outcome. These relevant terms were based on other similar reviews.[15 27] We searched the following databases from inception to 4 October 2022: Medline, the Cumulative Index to Nursing and Allied Health Literature, The Cochrane Central Register of Controlled Trials, SPORTdiscus and Embase and screened the reference lists of included studies and relevant systematic reviews.[15 16] The complete search strategy for all databases is presented in online supplemental file 1.

Study selection

First, two reviewers (SAK and PLR) independently assessed the titles and abstracts of all identified studies and studies within relevant systematic reviews to determine potential eligibility. Second, both reviewers retrieved the potentially eligible full-text articles and independently assessed against the a priori inclusion and exclusion criteria. Studies deemed eligible by both reviewers at this stage were included in the review. Any disagreements at either step were resolved through consensus with a third reviewer (KLP).

Data extraction

One reviewer (SAK) independently extracted data from included studies into a prepiloted data extraction form. A second reviewer (PLR) independently audited all extracted data for accuracy. Any disagreement was resolved through consultation between the two reviewers. If the two reviewers could not agree, a third reviewer (KLP) was involved until consensus was reached. We attempted to contact the study authors via email to request data that were either missing or published in graphical form. A reminder email was sent after 2 weeks if there was no response. Where the authors could not be contacted or declined to provide data, we used Web Plot Digitizer software (Ankit Rohatgi, California, USA; available at https://automeris.io/WebPlotDigitizer) to extract eligible data from graphical form.[28] Studies that could not be extracted using Web Plot Digitizer software were excluded. Information relating to the studies where authors were contacted for data can be found in online supplemental file 1. The following was extracted from eligible studies:

- Study characteristics: Sample size, inclusion/exclusion criteria and year of publication.
- Participant characteristics: Age, sex, population and whether they were apparently healthy or diagnosed with patellofemoral pain or osteoarthritis. Where applicable, we extracted the severity of patellofemoral joint pain or osteoarthritis according to the relevant measure used.
- Intervention and comparator characteristics: Where applicable, we extracted the brand, type, weight, heel-to-toe drop, angulation and heel height of the footwear and insoles used in the intervention and comparator conditions. If insufficient information was provided in the manuscript, we sourced it from either a similar publication by the same author or the manufacturer online. We listed N/A in our characteristics table (online supplemental file 1) if no information was available from these sources. In addition, we extracted the speed and the surface (eg, treadmill or runway) used for gait analysis.
- Patellofemoral joint load outcomes: All available data on the patellofemoral joint loads from each study's intervention and comparator arm were extracted, including the point estimate and the corresponding measure of variability (SD, p value or 95% CI). We established a priori decision rules in case a study reported multiple eligible outcome measures. Specifically, we used the following hierarchy to extract data, prioritising direct over indirect estimates of patellofemoral joint loads: (1) patellofemoral joint pressure, (2) patellofemoral joint reaction force and (3) external knee flexion/internal knee extension moment. All outcomes were the peak during stance.

Risk of bias assessment

Two reviewers (SAK and PLR) independently assessed the risk of bias for each study outcome using the Revised Cochrane Risk of Bias 2 tool for randomised cross-over trials.[29] We considered six domains: (1) bias arising from the randomisation process, (1S) bias arising from period and carryover effects, (2) bias due to deviations from intended interventions, (3) bias due to missing outcome data, (4) bias in measurement of the outcome and (5) bias in selection of the reported result. The two reviewers independently rated each domain as either low risk, some concerns or high risk of bias. In the case of disagreement, a third author (KLP) appraised the study independently, and the research team convened until consensus was reached. One study was not a cross-over trial,[30] thus, we omitted domain 1S.

Data synthesis and analysis

We pooled data across studies that were sufficiently similar by intervention (1) minimalist footwear, (2) medial support insoles or (3) rocker-soled footwear; comparator (1) conventional footwear, (2) no insole or (3) non-rocker footwear and task (1) walking, (2) running or (3) walking and running combined. The designation of the intervention and comparator shoes were based on the author's rationale of which footwear or insole type was more likely to reduce patellofemoral joint loads (ie, the one considered to be load-reducing intervention) or the characteristics (eg, weight, heel height, heel-to-toe drop) presented in online supplemental tables 1 and 2. Where a study investigated multiple variations of a given intervention and/or control, we used the intervention variant postulated to have the maximal load reducing effect on patellofemoral joint load and conversely, the control condition postulated to have the least load reducing effect. For example, where a study investigated different types of 'minimalist' footwear, we analysed data for the footwear with the least weight, heel height and/or heel-to-toe drop as the intervention condition. For insole interventions, we analysed data relating to the insole with the greatest degree of wedging or arch support as the intervention, given these are postulated to reduce patellofemoral joint loads.[10,12]

Standardised mean differences (SMDs) were calculated using Review Manager statistical software (RevMan V.5, Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014) with 95% CIs to allow for pooling and comparison of outcomes in individual studies. Where studies reported 95% CIs only, we calculated the SD according to Cochrane guidelines.[21] SMDs were interpreted as: minimal <0.2, small 0.2–0.49, medium 0.50–0.79 and large >0.8. Interpretation of effect estimates and Grading of Recommendations Assessment, Development and Evaluation (GRADE) findings followed published recommendations.[31] The SMDs were calculated so that a negative value represented a reduction in patellofemoral joint loads in the intervention footwear or insole relative to the comparator. Where there were three or more studies that were sufficiently similar, random effects meta-analysis with the inverse variance method was performed using Review Manager.[32] The random effects model was used as heterogeneity was expected in the intervention, comparator and population. Patellofemoral joint loads for individual studies and pooled estimates were summarised in forest plots for the following comparisons (due to available studies): minimalist footwear versus conventional footwear during running, and walking and running combined, rocker-soled footwear versus conventional footwear during walking and running combined and medial support insoles versus no insole during walking, running, and walking and running combined. Results for outcomes in studies ineligible for pooling are presented in tables 1 and 2 and as a narrative synthesis. Heterogeneity was assessed by visually inspecting forest plots and examining the χ^2 test for heterogeneity. I^2 values of 30%, 50% and 75% were considered moderate, substantial and considerable heterogeneity, respectively.[21,33] Assessment of publication bias was not possible as there were less than 10 studies in each pool.[21] We subgrouped each pooled analysis by population (eg, healthy, patellofemoral pain and patellofemoral osteoarthritis).

Quality of the body of evidence

We used the GRADE framework[31,34] to assess the body of evidence for each pooled analysis. Two reviewers (SAK and PLR) used GRADEpro software (McMaster University, 2015,

Table 1 Footwear study outcome data

Measure of peak patellofemoral loads	Unit	Study	Task measured	Intervention mean (SD)	Comparator mean (SD)	SMD (95% CI)
Results of studies that evaluated minimalist versus conventional footwear				**Minimalist**	**Conventional**	
Patellofemoral joint pressure	MPa	Bonacci 2018[36]	Running at self-selected speed on treadmill	10.39 (1.93)	12.27 (2.92)	−0.74 (−1.48, 0.00)
		Sinclair 2014[38]	Running over 22 m runway at 4.0 m/s±5%	9.65 (3.77)	10.28 (3.33)	−0.17 (−0.91, 0.57)
		Sinclair 2016A[39]	Running at 4.0 m/s±5%	11.59 (2.63)	13.34 (2.43)	−0.68 (−1.32, 0.04)
		Yang 2019[41]	Running over 20 m runway at 3.33 m/s±5%	12.08 (3.27)	13.48 (2.64)	−0.46 (−1.18, 0.27)
External flexion moment	Nm/kg	Esculier 2022[55]	Self-selected running on treadmill mean speed 2.3 m/s	0.91 (0.42)	0.99 (0.52)	−0.17 (−0.79, 0.46)
		Hannigan 2021[37]	Walking at self-selected speed±5% between trials	0.78 (0.36)	0.77 (0.33)	0.03 (−0.66, 0.72)
	Nm/kg	Sinclair 2016B[40]	Running at 4.0 m/s±5%	2.75 (0.90)	2.91 (0.78)	−0.18 (−0.90, 0.53)
Internal extension moment	Nm/kg	Ogaya 2022[56]	Walking on treadmill at 1.0 m/s	7.50 (3.80)	7.73 (3.79)	−0.06 (−0.66, 0.55)
Results of studies that evaluated rocker versus non-rocker footwear				**Rocker**	**Non–rocker**	
External flexion moment	Nm/kg	Buchecker 2012[43]	Walking at self-selected speed±0.2 km/hour	1.51 (0.32)	1.50 (0.30)	0.03 (−0.85, 0.91)
Internal extension moment	Nm/kg	Farzadi 2018[44]	Walking at self-selected speed, speed N/A	0.58 (0.43)	0.49 (0.40)	0.21 (−0.44, 0.87)
		Sobhani 2017[45]	Running at self-selected speed±5%	2.86 (0.20)	2.70 (0.20)	0.78 (0.06, 1.50)
Results of footwear studies ineligible to pool				**Boot**	**Trainer**	
Patellofemoral joint pressure	MPa	Sinclair 2015A[48]	Running over 22 m walkway at 4.0 m/s±5%	10.38 (1.34)	11.53 (0.93)	−0.96 (−1.82, 0.11)
Internal extension moment	Nm/%BM	Shamsoddini 2022[57]	Running at 3.3 m/s±5%	2.58 (0.28)	2.68 (0.33)	−0.32 (−1.00, 0.36)
				Low heel–to–toe drop	**High heel–to–toe drop**	
Patellofemoral joint pressure	MPa	Zhang 2022[46]	Running over 20 m runway at 4.0 m/s±5%	15.97 (5.30)	18.41 (4.21)	−0.50 (−1.16, 0.17)
External flexion moment	Nm/kg	Besson 2019[47]	Running on 15 m runway at 2.54–2.55 m/s	2.21 (0.54)	2.34 (0.47)	−0.25 (−0.97, 0.47)
				Trainer	**Men's dress**	
Internal extension moment	Nmm/kg	Lee 2011[49]	Running over runway at 4.0 m/s±0.02	2368 (563)	2413 (544)	−0.08 (−0.95, 0.80)
				Anti–pronation	**Neutral**	
Internal extension moment	Nm/kg	Jafarnezhadgero 2019[51]	Running on treadmill at 3.30 m/s in intervention and 3.29 m/s in control	1.32 (0.51)	1.62 (0.55)	−0.56 (−1.11, 0.00)
				Nike Vaporfly	**Adidas marathon**	
Internal extension moment	Nm	Hoogkamer 2019[52]	Running at on treadmill at 4.44 m/s	175.5 (25.5)	176.0 (26.4)	−0.02 (−0.89, 0.86)
				Oblique heel	**Short parallel heel**	
Internal extension moment	Nm/BW/H/LL	Liu 2020[53]	Running over 13 m runway at 3.0 m/s±0.1	0.213 (0.003)	0.212 (0.004)	0.28 (−0.35, 0.90)
				Energy boost	**Conventional**	
Patellofemoral joint pressure	MPa	Sinclair 2016C[54]	Running over 22 m walkway at 4.0 m/s	9.02 (1.71)	10.05 (1.87)	−0.55 (−1.45, 0.35)
				Minimalist	**Range of running shoes**	
Internal extension moment	Nm/kg/m	Bonacci 2013[50]	Running over 110 m runway at 4.48 m/s±1.6	1.92 (0.2)	1.91 (0.2)	0.05 (−0.54, 0.64)
				No midsole	**High midsole**	
External flexion moment	Nm/BW	Chambon 2014[42]	Running at 3.33 m/s±5%	2.78 (0.46)	2.76 (0.46)	0.04 (−0.67, 0.76)

SMD of <0.2, 0.2–0.49, 0.50–0.80 and >8.0 represents a minimal, small, medium and large effect, respectively; Intervention corresponds to the bold footwear in online supplemental table 1; Comparator corresponds to footwear in italics in online supplemental table 1.
%BM, percentage of body mass; BW, body weight; H, height; N/A, not available; SMD, standardised mean difference.

Table 2 Insole study outcome data

Measure of peak patellofemoral loads	Unit	Study	Task measured	Intervention mean (SD)	Comparator mean (SD)	SMD (95% CI)
Results of studies that evaluated medial support insoles versus no insole				Medial support insole	No insole	
Patellofemoral joint pressure	MPa	Almonroeder 2015[58]	Running at 4.0 m/s±5% on 15 m runway	11.00 (2.64)	10.40 (2.44)	0.23 (−0.42, 0.89)
		Sinclair 2018A[61]	Running at 4.0 m/s±5%	9.33 (2.71)	8.81 (2.68)	0.19 (−0.62, 0.99)
	KPa/BW	Sinclair 2018B[30]	Running at 4.0 m/s±5%	6.39 (1.51)	6.82 (1.66)	−0.26 (−1.10, 0.58)
		Sinclair 2018C[30]	Running at 4.0 m/s±5%	6.28 (2.59)	7.66 (2.64)	−0.49 (−1.64, 0.67)
	KPa/kg	Sinclair 2019A[62]	Running at 4.0 m/s±5%	70.56 (22.11)	68.92 (19.93)	0.08 (−0.62, 0.77)
		Sinclair 2019B[62]	Running at 4.0 m/s±5%	100.28 (24.13)	96.57 (17.88)	0.22 (-0.40, 0.84)
Patellofemoral joint reaction force	N(BW)	Peng 2020[66]	Walking at self-selected pace, speed N/A	1.179 (0.63)	1.324 (0.69)	−0.21 (−0.93, 0.50)
External knee flexion moment	Nm/kg	Burston 2018[59]	Walking at self-selected speed	0.86 (0.25)	0.89 (0.23)	−0.12 (−0.84, 0.59)
		Burston 2018 PFP[59]	Walking at self-selected speed	0.87 (0.25)	0.87 (0.28)	0.00 (−0.72, 0.72)
		Tan 2020[63]	Walking at self-selected speed on 12 m walkway	0.58 (0.23)	0.58 (0.25)	0.00 (−0.62, 0.62)
Internal knee extension moment	Nm	Maclean 2006[60]	Running at 3.6 m/s±5%	128.64 (27.14)	121.61 (22.11)	0.28 (−0.44, 1.00)
Results of studies ineligible to pool				11 mm heel lift	No heel lift	
Patellofemoral joint pressure	MPa	Mestelle 2017[67]	Running at 3.46 m/s±2.5%	11.56 (2.01)	12.04 (1.92)	−0.24 (−0.93, 0.46)
				Prefabricated insole	No insole	
Patellofemoral joint pressure	MPa	Sinclair 2015[64]	Running at 4.0 m/s	10.80 (3.04)	12.21 (2.81)	−0.47 (−1.20, 0.26)
				Semi-custom insole	No insole	
Patellofemoral joint pressure	MPa	Sinclair 2016D[65]	Running at 4.0 m/s±5% on 22 m walkway	9.30 (2.56)	8.18 (2.43)	0.43 (−0.38, 1.24)

SMD of <0.2, 0.2–0.49, 0.50–0.80 and >8.0 represents a minimal, small, medium and large effect, respectively; Intervention corresponds to the bold orthotic in online supplemental table 2.
BW, body weight; N/A, not available; SMD, standardised mean difference.

developed by Evidence Prime, available from gradepro.org) to assess the body of evidence for each outcome independently. Evidence was considered high certainty but was downgraded if there was a concern with the risk of bias, indirectness, inconsistency or imprecision. Any disagreement was resolved through consultation between the two reviewers. If there was disagreement between the two reviewers, a third (KLP) was engaged until consensus was reached.

Equity, diversity and inclusion statement

Our research and author team consisted of two women and four men with a range of experience, including two PhD students. We captured studies from a range of geographical regions, including North America, Asia, The Middle East and Europe. The studies included men and women with a mean age range from 23 to 59 years. Due to a lack of information, we are unaware if the studies included participants from marginalised groups. When considering the generalisability of our results and limitations, we acknowledge that our results do not explore the effects of sex or include the elderly or children. Finally, we limited our search to studies in English due to a lack of translation resources.

RESULTS

Study selection characteristics

The PRISMA flow chart for study selection is outlined in figure 1.[22 35] We identified 11 953 records through database searches and 9 through other sources, with 7377 remaining after removing duplicates. Thirty-three studies were included in the final review. Of these, 22[36–57] (n=371 participants) investigated the effect of footwear and 11[30 58–67] (n=207 participants) the effect of shoe insoles on patellofemoral joint loads. We did not identify any studies that investigated effects of taping or bracing. The populations in the included studies were apparently healthy (30 studies,[37–62 64–67] n=496 participants) and people diagnosed with patellofemoral pain (3 studies,[30 36 59] n=61 participants) or osteoarthritis (1 study,[63] n=21 participants). Measurement outcomes included peak external flexion/internal extension knee moment (18 studies,[37 40 42–45 47 49–53 55–57 59 60 63] peak patellofemoral joint pressure (14 studies[30 36 38 39 41 46 48 54 58 61 62 64 65 67] and peak patellofemoral joint reaction force (1 study.[66] Study outcomes are outlined in table 1 (footwear interventions) and table 2 (insole interventions). The participants' mean age, mass and height ranged from 23–59 years, 55–91 kg and 159–179 cm, respectively. Median sample size was 15 (range=10–36). Detailed study characteristics, studies that met the inclusion criteria but were excluded, and forest plots for subgroup analyses by population and studies ineligible to pool, are presented in online supplemental file 1.

Risk of bias

We rated 31 outcomes as 'some concerns'[30 36–42 45–55 57–59 61–67] and 4[43 44 56 60] as 'high risk' of bias (figure 2). The risk of bias was largely consistent between the studies and was mostly due to a lack of randomisation, a lack of information regarding the randomisation process (when randomisation was used), and/

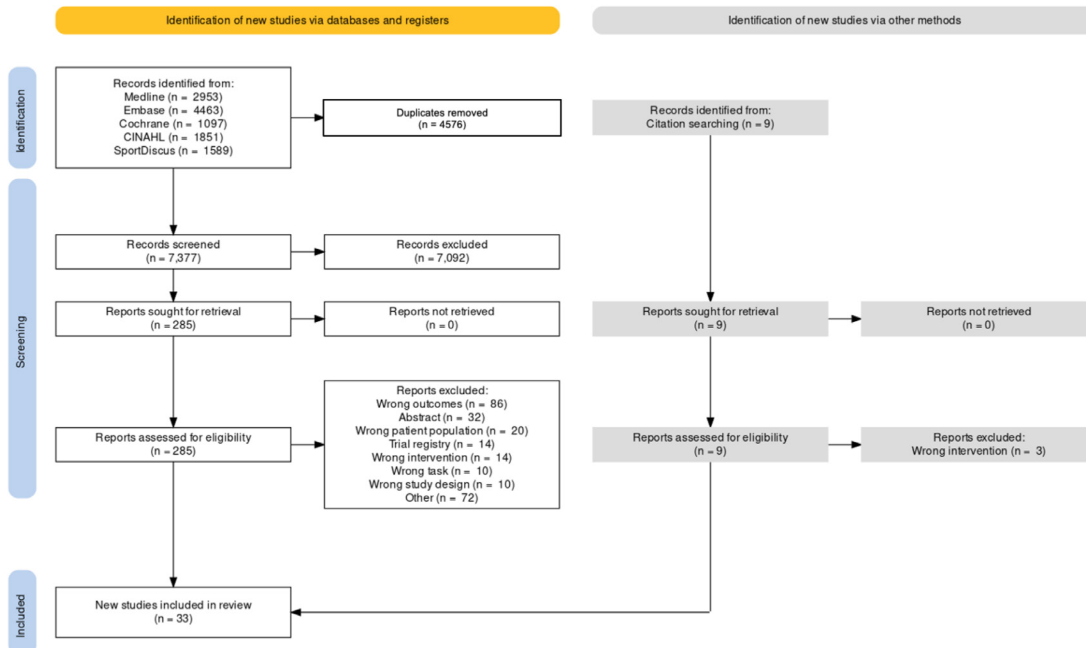

Figure 1 PRISMA flow chart. PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

or did not report sufficient rest time for carryover effects to disappear.

Data synthesis

Results from pooled analyses and certainty of the evidence are summarised in table 3.

Minimalist footwear

Eight studies[36–41 55 56] (n=136 participants) compared minimalist footwear with conventional footwear (figure 3A). Pooled analysis indicated that there is low certainty evidence with low heterogeneity (I^2=0%) to suggest that minimalist footwear leads to a small reduction (SMD (95% CI) = −0.29 (−0.53 to –0.05), p=0.02) in peak patellofemoral joint loads during walking and running combined when compared with conventional footwear. This equated to a 7.4% difference on average. After subgrouping by population, the effect estimate in those with patellofemoral pain increased (SMD (95% CI) = −0.74 (−1.48 to 0.00)), although this was based on runners in one study.[36] In contrast, in the apparently healthy subgroup,[37–41 55 56] the pooled effect estimate was no longer significant (SMD (95% CI) = −0.24 (−0.49 to 0.01)). After subgrouping by task, the pooled effect estimate for studies that used a running task increased (SMD (95% CI) = −0.40 (−0.68 to –0.11)) (figure 3B),[36 38–41 55] equating to a 9.5% difference on average. In contrast, the effect estimate for the studies that used a walking task were not significant.[37 56]

Rocker-soled footwear

Three studies[43–45] (n=44 participants) compared rocker-soled footwear with non-rocker footwear in healthy people only (figure 3B). There is very low certainty evidence to suggest rocker-soled shoes do not alter peak patellofemoral joint loads during walking and running combined (SMD (95% CI) = 0.37) (−0.06 to 0.79), p=0.09) with low heterogeneity (I^2=2%). After subgrouping by task, the effect estimates in two studies[43 44] for walking were non-significant. In contrast, the effect estimate during running showed patellofemoral joint loads were increased in rocker-soled footwear (SMD (95% CI) = 0.78 (0.06 to 1.50)), although this was based on one study.[45]

Medial support insoles

Eight (8) studies (n=163 participants)[30 58–63 66] investigated medial support insoles compared with no insoles (figure 3D). There is low certainty evidence to suggest that medial support insoles do not alter peak patellofemoral joint loads during walking and running combined (SMD (95% CI) = 0.03 (−0.18 to 0.25), p=0.75) with low heterogeneity (I^2=0%). After subgrouping by population and task, there was little

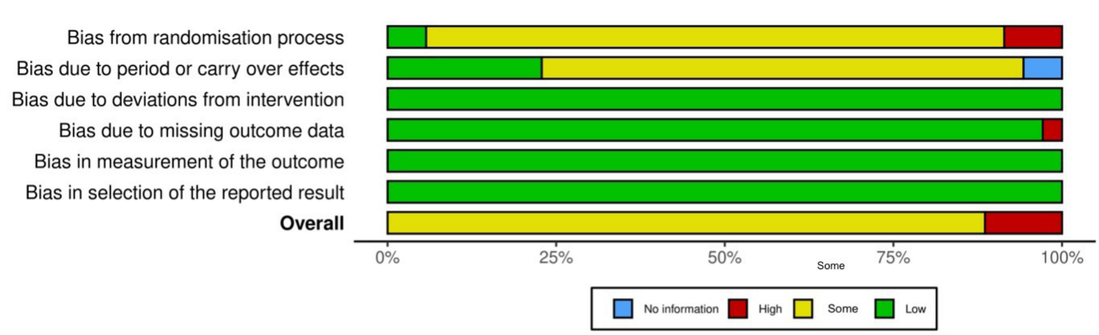

Figure 2 Risk of bias in included studies summary; each domain rated as high, some concerns or low risk of bias or no information.

Table 3 Summary of findings

Outcomes Task	SMD (95% CI)	№ of participants (studies)	Certainty of the evidence (GRADE)	Comments
Minimalist vs conventional footwear ***Walking and running***	**SMD 0.29 lower** **(0.53 lower to 0.05 lower)**	136 (8)	⊕⊕◯◯ Low	Downgraded because of indirectness (walking and running tasks, varied footwear and patellofemoral pain and healthy populations) and risk of bias within studies
Minimalist vs conventional footwear ***Running***	**SMD 0.40 lower** **(0.68 lower to 0.11 lower)**	99 (6)	⊕⊕◯◯ Low	Downgraded because of indirectness, (varied footwear and patellofemoral pain and healthy populations) and risk of bias within studies
Minimalist vs conventional footwear *Walking*	N/A	37 (2)	N/A	Two studies available, GRADE not performed
Rocker vs non-rocker footwear *Walking and running*	SMD 0.37 higher (0.06 lower to 0.79 higher)	44 (3)	⊕◯◯◯ Very low	Downgraded because of indirectness (walking and running tasks, variations in footwear) imprecision (wide CI) and risk of bias within studies
Rocker vs non-rocker footwear *Running*	N/A	16 (1)	N/A	One study available, GRADE not performed
Rocker vs non-rocker footwear *Walking*	N/A	28 (2)	N/A	Two studies available, GRADE not performed
Medial support insole vs no insole *Walking and running*	SMD 0.04 higher (0.17 lower to 0.24 higher)	163 (8)	⊕⊕◯◯ Low	Downgraded because of indirectness (walking and running tasks, varied footwear and patellofemoral pain/osteoarthritis and healthy populations) and risk of bias within studies
Medial support insole vs no insole *Running*	SMD 0.11 higher (0.17 lower to 0.39 higher)	98 (6)	⊕⊕◯◯ Low	Downgraded because of indirectness (varied footwear and patellofemoral pain/osteoarthritis and healthy populations) and risk of bias within studies
Medial support insole vs no insole *Walking*	SMD 0.08 lower (0.42 lower to 0.27 higher)	163 (3)	⊕⊕◯◯ Low	Downgraded because of indirectness (varied footwear and patellofemoral pain/osteoarthritis and healthy populations) and risk of bias within studies

Bold: significant SMD; **N/A**: Too few studies available for meta-analysis, SMD (95% CI) and GRADE not available.
GRADE Working Group grades of evidence:
High certainty: we are very confident that the true effect lies close to that of the estimate of the effect.
Moderate certainty: we are moderately confident in the effect estimate: the true effect is likely to be close to the estimate of the effect, but there is a possibility that it is substantially different.
Low certainty: our confidence in the effect estimate is limited: the true effect may be substantially different from the estimate of the effect.
Very low certainty: we have very little confidence in the effect estimate: the true effect is likely to be substantially different from the estimate of effect.
SMD of <0.2, 0.2–0.49, 0.50–0.80 and >8.0 represents a minimal, small, medium and large effect, respectively.
GRADE, Grading of Recommendations Assessment, Development and Evaluation; NA, not available; SMD, standardised mean difference.

change in the effect estimates for the healthy[58–62 66] (SMD (95% CI) = 0.10 (−0.16 to 0.36)), patellofemoral pain[30 59] (SMD (95% CI) = −0.18 (−0.67 to 0.31)), patellofemoral osteoarthritis[63] (SMD (95% CI) = 0.00 (−0.62 to 0.62)) (online supplemental file 1) cohorts, or for studies that used a walking[59 63 66] (SMD (95% CI) = −0.08 (−0.42 to 0.27)) (figure 3E) or running[30 58 60–62] (SMD (95% CI) = 0.11 (−0.17 to 0.39)) (figure 3F) task.

Studies ineligible for pooling

Of the 14 studies that were ineligible to pool, 7 footwear[42 47 49 50 52 53 57] and 2 insole[64 65] studies found no difference in peak patellofemoral joint loads. In contrast, Sinclair *et al*[48] showed a running trainer reduced peak patellofemoral joint pressure compared with a military boot; Sinclair[54] showed an energy boost shoe reduced peak patellofemoral joint pressure compared with conventional footwear; Jafarnezhadgero *et al*[51] demonstrated that anti-pronation footwear reduced peak internal knee extension moment compared with a neutral shoe; Zhang *et al*[46] observed that footwear with a 0 mm heel-to-toe drop reduced peak patellofemoral joint pressure compared with footwear with a 15 mm heel-to-toe drop; and Mestelle *et al*[67] showed an 11 mm heel lift reduced peak patellofemoral joint pressure compared with no heel lift.

DISCUSSION

Summary of findings

Our systematic review aimed to evaluate the effects of biomechanical foot-based interventions on patellofemoral joint loads in apparently healthy people and those diagnosed with patellofemoral pain or osteoarthritis. We identified 33 footwear and insoles studies and no studies investigating the effects of foot taping or bracing on patellofemoral joint loads. Pooled analyses indicated minimalist footwear may reduce peak patellofemoral joint loads slightly compared with conventional footwear during walking and running combined. However, after subgrouping, these differences were only evident during running. Medial support insoles may not alter patellofemoral joint loads during walking or running. Finally, the evidence is very uncertain about the effect of rocker-soled shoes during walking and running combined.

Minimalist footwear reduces patellofemoral joint loads

We found that minimalist footwear reduced peak patellofemoral joint loads by 7.4% on average compared with conventional footwear during walking and running combined. These findings are similar to a previous systematic review and meta-analysis that found high-heeled footwear increase the knee flexion angle and moment during walking.[10] The novel findings from our study show that even conventional footwear with a moderate heel and/

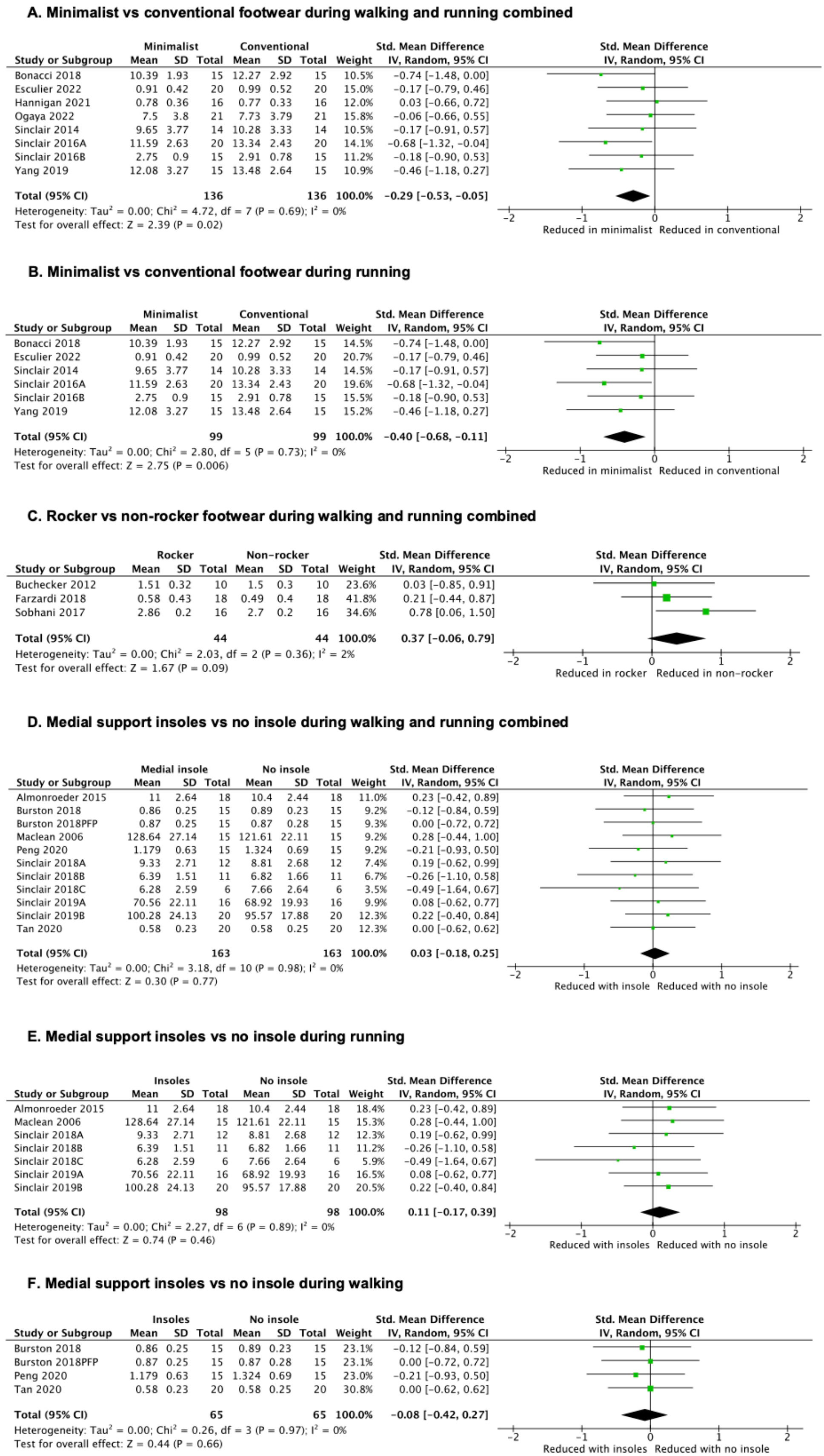

Figure 3 Forest plots (standardised mean differences and 95% CIs) for eligible meta-analyses. Forest plots for individual studies can be found in online supplemental file 1; PFP: patellofemoral pain.

or increased amounts of cushioning will increase patellofemoral joint loads when compared with minimalist footwear.

We attribute the reduction in patellofemoral joint loads observed with minimalist footwear to two primary mechanisms. First, minimalist footwear reduces step length (increasing cadence). A reduction in step length brings the stance limb closer to the centre of mass, reducing knee flexion and quadriceps demand.[38] Studies consistently show a shorter step length in minimalist footwear[39 50 68]; and an increased cadence reduces patellofemoral joint load.[36 69] The second factor is the combination of reduced stack height,[39] weight,[70] and heel-to-toe drop[46] and increased flexibility[70] in minimalist footwear. These characteristics lower the knee flexion angle, moment and quadriceps muscle force, resulting in a reduced patellofemoral reaction force.[71]

Interestingly, Mestelle *et al*[67] found a reduction in peak patellofemoral pressure when running in footwear with an 11 mm heel lift. The authors concluded this was due to an anterior shift in the centre of pressure during the heel lift condition, which can reduce patellofemoral joint load.[72–74] The same study showed no difference in step length, cadence and knee flexion between the heel lift and control conditions, possibly contributing to the contradictory finding.

After subgrouping by task (walking or running) or population (healthy, patellofemoral pain or patellofemoral osteoarthritis), differences in patellofemoral joint load between minimalist and conventional footwear were only evident during running (9.5% difference on average) or in participants with patellofemoral pain (although, only one study on runners was available). This suggests that minimalist shoes may only be effective during activities that provoke higher joint loads, such as running, or only in people with patellofemoral pain. Patellofemoral pain is particularly prevalent among runners,[1] likely because patellofemoral joint loads are high over numerous loading cycles. As such, the differences in patellofemoral loads will become greater when considering cumulative load. For example, runners will experience 18.28*BW (1462 kg for an 80 kg person) less joint force in minimalist footwear (despite an increase in cadence and the number of loading cycles) compared with conventional footwear over 1 km (based on a calculation of total force impulse (BW × stance time) × number of steps per kilometre).[39] Therefore, clinicians may consider recommending minimalist footwear to reduce patellofemoral joint loads in runners or people with patellofemoral pain.

Medial support insoles and rocker-soled footwear have no effect on patellofemoral joint loads

The results from our pooled analysis indicated that medial support insoles and rocker-soled footwear do not alter patellofemoral joint loads when compared with no insole and non-rocker footwear during walking, running, and walking and running combined. In contrast, two previous studies showed medial support insoles are effective for the treatment of patellofemoral pain. One was a cohort study[75] that gave insoles to people with patellofemoral pain over a 12-week period. The other was a randomised controlled trial that compared medial support insoles to 'wait and see'.[76] However, when comparing flat sham insoles to medial support insoles for the treatment of patellofemoral pain and osteoarthritis, studies have found no difference in pain between groups in the immediate,[77] medium (12 weeks),[78] and long-term (1 year).[78] Additionally, medial support insoles are of no additional benefit to a physiotherapy programme over the short, medium and long term,[78] although the same study did find medial support insoles were effective compared with sham insoles at 6 weeks.[78] Our finding of no load reduction with medial support insoles in combination with the above studies indicates that the pain reducing effects of insoles may largely be contextual, rather than biomechanical (medial support reducing pronation, femoral motion and patellofemoral joint pressure). Contextual effects contribute to a significant proportion of treatment effects in clinical practice. For example, researchers have found that contextual effects, such as a credible placebo/sham and a positive therapeutic relationship, are responsible for around 61% of the overall effect of interventions used to treat knee osteoarthritis.[79]

Clinical implications

We found that minimalist footwear reduces patellofemoral joint load during running. However, it is uncertain whether these biomechanical effects translate to symptomatic benefits. For instance, a recent systematic review found that patellofemoral joint reaction force did not differ between adults with and without patellofemoral pain during everyday activities, including running,[15] suggesting that increased patellofemoral joint loads are not a consistent feature of patellofemoral pain. Furthermore, the relationship between patellofemoral joint load and pain is uncertain. In fact, there is evidence that pain may be more closely related to factors other than load, such as kinesophobia.[80 81] Thus, even though minimalist footwear reduces patellofemoral joint loads, further research is needed to determine whether clinicians should advise patients to use minimalist footwear to manage patellofemoral pain.

Limitations

There were some limitations of our review processes. We did not search grey literature as the academic field is relatively mature,[26] and we also limited our search to English language studies, risking publication and language biases. Our subgroup analyses did not investigate the effects of sex on patellofemoral joint loads and we limited the number of subgroup analyses to minimise the risk of false-positives.[21] Finally, only one author conducted data extraction, which was audited for accuracy by a second author. Having two authors conduct an independent data extraction may have increased the accuracy. We mitigated this risk by having a third author resolve any discrepancies.

There are a number of limitations regarding the evidence included in our review. Most studies in this review estimate patellofemoral joint force using a 2D model of the knee in the sagittal plane and calculate patellofemoral joint pressure by dividing the force by a contact area from previous studies.[16] These methods will neglect any changes in patellofemoral joint contact area arising from a biomechanical foot-based intervention. Studies use these methods as in vivo measurements of joint force and pressure are invasive and impractical. The quality of the included studies is another limitation of the evidence. No studies were rated as low risk of bias—all were either rated as high (n=4) or some concerns (n=31) of bias. Additionally, each intervention in our pooled analyses had inherent differences that may have increased the variability of our findings. As a result, we had low certainty in the effect estimate for the minimalist footwear and medial support insole analyses. As the rocker-soled footwear result had very-low certainty, the true effect estimate may be different with more high-quality studies. Due to the paucity of research into biomechanical foot-based interventions in people with patellofemoral pain and osteoarthritis, we pooled these populations with healthy people in our analyses. We investigated this effect on our results by conducting subgroup analyses separately on apparently healthy and patellofemoral pain populations (online supplemental file 1). However, many of these analyses are based on only one or two studies, and we cannot make firm conclusions. Given the lack of research, future high-quality studies should investigate the effects of biomechanical foot-based interventions on patellofemoral joint loads in people with patellofemoral pain and/or osteoarthritis rather than apparently healthy populations. Finally, the populations in the included studies did not include the elderly or children and did not provide information regarding the representation of marginalised groups. As such, our findings may not be generalisable to these populations.

CONCLUSION

Minimalist footwear may reduce peak patellofemoral joint loads slightly compared with conventional footwear during running only. Medial support insoles may not alter patellofemoral joint loads during walking or running and the evidence is very uncertain about the effect of rocker-soled shoes during walking and running combined. Clinicians aiming to reduce patellofemoral joint loads during running may consider minimalist footwear.

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Acknowledgements We thank Nathan Parry (The University of Melbourne) for helping to adapt the searches to each database.

Contributors SAK, KLP, RSH, KLB and ALB devised the study. SAK wrote the first draft of the manuscript and all authors provided critical feedback. SAK ran the searches. SAK, PLR and KLP conducted the study screening, data extraction, risk of bias assessment and grading of evidence. SAK conducted the data analysis and synthesis. All authors have read and confirmed that they meet ICMJE criteria for authorship. All authors read and approved the final manuscript. KLP is the guarantor of the manuscript.

Funding RSH is supported by a National Health & Medical Research Council Fellowship (#1154217). KLB is supported by an NHMRC Investigator Fellowship (#1174431). KLP is supported by a National Health and Medical Research Council Emerging Leadership Investigator Grant (#1174229).

Competing interests None declared.

Patient consent for publication Not applicable.

Provenance and peer review Not commissioned; externally peer reviewed.

Data availability statement All data relevant to the study are included in the article or uploaded as online supplemental information.

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